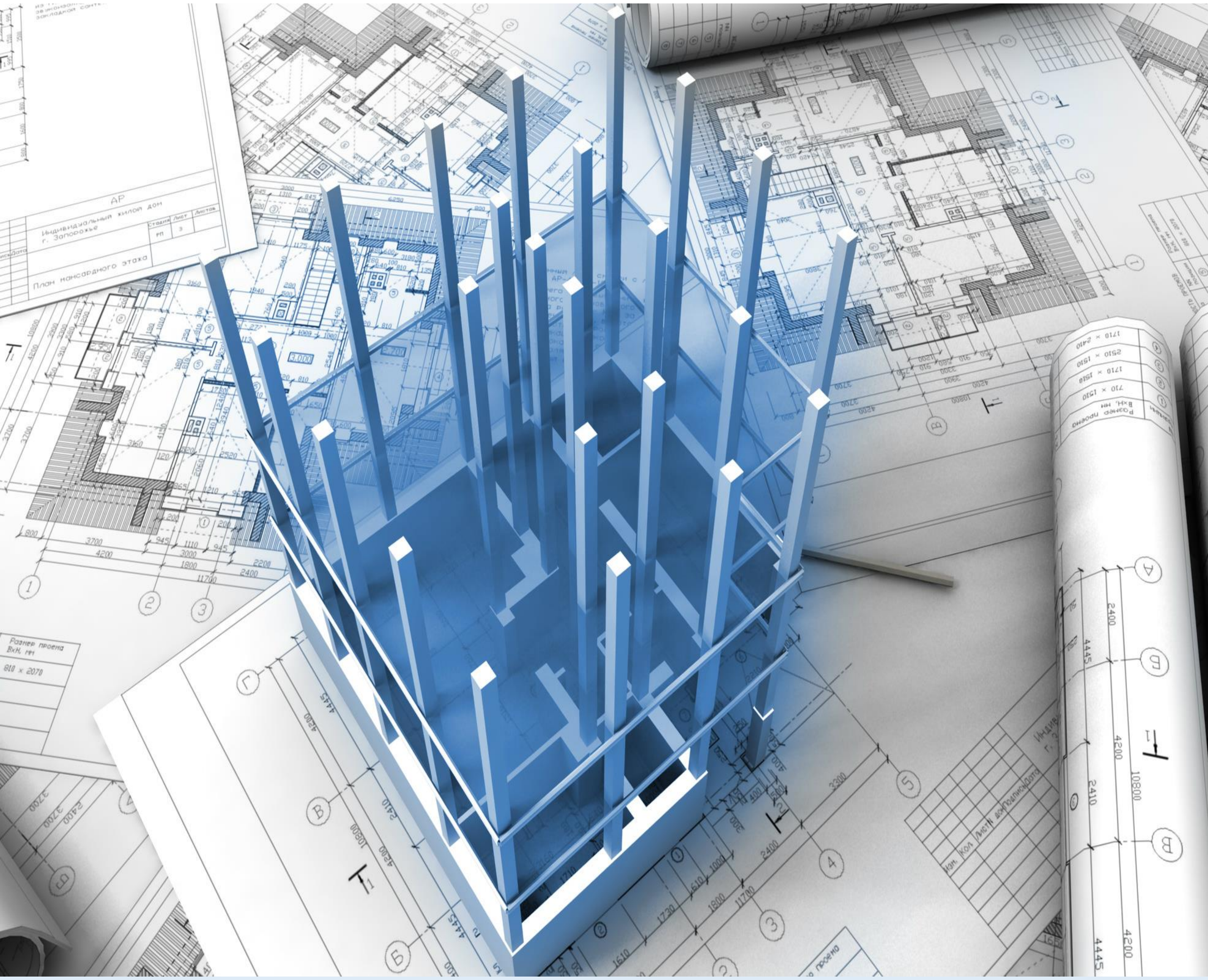

Towards 5D BIM: A Process Map for Effective Design and Cost Estimation Integration

Yara Kharoubi

August 2019

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Towards 5D BIM: A Process Map for Effective Design and Cost Estimation Integration

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Done in collaboration with Royal HaskoningDHV

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Preface

Before you lies the thesis report titled "Towards 5D BIM: A Process Map for Effective Design and Cost Estimation Integration". This graduation thesis fulfils part of the requirements of the MSc degree in Construction Management and Engineering at Delft University of Technology. The thesis report provides information on the topic of Building Information Modeling (BIM). The focus of the research is on designing and testing a process that integrates design and cost estimation while considering BIM concepts.

The research is conducted under the supervision of Prof. Dr. Hans Bakker, Dr. Ir. Louis Lousberg, and Dr. Jan Anne Annema from TU Delft. In collaboration with Royal HaskoningDHV and under the supervision of Drs. Ir. Jasper Hoeve, the research is completed during the period January 2019 – August 2019. The eight months research period demanded hard work but provided an irreplaceable learning experience. I enriched my experience by being in direct contact with practitioners and by joining a team working on a project in the Netherlands. I also gained knowledge related to the researched topics on design, cost estimation, and BIM application. I achieved the latter with the support of the committee that guided me throughout the research process and provided me with constructive critics to reach satisfactory results. For this purpose, I would like to thank the committee members for their effort.

I would like to thank the chair of the committee Hans Bakker for critically monitoring the research and steering it towards a preferable direction. I would like to express my gratitude to the supervisors Louis Lousberg and Jan Anne Annema for their time to discuss the different parts of the research and their effort to follow-up the research steps. Lastly, special thanks to Jasper Hoeve for his continuous involvement with motivating discussions on the various concepts of the research. Furthermore, Jasper facilitated the process of finding interviewees, investigating potential projects for the pilot case, and contacting the necessary actors during the implementation of the designed process.

Besides the committee members, I highly appreciate RHDHV family for their collaboration. They eased the research process and provided a friendly and inspiring environment. I would like to thank practitioners from different departments at RHDHV, especially the interviewees and members of the project I was involved in. They shared their ideas, experience, and knowledge. In addition, the project members were responsive to have discussions and perform certain tasks. I would like to thank the BIM experts who were interviewed for the validation of the designed process. They took the time to understand and reflect on the design approach and process map.

Finally, I would like to thank my family and friends for being part of the process. They motivated me to proceed when I encountered hard periods. Special thanks to Housam who supported me throughout this period. With the energy I gained from these caring people, I was able to accomplish a thesis that meets my desires. Adding value was my main concern and I believe I was able to achieve it.

Yara Kharoubi

Delft, August 2019

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Executive Summary

The construction industry faces problems in interoperability. Information is not easily interpreted nor accessed by participants. The insufficient level of interoperability occurs due to fragmentation between disciplines in the construction industry. To enhance interoperability, Building Information Modeling (BIM) formed a collaborative model that connects team members. However, the different disciplines continue to share information that cannot be directly used by others. This situation is present between designers and cost engineers. Despite working in a 5D BIM model that considers cost information, fragmentation between these disciplines persisted. Costs do not guide the design and they are computed after the model matures. Furthermore, the detachment of design and cost estimation processes led to the segregation of information in BIM. The model includes extensive information from the design team but does not always cover the relevant details for cost estimation. The information is added in different structures that result in the lack of uniformity and disruption of the connection between 3D objects and 5D cost information. Addressing the problem of fragmentation between processes, the research aims at investigating the main question: **How can design and cost estimation be effectively integrated using 5D BIM?**

In order to answer the latter, the research follows various steps. Desk research is performed to understand design-cost estimation interaction and BIM/5D BIM application in literature. Similarly, these topics are studied in practice in a single case study RHDHV. The collected information results in a conclusion on the fragmentation situation in practice with a closer look to this problem. Furthermore, a comparison of processes (design, cost estimation, and BIM/5D BIM) between literature and practice is provided. From the comparison, issues hindering design-cost estimation integration and 5D BIM application are pinpointed. These issues guide the design of the "Integrated Design – Cost Estimation 5D BIM Process". In addition, a specific 5D BIM method is selected and incorporated in the process. Then, the process is implemented in an embedded case study. The implementation is monitored to assess the effectiveness of the design-cost integration via 5D BIM that the process aims for. Finally, the designed process is validated based on interviews with BIM experts.

Following these steps, the case study research of RHDHV revealed that design and cost estimation are not always fragmented nor are they sufficiently integrated. Fragmentation is noted in terms of designing-estimating-redesigning. The case of integration considers the early involvement of the cost engineer and his consultations upon request throughout the process. However, this is limited to big projects due to budget and time availability. In the case of 5D BIM, the application is still developing as trials are performed. In general, the identified issues are: **[1]** unsteady involvement of the cost engineer in the design, **[2]** limited influence of the cost engineer on the design, **[3]** model complexity, **[4]** incompatibility of model information and cost estimation, **[5]** absence of standardized and uniform information representation, and **[6]** resistance of clients and practitioners to the application of BIM/5D BIM.

By countering these issues, the "Integrated Design – Cost Estimation 5D BIM Process" is designed to answer the research question. The integration between design and cost estimation via 5D BIM focuses on cost driving components which are components influencing costs. Accordingly, these components are considered as key for communication, discussions between designers and cost engineers, and model development. Focusing on cost driving components, the process balances the information in the model. The information in the model is checked for compatibility with the estimate's accuracy. Furthermore, the process proposes the consideration of the cost engineer's perspective in the design. Then, 5D BIM is incorporated in the designed process by standardizing information and following the

semi-automated approach for cost computation. With this approach, quantities are extracted from the model and costs are computed in Excel by the cost engineer. This semi-automated approach is adopted as means to clarify the workflow for BIM implementation and provide room for the cost engineer's interpretation.

To assess the effectiveness of the integration addressed in the research question, a pilot case is performed to test the process in a running project. From the observations, it is concluded that the process provided a standard representation of objects, enhanced the communication between the designer and cost engineer, and involved the cost engineer earlier in the design. Furthermore, the pilot case led to the conclusion on barriers to BIM implementation. These include: the cultural change from individual effort to collaboration, lack of support from the management and client, inadequate planning for BIM application, and the inexperience in applying 5D BIM. These factors limited the successful implementation to reach effective integration. Despite the limited integration achieved in the pilot case, project participants and interviewed BIM experts ensured that the process leads to effective integration. However, it is crucial to respond to the noted barriers to have effective integration between designers and cost engineers via 5D BIM.

Therefore, the thesis concludes that practice encounters fragmentation in design and cost estimation processes and problems in BIM/5D BIM application. To reach effective integration, the "Integrated Design – Cost Estimation 5D BIM Process" is proposed. This process tackles the noted issues and provides a workflow for the integration with clear BIM concepts. In this manner, the designed process is a stepping stone towards full automation. This is the main contribution of the designed process. Other processes in literature focused on the tools rather than the workflow. These processes did not incorporate potential solutions to deal with problems encountered in practice. Furthermore, the research concluded from the embedded case study the barriers that hinder the application of 5D BIM. These barriers were noted in literature. Nevertheless, this research provided case-based evidence of these barriers. Future research can investigate the identified barriers, provide approaches to deal with these obstacles, and improve the designed process accordingly. Furthermore, it is recommended to study the designed process without its isolation from other disciplines.

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Abbreviations

AI: Artificial Intelligence

BIM: Building Information Modeling

BEP: BIM Execution Plan

BoQ: Bill of Quantities

BPMN: Business Process Modeling Notation

CBS: Cost Breakdown Structure

CBR: Case-Based Reasoning

IFC: Industry Foundation Class

LOD: Level of Development

NN: Neural Networks

RHDHV: Royal HaskoningDHV

SSK: Standaardsystematiek voor kostenramingen

TOE: Technical, Organizational, and Environmental framework

WBS: Work Breakdown Structure

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1 Introduction

1.1 Problem

Although construction projects rely on intensive information (Matthews et al., 2015), interoperability is a major problem (Shen et al., 2010). The different parties fail to generate data that can be appropriately interpreted by others. Accurate data, information, and knowledge are not easily accessible during the project lifecycle. This lack of interoperability originates from fragmentation within the construction industry (Shen et al., 2010). The problems in interoperability can be reduced with the utilization of Building Information Modeling (BIM) (Matthews et al., 2015). BIM is about sharing knowledge in a single data repository that develops during the project's lifecycle (Cheung, Rihan, Tah, Duce, & Kurul, 2012). However, BIM and the information it possesses are influenced by the detached working processes in the industry (Stanley & Thurnell, 2014). Therefore, fragmentation is a crucial issue hindering interoperability and hampering the possibility to improve it through BIM. Focusing on 5D BIM which considers cost information in the model (Stanley & Thurnell, 2014), the problem of fragmentation between design and cost estimation in general and within BIM environment is studied.

1.1.1 Design – Cost Estimation Fragmentation

The traditional process separates the design and costing processes such that the design is completed then costs are estimated. Cost estimation feedback and design development are separated with a time-lag (Cheung et al., 2012). Architects work closely with clients to translate their requirements to a suitable design. Then, the cost of the design is estimated and compared to the budget of the client. Most often, the estimated cost exceeds the client's budget. This leads to redesigning and re-estimating till the budget is met (Ballard, 2006). Throughout this design process, changes are not communicated in a timely manner. The delay in communication leads to disruptions of the cost estimation process and conflicts with the design process (Aibinu & Venkatesh, 2013). Furthermore, the incorporation of changes also induces intensive rework. The design information is updated, then quantities and costs are recalculated (Kim & Park, 2016).

Therefore, the described design-cost rework process is inefficient (Ballard, 2006). It yields ambiguities and conflicts which disrupt the whole project (Namadi, Pasquire, & Manu, 2017). It also deduces the cost from the design rather than having it a criterion for acceptable designs (Ballard, 2006). Costs are a decisive measure for the design (Günaydın & Doğan, 2004), yet they are estimated at late stages. Thus, the ability to assist stakeholders in decision-making is limited (Moses & Hampton, 2017) and decisions based on financial implications during early design phases are challenged (Kim & Park, 2016).

To counter fragmentation, the concept of a design-cost model is set as a 5D design-cost model that reveals the cost implications with design actions. In such a model, design changes are directly reflected to align the designs with target costs (Jacomit, Granja, & Picchi, 2007).

1.1.2 Design- Cost Estimation Fragmentation in BIM

Although BIM permits the use of the latter 5D design-cost model, fragmentation endured. Costs remain unknown till the model matures, functional efficiency of the design is not tested in early stages, and the design team is not supplied with real-time cost feedback (Mitchell, 2012). Furthermore, this fragmentation in the construction industry influences information exchange. The separation between the parties leads to the segregation of the information necessary for BIM (Stanley & Thurnell, 2014). Since designing via BIM is the longest-standing activity (Ding, Zhou, & Akinci, 2014), the model for cost estimation results from the design team. However, this model does not form a basis for cost estimation (Lu, Lai, & Tse, 2018).

The development of advanced BIM models with compulsory information for desired purposes is a key challenge (Ding, Zhou, & Akinci, 2014). The data has to be integrated and managed to cover the different disciplines (Olatunji & Sher, 2014). For instance, estimating with BIM is attained based on the collaboration between designers and cost engineers in the design of the digital model. In this manner, they create a BIM model having the compulsory information for cost estimation (Sattineni & Bradford, 2011). However, the current situation in literature mentions that cost managers complete their tasks based on models prepared by other teams. This leads to a 5D BIM model having objects that do not possess the necessary information for cost computations (Smith, 2016). Furthermore, cost engineers interviewed in previous research mentioned that the information in the model is sometimes extensive but irrelevant for cost estimation (Stanley & Thurnell, 2014). Extra details for better accuracy and reliability of the cost estimates can be added, yet this increases the time needed for modeling and creating links (Monteiro & Martins, 2013).

Another problem with BIM input and output information is the structure. The automated process is challenged in terms of BIM data whose structure requires modification to meet the requirements of the estimator (Olatunji & Sher, 2014). Therefore, the issue of incompatibility is raised. The incompatibility between the model and cost estimation is related to the lack of uniformity in modeling and adding information. This leads to problems in matching the descriptions of 3D objects to the same objects in a 5D software for estimating (Stanley & Thurnell, 2014). These variances in modeling hamper the automated cost estimation process (Smith, 2016). Furthermore, the absence of standard rules defining elements and organizing measurements triggers users to follow their preferred method. The method is selected irrespective of its fitness with the overall information management and exchange (Monteiro & Martins, 2013).

In brief, the design and cost estimation processes of the construction industry encounter fragmentation. An integrated design-cost model, 5D BIM, is introduced to align design and costs. Yet, fragmentation of the processes persisted. This fragmentation also led to incompatible design and cost estimation information in BIM and hindered the implementation of 5D BIM.

1.2 Research Relevance

The loosely coupled structure of the construction industry creates a barrier to the implementation of BIM. To overcome this limitation, project teams shall be aligned, and their processes integrated as required by BIM-based tools (Hartmann, Van Meerveld, Vossebeld, & Adriaanse, 2012). BIM can successfully change work processes by removing waste from the process in terms of unnecessary or repetitive work (Tauriainen, Marttinen, Dave, & Koskela, 2016). In the case of 5D BIM, the incorporation of information to BIM begins in the design process and the integration of the cost estimation process shall be with information management during the design (Moses & Hampton, 2017). Necessary information is added to the model (Monteiro & Martins, 2013) such that information from architects in 3D models and the additional cost-related information shall be balanced (Stanley & Thurnell, 2014).

Accordingly, the research focuses on studying from practice the case of fragmentation addressed in literature and provides a closer look to the issues leading to fragmentation and ineffective 5D BIM application. Based on that, an effective integration between design and cost estimation processes via 5D BIM is proposed in a process. The relevance of the research lies in the close study of processes in the field and deriving an integrated 5D BIM-based design and cost estimation process. Furthermore, covering BIM from the perspective of project management is a topic merely covered in literature (Bryde, Broquetas, & Volm, 2013). Mitchell (2012) states that limited work is done in the field of 4D and 5D BIM. Monteiro and Martins (2013) show that knowledge on the link between estimation and BIM is not shared as organizations develop their own internal execution plan. Thus, there is a need to standardize the BIM process, set the guidelines for its implementation, and establish general protocols to ensure uniformity (Azhar, Khalfan, & Maqsood, 2015).

Considering previous research, the study by Hartmann et al. (2012) considered the ability of BIM to support construction management work processes. It focused on BIM tools to support the estimation process with automatic extraction of quantities. The consideration of the design is limited to [1] discussions to build a compatible model for extracting quantities and [2] direct cost reflections of design changes. Therefore, the research does not cover the integration of design and cost estimation processes to complete a design made to cost. Another recent research by Lu, Lai, and Tse (2018) looked deeper into the topic of cost estimation in BIM. BIM is noted as a powerful tool that tackles fragmentation in construction. Based on that, the research considered BIM along with the collaboration between design and cost estimation to generate a model optimizing both processes. Together, design and cost estimation enrich the BIM model with extra and clear information. The model would be used to estimate costs for the design and keep them below budget (Lu, Lai, & Tse, 2018). This study focuses on building the model and connecting it with databases to automate costs with various tools. It considers integration based on communication to prepare the model and check estimates derived from the costing software. Therefore, the process from this study requires the availability of databases and suitable tools. The process also focuses on compatibility of information but does not address the increasing complexity of the model as information is added. Furthermore, standardization of information is not addressed. Even though costing software is used, the uniformity between the model and the software is not always achieved (Stanley & Thurnell, 2014). For these reasons, the process to be designed addresses the problems noted earlier on standardization, compatibility, and complexity. Therefore, the research gap that the thesis is trying to fill is the absence of a way to integrate design and cost estimation processes via 5D BIM while addressing the various problems from literature and practice.

1.3 Research Design

Based on the identified problem and research relevance, the research considers:

- Studying the interaction of design and cost estimation in practice to reflect on the case noted in literature on the fragmentation between these parties in the construction industry
- Designing a process for the effective integration of design and cost estimation via 5D BIM and implementing it to provide further recommendations

Thus, the research objective is to design a process for the effective integration of design and cost estimation via 5D BIM based on the current case in practice. Tackling fragmentation and utilizing BIM improves interoperability. Therefore, the ultimate goal of the research is to contribute to the enhancement of interoperability between designers and cost engineers. The defined research objective leads to the research questions:

Main Research Question: <u>How can design and cost estimation be effectively integrated using 5D BIM?</u>

In the main question, the definition of the term "integrated" adopted is: Integration is the merging of diverse disciplines having different goals and requirements into a unit based on mutual support. Such an approach necessitates team work to attain shared project goals by sharing information. Thus, the diverse processes have to be aligned (Baiden, Bernard, Price, & Dainty, 2006).

1. <u>What is the current interaction between design and cost estimation processes?</u>

This sub-question clarifies the interaction between design and cost estimation processes as noted in standards and literature. Based on this information, the case of fragmentation in practice is assessed.

2. <u>What are possible ways for the preparation and utilization of 5D BIM?</u>

To incorporate BIM in the process, this sub-question identifies the approach for BIM utilization and BIM's connection with design and cost estimation. Furthermore, the application of BIM in practice is compared with literature.

3. <u>What are the issues of design-cost estimation integration and BIM utilization noted in practice?</u>

Based on the comparison between literature and practice, issues disrupting design-cost estimation integration and BIM utilization are derived.

4. Which method for 5D BIM utilization is adopted for the process on the integration of design and cost estimation?

This sub-question adopts 5D BIM application method for the process. The selection is based on cost computation methods and discussions on the different 5D BIM methods.

5. What is the process map for the integration between design and cost estimation processes via 5D BIM?

This sub-question translates the propositions for tackling the issues and incorporating BIM to the process to a process map showing actors, tasks, and information flow.

6. Does the suggested process lead to effective integration between the design and cost estimation processes via 5D BIM?

The term "effective" is used in the research question to check if the proposed process leads to: [1] more interaction between design and cost estimation, [2] monitoring costs during the design to reach a design made to cost, and [3] exchange of suitable and coordinated information.

1.4 Concept of BIM and 5D BIM

The problem and research relevance continuously mention BIM and 5D BIM. For this purpose, these concepts are basic for the research and are introduced in this section prior to the thorough exploration of their application in the chapter 3.

Traditionally, stakeholders communicate and run construction processes via paper-based tools which are being replaced with BIM. "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." (Lu, Lai, & Tse, 2018) BIM's significance is in the "Information" connected to the model from the various applications (Abanda, Kamsu-Foguem, & Tah, 2017). Information from the different stakeholders is stored and shared in a collaborative working process (Cheung et al., 2012). This collaborative multidisciplinary environment is based on a model (Martínez-Rojas, Marín, & Vila, 2015). The model consists of objects which possess parametric 3D geometric representation accompanied with properties and relationships (Preidel & Borrmann, 2018). Furthermore, the data in the model can be used in other information system tools to streamline different tasks within the construction process (Martínez-Rojas, Marín, & Vila, 2015).

BIM provides the ability to deliver projects from initiation to maintenance at higher efficiency levels (Ding, Zhou, & Akinci, 2014). It enhances profitability, reduces costs, provides reliable time schedules, tightens customer-client relationships, and supports the execution of complex building (Azhar, Khalfan, & Maqsood, 2015). The latter benefits are attained depending on the dimension to which BIM is exploited. Figure 1.1 introduces the different dimensions of BIM and the features consisting each dimension.

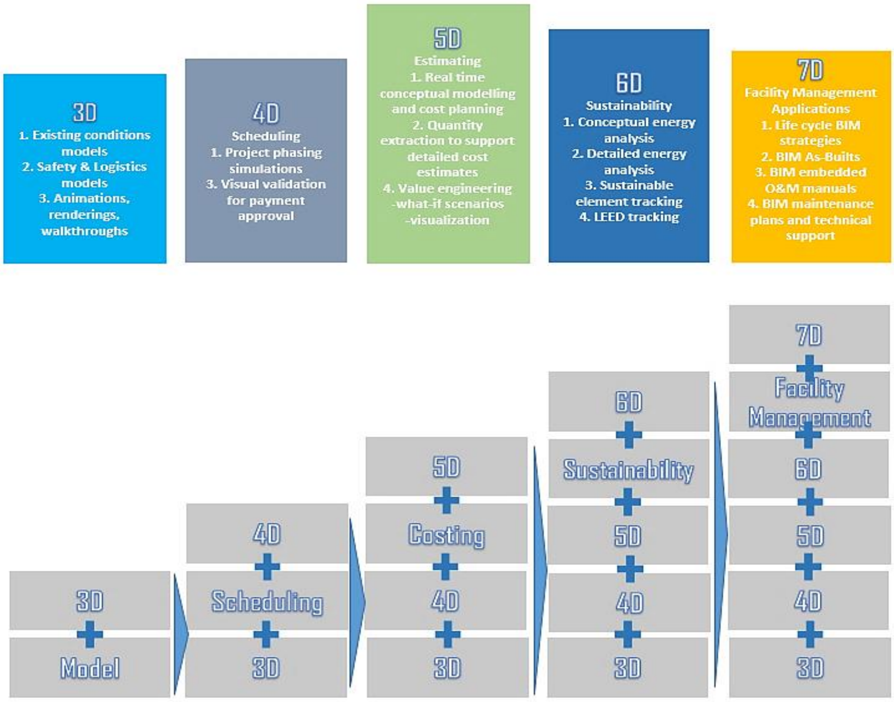

Figure 1.1 BIM dimensions. Reference: (Dallasega, Marengo, Nutt, Rescic, Matt, & Rauch, 2015) and (Eleftheriadis, Mumovic, Greening, & Chronis, 2015)

The introduction of costs to BIM introduces the fifth dimension. 5D BIM is defined as the addition of costs to the 4D model which links the construction schedule to the 3D model, visualizes the construction process, and communicates activities in time and space (Eastman, Teicholz, Sacks, & Liston, 2011). The approach targets the addition of cost information to the model. The cost characteristics derived from cost data are either incorporated within objects of the model or lively linked to estimating software to have fully exchangeable data. Therefore, the model becomes the repository of information for cost estimators. The information for costing is extracted and the 3D model is visualized to make less assumptions about the design for costing (Stanley & Thurnell, 2014). Then, the costs are produced with reduced errors, improved accuracy, and enhanced reliability (Eastman et al., 2011).

Furthermore, the parametric ability of the software ensures that changes in parameters lead to direct modification of the model and other features such as bill of quantities, sections… (Olatunji & Sher, 2014). The impact of design adjustments on the budget is reflected with accurate measurements (Doumbouya, Guan, Gao, & Pan, 2017). Thus, the integrated 5D BIM model responds to design changes with automatic updates of time and cost features. Such a model enables the design team to analyze various options during the early phases, explore the impact of the changes, and monitor the scope and cost (Bryde, Broquetas, & Volm, 2013). Furthermore, BIM-based planning improves the design quality as it enables the production of a complete digital model, the coordination of requirements, and the analysis of design decisions (Borrmann, König, Koch, & Beetz, 2018).

To attain these benefits, the application of BIM shifts the design effort to become more intense in earlier phases in comparison to conventional planning process as shown in figure 1.2. Furthermore, BIM-based planning process grasps the opportunity to influence cost with lower expense of design changes in the early phases (see figure 1.2).

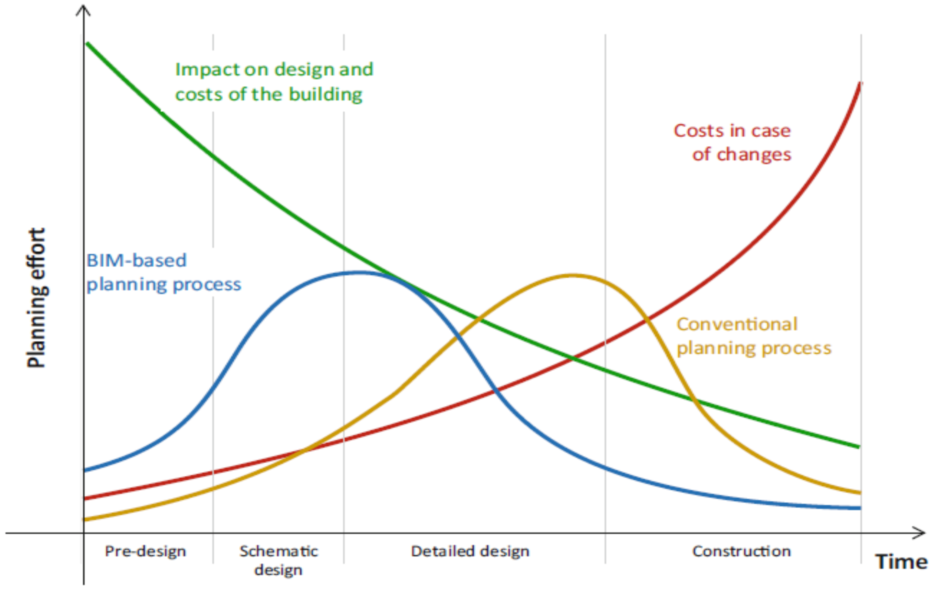

Figure 1.2 BIM-based planning process in comparison to the conventional planning process while considering cost of design changes and impact on design and cost. Reference: (Borrmann, König, Koch, & Beetz, 2018, p.9)

1.5 Report Outline

The thesis report proceeds with further clarification of the research method in chapter 2. In chapter 3, the theoretical background covers the relevant points for the process design from the sub-topics: design, cost estimation, and BIM. In chapter 4, the findings of the case study research are reached. These findings include the description of the current state in practice of design, cost estimation, their interaction, and BIM utilization. Furthermore, comparison of the latter is made with literature to identify the issues of design-cost estimation integration and BIM utilization. These issues form the basis of the process design in chapter 5. In this chapter, the issues are countered based on information from literature and practice. Accordingly, the process is designed for the integration of design and cost estimation. The incorporation of 5D BIM is based on the selected method discussed also in chapter 5. In this manner, the process is completed and translated to a process map. Then, chapter 6 covers the embedded case study in which the process is implemented, and its effectiveness is tested. In chapter 7, the validation based on interviews is addressed, the research results are discussed, and reflection on the overall research is shared. Finally, chapter 8 concludes the research study and provides recommendations for process improvements and further research.

2 Research Method

The research follows the process illustrated in figure 2.1. The process starts with the comparison of literature and practice in terms of: design process, cost estimation process, cost computation, BIM utilization, and 5D BIM application. The comparison leads to the identification of issues to be addressed in the design of the process. Furthermore, information from practice provides suggestions for improving designers-cost engineers interaction and the utilization of BIM/5D BIM. The latter is used along with concepts from literature to design the process for effective design and cost estimation integration via 5D BIM. Having the process set, it is implemented in practice. Then, the implementation is evaluated to notify successful or failed effective integration via 5D BIM. The evaluation is based on observations and participant's feedback in interviews. Accordingly, further recommendations for improvement are proposed. The research process can continue by adapting the suggested improvement into the design, reimplementing, and deriving further recommendations. However, due to time limitation, the process is stopped after the first set of recommendations. Therefore, validation is made with BIM experts to enhance the research.

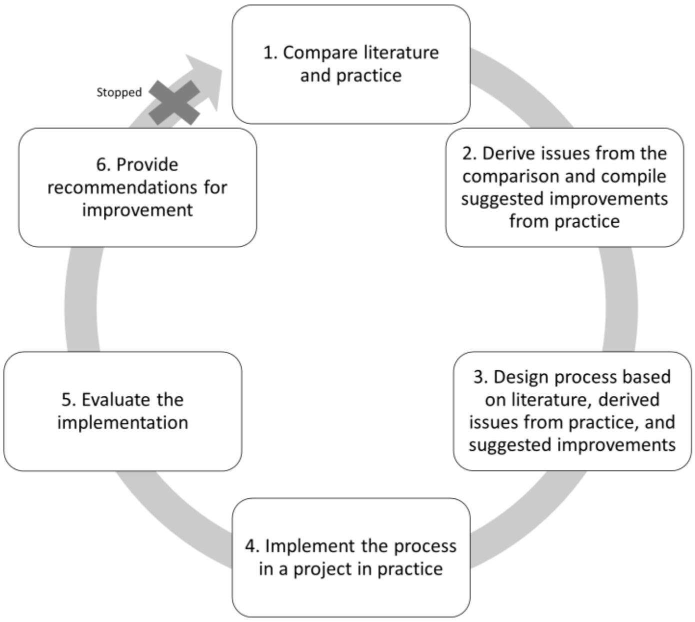

Figure 2.1 Schematic of the research process

Following these steps, the research method consists of: [1] desk literature, [2] case study research to gather information from practice, [3] process design, [4] embedded case study to implement the process in a project, and [5] final semi-structured interviews for validation. These are applied in the latter order and are explained in the following sub-sections.

2.1 Desk Research

The research starts with a Desk Research to elaborate on the different topics addressed in the research questions. The desk research is necessary to provide basis for comparison and assessment of the current design-cost estimation and 5D BIM utilization in practice. Furthermore, the literature study aids the development of the process.

To perform the desk research, theories relating to sub-topics from research questions are studied. Table 2.1 clarifies the relation between research sub-questions and sub-topics. Accordingly, data is gathered from knowledge sources to access information on available insights and theories (Verschuren & Doorewaard, 2010).

Table 2.1 The relation between research sub-questions and sub-topic investigated in literature

Research sub-question	Sub-topic
Sub-question 1: Interaction between design and cost estimation processes	Design process is described to derive the consideration of costs in this process.
	Cost estimation process is described to derive its relationship with the design.
	Design-cost estimation interaction is described to note the interaction points throughout the design process.
Sub-question 2: Possible ways on 5D BIM preparation and utilization	BIM utilization is addressed to be related with design and cost estimation. Furthermore, the essential considerations for the utilization of any dimension of BIM are noted.
	5D BIM utilization is addressed to provide the different methods for achieving 5D BIM.
Sub-question 3: Issues in design and cost estimation integration and BIM utilization from practice	All earlier sub-topics are utilized to compare literature and the situation of design-cost estimation integration and BIM utilization in practice. Accordingly, the current situation is assessed, and issues are derived.
Sub-question 4: Method of 5D BIM adopted	Cost computation is described in literature and compared with practice. Based on the comparison, the suitable 5D BIM method is selected for the process.
	5D BIM utilization is necessary to describe the adopted method.
Sub-question 5: Process map	All sub-topics are utilized to aid the design of the process for effective integration of design and cost estimation.

2.2 Case Study Research: Royal HaskoningDHV

The case study approach is an up-close and deep empirical investigation of a current phenomenon as it occurs in real-life (Yin, 2011). The first feature of the case study research method 'up-close' enables the researcher to deeply study one or several objects or processes by looking into a small domain of strategically selected research units and generating data intensively (Yin, 2015). Through observing on location, interviewing involved individuals, and studying available documents, the researcher gains deep perception and interpretation of the way various processes happen and develop (Verschuren & Doorewaard, 2010). The second feature of the case study is 'real-context' which leads to complete and accurate understanding of the case in an actual setting without isolation (Yin, 2015). Furthermore, the case study approach is the most suitable investigation method of latest information technologies. The case study becomes an initiating point for practitioners on the application of BIM (Barlish, & Sullivan, 2012).

For the latter reasons, case study research approach is selected. Following Yin's (2014) third rationale on having a representative case, a single case is selected. This case is typical such that it depicts the current situation of design, cost estimation, and 5D BIM implementation in practice. For this purpose, "Royal HaskoningDHV (RHDHV)" is chosen as a relevant case especially that it applies BIM and explores the advanced BIM/5D BIM application.

The focus of the case study research RHDHV is to investigate and assess the interaction of design and cost estimation processes as fragmented or integrated. Furthermore, the utilization of BIM and 5D BIM in practice is interpreted with this case study research. Based on the close study in practice, problems in the design-cost interaction and BIM application are pinpointed. Relating the latter information to literature, the "Integrated Design – Cost Estimation 5D BIM Process" is designed. Therefore, the case study questions are sub-questions (3), (4), and (5) listed below:

- What are the issues of design-cost estimation integration and BIM utilization noted in practice?
- Which method for 5D BIM utilization is adopted for the process on the integration of design and cost estimation?
- What is the process map for the integration between design and cost estimation processes via 5D BIM?

Throughout the case study research RHDHV, information is gathered in two sources: documentation and interviews. These two sources are addressed in the following sub-sections.

2.2.1 Documentation

Documentation considers formal studies, internal records, reports, and others. Through these documents, evidence from other sources is validated. Furthermore, the researcher can make inferences from which questions are raised and further investigations are considered (Yin, 2009). The documents used from the case are either shared by professionals or are available in RHDHV's shared folders. The documents which have information relevant to the study are:

- **Document depicting the cost estimation process:** This document shows a clear description of the standard cost estimation process agreed on within the company. Having this available, the researcher investigates the considered interaction between designers and cost engineers. Furthermore, the cost estimation process can be analyzed in terms of as set and as practiced in the company.
- **Documents on cost estimation method:** These are Excel documents having information on the cost estimation methodology. From these documents, the link of costs with other disciplines and BIM is noticed.
- **Documents on quantity extraction in Civil 3D:** Several documents were shared on this topic to learn the procedures and tools used for quantity extraction. Based on these documents, the researcher becomes aware of the methods used in performed trials for connecting design and cost estimation disciplines. Then, possible approaches are clarified, and further modifications are considered in the research.

2.2.2 Interviews

Interviews conducted in the research are semi-structured focused interviews. Focused interviews lasting an hour cover open-ended questions (Yin, 2009). These semi-structured interviews follow pre-determined questions that allow the researcher to collect information on key elements while providing flexibility. In this manner, specific data on preset categories is captured and could be coded for analysis (Chism, Douglas, & Hilson, 2008). To reach the latter, the preparation and analysis is planned in line with the case study questions. Accordingly, the questions are set such that they enable mapping the current state of design, cost estimation, and BIM utilization in practice.

Different categories with related questions are prepared to cover various topics with the designer, cost engineer, and BIM expert. The questions are grand tour questions, focusing questions, and questions with probes. These types are of increasing specificity. Grand tour questions are broad and open-ended. They are supported with focusing questions to target specific responses. For rapid responses and clarifications, probes are used. Accordingly, questions are written starting with a wide perspective then narrowing to more specific questions (Chism, Douglas, & Hilson, 2008). Figure 2.2 clarifies the interview sets and the categories covered in each.

Design Interview:	**Cost Interview:**	**BIM Interview:**
Categories covered: • Design process followed • Design process management • Design representation • Changes in the design • Relation with cost • Communication with cost engineers	Categories covered: • Cost process and management • Cost methods • Cost accuracy/level of design • Information extraction • Value engineering and involvement of cost estimation • Design-cost communication	Categories covered: • BIM execution plan and process • BIM modeling • BIM and people • BIM added-value/complications

Figure 2.2 Interview sets with the categories covered

An hour interview is conducted with each interviewee. 8 designers, 6 cost engineers, and 5 BIM experts were interviewed. The professionals have different specialization and experience. Furthermore, designers and BIM experts interviewed are at the management and technical levels. This variety enables capturing more information and supporting it by several professionals. Thus, precise mapping of the current state is achieved. The details of the interviewees and their assigned codes are available in Appendix A. The given codes have numbers and letters that distinguish them per profession (D for designers, C for cost engineers, and B for BIM experts).

At the beginning of the interview, the interviewee is asked for permission to record the interview to reach accurate transcripts. Having done that, the interviews are summarized and sent to the interviewees for approval. With the summaries approved, the content of the interviews is organized and analyzed as noted below.

Coding or categorizing the data is applied to facilitate the analysis. The data is condensed and organized to become manageable for the analysis. Therefore, the data is divided according to codes which are meaningful labels assigned to information. These codes are tagged to words, phrases, sentences, or whole paragraphs. The naming of codes is straightforward such that names are derived from concepts in literature or phrases from interviewees. With these codes, a link is created between a concept and the location of its corresponding data (Basit, 2003). Accordingly, categories and codes are specified below based on topics required to answer the case study questions. To easily allocate information, codes are added with parentheses to the transcript.

- Category "Design and Cost estimation interaction" has code DC
- Category "Design Aspects" has code DA
- Category "Cost Aspects" has code CA
- Category "BIM Utilization in practice" has code BU
- Category "Design and Cost estimation interaction Improvements" has code DCI
- Category "BIM Desired Utilization" has code BDU

2.3 Process Design

The design of the process is based on three steps going from issues encountered in practice to a process map providing details on the process as shown in figure 2.3. At the highest level, the issues pinpointed in the case study research RHDHV are used. These issues are derived based on comparing the design, cost estimation, and BIM utilization processes in literature to those in practice. At the second level, the process at a general level is designed. The design is based on analyzing and countering the identified issues based on information from literature and suggested improvements. Furthermore, the incorporation of BIM is considered by adopting a 5D BIM method. The method is selected based on the comparison made earlier and literature on cost computation and BIM utilization.

The connection between the different steps composing the process at the general level is based on logical order and critical thinking.

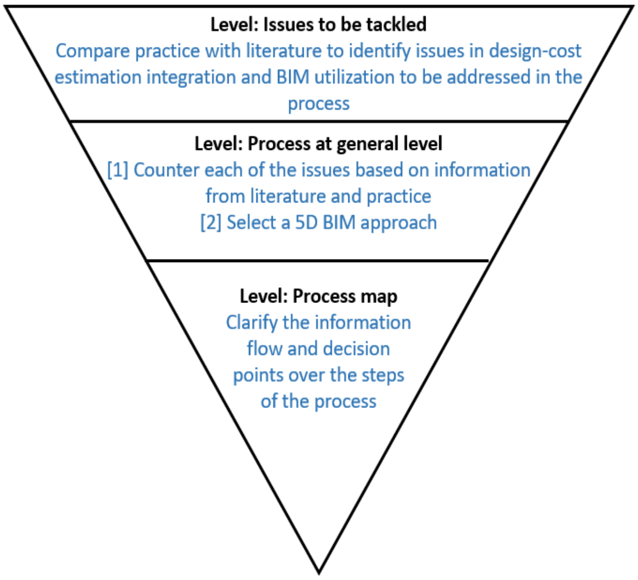

Figure 2.3 Process design from general to detailed process map

At the most detailed level, the information exchange, interaction, and decision-making between the design team and cost engineer are clarified. For this purpose, the process at a general level is translated to a process map. The process map describes the logical sequence of activities of a specific process, the actors involved, and the information required or delivered. The information could be data shared from an external or internal source. It is recommended that process maps are drawn based on the Business Process Modeling Notation (BPMN) (ISO, 2017). BPMN considers the process properties: [1] actors and their relationships to clarify the transmitter and the receiver, [2] dependencies to show the moment of information exchange, and [3] documents or models to specify the information shared (Borrmann, König, Koch, & Beetz, 2018). The latter points are derived from the higher levels "Issues to be tackled" and "Process at general level" and used to draw the process map based on BPMN rules and annotation as defined in ISO (2017). More details on the annotation and rules for using BPMN to draw a process map are available in Appendix B.

2.4 Embedded Case Study: The Pilot Case

Having the process designed, it is implemented in practice in a running project that enables exploring the integration in real context. The project is designed and estimated by RHDHV. Accordingly, the project is an embedded case study within the case study RHDHV. Before initiating the study of the process, a clear protocol is prepared. The protocol introduces the embedded case study and clarifies the implementation and data collection approach. This is considered in chapter 6 where the focus is on the embedded case.

The embedded case study research focuses on evaluating the effectiveness of design-cost integration through 5D BIM proposed in the designed process. This leads to answering sub-question (6). Effectiveness of the integration being tested is defined as: The application of the process yields to closer interaction between design and cost estimation, design made to cost, and synchronized information flow based on relevant and desired information.

The embedded case is studied by being involved for 2 months in a selected running project. The role of the researcher in the case starts with presenting the process to the project team. Throughout the process, the researcher clarifies the steps for the implementation. To observe the interaction and collect results, the researcher attends meetings and explores the model and available information. At the end of the implementation, the researcher interviews the participants of the project. The designer, cost engineer, and project leader evaluate the process in terms of concepts which led to effective integration and those that failed to do so. Furthermore, they provide feedback on reasons for success or failure of implementation and further recommendations.

The observations in the embedded case are direct and participant observations. Direct observations study actions as they occur and provide information on behavior. The reliability of the observations is increased upon having multiple observers (Yin, 2009). Accordingly, team members reflect their observations throughout the process in the interviews. Direct observations have a weakness in terms of reflexivity such that the events occur differently due to the presence of the researcher (Yin, 2009). However, the case study considers human interaction for integration followed by a technical task such as drawing or estimating. The result of the technical task reflects if the agreement made on integration is met or not. Thus, it becomes possible to judge if the observations made during discussions are made due to the observers' presence or not.

Participant observations are made since the researcher is considered as part of the team. Being a participant is necessary to attend meetings, be included in communications via email and have access to documents, models, and information management platform. The researcher also calls for discussions and attends meetings but does not perform design or estimation tasks. Through the arrangement of meetings, the researcher does a manipulation to create the situation for data collection. Despite the opportunities provided by participant observations, biases could happen (Yin, 2009). Biases are reduced by having evaluation from participants. Participants' evaluation allows self-assessment and criticism of the research process. With various views, validity is enhanced, and biases are reduced (Mackenzie, Tan, Hoverman, & Baldwin, 2012). Accordingly, the final interviews with project members are performed.

2.5 Interviews for Validation

At the last stage of the research, the designed process is validated by conducting semi-structured interviews with two professors from TU Delft and a BIM expert from practice. The interviewees are not involved in the case study RHDHV nor in the embedded case. This enables considering views from individuals who possess a research background and another from a company specialized in digitalization. In this manner, the process is explored away from the prevailing work routine of RHDHV professionals. This leads to additional perspectives on the designed process. The information from the interviewees is used in chapter 7 with reference codes 1V, 2V, and 3V. The transcripts are provided in Appendix I.

Validation interview questions focus on the idea of cost driving components, 5D BIM semi-automation, standardization, and effectiveness of integration of the designed process. Furthermore, the illustration of the process at the general level and the process map are shared with the interviewees for further feedback.

2.6 Addressing Validity and Reliability

The criteria to judge the quality of the research are validity and reliability. Construct validity is having the right operational measures for the studied concepts. External validity is the generalizability of the study findings to a broader theory. Reliability is to ensure that following the same procedures for the same case study leads to the same findings and conclusions. The aim of reliability is to reduce biases in the study (Yin, 2009).

Construct validity is ensured by relying on multiple sources of evidence by using more than one method for data collection (Yin, 2009). During the involvement in each of the cases, information is collected from multiple sources. In the case study RHDHV, documentation and interviews are used to collect data on the processes as they occur in practice. For the embedded case study, direct observations, participant observations, and interviews are applied to collect results of the implementation of the process and assess its effective integration. External validity is achieved through generalization (Yin, 2009). The generalization of results is specified for the case study and embedded case in section 7.2.5.

Reliability is attained by following a set case study protocol and collecting data from multiple sources. Dealing with the biased view of the researcher, comprehensive evidence is reported fairly and transparently to improve the credibility of the case study (Yin, 2015). Thus, the research summarized the meetings and provided their main outcomes in chapter 6. Furthermore, reliability is improved as the researcher clarifies [1] the data collection approach and analysis for RHDHV case study and [2] the protocol (provided in chapter 6) for the embedded case study.

2.7 Conclusion

In brief, the research considers different steps depicted in figure 2.4. The figure pinpoints the steps and the sub-question answered. The research starts with literature of the different sub-topics design, cost estimation, and BIM. Then, a case study research is adopted to map the current state in practice on design, cost estimation, and BIM. The current state in each of the noted topics is derived from interviews and documentation. Having the case from practice described, it is compared with literature to derive issues of design and cost estimation integration and BIM utilization in practice. Based on the latter and the adopted 5D BIM method, the process is designed and translated to a process map. Then, the process is implemented, and its effectiveness is tested in an embedded case study research. Furthermore, interviews with professionals not related to the case study nor the embedded case are performed to validate the process. Finally, results from the embedded case study and interviewees are utilized to provide recommendations and conclude on the designed process.

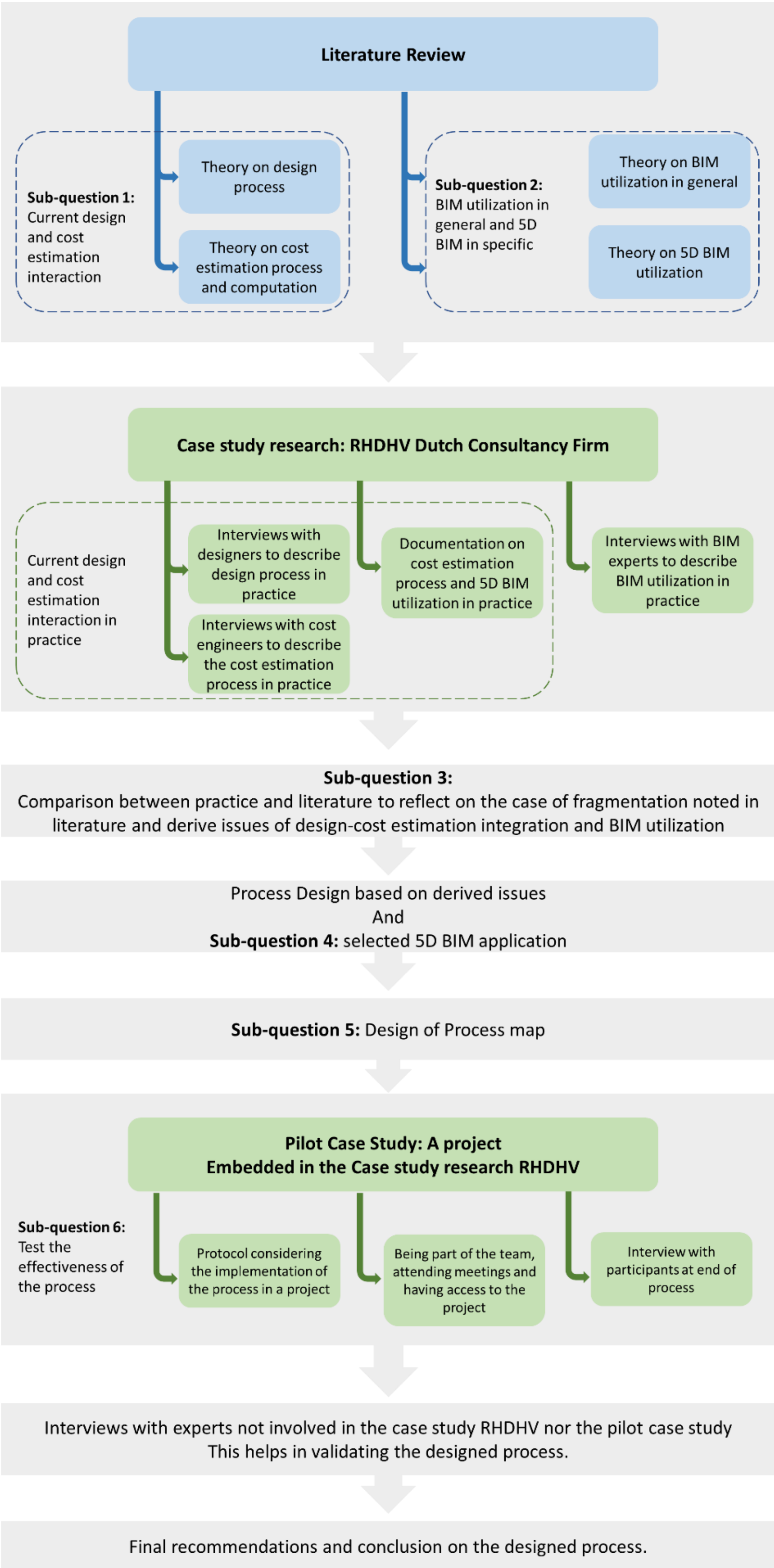

Figure 2.4 Research method

3 Theoretical Background

The chapter studies the different concepts on the integration between design and cost estimation through 5D BIM. In the first section, the integration between design and cost estimation as noted in standards and literature is investigated. For this purpose, the design and cost estimation processes are described thoroughly to finally reach the interaction between the processes as addressed in literature. Based on the latter, the major points of interaction are identified to answer sub-question (1) provided below.

"What is the current interaction between design and cost estimation processes?"

In the second section, the computation of cost estimates and their interpretation are explored. This is essential to incorporate the cost computation methodology with the application of BIM in the design of the process. Finally, the third section explores the preparation and utilization of 5D BIM. The study initiates with clarifying the connection of BIM to the design and cost estimation processes. In this manner, the link between the concepts of the study is made and the introduction of BIM as an additional link to the interaction between design and cost estimation is shown. To attain the link with BIM, the preparation for its implementation is studied along with methods to compute costs via 5D BIM. Then, limitations to BIM-based cost estimation are addressed. Finally, the study in this section is summarized to answer sub-question (2) provided below.

"What are possible ways for the preparation and utilization of 5D BIM?"

3.1 Design and Cost Estimation Integration

The integration between design and cost estimation processes in the construction industry is explored in this section. The integration is noted by identifying the moments at which the cost engineer and designer interact in the described design and cost estimation processes. Accordingly, the first sub-section covers the design process based on standards and literature. In the second sub-section, the cost estimation process in terms of planning and estimating is clarified. Having the processes presented, the interaction between designers and cost engineers is clarified in the last sub-section. This theoretical study is used in chapter 4 (section 4.1.4) to compare theory with practice, assess the case of fragmentation in practice, and derive issues in practice.

3.1.1 Design Process

The design process is described in terms of design stages and their management. For the different stages, the Dutch NEN2574:1993 "Drawings in the construction sector" and DNR-STB "De Nieuwe Regeling - Standaardtaakbeschrijving" are considered to represent the national adopted process. The description of the process is used to compare the situation in practice with that in literature in chapter 4, sections 4.1.1 and 4.1.4.

The design starts with the **Schematic Design** that aims at studying the project in general on an urban scale. The urban plan is created, and the solutions are considered within this area (BNA & NLingenieurs, 2014). Therefore, the schematic phase yields to an outline of the project. The outline has a basic functional package, sketch of the design, simple layout, and setup for the financial program. Based on the latter outline, alternatives are identified in the **Pre-Design or Preliminary Design** stage. During the pre-design stage, information is developed in terms of functional layout, technical packages, financial scheme, and preliminary designs (NEN, 1993). By the end of this stage, an overall illustration of the facility with its functional, structural, and architectural aspects is reached (BNA & NLingenieurs, 2014). Upon focusing on a single alternative and considering the client's requirements and legislations (NEN, 1993), the detailed representation of the facility is developed in the **Definitive Design** stage. At this stage, the architectural appearance is fixed, the urban plan from earlier phases is finalized, and the spatial layout is defined. Finally, the design decisions made, and principles followed to reach the latter outcomes are specified. The design is further elaborated in the **Technical Design** stage during which design units are integrated, and technical drawings of the construction design and installations are prepared. With the details specified, the definite pricing is computed (BNA & NLingenieurs, 2014). This phase description coincides with part of the **Construction Documents** phase of the NEN2574 which also includes the application for permit and preparation for contracting (NEN, 1993). Finally, the **Execution Ready Design** stage develops the design drawings of architectural, construction, and installation technical components (BNA & NLingenieurs, 2014). Similarly, the **Work Preparation** phase of the NEN2574 focuses on the elaboration of the designs in work drawings that facilitate the execution (NEN, 1993).

Throughout the stages, continuous information exchange and interdisciplinary dependency are practiced. These require the collaboration of members and coordination of concepts and plans to reach an integrated design meeting the requirements of the client and users (BNA and NLingenieurs, 2014). For this purpose, the management of the design team is crucial. The management of the design process occurs at different levels. Figure 3.1 clarifies the design team hierarchy.

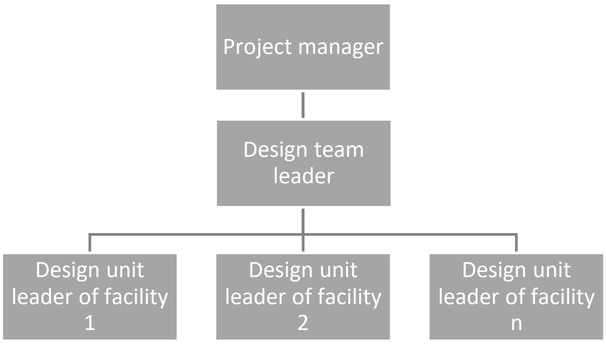

Figure 3.1 Design team hierarchy

At the highest level, the project manager monitors the design process by interpreting progress reports from design team meetings relative to the agreed plan (British Standards Institution, 1996). Then, the design team leader creates the link between project management and design management. Accordingly, his management involves establishing client requirements, preparing and monitoring parts of the project plan on the design, collecting cost and time information for the design units, and forming congruous design interfaces. Furthermore, the design team leader manages the design units preparing the design. At the end of each stage, the design team leader runs design team meetings (British Standards Institution, 1996). The aim of these sessions is to [1] review and report the design and cost factors, [2] determine or review client decisions, [3] advise on design or cost changes, [4] coordinate design activities and information (Chartered Institute of Building, 2014), and [5] evaluate the design against requirements, criteria, and standards (British Standards Institution, 1996). At the lowest level, the design unit leaders supervise the different design units each of which is responsible for developing part of the design (British Standards Institution, 1996).

This management process is detailed in the design management plan prepared by the team and other consultants at the beginning of the design. The design management plan covers topics on procedures to regulate design changes, cost acceptance, and information management (Chartered Institute of Building, 2014). Further details on the information management within the design process is considered in the communication plan. The plan identifies all communication channels and procedures to prepare, share, and store information between disciplines (British Standards Institution, 1996). Design participants interact by exchanging information and illustrating ideas (Knotten, Svalestuen, Hansen, & Lædre, 2015). They communicate on project information in various ways: verbal, written, or electronic (British Standards Institution, 1996). The electronic communication considers software networks. These networks connect the input and output of the design units that use their own software tools (Chartered Institute of Building, 2014).

3.1.2 Cost Estimation Process

The cost estimation process is extracted from the project cost management which covers the cost aspect throughout the project. The described process is compared with the case in practice in chapter 4 section 4.1.2 and 4.1.4.

Project cost management considers the stakeholders' needs, resources required for the completion of project activities, and the design process. The relation with the design process is essential to enable designing to cost and facilitating the preparation of the Bill of Quantities from drawings and specifications. To validate the cost of the project, the cost driving components are set early in the design and monitored continuously. Furthermore, cost estimates are prepared at the different stages of the design (Project Management Institute, 2016).

Project cost management includes the processes: plan cost management, estimate costs, determine budget, and control costs. The planning process defines the basis of the subsequent cost management processes. The estimating process develops approximate values of monetary resources necessary to complete the project. The budgeting process sums the estimated costs of individual activities to establish a cost baseline. Cost estimating and cost budgeting processes interact with one another and with processes from other disciplines. Finally, the controlling process monitors the progress to update costs and manages changes to the cost baseline (Project Management Institute, 2017). Therefore, cost management takes part in the preparation, design, and construction phases in the form of processes with different aims (Lu, Lai, & Tse, 2018). The focus of the research is on the planning, estimating, and budgeting processes since they interact with the design process. The figure 3.2 depicts the project cost management processes.

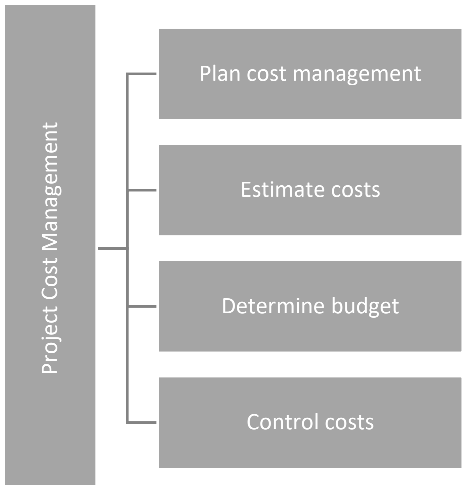

Figure 3.2 Project cost management processes

In the plan cost management process, the guidelines to proceed with the cost processes and manage the costs of the project are set based on project information (including requirements, risks, schedule). The details on the processes along with other aspects are set in the cost management plan to reach effectual and harmonized processes (Project Management Institute, 2017).

Based on the set plan, the estimating process starts. Cost estimating forecasts the costs and resources for project completion depending on the given level of design detail (Halpin, Lucko, & Senior, 2017). The estimate is based on information provided, alternatives analyzed, and risks identified. Therefore, the cost estimating process considers input information from various sources to initiate the computations using methods and tools which facilitate the production of the final output (Project Management Institute, 2017). The final output consists of activity cost estimates, basis of estimates, and project document updates. The activity cost estimates are the forecasts on costs of project work in general or in detail. The basis of estimates are the supporting details for the computation of the costs. These include assumptions made, constraints noted, range of expected costs, and confidence level of the final estimate. The project document updates record the changes made in other documents (Project Management Institute, 2008).

After approving the cost estimate, cost budgeting is initiated to determine the cost baseline for the project. The project budget is calculated upon aggregating the estimated costs of the construction work packages based on the work breakdown structure (Project Management Institute, 2016). When determining the budget, experts shall be consulted to consider their experience, knowledge, and skills. Such information is extracted from disciplines within the organization, consultants, professional association, industry groups, or other sources. The final outcomes of the budget determination are the cost performance baseline which is a time-phased budget necessary for later stages (measure, monitor, control) and project document updates in risk register, cost estimates, project schedule and others (Project Management Institute, 2008).

3.1.3 Design and Cost Estimation Interaction

The connection between design and cost estimation is clarified by pinpointing the activities involving the cooperation of the two disciplines. The cost engineer's tasks are related to the design stages as illustrated in Figure 3.3. It pinpoints the cost engineer's tasks relative to the design stages of the RIBA Plan of Work. The cost engineer's tasks are listed under the project cost management.

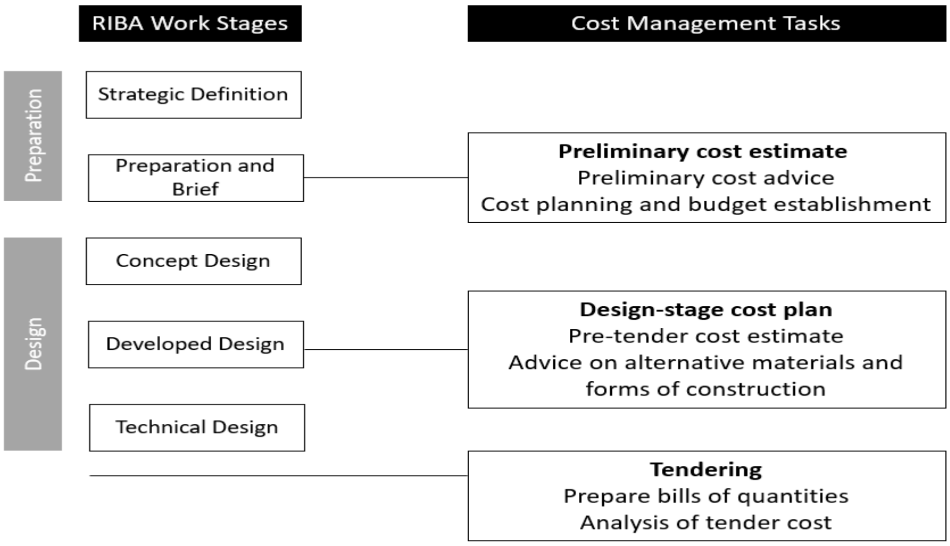

Figure 3.3 Cost management tasks linked to design stages of the RIBA Plan of Work. Reference: (Lu, Lai, & Tse, 2018, p.4)

In general, the cost engineer is considered in the large team of the design process (Czmoch & Pękala, 2014). The cost engineer works closely with the designer to consider changes and control the overall project cost. To have timely access to information, the cost engineer agrees with the designer on the information to be delivered and its delivery moment (Lu, Lai, & Tse, 2018). Throughout the design process, the cost plan which defines the customer's budgetary requirements and cost boundaries develops. The cost plan is not just a document, it is a team conversation during which interpretations and explanations occur before proceeding with the design (Eynon, 2013). During the process, the cost engineer shares his understanding of the design with clients and designers to clarify design ambiguities. With the adequate detail and clarity of information, the cost engineer computes accurate estimates. However, the cost engineer's role is not limited to computations. He provides advice on crucial cost implications and prepares comparative cost estimate studies on alternatives to expensive designs or materials. As the details develop and the estimates become more accurate, the economic viability of functional units against the total costs are justified (Lu, Lai, & Tse, 2018). The design and cost information are compared to consider design developments and their objectives. Accordingly, the update to the cost plan and alignment of the design solution with the cost are performed at the end of each design stage. With the described interaction, the design-cost communication remains synchronized (Eynon, 2013).

Conclusion on Design-Cost Estimation Integration:

Based on the design process, cost process, and interaction noted in literature, sub-question (1) on the current interaction between designers and cost engineers is covered. From the interactions pinpointed, it is clear that design and cost estimation are integrated to form a process yielding to a design made to cost. The points of interaction are stated below:

I. *The cost engineer is considered part of the design team. The cost engineer works closely with the designers to reach a design meeting the budget.*

II. *Planning between the disciplines is considered to synchronize the processes, manage input and output information, and plan for information exchanges. The design plan is prepared by the design team and other consultants, thus indicating the consideration of the cost engineer. Similarly, the cost discipline sets a plan which clarifies information required and its exchange. This is crucial since the information from the design team influences the cost estimate and its accuracy.*

III. *In the early design, the cost driving components are pinpointed to be monitored throughout the design process.*

IV. *The design team is provided with cost information.*

V. *Throughout the design process, alternatives and changes are assessed in terms of costs.*

VI. *The cost engineer discusses with the team the design and its ambiguities.*

VII. *The budget is tracked to ensure that the design made to cost. This is reached by discussing and comparing design and cost estimation at the end of each design stage.*

VIII. *As the design develops, the cost becomes more accurate and allows checking the value of the design (considering the function and the costs).*

IX. *At the technical design stage, the definite price is computed.*

X. *In the last phases, cost budgeting is performed based on information and consultations from the various disciplines, some of which relate to the design.*

XI. *With all the computed estimates, the cost engineer provides supporting details of the estimate. These include assumptions and accuracy, both of which are important for interpretation of design.*

3.2 Cost Estimate Computation

Regardless of the tool used, the cost estimate computation follows procedures and techniques that result in the cost value. Based on the different levels of project definition and design details, estimation methods are adopted. The section describes the computation of the preliminary estimate in the first sub-section and the estimate for the different design phases in the second sub-section. More details on the different estimation methods are provided in appendix C. The clarification of the computation method is compared with the case in practice in chapter 4 (section 4.2). Based on the comparison and its analysis, a 5D BIM cost estimation method is selected for the process design in chapter 5 (section 5.2). In the last sub-section, the interpretation of the computed estimate is provided to relate the design stage with the estimate's accuracy and other features. This is necessary for the preparation of the estimate and its communication between designers and cost engineers. Accordingly, this concept ensure compatibility between design and cost estimation which is used in chapter 5 (section 5.1.4).

3.2.1 Preliminary Cost Estimate

At the beginning of a project, the cost estimate is produced to check the affordability of the project and set a realistic cost limit for the client. The initial estimate is derived from information on site location, building use, requirements, planning, restraints, budget, and other specifications. From the architect, the estimator needs information on the design sketches, drawings of alternatives, design specification, and other specifications. Other disciplines such as mechanical and structural also provide the estimator with information on their specifications and risks. At this stage, alternatives and their costs are considered to reach alternative scenarios known as option costs (Royal Institute of Chartered Surveyors [RICS], 2012a). Irrespective of its low accuracy, the preliminary estimate is compulsory for high-level decision-making in the early phases of the project (Project Management Institute, 2016). It influences the feasibility and profitability of the project (Lu, Lai, & Tse, 2018).

The preliminary cost estimate is computed from little information which includes parameters at the general level of the project (such as size, location, type). The information is analyzed with respect to previous similar projects to provide an estimate with a low level of accuracy (Lu, Lai, & Tse, 2018). Several methods can be utilized to provide an estimate by referring to previous projects. The initial estimate can be computed using any of the following methods: [1] parametric estimate calculated from statistical data, [2] an analogy estimate inferred from the comparison of features of the given project to those of completed projects and adjustments of costs according to differences, or [3] an estimate based on expert judgment providing specialized knowledge from previous work (Kerzner & Kerzner, 2017). Other predictive approaches evolved with the introduction of artificial intelligence (AI). One interesting approach is Case-Based Reasoning (CBR) which has been successfully used within the domain of cost estimation (Ahn, Park, Lee, Ahn, Ji, Song, & Son, 2017). CBR is a problem-solving method which exploits cognitive learning and applied adaptations of intuitive solutions from past experiences to suggest solutions for present cases (Chou, 2009). Another AI method is Neural Networks (NN) which enables multi- and non-linear relationships among studied variables (Günaydın & Doğan, 2004). As a model, NN considers unrestricted sets of input and output variables linked by weights derived by a learning algorithm (Kim, An, & Kang, 2004) which depends on historical data (Günaydın & Doğan, 2004).

3.2.2 Estimates during the Design

During the design stages, an elemental cost plan is prepared. The cost plan is the decomposition of the project's cost limit into cost targets assigned to each element of the project. Having the elements defined, the elemental cost plan is made to distribute the budget into target costs for each of the elements forming the project. The target costs suggest a total expense of an element as derived from sub-elements and components. Therefore, the plan shows the proposed distribution of the budget based on the project and design team's perspective and sets the limits to develop the design with cost control. Furthermore, the plan considers the Work Breakdown Structure (WBS) and Cost Breakdown Structure (CBS) (RICS, 2012a). The WBS develops with the cost plans as the project is successively broken down to main components and sub-components. During the process of forming the cost plans, the CBS progresses by allocating costs to elements at the different levels of the WBS (RICS, 2012b). Both breakdown structures are coded to enable the easy formation of work packages. Moreover, the coded plan is used as a reference to check cost targets and cost limits as information develops. This cost plan process iterates as design details increase (RICS, 2012a).

The computation of the detailed estimate could be based on three-point estimate, Monte Carlo simulation, or bottom-up analysis. Three-point estimating calculates 3 estimates based on an assumed distribution. From these 3 points, an expected cost and an uncertainty range are reached. Monte Carlo simulation adopts statistical distributions to model the construction costs (Project Management Institute, 2016). The bottom-up method is done based on defined engineering data from complete plans, specifications, (Kerzner & Kerzner, 2017) detailed working drawings, and chosen construction methods (Halpin, Lucko, & Senior, 2017). With the complete information, the estimator uses unit pricing. Unit pricing is the application of price per unit cost from the company's records and correction factor to the specific quantity. The reserved historical data on unit prices are based on average values obtained from recent jobs whose crew composition and production rates are different. To consider the uniqueness of the job, the estimator applies his intuition to adapt values to conditions of the project and characteristics of the job. More accurate cost analysis is applied to big ticket items which require deep analysis since they influence the overall estimate (Halpin, Lucko, & Senior, 2017).

With the detailed design made available, the detailed estimate is computed after analyzing elements listed in the Bill of Quantities (BoQ) following elemental cost planning (Lu, Lai, & Tse, 2018). Based on the WBS from earlier cost plans, the BoQ is prepared. The BoQ provides a coordinated list of items, their descriptions, and quantities. The quantities are extracted from drawings, schedules, and detailed specifications on material, workmanship, and performance criteria (RICS, 2012b).

3.2.3 Cost Estimate Interpretation

A general guideline is set to avoid the miscommunication between stakeholders preparing the estimate and those using it. The guideline also reduces the space of misinterpretation of the cost estimate and its use. This guideline categorizes cost estimates according to various characteristics to reach a generally accepted classification system. Primarily, the estimate classes are formed based on project definition. Then, the estimate classes are linked to secondary characteristics which include: estimating methodology, expected accuracy range, and effort (resources, time, and cost). Furthermore, the estimates are related to the typical phases and gates for decision-making, approval, and execution. (Christensen & Dysert, 2003). Table 3.1 depicts this classification system with the different characteristics which are briefly explained in the table headings. This table enables checking for compatibility between design and cost estimation as considered in chapter 5 (section 5.1.4).

Table 3.1 AACEI Generic Cost Estimate Classification Matrix

	Primary Characteristic	*Secondary Characteristic*			
ESTIMATE CLASS	**LEVEL OF PROJECT DEFINITION** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical +/- range relative to best index of 1 [a]	**PREPARATION EFFORT** Typical degree of effort relative to least cost index of 1 [b]
Class 5	0% to 2%	Screening or Feasibility	Stochastic or Judgment	4 to 20	1
Class 4	1% to 15%	Concept Study or Feasibility	Primarily Stochastic	3 to 12	2 to 4
Class 3	10% to 40%	Budget, Authorization, or Control	Mixed, but Primarily Stochastic	2 to 6	3 to 10
Class 2	30% to 70%	Control or Bid/ Tender	Primarily Deterministic	1 to 3	5 to 20
Class 1	50% to 100%	Check Estimate or Bid/Tender	Deterministic	1	10 to 100

Notes: [a] If the range index value of "1" represents +10/-5%, then an index value of 10 represents +100/-50%.
[b] If the cost index value of "1" represents 0.005% of project costs, then an index value of 100 represents 0.5%.

Note: Source (Christensen & Dysert, 2003)

3.3 Application of BIM

The application of BIM for cost estimation is studied in this section. First, the connection between design, cost estimation, and BIM is clarified. This sub-section is necessary to incorporate BIM into the design-cost estimation process to be designed in chapter 5. The consideration of BIM is further clarified in the second and third sub-sections. The second sub-section presents the preparation for BIM utilization and the third sub-section introduces some of the ways mentioned in literature on BIM-based cost estimation. Finally, the limitations addressed in literature are noted. These limitations shall be avoided in the process designed.

The application of BIM in theory is compared to the case in practice in chapter 4 (section 4.3.3) to identify issues hindering the utilization of 5D BIM. Furthermore, theory on the connection of BIM with design and cost estimation along with the preparation and utilization of BIM are considered in the design of the process in chapter 5 (sections 5.1.3, 5.1.4, 5.1.5, and 5.2). They aid the specification of BIM-related tasks, parties involved, and agreements to facilitate the implementation.

3.3.1 Connection between BIM, Design, and Cost Estimation

BIM offers flexibility of information exchange, interoperability, and digital representation. This ability improves collaboration and communication between project participants. However, it requires configuration and alignment of BIM with project work processes (Hartmann et al.,2012). In the early phases of the project, the conceptual design considering alternatives is facilitated by BIM as options are developed quickly and discussed with stakeholders. Furthermore, BIM provides information and simple visualizations that aid the assessment of the different techniques, cost implications, and environmental factors. With such capabilties, the feasibility study of the design options and the selection of the preferred alternative is equiped with necessary information (Chartered Institute of Building, 2014). For this purpose, schematic BIM models considering simple geometries with generic and standard components are designed. These models are made flexible to enable iterations in early design phases (Sabol, 2008). From these models, the preliminary estimates are computed based on extracted parameters and linked cost database (Lu, Lai, & Tse, 2018). As the project progresses to the detailed design, complexity and level of detail increase. Accordingly, quantities are extracted and linked to cost estimating assembly items to eventually find the detailed estimate (Lu, Lai, & Tse, 2018). As described above, figure 3.4 shows the BIM use for connection to design process defined in the RIBA work stages and cost management stages.

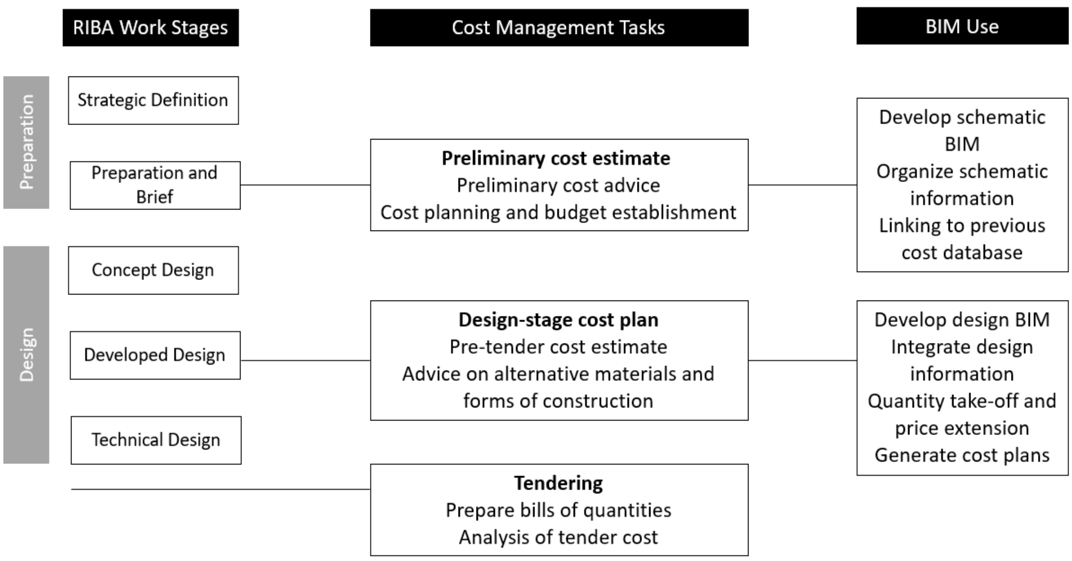

Figure 3.4 Cost management tasks and BIM use linked to RIBA Plan of Work stages. Reference: (Lu, Lai, & Tse, 2018, p.54)

3.3.2 Preparation for BIM

The implementation of BIM is based on BIM Execution Plan (BEP) which shows the workflow and clarifies the interaction between processes. With the BEP, the input information is made compatible for future uses and delivered efficiently (Hadzaman, Takim, & Fadhil, 2016). Beginning with the end in mind, downstream uses of BIM are set to specify supporting information and exchanges. The details of the synchronization between information and objectives are illustrated in process maps which are part of the BEP. Having the plan with the process maps, the team implements BIM by following, monitoring, and updating the plan (Computer Integrated Construction Research Program, 2010).

For the case of cost estimation, the cost engineer's view is necessary for identifying the information for estimating, level of detail, and object development. The required level of detail is dictated from project phases since cost estimation via BIM can be performed throughout the project lifecycle (Sabol, 2008). Furthermore, design and cost estimation teams collaborate to define the level of detail (Lu, Lai, & Tse, 2018). Concerning the level of development (LOD) of the model, it is considered for each phase to ensure the input of compulsory data (Monteiro & Martins, 2013). With the LOD framework, model authors can identify the tasks their model supports, and downstream users can note the usability and limitations of received models (Smith, 2016).

The available information can be exchanged between BIM and costing applications by adopting the approach Standardizing Data Models and Definitions. This approach ensures consistent definitions and formats of objects (Sabol, 2008). Thus, the information in BIM considers specifications from external tools, classification systems, and standardized representation of objects with associated attributes (Mukkavaara, Jansson, Holmberg, & Sandberg, 2016). Metadata attributes are used to represent aspects of the objects to clarify their content, identify them, or provide technical properties (Schapke, Beetz, König, Koch, & Borrmann, 2018). Accordingly, object-based 3D model with metadata is formed to enable information sharing and collaboration (Shim, Yun, & Song, 2011). One crucial metadata is the standard coding of elements. The unified code with predefined vocabulary follows established standards of classification systems which standardize the data structure (Afsari & Eastman, 2016; Schapke et al., 2018). A specific example of the standardizing approach is Industry Foundation Class (IFC) that is used to facilitate the information exchange among participants (Sabol, 2008). IFC is a vendor-neutral data exchange format that covers geometric and semantic information on properties and relationships using an object-oriented approach (Borrmann, Beetz, Koch, Liebich, & Muhic, 2018). Through IFC and its object-oriented data model class-based structure, information sharing and communication between applications are facilitated. Therefore, the application of standards and IFC yield to interoperability such that systems within an organization are integrated and collaboration is triggered (Chartered Institute of Building, 2014).

Figure 3.5 shows the transformation of work practice upon the introduction of IFC. Construction tools are considered islands of automation since they either do not support data exchange or have limited capabilities. For this purpose, data exchange format between applications shall be uniform with clear geometric information and meaning (Borrmann et al., 2018). Thus, IFC ensures the latter and connects the different disciplines to a shared model.

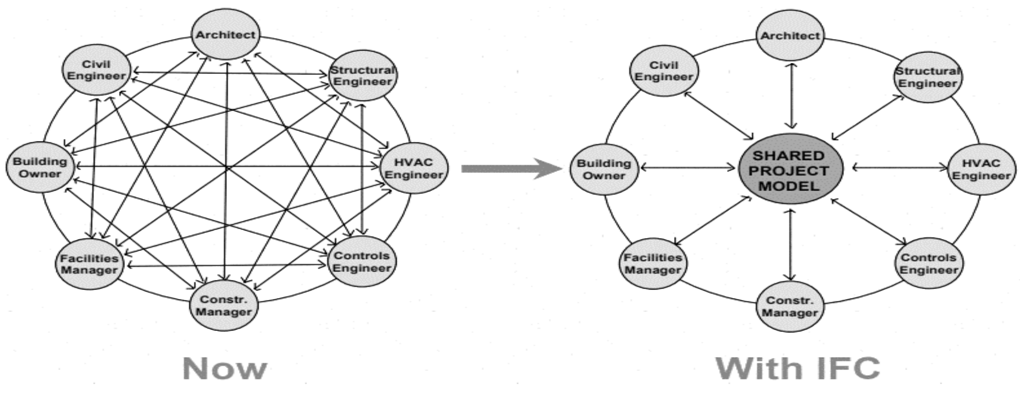

Figure 3.5 Integrated project model using IFC in comparison with traditional practice. Reference: (Tulke, Nour, & Beucke, 2008)

3.3.3 BIM-based Cost Estimation – 5D BIM

The estimation of costs through BIM can be attained in different ways. Three options are described: IFC for cost estimation, BIM-based quantity take-off, and cost estimating software. The last sub-section is dedicated to list some limitations to cost estimation via BIM. The information in this section is important for the incorporation of 5D BIM to the designed process in section 5.2. Furthermore, the methods consider checks to ensure compatibility. These are adopted in section 5.1.4.

<u>[1] IFC for Cost Estimation:</u>

IFC can provide meta-models that cover various semantic extensions relevant for numerous applications. This flexibility enables the creation of unique schemas to be added to a model, transported to other tools, and read by the software. The consistency of information organization is described in metadata schemas (Schapke et al., 2018). A schema or model is composed of entities, attributes and relationships (Xu, Liu, & Tang, 2013). Within the schema of the IFC model, objects' characteristics can be defined using attributes. These characteristics are added using static attributes available in the schema or dynamically created properties. Unlimited number of properties can be added with its own object property definition which includes name, type, and unit (Borrmann et al., 2018). For cost estimation based on IFC standards, a study built an information model for BIM-based costing application. The model focused on cost estimating for tendering in China using entities that are connected to form the cost estimation model. The addition of relationships is done using entities and algorithmic association which are utilized to establish any mathematical model (Zhiliang, Zhenhua, Wu, & Zhe, 2011).

<u>[2] BIM-based Quantity Take-off for Cost Estimation:</u>

With information organized by the WBS and structured by classification systems, automation of cost estimation becomes possible. The WBS can be decomposed to different classification systems such as UniClass, MasterFormat, OmniClass, or Uniformat. The classification systems lead to an organized grouping of quantities. For instance, if a classification system based on physical space is used, the model considers merging elements to get the quantities corresponding to a package of the WBS depicting space (Mattern, Scheffer, & König, 2018). Furthermore, the grouping of components in BIM shall match the grouping of quantities into cost items set by the estimator. Otherwise, the estimator has to edit the quantities manually (Lawrence, Pottinger, Staub-French, & Nepal, 2014). Thus, the WBS can be integrated to the CBS. The information on cost can be considered for the items of the third level of the WBS as shown in figure 3.6 (Liu, Lu, & Al-Hussein, 2014).

Having the WBS set, the model requirements can be derived so that the model matches the WBS. Accordingly, quantities are extracted from the model based on the WBS. These quantities become the basis for pricing and generating BoQ. (Mattern, Scheffer, & König, 2018) The figure illustrated a WBS for shell work based on Uniformat II classification.

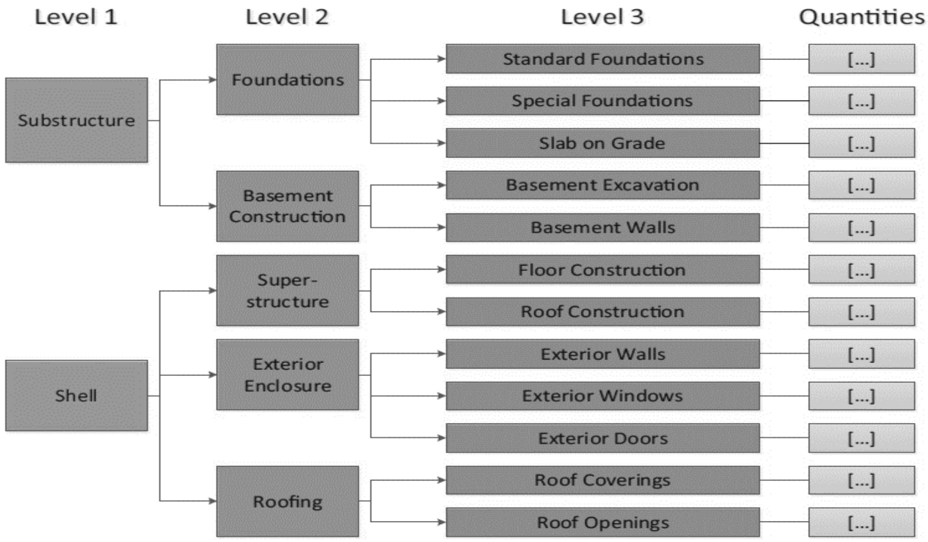

Figure 3.6 WBS relation to quantities example. Reference: (Mattern, Scheffer, & König, 2018, p.385)

A BIM-based Quantity-takeoff requires the alignment of BIM with the estimating process such that there is compatibility between the level of detail of the model and the estimate to be generated (Hartmann et al., 2012). Figure 3.7 illustrates the work flow to reach a BIM-based quantity take-off. The elements between the WBS and BIM model are linked given that the level of detail of both is compatible. Otherwise, the model is revised till object linking is enabled. In case of low level of detail of WBS, elements are grouped before linking. Both cases occur as the project progresses with disciplines having different levels of detail. Furthermore, elements which require high effort to be added to the model are identified from the WBS and considered for manual calculations (Mattern, Scheffer, & König, 2018). This workflow is used in section 5.1.4 to ensure the compatibility between design and cost estimation.

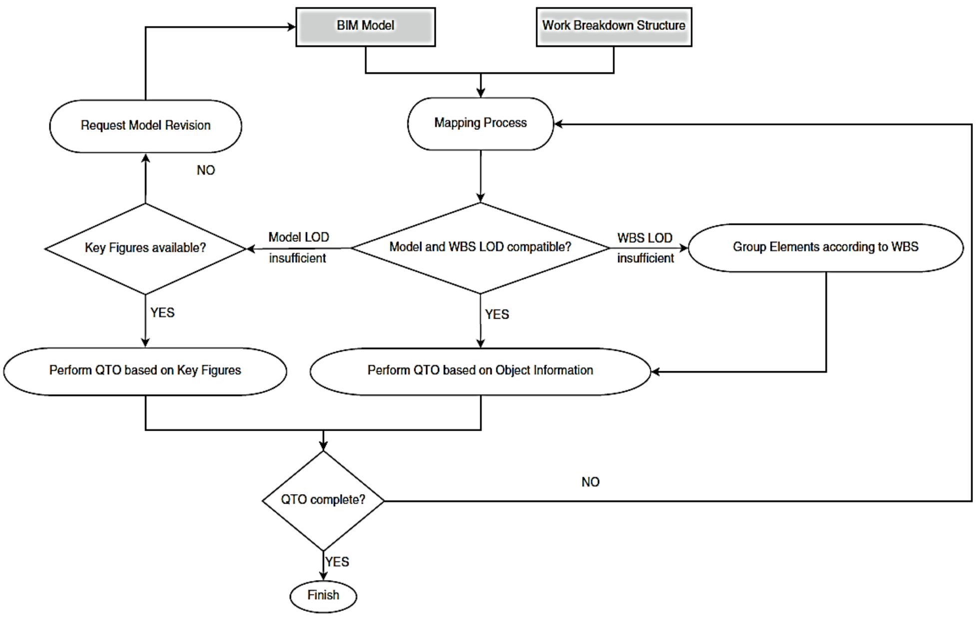

Figure 3.7 Work flow of BIM-based QTO. Reference: (Mattern, Scheffer, & König, 2018, p. 389)

For the computations, the cost engineer adds manually some input data even though quantities are extracted automatically (Monteiro & Martins, 2013). The BIM model with its level of information do not realize all quantity take-off requirements. Quantity take-off does not depend solely on geometric information and physical elements, it requires information on the functionality and properties such as material. For this purpose, modeling rules shall be defined in the initial project phases (Mattern, Scheffer, & König, 2018) and the modeler shall collaborate with the estimator to build the suitable model (Hartmann et al., 2012). Having done that, the quantities are extracted. Most BIM tools can extract quantities and export them to a spreadsheet or external database. The use of Excel is sufficient, yet it requires setup and standardization of the modeling process (Eastman et al., 2011). Spreadsheet for cost estimation is noted as effective and efficient since it can be imported and exported to most BIM tools. Therefore, the combination of BIM software and Excel leads to practical 5D BIM considering the knowledge and experience of cost engineers (Kim & Park, 2016).

[3] Cost Estimation Software:

BIM-based cost estimation could be performed by having a BIM software and a cost estimating tool communicating unidirectionally or bidirectionally. The information must at least be transferred from BIM and read by the cost tool. For this purpose, standardization using interoperability language such as IFC is crucial for the different tools. Furthermore, classification systems are adopted by the software (Abanda, Kamsu-Foguem, & Tah, 2017).

This is done based on object-oriented approach that enables direct information sharing using standard data format or an add-in program (Niknam & Karshenas, 2015). Through plug-ins such as Sage Timberline and Vico estimator, the estimate can link model-objects to cost database and recipes of an estimating package (Eastman et al., 2011). Despite the various capabilities of software, professionals prefer the utilization of simple cost models which are based on quantities (Cheung et al., 2012). Furthermore, there is not a tool with the capability of full-automatic estimation from the model since only a portion of the information required for the cost estimate is provided in the model. The remaining information is added by the estimator based on rules and analysis (Eastman et al., 2011).

3.3.4 Limitations and Conclusion

From literature, various limitations for the application of BIM for cost estimation are identified. Some of these limitations are listed below.

- Currently, IFC focuses on buildings, but extensions to describe civil engineering infrastructure are in development (Borrmann et al., 2018). Furthermore, there are some issues noted with the use of BIM tools whose object schemas are not compatible with the IFC objects and properties (Cheung et al., 2012).

- Usually, cost estimation uses databases on unit costs and supplier data which shall be frequently and manually updated. This is necessary to consider the economic and supply/demand fluctuations that influence the price (Niknam & Karshenas, 2015).

- Design changes do not impact quantities solely, other aspects (such as construction methods) may be affected but are not easily detected (Lawrence et al., 2014).

- Cost estimation requires the assessment of conditions whose automatic identification remains a challenge for BIM tools. These conditions include the uniqueness of components, assembly, or site conditions (Lawrence et al., 2014). Furthermore, the information on construction processes is important for labor and equipment considerations that are part of the cost estimate. However, such information is not available in the model. Thus, this challenges the automation of this part of the estimate (Shen & Issa, 2010).

Conclusion on BIM-based cost estimation:

The section on BIM application addressed sub-question (2) on the application BIM/5D BIM. The answer to this question summarizes the outcome of section 3.3 that is used in chapter 4 (section 4.3.3) for the comparison between literature and practice to identify the obstacles to 5D BIM application. Furthermore, the concepts of this section enable incorporating BIM to the integrated design and cost estimation process in chapter 5 (sections 5.1.3, 5.1.4, and 5.1.5).

The preparations for BIM include the BIM execution plan and the process maps. These are necessary for the successful implementation of BIM since they ensure synchronization and flow of required information. This relies on thinking with the end in mind. Furthermore, the standardization of data and object representation is stressed. This is essential for the interoperability of information between disciplines.

For the specific application of 5D BIM, BIM-based cost estimation methods investigated from literature are described briefly. The studied methods are:

I. *IFC models that link entities and their attributes with relationships can be prepared for cost estimation. These models are readable by various software. However, a major limitation of IFC is noted. It is developing so it is currently limited to buildings. Moreover, issues arise with some BIM tools.*
II. *BIM-based quantity extraction facilitates cost estimation by having structured information and following the WBS. The quantities of elements can be merged in a way suitable for the cost engineer. In this method, the cost engineer collaborates with the modeler to have a suitable model. Moreover, he has to proceed with manual inputs and manual calculation of complex elements.*
III. *Another method is related to the different software to be used. Some are related to exporting quantities to Excel or importing quantities with specific tools while others link the components to costing software. There are various tools with special features. However, the utilization of simple tools is preferred by professionals.*

A final inference on the application of BIM for cost estimation is as follows:

Despite the deviation towards automation and digitalization, the responsibility of the outcomes remains with the engineer who shall periodically check the results. Accordingly, the translated guidelines or codes must be machine and human readable. The target is not only to cover the different information but to have it understandable and traceable for the users. Full-automation without user-involvement is not desirable due to the loss of trust in the system that lacks transparency. Therefore, full-automation is replaced with semi-automated approach enabling human interpretation. (Preidel & Borrmann, 2018)

4 Findings from Case Study Research: RHDHV

The chapter focuses on the case study RHDHV. The case study enables studying the current situation of design, cost estimation, their interaction, and utilization of BIM in practice through interviews and documentation. In the first section, the design and cost estimation processes are described in practice to explore the relation between the two disciplines and compare it to literature. Accordingly, the status of integration between design and cost estimation in practice is concluded. In the second section, the computation approach is studied in practice and compared to literature. In the third section, the application of BIM/5D BIM in practice is described. Then, they are compared to literature to conclude the connection of design and cost estimation via BIM. Finally, the last section derives the issues noted in practice. These issues are addressed in the design of the process. Furthermore, the suggestions for improvements noted by designers, cost engineers, and BIM experts are presented. These will be adopted to the process design. The interview transcripts used in this chapter are in appendix D.

4.1 Design and Cost Estimation Integration in Practice

This section studies the integration between design and cost estimation in practice. First, the design and cost estimation processes are described separately. Then, the interaction or fragmentation identified in interviews are presented. Based on the latter three sections, a final comparison with literature and assessment of integration in practice is made in the last sub-section.

4.1.1 Design Process in Practice

Through interviews with 8 designers, the design process is derived. The designers have different experiences in infrastructure projects. The diversity of the interviewees enables the thorough description of the design process. The information that is used to describe the design process is coded with DA in the transcripts. Accordingly, the design process is described below.

At the beginning of a project, the focus is on the scope (interviewee 8D, 2019) that is derived from discussions with the client (interviewee 4D, 2019; interviewee 7D, 2019). With the information from the client and basic information from standards, the design is initiated (interviewee 3D, 2019). The team members attend a kickoff meeting to define the goal and set the planning (interviewee 5D, 2019; interviewee 7D, 2019; interviewee 3D, 2019). Ideally, all disciplines join to clarify the description of the project, set the requirements, request input information, and identify the procedure to reach the specific outcome (interviewee 3D, 2019). Then, the budget is set, and the project is decomposed into different breakdown structures which clarify the workloads and packages (interviewee 8D, 2019).

In the preliminary design stage, different alternatives and their costs are studied. The choices made are reported with justifications from guidelines. In the early stages, major changes to the design are made to meet the client's desire (interviewee 5D, 2019). Throughout the process, the client's requirements are defined and evaluated relative to scope and budget (interviewee 7D, 2019; interviewee 8D, 2019). Furthermore, the design is discussed with the client who gives feedback on the design (interviewee 2D, 2019) by approving or disapproving it and requesting changes (interviewee 4D, 2019; interviewee 7D, 2019). In case of changes in the design, the design leader takes the decision to make the change. If necessary, the design leader also discusses the impact of the change on cost with other teams to allocate the additional costs to one of the teams (interviewee 6D, 2019). However, changes related to safety are applied directly and other teams adapt to the changes (interviewee 3D, 2019; interviewee 5D, 2019; interviewee 6D, 2019). Reaching the detailed design, design flexibility decreases (interviewee 7D, 2019) and optimization prevails (interviewee 3D, 2019). During the design, the design units meet at design moments to share and discuss the design (interviewee 4D, 2019). Weekly or biweekly meetings are held for communicating changes (interviewee 1D, 2019; interviewee 5D, 2019). It could also be the case that questions, clash detections, and changes are shared via email (interviewee 5D, 2019; interviewee 7D, 2019; interviewee 8D, 2019).

The composition of the design team differs depending on the project size. For small projects, the design leader with a draftsman complete the design. For big projects, the team is composed of a manager, leaders, and their teams from different disciplines (interviewee 2D, 2019). Furthermore, big projects have a BIM coordinator (interviewee 6D, 2019). The BIM expert receives the models from the different design units and merges them into one (interviewee 5D, 2019). The design models are prepared to a level of detail required by the client and the design stage (interviewee 3D, 2019).

4.1.2 Cost Estimation Process in Practice

The cost estimation process in practice is described based on interviews with 6 cost engineers. The cost engineers with various experiences enable the deep investigation of the cost estimation process. The information that is used to describe the cost estimation process is coded with CA in the transcripts. Furthermore, the document illustrating the cost estimation process at the firm is studied to help in the process description.

Cost estimation starts with the interpretation of the scope, requirements, input needed, method, and output (interviewee 1C, 2019; interviewee 2C, 2019; interviewee 4C, 2019; interviewee 5C, 2019). The consideration of cost estimation throughout the design depends on the project manager. The project manager decides if the cost engineer is an advisor involved from the start or an estimator approached at the end of the project. Either way, the cost engineer has the responsibility to estimate and review his results with others (interviewee 3C, 2019). Furthermore, the cost engineer follows his own procedure without a specific plan to reach the estimate (interviewee 4C, 2019). Yet, the cost engineer relies on project information to get the planning for the delivery of the input to compute estimates (interviewee 1C, 2019).

The cost engineer is introduced to the project based on specific information. The cost engineer does not look at all the information but focuses on information necessary for his job (interviewee 2C, 2019). Based on project information, the cost engineer clarifies the type of cost estimate (interviewee 2C, 2019; interviewee 4C, 2019; interviewee 5C, 2019). Furthermore, discussions are made in the early phases to pinpoint the information required for the cost estimate's accuracy (interviewee 1C, 2019).

The input for cost estimation is affected by deliverables from other teams (interviewee 4C, 2019). The input is comprised of drawings, quantities, risks, geotechnical reports, and other necessary reports (interviewee 1C, 2019; interviewee 2C, 2019). Teams delivering the information to the cost engineer are contacted for further clarifications (interviewee 2C, 2019). In case information is missing, the team who delivered information for the cost engineer is approached. If the information is still missing, the cost engineer makes his own assumptions, adds a risk for this value, and communicates it (interviewee 1C, 2019). Information could also be derived from Dutch government sources and open databases such as google Earth or google maps (interviewee 4C, 2019). From the different sources, information is used to make estimates. These sources of information are provided in the estimate's document (interviewee 1C, 2019; interviewee 3C, 2019). Furthermore, from the project information, the cost engineer uses the work breakdown structure that is unified for all teams to interpret the elements (interviewee 4C, 2019). Using the WBS, the cost driving components are identified (interviewee 4C, 2019) and interpreted (interviewee 5C, 2019). These items become the focus for alternatives and detailing (interviewee 3C, 2019; interviewee 4C, 2019; interviewee 6C, 2019).

When considered as an advisor, the cost engineer discusses with the team alternatives and constructability of the design during the process (interviewee 2C, 2019). Having the input, the estimate is computed based on quantities and prices (interviewee 3C, 2019). When design changes occur, the estimate is updated. However, the information is generally not coded, so it is not easy to make changes and update the estimate document (interviewee 4C, 2019).

Besides the process derived from the interviews, the document on cost estimation process referred to by some of the cost engineers is investigated. The cost estimation process follows a one sheet prepared by the company. This sheet describes the process along with a list of input, checks, and questions to be considered (interviewee 5C, 2019). The process is expected to be followed to facilitate the interaction between cost engineers, designers, and project manager (interviewee 1C, 2019). However, it is not followed by everyone (interviewee 5C, 2019).

Based on the document, the process is described as follows. The process initiates with coordination led by the project leader who determines aspects listed in the checklist such as customer, estimate goal, and information exchange. Then, the designer, project leader, and cost engineer meet to determine objects and posts. Thus, the actors clarify the decomposition of the estimate (objects) and the information to be extracted by the designer (posts). Afterwards, the design starts without the involvement of the cost engineer. However, the cost engineer and designer clarify the format for exchanging the quantities. After the design is done, the designer extracts the quantities and sends it to the cost engineer to add the price list. The latter step leads to the posts list which is checked relative to the list agreed on in the earlier step. Then, the cost engineer adds to the posts list the risks identified from the risk register that is shared with the project leader and designer. For probabilistic estimates, he adds lowest/extreme values identified in the meeting with the designer and project leader. Having done that, the cost engineer proceeds to calculate the estimate and accompanies it with a letter clarifying the assumptions made.

4.1.3 Design and Cost Estimation Interaction in Practice

The interaction of the design and cost estimation processes in practice is not standard. Some information from the interviews show integration while others show fragmentation. This coincides with the statement mentioned by an interviewee "The design and cost estimation processes could be in parallel or fragmented depending on the project" (interviewee 5C, 2019). For this purpose, both cases are described below. The information used is coded with DC in the transcripts.

<u>Consideration of Cost Engineer in the Design Process:</u>

The cost engineer's input is the designer's output (interviewee 2D, 2019). The cost engineer is responsible for identifying the information required and discussing frequently with the designer the project's inputs and outputs. Then, the designer is responsible for knowing and providing the relevant information (interviewee 2C, 2019). In the case of early consideration of the cost engineer, discussions are held in the project start-up meeting. In some cases, the cost engineer is involved in the discussions on input and output information (interviewee 5C, 2019; interviewee 4C, 2019). In other cases, the designer sits with the cost engineer in the preliminary stage to clarify the information needed (interviewee 3D, 2019), or the cost engineer prepares a list of requirements for his calculation before the initiation of the design. With the list available, the design and cost estimation processes move in parallel with direct verbal communication of changes (interviewee 4D, 2019). Therefore, the design and cost estimation teams are not integrated through software but through verbal communication (interviewee 6D, 2019). The process flows as follows.

During early discussions, the designer and cost engineer consider information that facilitates the cost estimation process. This includes object detailing in relation to quantity extraction, format for exporting to Excel, (interviewee 1C, 2019), and coding of elements (interviewee 5C, 2019). At the beginning of the design process, collaboration with the cost engineer aims at discussing alternatives in meetings (interviewee 4C, 2019; interviewee 3D, 2019). However, this is limited to big projects which consider frequent meetings between the team, including the cost engineer (interviewee 1C, 2019). During the process, discussions between the designer and cost engineer could be held to improve the design, increase the efficiency of sitework, and reduce costs. Accordingly, the cost team is consulted to make changes that reduce the cost of the project (interviewee 6D, 2019). At the agreed delivery moment, the designer extracts quantities and shares them and their explanations with the cost engineer (interviewee 1D, 2019). Then, the cost engineer proceeds with his task. If information is missing, the cost engineer asks other teams to provide missing information or the reference in the company's repository (interviewee 2C, 2019). When the design changes, it is the cost engineer's task to track changes, update the estimate, and note the changes made (interviewee 5C, 2019).

Throughout the process, communication between the designer and cost engineer aims at discussing input/output information, requesting measurements, asking for reviewed calculations, and checking values in 3D models (interviewee 1C, 2019). Communication could be made face to face or through emails to discuss questions, provide advice (interviewee 5C, 2019), and clarify problems or changes (interviewee 4D, 2019). Communication could also be done digitally using drawings to clarify explanations and specify design versions on design changes (interviewee 1C, 2019; interviewee 5D, 2019).

<u>Design - Cost Estimation Fragmentation:</u>

The fragmentation between the design and cost estimation processes is encountered at the company (interviewee 2C, 2019) due to project size, budget constraints, and time limitations. For small projects, the information is passed to the cost engineer upon completing the design. Budget constraints do not allow the early involvement of the cost engineer (interviewee 3C, 2019). In other cases, time limitations prohibit the early communication with the cost engineer (interviewee 3D, 2019).

In the case of fragmentation, the design develops without close interaction between the design and cost teams (interviewee 2D, 2019). The cost engineer is introduced to the project at the end (interviewee 1C, 2019; interviewee 2C, 2019: interviewee 5D, 2019). Moreover, he is provided with quantities to compute the estimate (interviewee 2C, 2019). Thus, the cost engineer reacts but does not interact in the process (interviewee 8D, 2019). In such cases, the focus is on safety guidelines, so costs are neglected (interviewee 3D, 2019; interviewee 7D, 2019) and changes are not communicated to the cost engineer (interviewee 4C, 2019). Furthermore, communication is limited to answering questions (interviewee 2D, 2019). As the cost engineer estimates costs, he will frequently ask questions about the design since he was not considered earlier (interviewee 3D, 2019; interviewee 5D, 2019).

Being introduced at the end of the process, the cost engineer is provided with lots of information for the large number of involved components. Then, it becomes hard for the cost engineer to find the needed information (interviewee 3C, 2019). Furthermore, problems in compatibility between cost estimation accuracy and design details might arise. This happens due to the absence of guidelines to specify the information required for a certain level of accuracy (interviewee 7D, 2019). Neglecting cost information might lead to rework to adapt the design representation to consider cost estimation information (interviewee 2D, 2019). Resolving arising issues and reaching the final estimate, the budget is assessed. If the estimations exceed the budget, design optimization and rework dominate till the budget is met (interviewee 8D, 2019; interviewee 3D, 2019). Such a situation happens since the designer does not consider the cost aspect (interviewee 7D, 2019).

4.1.4 Design and Cost Estimation Integration: Comparison and Conclusion

Upon studying the design and cost estimation processes in general, the comparison with standards and literature is made. The comparison shows the similarities in terms of information extracted from both literature and practice. The differences noted correspond to details mentioned only in literature or only in practice. Starting with the design process, figure 4.1 clarifies the comparison made with the process described in literature in section 3.1.1.

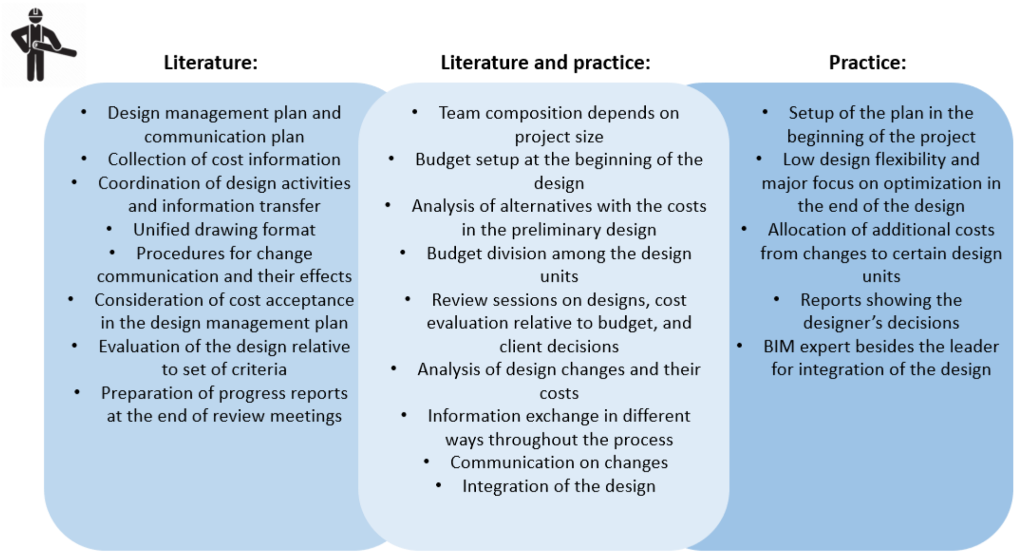

Figure 4.1 Comparison of design process, literature vs. practice

Based on the comparison above, the design process in practice coincides with most parts from literature. This is especially the case for cost-related activities as listed in literature and practice section of the figure. The differences noted are mainly related to the management and communication plans. The plans are considered in detail in literature. On the contrary, practice mentions briefly the setup of the plan considering inputs and procedures to reach the output. However, throughout the design process in practice, it is clear that aspects from the plans (such as change communication, cost acceptance, coordination of activities) as described in literature are addressed. Another difference is the focus on optimization at the end of the design in practice while literature states design detailing at this stage. Therefore, practice continues to redesign till late stages while literature focuses on detailing the selected option.

Considering the cost estimation process from literature in section 3.1.2 and practice, figure 4.2 shows the comparison.

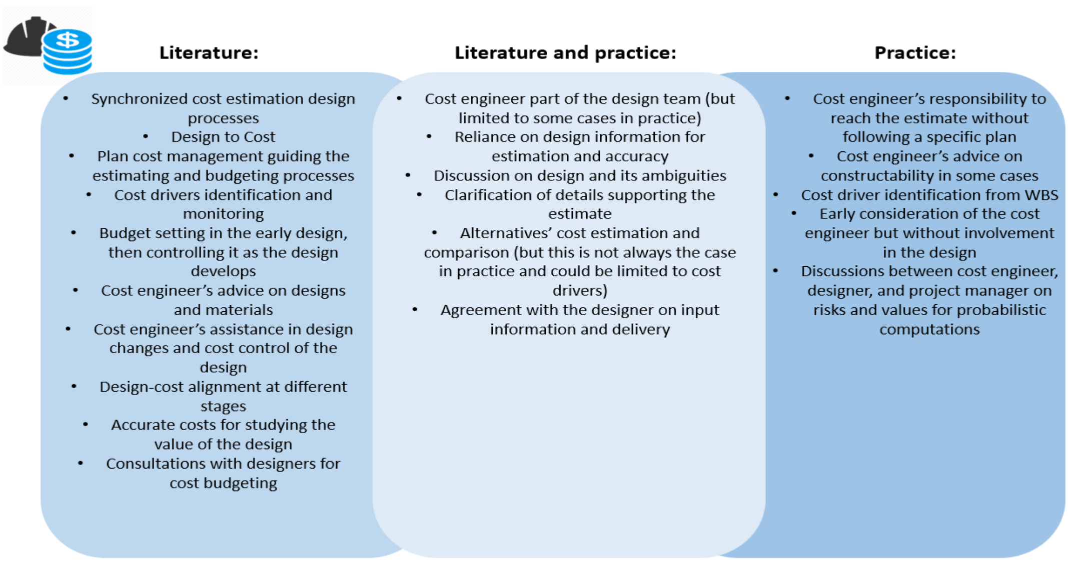

Figure 4.2 Comparison of cost estimation process, literature vs. practice

From the above comparison, the cost estimation process in practice lacks major points found in literature. Most of the points in literature which show the involvement of the cost engineer in the design process are not communicated in practice. The early consideration of the cost engineer is noticed in practice, but points showing his involvement throughout the process are missing or are limited to certain cases. For instance, the identification of cost driving components at the start of the project is common with literature but the latter further mentions monitoring these costs. Due to these differences, the cost estimation process in practice does not always flow with the design process.

After looking at each of the processes, it is concluded that the difference between the designers' perspective and cost engineers' perspective is major. On one hand, designers mention in their process description the involvement of the cost engineer in a way similar to that in literature as described in section 3.1.3. On the other hand, cost engineers show their limited involvement in the design process. This situation is also reflected in the design and cost estimation interaction derived from both disciplines. The close investigation of the interaction had information showing fragmentation and others showing the consideration of the cost engineer. The case of fragmentation is communicated by all 8 interviewed designers and 5 out of 6 cost engineers. The case of early consideration of the cost engineer was addressed by 4 out of 8 designers and 4 out of 6 cost engineers with interviewees 3D, 1C, 3C, 4C, and 5C mentioning its limitation to big projects. Looking at these results, designers' perspective changed as they all mentioned fragmentation. This is justified by the fact that the description of the design process considers the cost component at a general level in terms of budget, alternatives' costs, and budget evaluation. However, the elaboration on monitoring this cost component throughout the process is not concrete. Therefore, when designers were asked specific questions on their interaction with cost engineers, their perspective changed. Since monitoring the cost component in the design is a core idea of the cost estimation process, the perspective of cost engineers remained the same after the detailed discussion on interaction. They still mentioned the early consideration and limited involvement in the design.

In conclusion, the interaction in practice is not completely fragmented nor sufficiently integrated. The case of fragmentation is reported by most of the interviewees and the case on integration is limited to certain cases (big projects and depending on availability of budget and time). Thus, one could infer that cost estimation is not sufficiently incorporated in the design process as noted in literature in section 3.1.3. Furthermore, the current situation of limited integration in practice is not effective since design is not made to cost. Interviewees mentioned that design optimization prevails at the end of the process in order to meet the budget.

4.2 Cost Estimate Computation

For computing the estimate, the cost engineer applies his own coding scheme and grouping to facilitate his job and track changes (interviewee 1C, 2019). The coding is agreed on with the project manager but is not linked to other input information. For the first estimation, the cost engineer uses expert judgment to set the budget (interviewee 4C, 2019). Then, the cost engineer identifies the cost driving components which cover 80% of the costs and make up 20% of the items (interviewee 3C, 2019; interviewee 4C, 2019; interviewee 6C, 2019). During the process, the bottom-up method is used for estimation in the different design phases (interviewee 5C, 2019). The accuracy of the computed estimate is defined based on the client, project phase, (interviewee 1C, 2019; interviewee 4C, 2019) and level of information provided (interviewee 2C, 2019).

For the computations, quantities and unit prices are analyzed together to reach an estimate (interviewee 4C, 2019). The quantities provided are checked based on samples from cost driving items (interviewee 5C, 2019). The unit prices are influenced by many factors. They are derived from experience, market, or database (interviewee 2C, 2019; interviewee 3C, 2019; interviewee 4C, 2019). Moreover, they are derived from past projects which are used as a reference for the cost engineer (interviewee 1C, 2019; interviewee 5C, 2019). However, the information from past projects is not preserved in structured databases (interviewee 1C, 2019; interviewee 5C, 2019). Even if quantities are automatically computed, the cost estimating process requires the analysis of the engineer. The cost engineer interprets the process, necessary items, and risks (interviewee 6C, 2019). In addition, the quantities extracted are not always finalized. The cost engineer adds information to the quantities to calculate the estimate (such as adding information to find the volume or split the design in another way) (interviewee 2C,2019; interviewee 5C, 2019).

Having the necessary information, the estimate is computed based on the Standaardsystematiek voor kostenramingen – SSK 2010 (SSK) (CROW, 2010) model in Excel (interviewee 1C, 2019; interviewee 2C, 2019; interviewee 3C, 2019; interviewee 4C, 2019; interviewee 5C, 2019). The SSK model referred to is studied from the available document. The SSK model investigated from the company's repository is an Excel file with general headings. The headings mention titles such as direct cost without further detailing. Therefore, the Excel SSK model does not cover lists of elements with standard codes. The cost engineer fills all necessary information and outcomes in the Excel file. He adds the codes (if agreed on to use), the quantities, the prices, and the variations.

Compared to literature in section 3.2.2, the cost estimate computation in practice relies mainly on two methods, expert judgement and bottom-up approach. Furthermore, the cost engineer's interpretation, information addition to compute the estimate, and evaluation of the estimate's accuracy are mentioned in practice as in literature. Another similarity is that Both, practice and literature, mention the focus on big ticket items that influence the estimate. However, a major difference is that literature mentions the setup of target costs in a plan to control the cost of the design as it develops while practice disregards this point. Furthermore, the organization of the estimate in practice is different from literature. In practice, codes are only used by the cost engineer to facilitate his job. On the contrary, the codes in literature are synchronized between the WBS and CBS to have an easily accessible reference for checking target costs.

4.3 BIM in Practice

The section on BIM considers the preparation and implementation of BIM/5D BIM as experienced in practice. This shows the strategies applied in trials for 5D BIM implementation in RHDHV. Finally, BIM application in practice is compared to literature on BIM. The information on BIM is coded with BU in the transcripts.

4.3.1 BIM Preparation in Practice

BIM manages the information through structuring, presenting, and transferring the information for all parties (interviewee 4B, 2019). For this purpose, BIM-based projects start with preparations of BIM execution plan which includes process maps. The execution plan clarifies the workflow by considering the level of development of BIM at specific moments in the project lifecycle (interviewee 2B, 2019). Furthermore, the team clarifies the process to collaborate and complete the project (interviewee 8D, 2019). With the execution plan, the information is structured, the processes are made explicit, and the agreements are clarified (interviewee 2B, 2019; interviewee 3B, 2019).

To prepare the execution plan, discussions are held with the client (interviewee 1B, 2019). Moreover, the team discusses the conditions and process to complete the project in BIM (interviewee 2B, 2019). The different disciplines in the team provide information on their tasks (interviewee 2B, 2019; interviewee 3B, 2019). These are considered in the process map which brings everything together. The map considers the input, output, software, and integration of models (interviewee 1B, 2019). Accordingly, the agreed process and management of information are set (interviewee 2B, 2019). Throughout the project, the execution plan progresses with the project and is communicated with the involved engineers. Furthermore, the BIM coordinator manages the integration and connection between the various processes and models (interviewee 3B, 2019).

4.3.2 BIM Implementation in Practice

The projects are designed in 2D or 3D, depending on the size of the project (interviewee 4D, 2019). For the preparation of the 3D model, specific objects are detailed more than others (interviewee 5B, 2019). Furthermore, some components of the 3D model could be detailed in 2D drawings for simplification (interviewee 6D, 2019). Detailing the whole model is time-consuming, so the 3D modeler tries to make a model fit for purpose (interviewee 5B, 2019). However, miscommunication still occurs, thus leading to unnecessary information in the model (interviewee 1B, 2019).

To prepare the model, communication between different actors is necessary. The information from the different actors is added and linked to the complex model (interviewee 3B, 2019). Therefore, the features added to the model depend on the client's needs and deliverables (interviewee 2B, 2019) along with the input requested from the different disciplines (interviewee 4B, 2019). However, the addition of too much information leads to a big model that cannot be well structured or easily understood (interviewee 3B, 2019). Therefore, the strategy is to look ahead to consider later stages and information extraction (interviewee 1D, 2019, interviewee 7D, 2019). Accordingly, the BIM manager, BIM coordinator, and project manager have discussions to identify the features to be considered in the model. Furthermore, the model outputs are discussed with the modeler before including them in the process. The modeler checks if the desired output can be reached. The BIM modeler also gives insight for integrating information and reaching faster processes (interviewee 1B, 2019). The engineers who produce the model are also consulted. The consultations lead to the preparation of a model with suitable characteristics such as attributes, classification system, and level of detail (interviewee 2B, 2019). The level of detail of the model is agreed with the client since it depends on the budget allocated and time given (interviewee 1B, 2019). As the model develops throughout the project, the progress in terms of detailing the model has to be monitored to ensure that allocated time and effort are synchronized (interviewee 3B, 2019).

In case cost estimation is considered in the model, the following points are crucial for model development: [1] the investment in time to prepare a live integral process, [2] the formation of a credible 3D model, [3] the early development of a list of the required information for the computation of the estimates, [4] the preparation of good standardized templates to link the BoQ, and [5] the frequent communication, verbal and electronic through BIM (interviewee 4D, 2019). With such a model, the design changes are directly reflected in the linked models (interviewee 6D, 2019). For the cost component, the quantities can be extracted from the model, but the price is not directly connected. Since pricing depends on suppliers or other conditions and the cost engineer considers different details to set a value, the addition of prices to the model is complicated (interviewee 1B, 2019).

Even though the automation of the cost estimation process is challenged, trials have been made to consider the cost information in the model. Some of these strategies are described below.

<u>Applied Strategies:</u>

Connecting the design to cost estimation, engineers are currently working on automating the system based on bottom-up approach (interviewee 5C, 2019). The connections through IFC are not always considered since they are not used in the Netherlands (interviewee 2B, 2019). IFC is still developing and problems in its utilization are noted as the file is not being read in the same way by different software (interviewee 1B, 2019). Thus, other approaches are followed.

In one of the trials to integrate the design and cost estimation processes, the teams made their own codes for elements. During the implementation, the complexity increased as the project progressed. This led to complications in keeping the codes of the 2 teams consistent (interviewee 3C, 2019). Difficulties occurred when the project became complex and the engineers tried to catch all the details. This strategy leads to lots of work and increases the risk of making mistakes (interviewee 6C, 2019). Therefore, this attempt was considered not satisfactory (interviewee 5D, 2019).

Another strategy is derived from a 3D modeler for dike designs. The interviewee considers this process more efficient compared to earlier approaches. For this purpose, information on the process is studied from this interviewee's transcript and shared documents (Excel files and presentation on the process). First, the necessary requirements and their representation are discussed. The discussions are monitored with a checklist on agreements to be made before the start of the project. The agreements cover the attributes, codes, and standards considered in the model. In the model, the attributes and codes are mapped to the quantities extracted using Navisworks. The quantities are checked based on a prepared review sheet. Finally, an Excel sheet with the attributes is exported to proceed with the calculations (interviewee 5B, 2019). The Excel sheet follows the WBS and its codes which are linked to the standard codes prepared for dike design.

This strategy is described in a standardized process relying on guidelines and a prepared manual. These clarify elements, cost and software codes, specifications for drawing styles, and identification of quantities to be extracted (length, area, or volume). The prepared codes are applicable to the different phases of the design. As the design develops, the codes become more detailed. The used codes in the model are checked for compatibility with those identified in the manual. Checking the documents on the process, figure 4.3 reflects the observations made.

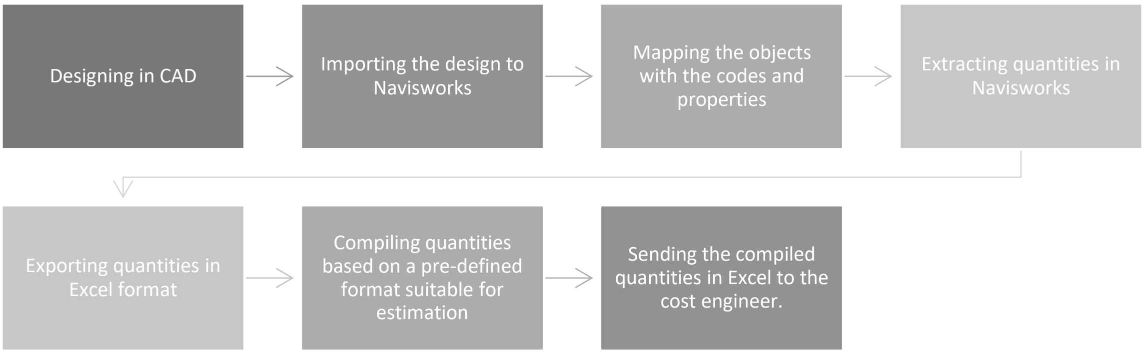

Figure 4.3 Steps of the observed process on 5D BIM trial

4.3.3 BIM Utilization: Comparison and Conclusion

The utilization of BIM in practice is compared with that from literature (in section 3.3) to reach a conclusion on the effective integration of design and cost estimation via 5D BIM in practice. The comparison is made for the preparation, utilization, and cost estimation computation in BIM.

Preparation: Similar to literature (in section 3.3.2), the consideration of BIM in practice starts with the preparation of the execution plan and process maps. The preparations are based on discussions with the client and team whose input and output information are added to process maps. Based on look-ahead thinking and discussions, the features are selected to be added to the model. With the help of the modeler and involved engineers, the features identified by the management are added to the model. Ideally, the model is prepared fit for purpose. Thus, some items are detailed more than others and some details are prepared in 2D drawings for simplicity. This is the target, yet it does not always succeed as unnecessary information is still added to the model. Having too much information leads to a complex model that is not well structured. Literature mentions collaboration to define the level of development and detail to balance information. However, practice relates budget and time to the development of the model and its elements, thus limiting the collaboration to build the model.

Implementation: Regarding the implementation, literature (in section 3.3.2 and 3.3.3) stresses the importance of standardization using consistent definitions, representations, classification systems, and metadata. IFC is a specific method of the standardization approach, yet it is not always adopted in practice for reasons also noted as limitations of IFC (it is developing and problems in its utilization are noted). Practice mentions the latter standardization points and shows their application in one of the strategies. Thus, practice supports the importance of these aspects for BIM/5D BIM utilization. From the studied strategies, the successful implementation is limited to the design of dikes. In another trial for design and cost connection, the highway design project considered standard codes prepared by the team. However, the involved engineers mentioned that the model's complexity increased as the details of the design increased. The complexity and complications prevailed when the team tried to capture all details to the model. Furthermore, it was hard to keep the codes consistent. Therefore, practice follows the concepts from literature (in section 3.3.3), yet their application is not always successful.

Cost Estimation in BIM: For the preliminary estimate, literature (in section 3.3.1) proposes the use of schematic BIM and cost databases. However, this is not considered in practice which does not have structured databases of past projects. Interviewee 5C (2019) mentioned that preserving information from past projects in databases is complicated because they rely on actual values which are stored in various sources. Therefore, the ideal application of BIM from earlier phases based on schematic drawings and databases is not supported in practice.

In practice, the implementation of 5D BIM relies on the bottom-up approach for computations. The focus is on the extraction of quantities and prices are added by the cost engineer. This approach coincides with literature's (in section 3.3.3) proposition of a semi-automated process due to challenges in adding all aspects that the cost engineer needs to find costs. Literature mentions the manual computations for complex items and the consideration of the cost engineer's perspective to extract quantities. This is mentioned in practice in terms of monitoring the effort and time to build the model with the details and the discussions with the modeler and involved engineers. BIM discussions are held with the designers from the initial phases to clarify the design methodology that facilitates quantity extraction (interviewee 1C, 2019).

For the extraction of quantities, literature (in section 3.3.3) mentions that it is done based on the WBS and grouping of elements as required for estimation. The compatibility of the level of detail between the WBS and model is checked to enable cost estimation. This is not mentioned in BIM utilization in practice but was addressed by cost engineers in general. Cost engineers stressed the fact that information provided shall be suitable for the computation of the estimate at the required accuracy. Furthermore, literature states the connection between WBS and cost estimation using codes. Practice shows the connection between the WBS and cost codes for some cases. However, there is no uniformity of codes between WBS and cost codes. Although the connection is made, standardization and coordination are not completely achieved as codes vary between WBS, cost codes, and model codes. A single code applicable to all would facilitate the access to information.

In conclusion, practice considers the different concepts for BIM/5D BIM utilization. The implementation of 5D BIM is still developing to ensure the integration of design and cost estimation. The ideas for integration coincide with those from literature, however the application is not always yielding effective integration. Furthermore, practice lacks a standard and general process for the integration of design and cost estimation in BIM. Such a process is important for the alignment of BIM with design and cost estimation processes as noted in literature (in section 3.3.1).

4.4 Conclusion: Towards Process Design

The design and cost estimation processes along with their interaction in practice was studied in comparison to literature. The study showed that neither fragmentation nor effective integration prevail. The integration is disrupted by issues (I and II listed below) derived from this study in section 4.1.

Furthermore, the effective integration via BIM is still under study in practice with successful and failing trials. Upon comparing the case in practice with literature and analyzing it, the issues hindering the effective integration via 5D BIM are concluded as issues (III to VI) listed below. These issues form the basis of the proposed process in chapter 5 as noted in section 2.3. By countering the issues based on literature concepts and suggestions from practice, the problems hindering effective design-cost estimation via 5D BIM are tackled and the process is designed.

Issues of integration and BIM utilization in practice answering sub-question (3):

I. *The cost is derived from design and does not guide the design. The cost engineer is not involved continuously in the project and optimization to meet the budget prevail at the end of the process. Therefore, the designers and cost engineers work in silos, following a process of design-estimate-redesign to reach budget.*

II. *Throughout the process, the cost engineer's influence on the design is limited to requested consultations on changes that reduce the project costs or to big projects which consider discussion of alternatives.*

III. *Engineers try to capture most of the details in the model which leads to complexity of the model, thus hindering the connection between design and costs.*

IV. *Information is not sufficiently managed due to the following reasons:*
   - *Information is incompatible with the level of accuracy of the estimate*
   - *Information is not complete and requires modification to meet the cost engineers' requirements*
   - *Miscommunication leading to the addition of unnecessary information to BIM*
   - *Loads of information are provided to search in*
   - *Designers' miscommunication of changes to cost engineers*

V. *The standardization approach is successfully applied in a case from practice. Yet, the codes used are not unified for WBS, design, cost, and model as proposed in literature.*

VI. *Challenges from practice include resistance to the utilization of BIM by practitioners and clients. The older generation and clients have resistance to BIM since they are used to certain processes or are not aware of the benefits of the technology (interviewee 1B, 2019; interviewee 3B, 2019). Clients are not giving room for innovation to consultants who follow their rules (interviewee 6C, 2019). Moreover, clients are not always aware of the options for preparing the design (interviewee 1B, 2019). These cases correspond to a major barrier to BIM utilization since resistance decreases the potential to cooperate and work together in a similar environment (interviewee 3B, 2019).*

Considering the above issues, suggestions from practice provide ideas for tackling these issues and designing the process. The suggestions for better design-cost estimation integration and suggestions for better BIM utilization are provided below in table 4.1 and table 4.2 respectively.

Table 4.1 Suggestions to improve the Design and Cost Estimation interaction from interviewees

Suggestions to improve the interaction	Interviewees
Communicate face to face – Same location	3D, 6D, 8D, 1C, 2C
Work closely from the beginning – Parallel processes	1D, 2D, 3D, 5D, 3C, 4C
Involve the cost engineer in start-up and follow-up meetings: in the first few meetings he checks milestones of designers and becomes informed of the outputs' deliveries that are necessary for the cost engineer (it is not important to be present in all meetings)	2C, 4C, 5C
Communicate within the team on the process, risks, and cost driving components	5C, 8D
Share within the team project information and their interpretation	5C
Involve cost engineer in decision-making	5C, 8D
Become a proactive team by offering more than just designing to requirements (considering the cost engineer from the beginning and applying value engineering)	2C, 4C
Decide on data sharing method and identify the relevant data	6C
Design model considering cost properties	1D, 8D

Note: The information in the table is coded with DCI in the interview transcripts.

Table 4.2 Suggestions to improve BIM utilization from Interviewees

Suggestions to improve the BIM Utilization		Interviewees
Semi-automation: Connection of Excel with Design software	Even if design and cost estimation are linked through software to immediately reflect the design changes, human judgment is still required.	1D, 5D, 6C, 4B
	The price is kept as a property to be added by the cost engineer.	1B, 4B
Standardization:	Synchronization of codes based on early agreements.	1C, 3C
	The right people work together from the start to unite the use of codes. They discuss the end product and make the breakdown structure accordingly.	2C, 2B
	The team with different disciplines meets to specify the standard and other items to be used.	1B, 3B
Connect People:	The BIM coordinator and design coordinator shall connect the people.	8D
	The project manager shall be the BIM coach who introduces BIM and the model to the different individuals.	2B
	The experience of the old generation is needed since they know best about expected results. The innovation from the new generation is essential to think of new ways and styles to do the same process.	6C
Consider the cost engineer's perspective: The cost engineer thinks of a model in a different way from the designer. The cost engineer has to be involved in modeling to point the interesting items to be considered in the model.		6C
Focus on cost driving components: The focus has to be on the cost driving components for which details and connections are made.		6C

Note: The information in the table are coded with BDU in the interview transcripts. More details are provided in appendix E.

5 Process Design

The case study RHDHV provided insight to issues hindering the effective integration between design and cost estimation via BIM in practice. The pinpointed issues in section 4.4 guide the design of the process. In this chapter, the issues are countered with solutions inferred from [1] concepts from literature on integration and BIM/5D BIM utilization and [2] suggestions from practice. Furthermore, the adopted 5D BIM approach is clarified. Based on the proposed solutions and specified 5D BIM method, the "Integrated Design – Cost Estimation 5D BIM Process" develops with tasks for the general level of the process. Finally, the process is translated to a process map that clarifies tasks, responsible stakeholders, and information exchange.

5.1 Countering the Issues in the Process

The issues derived from interviews are tackled based on information collected from literature and practice. The literature used is summarized in the end of sections 3.1 and 3.3 where sub-questions (1) and (2) are answered to aid the design of the process. From practice, relevant suggestions provided by interviewees for better integration and 5D BIM implementation are used to tackle the different issues. Having done that, certain steps of the proposed process evolve. Investigating the following 6 issues, a major part of the process is developed.

5.1.1 Issue I: Cost Engineer's Limited Involvement in the Design

The cost is derived from design and does not guide the design. The cost engineer is not involved continuously in the project and optimization to meet the budget prevail at the end of the process. Therefore, the designers and cost engineers work in silos, following a process of design-estimate-redesign to reach budget.

The issue stresses the lack of monitoring costs throughout the process and the limited interference to reach a design made to cost. Literature (in section 3.1.3) mentions the alignment between design and cost estimation at different stages of the design by monitoring cost driving components and controlling the budget. However, practice neglects the latter due to project size, budget constraints, and time limitations. Literature's procedure for cost consideration and monitoring (section 3.1), the time and budget constraints, and the following suggestions are considered for the design.

- Work closely from the beginning
- Involve the cost engineer in start-up and several follow-up meetings
- Share within the team project information and their interpretation
- Communicate within the team on the process, risks, and cost driving components

The limitations of budget and time reflect that complete integration of cost engineers by attending all meetings and constantly computing costs throughout the design is not suitable. Therefore, the proposed solution is the integration based on cost driving components to reduce the frequency of updating costs and having discussions. The cost driving components cover 80% of the costs while making 20% of project elements. Despite the less frequent design-cost interaction, the design can be made to cost by focusing on the cost driving components. Thus, effective integration is possible.

Working closely from the beginning, an initial meeting is held since it is essential for the interpretation of the project and sharing of project understanding among project team. Budget setting, risks, cost driving components along with their target costs are communicated with the team. Based on these components, the communication plan is set. The meetings and discussions involving the cost engineer are scheduled depending on the design of cost driving components. Furthermore, the cost engineer frequently estimates the costs of these items and compares them to their target costs. The overall budget is updated at the end of the design phase.

The proposed interaction between design and cost estimation is shown in figure 5.1 below in comparison to the case of fragmentation in practice and intensive interaction in literature as stated in section (3.1.3).

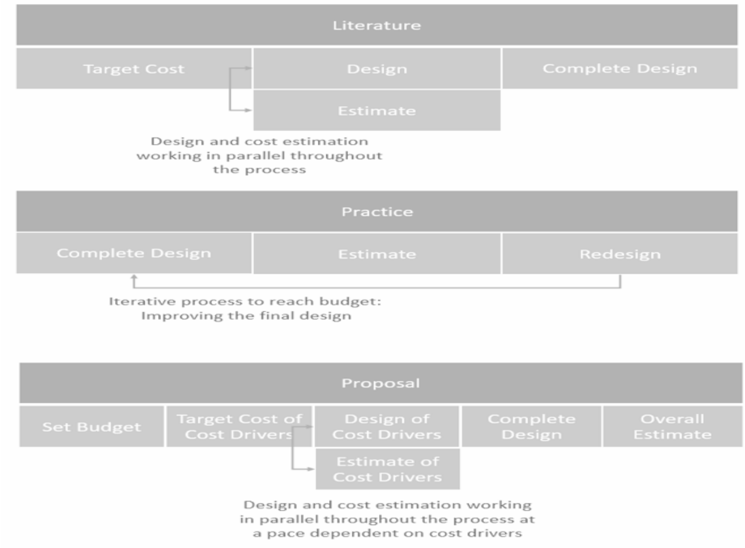

Figure 5.1 Considering the cost engineer throughout the design in practice, literature, and proposal

Considering the proposal illustrated above and described to tackle "Issue I", the following steps (in figure 5.2) of the process are set in the proposal. It is important to note that the design, cost estimation, and discussion over the cost driving components is iterative since the steps repeat till all cost driving components are covered.

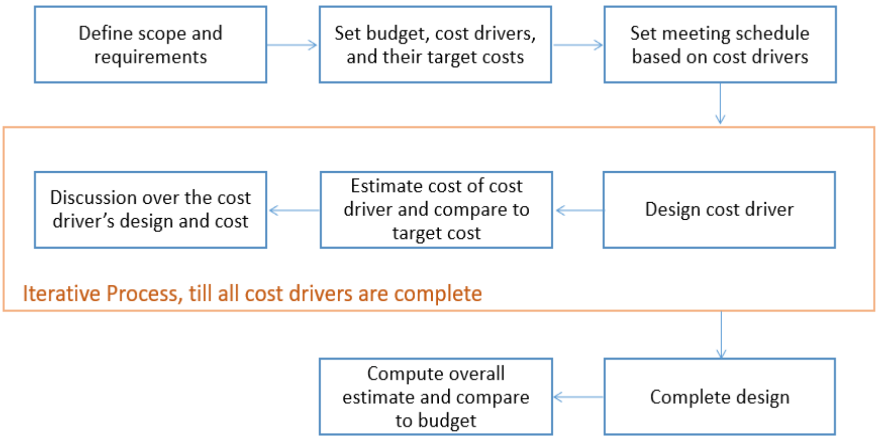

Figure 5.2 Steps of the proposed process based on issue I (at a general level)

5.1.2 Issue II: Cost Engineer's Influence on the Design is Limited

Throughout the process, the cost engineer's influence on the design is limited to requested consultations on changes that reduce the project costs or to big projects which consider discussion of alternatives.

The issue shows that the cost engineer is acting as an estimator rather than an advisor to the design. From practice, alternatives are studied for big projects in the early phases. At late design stages, cost engineers are approached for design optimization and evaluation of changes to meet the budget. Seldomly, designers consult cost engineers on costs versus efficiency of sitework to finalize their designs. The cost engineer's involvement is restricted by budget and time constraints. However, literature ensures the advisory role of the cost engineer by assessing changes and alternatives, assisting in expensive designs and materials, and studying the value of the design. Therefore, the points from literature (in section 3.1) along with the following suggestions are considered for tackling this issue.

- Become a proactive team by offering more than just designing to requirements
- Involve the cost engineer in decision-making

The proposed process recommends the cautious expansion of the points in which the cost engineer can influence the design. Accordingly, the cost engineer consults over the cost driving components, mainly at two points: [1] Before the design to discuss alternatives of cost driving components, constructability concerns, and other important features such as material and [2] After estimating the costs of cost driving component's alternatives for comparison and decision-making. The latter is done in the discussions on the cost driving components after computing estimates already mentioned in Issue I. Furthermore, in these discussions, the cost engineer can assist in further optimizations and changes to cost driving components can be made. After computing the overall estimate, further discussions are held. These discussions coincide with literature's consideration of aligning design and cost at the end of each design stage. Therefore, the highlighted steps (figure 5.3) are considered in the proposed process based on Issue II. To consider optimizations and changes, the dashed arrows are placed.

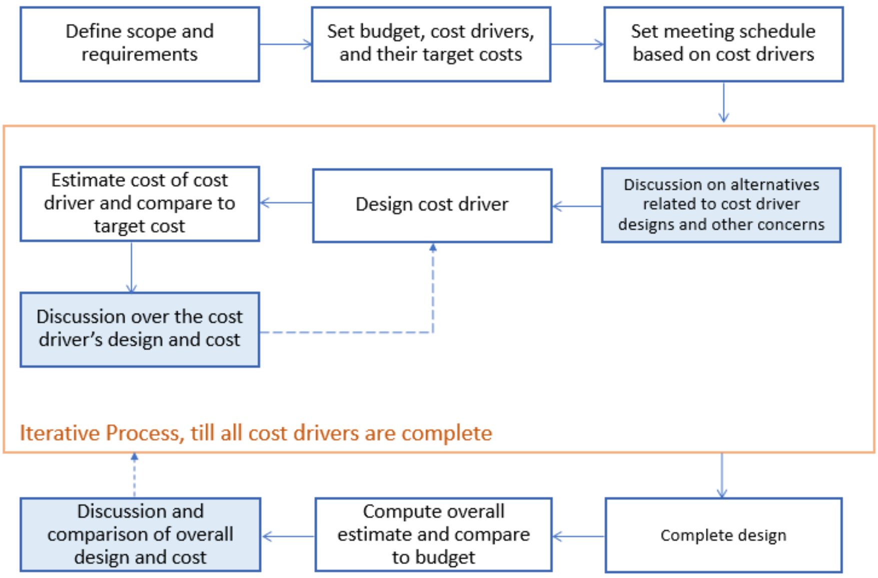

Figure 5.3 Steps of the proposed process based on issue II (at a general level)

5.1.3 Issue III: Complexity of Model

Engineers try to capture most of the details in the model which leads to complexity of the model, thus hindering the connection between design and costs.

The issue shows failure in BIM implementation to connect design and costs due to model complexity. The attempt to add all information into the model leads to complications such that information cannot be easily understood. To avoid such cases, the model must be made fit for purpose. This is specified in the BIM execution plan and process maps that ensure the synchronization of processes with necessary information flowing between parties as noted in sections 3.1 and 3.3.

Since the purpose of the model is connecting design and cost estimation, a model enabling the effective connection of the latter is considered. As mentioned earlier (in section 5.1.1), the synchronization of the processes is based on the cost driving components. Similarly, the information added to the model shall focus on cost driving components as suggested by interviewees. Therefore, instead of capturing details for all elements, the information is considered for only 20% of the elements. For this limited number of elements, details and connections between design and cost estimation are made. The steps added to the process based on this issue are highlight in figure 5.4.

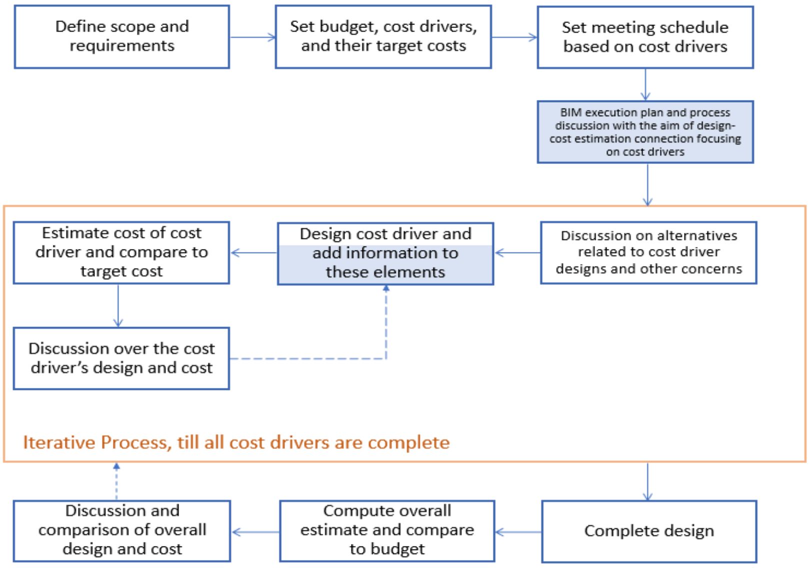

Figure 5.4 Steps of the proposed process based on issue III (at a general level)

5.1.4 Issue IV: Inadequate Information Management

Information is not sufficiently managed due to the following reasons:

- *Information is incompatible with the level of accuracy of the estimate*
- *Information is not complete and requires modification to meet the cost engineers' requirements*
- *Miscommunication leading to addition of unnecessary information to BIM*
- *Loads of information are provided to search in*
- *Designers' miscommunication of changes to cost engineers*

The issue shows the inappropriate preparation and exchange of information. From the points noted in the issue, it is inferred that the cost engineer's perspective is not always considered. Furthermore, the provided information for cost estimation is not updated with design changes. Both, practice and literature, stress on the need for preparations that involve the relevant stakeholders and consider inputs, outputs, and exchanges. However, literature specifies means that ensure compatibility between design and cost estimation information. To tackle the major issue with various problems, the following suggestions are noted.

- Consider the cost engineer's perspective since the cost engineer thinks of the model in a different way
- Decide on data sharing method and identify the relevant data
- Design model considering cost properties
- Communicate face-to-face

Firstly, all discussions and compatibility checks are made in face-to-face meetings to avoid the misinterpretation of written communication. Secondly, the preparation of the model involves the designer, cost engineer, and 3D modeler. In the preparation, the cost information is collected and possibilities to incorporate it in the design model are studied. This cost information covers general information for the overall model and specific information for the design of the cost driving components. The general information includes basic requirements that enable the cost engineer to compute costs from the model. The specific information is detailed information on cost driving components from the perspective of the cost engineer. This information is crucial since the process proposes the focus on detailing and adding metadata attributes to cost driving components only. Metadata attributes cover the required cost properties (for example: metadata attributes for referencing design information and estimate's supporting details). In this manner, the effort to prepare the model while considering the designer and cost engineer's perspectives is restricted to items that cover a major portion of costs. Moreover, the cost engineer is provided with a reasonable amount of information that is continuously checked. These input and output information along with its exchange are set in the process map and planning document.

Thirdly, the means to check the information are derived from literature. Literature (in section 3.2.3) stresses the importance of aligning stakeholders for the preparation, communication, and interpretation of the estimate in terms of accuracy, project definition, and other properties. Moreover, literature proposes (in section 3.3.3) checking the compatibility of the model with the WBS that is also used for cost estimation. Ultimately, both checks relate to the level of detail of the model with the estimate to be computed. These checking points are adopted to the process with the former applied to the whole design and the latter only to the cost driving components' design. Furthermore, literature (in section 3.1) suggests setting fixed procedures for change communication. Therefore, change communication and discussions on design ambiguities are included in sessions for checking the compatibility of the design. For the rest of the design, the team discusses general considerations in the design to ensure a design level compatible with the estimate's accuracy. The compatibility checks, design changes, and design ambiguities are added in single tasks in the process. One task is limited to cost driving components due to the check limited to these components and the other is for the complete design. Accordingly, the process becomes as follows (figure 5.5), with highlighted steps that tackle this issue.

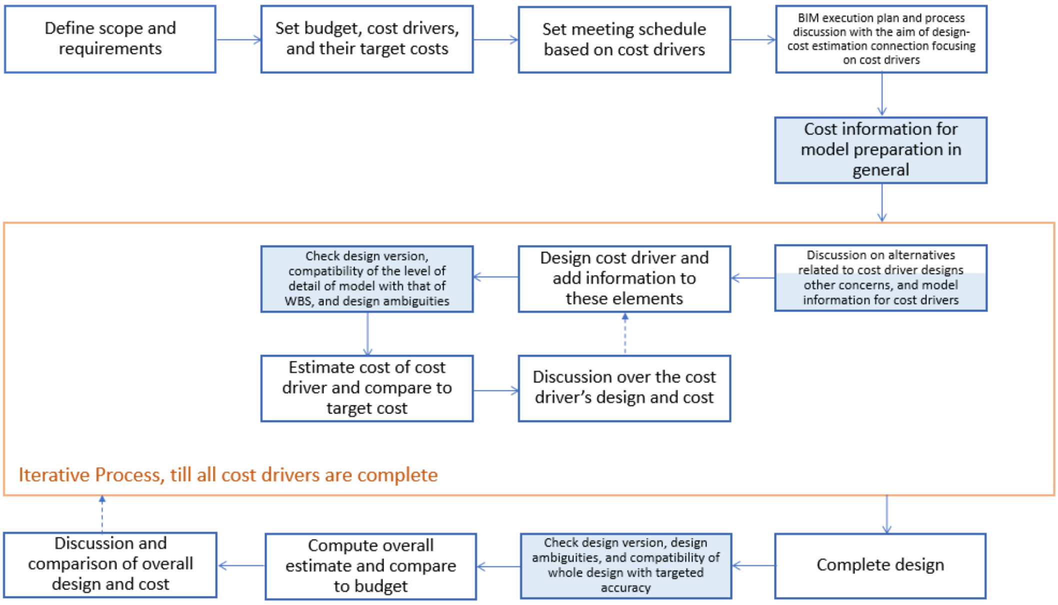

Figure 5.5 Steps of the proposed process based on issue IV (at a general level)

5.1.5 Issue V: Lack of Uniformity

The codes used are not unified for WBS, design, cost, and model.

The utilization of BIM focuses on standardization to have consistent object definition and representation. In specific, automating cost estimation relies on taxonomies which are techniques of classification and constant organization of components (Sabol, 2008; Afsari & Eastman, 2016). Using 5D BIM, the objects of the CBS and WBS are linked with codes to facilitate tracking target costs during the design. This approach relies on classification systems that provide codes to the different objects, at different levels of the design. For example, the classification system UniClass 2015 which is considered compliant with the Dutch standards can be used (interviewee 2B, 2019). UniClass 2015 provides unified coding scheme for buildings, landscape, and infrastructure over the project's lifecycle. It provides hierarchical tables that allow the definition of project from the broadest to the most detailed view.

These classification codes can be mapped to costing work (Delany, 2015). In practice, different project parties set their own codes. Then, mapping becomes necessary to have the different codes connected to the same object. This solution complicates communication and information exchange among the users since they speak of different codes.

Without a standard, professionals use different classifications to represent elements and organize quantities. This leads to problems of mapping the different representations (Monteiro & Martins, 2013). Therefore, following classification systems which provide frameworks for information are crucial for interoperability (Afsari & Eastman, 2016). Furthermore, a shared classification system improves the reliability of datasets and information (Kim & Park, 2016). Therefore, it is proposed to follow classification systems that enable uniting the codes among the different disciplines. These codes from a classification system are constant and have definitions that refer to all objects of same characteristics instead of being customized to each project. Thus, the analysis of similar objects and preservation of structured data is facilitated. A standard way for classifying building components initiates the preparation of component's libraries (Afsari & Eastman, 2016).

Therefore, the process considers the agreement on a standard classification system to tackle the issue of this section (highlighted in figure 5.6). In the early discussions of the process, agreements are set on the adoption of a suitable classification system common for all users. The codes representing objects are added to the model.

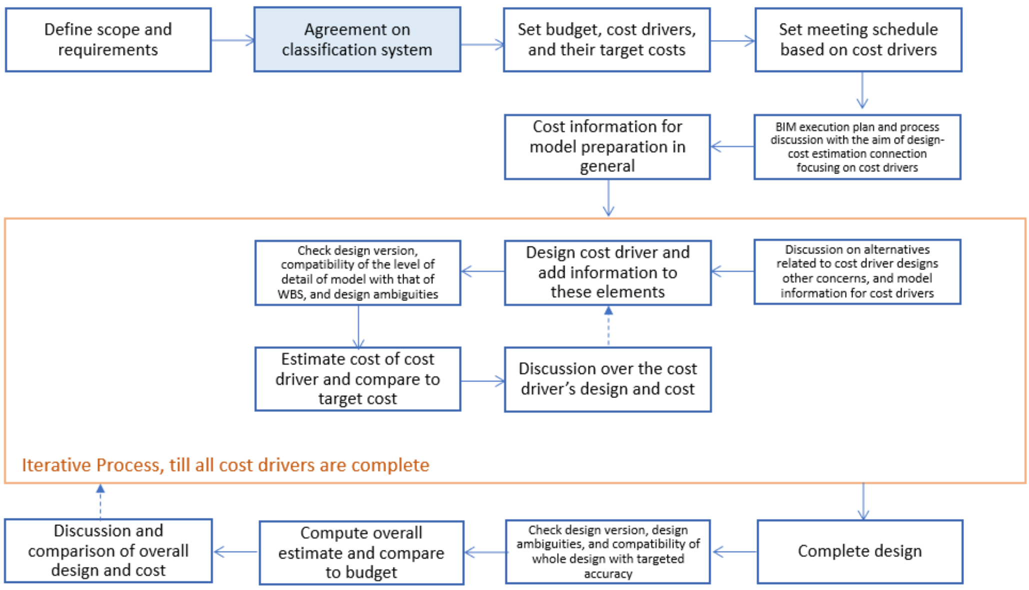

Figure 5.6 Steps of the proposed process based on issue V (at a general level)

5.1.6 Issue VI: Resistance and Unawareness of Practitioners and Clients

Challenges from practice include resistance to the utilization of BIM by practitioners and clients. The older generation and clients have resistance to BIM since they are used to certain processes or are not aware of the benefits of the technology. Clients are not giving room for innovation to consultants who follow their rules. Moreover, clients are not always aware of the options for preparing the design. These cases correspond to a major barrier to BIM utilization since resistance decreases the potential to cooperate and work together in a similar environment.

The resistance of some practitioners and clients or their inexperience with BIM and its benefits hinder collaboration and implementation of BIM. The process considers this issue briefly by looking at information from literature, practice, and the following interviewees' suggestions:

- The BIM coordinator and design coordinator shall connect the people.

- The project manager shall be the BIM coach who introduces BIM and the model to the different individuals.
- The experience of the old generation is needed since they know best about expected results. The innovation from the new generation is essential to think of new ways and styles to do the same process.

Literature (in section 3.3) mentions teamwork for setting, following, and monitoring the execution plan and process maps. Practice identifies that this is based on the cooperation of managers, modelers, and involved engineers. The client is also involved in the discussions on the execution plan. With the different parties attending meetings and illustrating ideas, the innovation space that BIM offers is clarified. Furthermore, the client becomes aware of the possibilities of information management throughout the life of the project. Practice also states the need for collaboration between [1] specialists who describe their processes and requirements and [2] modelers who innovate in the model to reach the latter. Then, specialists assess the accuracy of the results from BIM-based processes. The proposed process considers the discussed points by expanding the attendees of meetings on discussions/preparations for the project and BIM in general (not cost driving components). Therefore, as in literature and practice, initial meetings include all parties. During the design, designers and cost engineer work closely. In these meetings, the results from BIM are interpreted to ensure their accuracy. At the end of each design phase, meetings with all parties are arranged.

5.2 Incorporating Cost Computation via 5D BIM to the Process

Having the interaction between design and cost estimation clarified, the computation of costs via 5D BIM is incorporated in the process. A computation method is selected from the different methods mentioned in literature (section 3.2). The selection is based on the analysis of literature (sections 3.2, 3.3.3 and 3.3.4) and the case in practice along with the interviewees' propositions (sections 4.2 and 4.4). Accordingly, this section answers sub-question (4).

The computation of the design's cost using 5D BIM is based on the semi-automated method which relies on BIM-based quantity extraction and utilization of Excel. The selection is made due to the following. First, estimating software with direct links connects quantities to databases to dynamically find costs. However, literature and practice mention obstacles to develop cost databases due to continuous fluctuations in prices based on the economy and suppliers. Furthermore, practice mentions the difficulty of building the databases from past projects since it is based on actual values which are registered in several systems. Second, for dynamic estimations, equations can be added to the model to provide the cost estimator with the ability to add unit prices after the analysis. However, cost engineers analyze various conditions (such as logistics, labor, construction methods) to reach an estimate. These conditions cannot be automated or require intensive work to model. Third, the desire of automation is to quickly realize the impact of design changes on costs. However, changes are not related only to quantities based on which automation operates. Fourth, special quantity take-off tools form links with components based on built-in features which limit the flexibility of quantity extraction to rules and features imposed by the software. Fifth, the option of IFC is not supported by literature and practice since it is restricted to specific structures and it is still developing. Based on the latter reasons, the options of using estimating software, special quantity take-off tools, and IFC are disregarded.

With quantities extracted from the model and Excel used for computation, a practical approach of 5D BIM is set. The process proposes extracting quantities based on the agreed classification system and its WBS. With a structured and standardized approach, the utilization of Excel is considered effective. Having selected a general approach for 5D BIM, the computation of estimates at the different stages of the process are clarified based on sections 3.2, 3.3.1, 3.3.3, 4.3.2, and 4.3.3. First, the method for computing the preliminary estimate is justified. Then, the computation of estimates for cost driving components and the complete design are described.

5.2.1 Computing the Preliminary Estimate

The preliminary estimate computed at an early design stage allows setting the budget, checking affordability, and having initial distribution of the budget in the cost plan. The distribution of the budget shows target costs for cost driving components in the case of the proposed process. To compute the estimate, literature mentions various methods. These could be based on statistical analysis, artificial intelligence, analogy, or expert judgement. Practice focuses on expert judgement and analogy for the preliminary estimate by looking at previous projects. For any of the methods, the drawings, alternatives, and other specifications are required. However, methods relying on the statistical approach or artificial intelligence require organized historical data. Such databases are not always available due to the difficulties in forming them as mentioned earlier. Therefore, these methods are not considered. Yet, for future consideration, BIM structures the information to enable the use of these methods. For the process being designed, expert judgment or analogous estimating are proposed. Therefore, the cost engineer infers the preliminary estimate by visualizing and analyzing the model with its conditions while referring to models with estimates from previous projects.

5.2.2 Computing Estimates throughout the Design

As the design starts, the elemental cost plan mentioned in literature is adopted to compute the different estimates. The elemental plan is based on WBS linked to CBS with codes to track target costs. Standard codes are added to the WBS, model, cost plan, and planning. These codes are derived from the classification system considered in the WBS that is agreed for the project. Based on the classification system's structure, the elements are grouped which in turn groups quantities for cost estimation. The grouping of elements depends on the level of detail of WBS and model. As the design develops, the elemental cost plan evolves to become detailed. The WBS decomposes to main components and progresses to reach lower levels of sub-components. Similarly, costs are allocated to elements at different levels. After checking compatibility between the level of details of WBS and model as set earlier in the process, quantities are extracted. The process of WBS and model development, grouping, checking compatibility, and extracting quantities is repeated throughout the design to extract quantities for the different alternatives and levels of detail.

For the cost driving components noted earlier, quantities are extracted based on the cost engineer's specifications. Furthermore, metadata attributes are added to the model and extracted with the quantities. These attributes depend on the agreement of the team on information to be tagged to cost driving components. It is proposed that the classification codes, material, time information, and reference information are considered in the model and are mapped to cost driving components and their quantities. This is limited to cost driving components in order to reduce the complexity of the model. For the remaining components, quantities are extracted based on general specification provided by the cost engineer. Furthermore, elements that require intensive effort to build in the model are identified and estimated manually. Having the quantities extracted with their attributes to Excel, the cost engineer proceeds with his usual task of analyzing conditions and considering other aspects to set unit prices and estimate costs. Finally, the BoQ is prepared with coordinated items and their subsequent details.

Based on the described 5D BIM computation approach, the process is updated in figure 5.7 with highlighted computation steps.

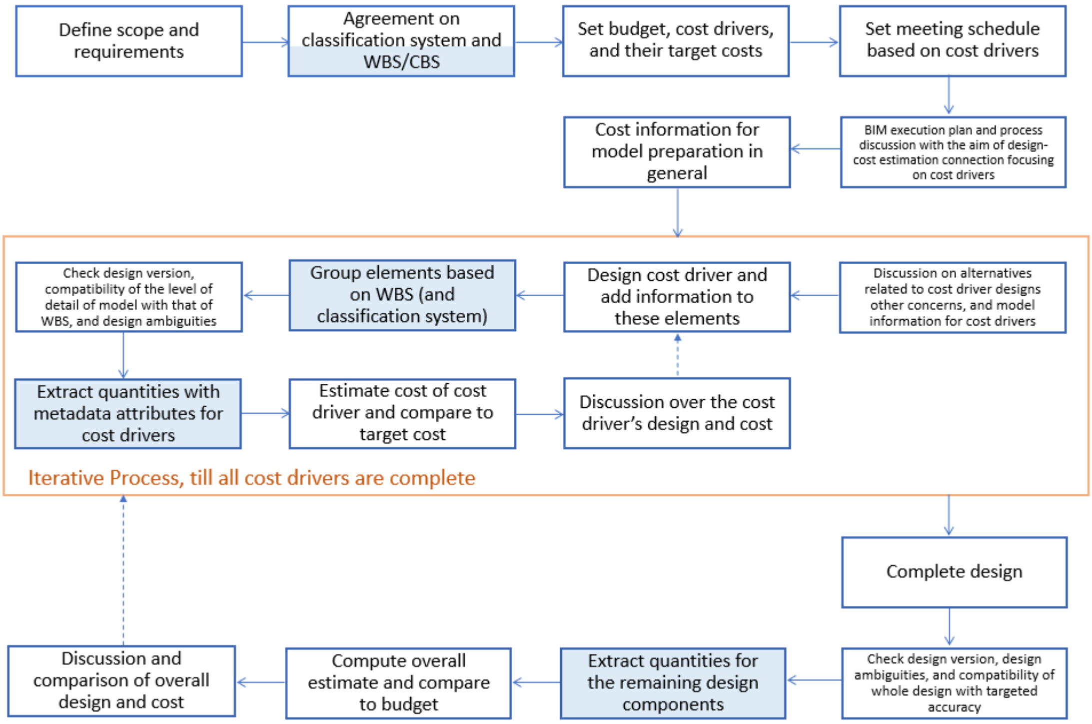

Figure 5.7 Steps of the proposed process based on 5D BIM cost computation approach (at a general level)

5.3 Conclusion

The general level of the process is designed based on tackling the issues that hinder integration and BIM utilization as noted from practice and cost estimation via BIM methodology. In this section, 6 issues have been tackled based on information from literature and practice. Then, the estimation of costs in 5D BIM is addressed to select a method for computation. The method is incorporated in the designed process. The result is a single general process considering design, cost estimation, and their utilization of BIM. Accordingly, the research approach for the integration of design and cost estimation via 5D BIM is illustrated in a designed "Integrated Design - Cost Estimation 5D BIM Process".

The designed process considers the aspects of the different design stages but does not clearly show the separation between the stages. To clarify the design phases within the designed process, the steps allocated to the different phases are grouped as shown in figure 5.8. The early phases relating to preparation for BIM and schematic design are covered by the first portion of tasks. At this stage, the cost engineer does not interact with the designers working on the sketch of solutions to the problem in the urban plan. The preparation of this sketch design is not noted since the process focuses on the interactions between designers and cost engineers.

The development of the design with the cost engineer prevails in the remaining tasks. It is important to note that preliminary and definitive design are covered by the same tasks. However, the distinction between the phases is based on the level of detail of the design and its flexibility. In the preliminary design, alternatives of the main components are studied, and changes/optimizations lead to iterations. In the definitive design, flexibility for design changes is low so fewer or no iterations are made. At this stage, the design is developed to consider more details. Alternatives can be briefly discussed for these details which are the sub-components.

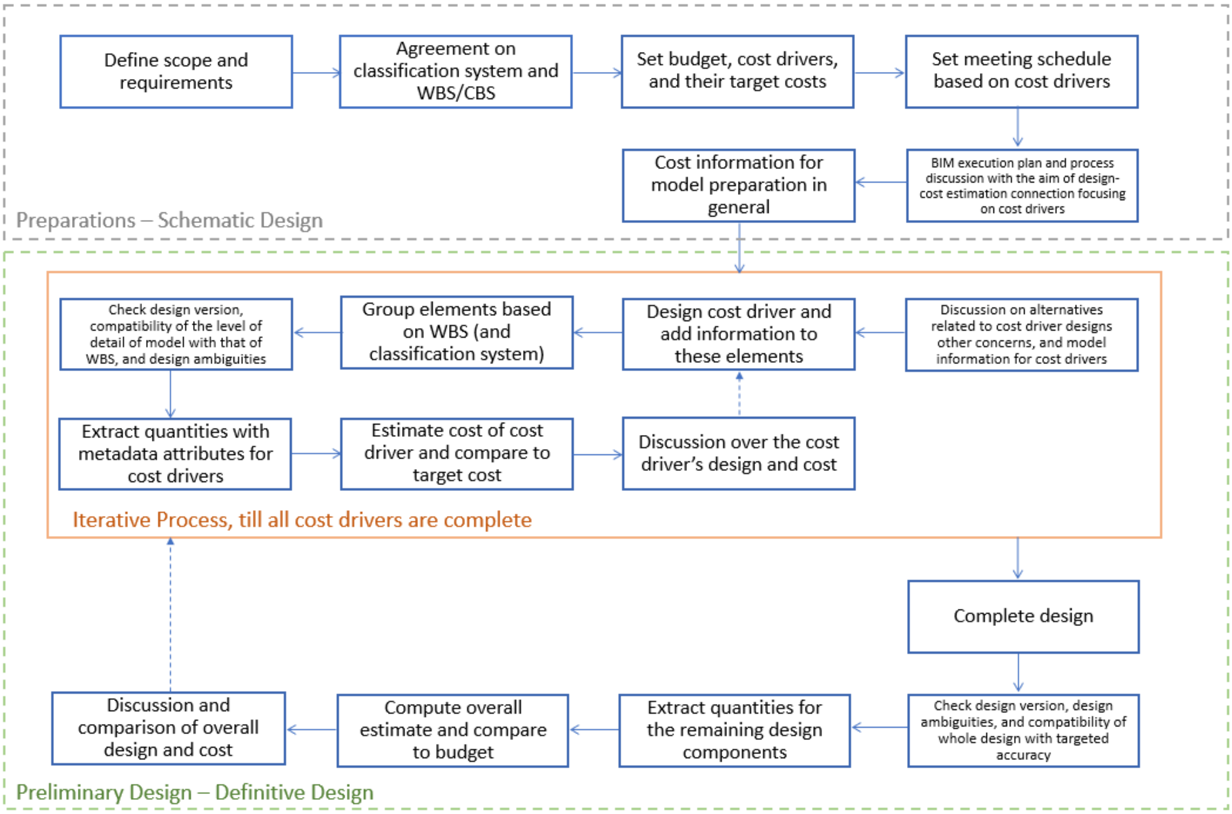

Figure 5.8 Final design of the process (at a general level): Integrated Design - Cost Estimation 5D BIM Process

This general process is translated to a process map having [1] the pool as the organization developing the design and [2] the lanes on internal roles as the designer and cost engineer within this organization. The process map also illustrates: [1] reference information considering the resources of information that are required for the process and [2] information exchange clarifying the information shared between parties (Computer Integrated Construction Research Program, 2010).

The process map in figure 5.9 focuses on the tasks performed by each party and the information flow between them. Therefore, some of the steps of the general process are not considered in the process map. These are steps involving both parties or group meetings. The figure answers sub-question (5).

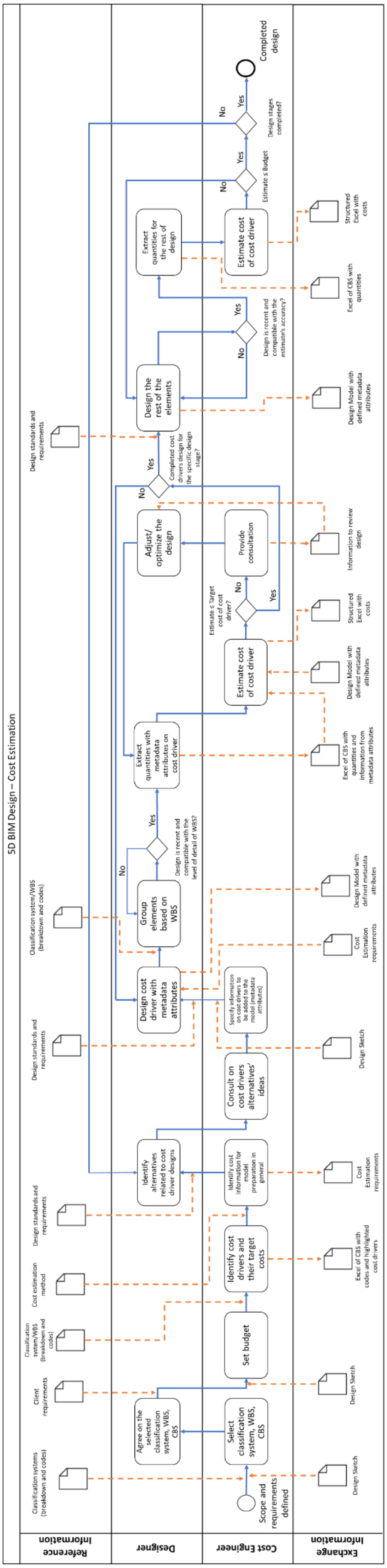

Figure 5.9 Process Map of the "Integrated Design - Cost Estimation 5D BIM Process"

6 Embedded Case Study: Pilot Case

Having the process designed, it is tested in a regular RHDHV project. The project is a pilot case embedded in the case study RHDHV described in chapter 4. The embedded case study research allows answering sub-question (6) which focuses on the effectiveness of the process designed. This is reached upon performing different steps considered in this section. First, the protocol for the pilot case is set. Second, the pilot case is described in terms of scope and setup. Third, the implementation of the process in the pilot case is explained by presenting the data collection relevant for each step of the designed process. Fourth, the participants of the project are interviewed, and their feedback is summarized. Finally, the results are discussed and concluded to answer sub-question (6).

6.1 Pilot Case Study Protocol

The case study protocol improves the reliability of case study research, guides the researcher during the data collection process, and ensures the focus on the target. In the overview of the protocol, the case study project is introduced with background information. Furthermore, the selection of the case is clarified. Then, the case study question section poses questions for the researcher to consider during data collection. Data collection from people and the engineering firm in its normal working routine is addressed based on an approach. The approach is designed and planned in the field procedures section (Yin, 2009). Accordingly, the protocol of the single case study is set. The overview is provided below, the remaining sections on case study questions and field procedures are provided in appendix F.

6.1.1 Overview

The overview section provides background information on the case study project and clarifies the selection criteria of the case.

<u>Background Information:</u>

In collaboration with RHDHV, the researcher tests the designed process "Integrated Design - Cost Estimation 5D BIM Process" with a team working on an ongoing project in the Netherlands. The research aims to investigate the effectiveness of the integration in practice and the implementation of 5D BIM. Through this application, the features of the proposed process and the concepts leading to its design are assessed based on the case study questions in appendix F. The ultimate question to be answered with this case study research is sub-question (6) of the research:

"Does the suggested process lead to effective integration between the design and cost estimation processes via 5D BIM?"

<u>Case Selection:</u>

Multiple criteria are utilized for the selection. These criteria are included within the categories: Project characteristics, Team composition, and Tools. A simple matrix is set to aid the selection of a suitable project. The project(s) with the highest points is noted as potential pilot case(s). The final agreement on the case is based on consultations with involved parties of the project. The following criteria are selected from the different categories.

Category "Project Characteristics": This category focuses on the project's general characteristics being complexity and type. These criteria are essential for the successful testing of the process within a limited time frame of 2 months.

a. Complexity of projects is related to structural elements, dynamic elements, and their interactions. Considering Technical complexity, Organizational complexity, and Environmental complexity, the TOE framework identifies elements in each of the mentioned categories to cover various aspects of projects' complexity (Bosch-Rekveldt, Jongkind, Mooi, Bakker, & Verbraeck, 2011). Since the TOE framework provides various elements to assess complexity, it is utilized to extract the relevant elements representing the complexity selection criterion. The focus is only on complexity in terms of components and changes. For this purpose, the elements "Scope largeness" and "Uncertainties in scope" are used. Scope largeness is interpreted in terms of the quantity of deliverables, components, decisions, and information. Uncertainties in scope element is related to the changes' frequency and impact (Bosch-Rekveldt et al., 2011). The desired level of complexity of these elements is average.

i. **Criterion 1: A reasonable level of complexity in terms of scope largeness** is required to facilitate the implementation of the process due to several reasons. The process considers the focus on cost driving components for the integration between design and cost estimation and their information in a BIM model. Low complexity with few components in the project would not be sufficient to test the effectiveness of focusing on cost driving components. Having high number of elements with interrelations leads to a complex project that requires more effort and time to link information in the model. However, the time for the case study is limited and effort to be made by the team members cannot be increased drastically.

ii. **Criterion 2: An average level of complexity in terms of uncertainties in scope** is important especially for communicating changes and considering alternative designs. The low dynamic character will delay the observation of the communication of changes and will limit the consideration of alternatives. On the other hand, a very dynamic project will not enable observing, tracing, and analyzing the consideration of alternatives and changes with their communication.

b. **Criterion 3: The type of project criterion focuses on ensuring a standard project** representing a regular design and cost estimation workflow. Accordingly, the results and recommendations shared are related to frequent tasks and could be applied to a larger number of projects.

Category "Team composition": This category focuses on individuals working on the project, their interaction, and their characteristics. The following criteria are established.

a. **Criterion 4: Project with team members (especially designer and cost engineer) encouraged to have intensive interaction with the researcher**. During the test of the process, their availability to share ideas, communicate tasks, and reflect on their feedback are essential to collect data. This criterion is assessed based on the involvement of members from the infrastructure department which is the department in which the researcher is involved. Working within the same department facilitates communication and interaction.

b. **Criterion 5: Openness and flexibility of team members** are necessary for introducing the process and testing it in practice. The projects considered for selection are those with team members (project manager, leader, designer, cost engineer, BIM modeler) who are open to introduce new ideas to their practice. To put these ideas to practice, the team members shall show flexibility to make changes to their own way of working.

Category "Tools used": Since 5D BIM is part of the process, it is necessary to ensure the ability to form such a model. For this purpose, **criterion 6 notes the ability to introduce 5D BIM to the project**. Since the utilization of BIM is a continuously developing within RHDHV, a case not considering the implementation 5D BIM is suitable. This provides the flexibility in applying the designed process instead of following one already planned by the team.

The analysis made on 9 potential projects based on the above 6 criteria is provided in table 6.1. Table 6.2 clarifies the meaning of the numbers used in table 6.1.

Table 6.1 Analysis for case selection

Projects	Complexity: Scope largeness	Complexity: Uncertainties in scope	Standard project	Team members encouraged to interact	Open and flexible members	5D BIM not yet applied	Total
Project A	1	0	1	1	1	1	5
Project B	0	1	1	1	1	1	5
Project C	1	0	1	0	1	0	3
Project D	0	0	0	1	0	1	2
Project E	1	0	1	0	1	1	4
Project F	0	0	0	1	0	1	2
Project G	0	1	1	0	1	0	3
Project H	0	1	1	0	1	0	3
Project I	0	0	1	0	1	0	2

Table 6.2 Score description

Score	0 = not the desired case	1 = desired case
Complexity: Scope Largeness	Involves many elements, more than 3 designers, Project larger than €50 million OR Involves few elements, one or two designers, project less than €20 million	Involves average elements, more than 2 designers, project between €20 and €50 million
Complexity: Uncertainties in scope	No changes in design resulting in changes in cost estimate OR 2 or more change in design resulting in changes in cost estimate per 4 weeks	1 change in design resulting in changes in cost estimate per 4 weeks
Standard project	Not a standard project	Standard project
Team members encouraged to interact	No colleagues working on the project are from the same department as the researcher OR 1 colleague is working on the project from the same department as the researcher	2 or more colleagues are working on the project from the same department as the researcher
Open and flexible members	Project team has an active aversion against BIM 5D OR Consideration of 5D BIM is still not decided	Project team is actively looking to incorporate BIM 5D into their project
5D BIM not yet applied	Fully integrated BIM 5D model in place OR Some dynamic linking between cost estimate and design in place	Only conceptual link between design and cost estimate

Based on the analysis, two projects **Project A** and **Project B** are potential cases. The final round of discussion with the project team members led to the selection of **Project A** as the pilot case. For confidentiality reasons, parts of the subsequent sections are removed. Thus, the project description is made vague and illustrative images are disregarded from this version of the report.

6.2 Pilot Case Description

The case study is **"Project A"** which is led by a public client who aims at tackling the issues of road safety, traffic management, and spatial quality. The city council investigated the improvement of the station environment such that it becomes easily accessible for vehicles, pedestrians, and cyclists to move smoothly and safely in an attractive, green, and inviting environment.

Many stakeholders are involved in the project: municipality, ProRail, NS, province, property owners, and residents. An independent advisory team appointed by the municipality investigated the complex spatial issues. The architectural firm is given the lead over the several groups representing the local population, entrepreneurs, and institutions to study the area and provide recommendations for improvements. To solve the conflicts in traffic, the existing level crossing on the railway line will be replaced by an underpass. Three variants of the position of the underpass and its connection with the existing road network were studied. By the end of the schematic design, the variant with an underpass specific for vehicles at the location of the level crossing is selected. Furthermore, the cyclists will be provided with a separate underpass. In this manner, vehicles, railway, and cyclists have their own route. Therefore, the scope of the project becomes the realization of two fully functional underpasses and lifting of the level-crossing at two roundabouts and the overpass at the station. Despite the definition of the scope, the alignments of the routes are still dynamic with frequent changes in the design.

RHDHV is part of the primary team of the municipality and will be responsible for the preliminary design stage. This design phase is planned to last 10 months with a planning initiating cost estimation after completing the design in July. By the end of the preliminary design, the design shall be ready for decision-making and the cost estimate shall have an accuracy range of 15%. This is specific to the underpasses that will be constructed with a contract between the municipality and ProRail. The approach of the tunnel contract is to emphasize project preparation and minimize setbacks in later phases. Therefore, the municipality makes a well-motivated investment decision on the project. Similarly, the remaining of the project is the public space design is studied by the municipality prior to contracting the project. Figure 6.1 illustrates the organization of the project.

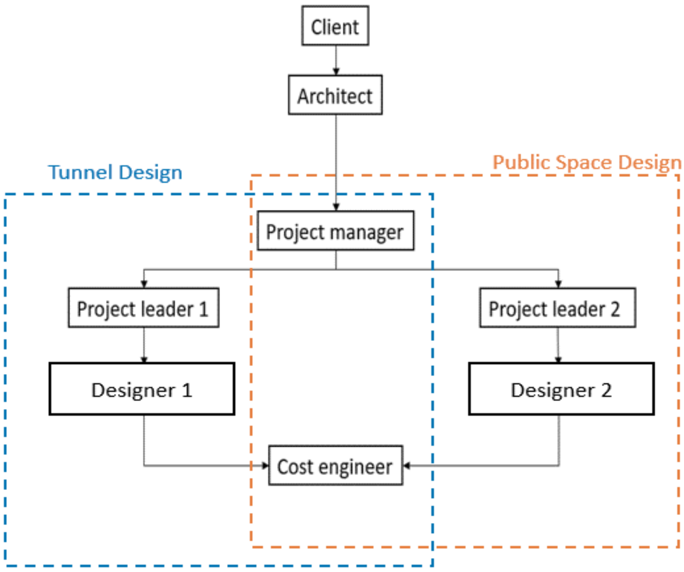

Figure 6.1 Project A team organization

Since the case is studied during the months of May and June 2019, it is planned that only part of the preliminary design phase is considered. The preliminary design of the public space is covered during this period. During this time, the researcher is actively involved in a sub-team from RHDHV working on the design of the public space. This team consists of project leader for the public space, the designer, and cost engineer.

6.3 Process Implementation

The designed process is implemented in the pilot case study. Since the team is only responsible for the preliminary design, the process is implemented to the end of the preliminary design. Even though the team is not responsible for the schematic design, the part of the process on "preparations – schematic design" is still considered. This is essential for the team to understand the project and agree on the workflow. Considering this condition, the section describes the implementation of the process in practice. Each of the process steps is covered separately.

6.3.1 Define Scope and Requirements

Scope definition and requirements setup are studied in biweekly meetings involving the team, client, architect, and other relevant stakeholders for the session. The researcher is not involved in the meetings. Yet, the team members provided reference documents and information covered in these meetings.

The scope is defined in general in the project documents as described in section 6.2. However, the design and requirements were not defined at the beginning of the preliminary design. The project leader mentioned that the project is led by the client and architect. They were still sketching when the schematic design was supposed to be completed and preliminary design initiated. Furthermore, the project leader noted that no specific requirements or budget are set to aid decision-making. Decisions were not made based on multiple criteria analysis.

Regarding the design, there was lack of specifications for the team working on the public space. The client did not specify the level of detail for the design and accuracy of the estimate. However, for the tunnels, it was clear that the design shall have a level of detail that allows 15% estimate's accuracy. The project leader mentioned that it is not clear whether both tunnel and public space designs shall follow the same accuracy. Upon consulting the cost engineer, it was proposed to have 15% accuracy for the overall estimate. Therefore, both designs shall have a level of detail suitable with the 15% accuracy.

At later stages of the project, the client provided some requirements and specifications which were managed in Relatics. In Relatics, the different objects of the design were linked to their requirements and specifications.

6.3.2 Agreement on Classification System – WBS – CBS

The breakdown structure was set after the initiation of the design. In the start-up meeting involving the researcher, designer, cost engineer, and project leader, Uniclass 2015 classification system was considered. The team agreed to use it knowing that it is confirmed by the company. However, Uniclass classification system was disregarded throughout the process. The team prepared their own breakdown structure and object codes.

The project leader requested from the cost engineer the preparation of a breakdown structure suitable for estimation. Since the project manager did not specify the WBS and objects for estimation, the cost engineer stated that it would be at an abstract level. Furthermore, the cost engineer informed the team that the project manager prefers that the cost engineer does not start working until the design is developed in order to avoid double work. After receiving the green light from the manager to set the breakdown structure, the cost engineer proposed a structure that enables splitting costs based on contracts of the two designs and stakeholders.

During the analysis of the breakdown structure, the cost engineer struggled to decompose the structure to detailed elements. The struggle was mainly related to the identification of the boundaries of each structure (the tunnels, the roundabout, the station, the roads… etc). The agreed boundaries by stakeholders were necessary to distinguish costs related to ProRail from those related to the municipality. Furthermore, the cost engineer needed clarifications on phasing, demolition, real estate, temporary objects, and landscaping. The cost engineer and project leader stressed on the importance of this information for the overall budget estimate. The area is changing completely so demolition and temporary solutions shall be configured to estimate costs. Clarifications on landscaping were also needed since the area will become greener. Therefore, considerations on cut/fill plan, planting scheme, tree cutting, building demolition… etc were necessary. Lots of questions were raised regarding these aspects since they have a huge influence on the design and cost estimate. The cost engineer requested a meeting with the client to clarify the latter points and set the structure, but the project manager preferred delaying the meeting. The project leader also raised the questions to the client, yet no response was given. For this purpose, these aspects were disregarded in the breakdown structure.

After the discussion between the cost engineer and project leader, the team reached a breakdown structure that aids the connection of design and cost estimation as shown in appendix G. This breakdown structure was derived from Relatics and it represented the object tree rather than the WBS. The objects have unique codes produced by Relatics. The designer agreed on the structure and the cost engineer confirmed the suitability of this structure with the estimate. Therefore, the team agreed to use the objects division, their names, and codes for design and estimation. However, the cost engineer mentioned that the object tree was at an abstract level and pinpointed the addition of several elements. These include the bike's parking space near the station and other elements based on ProRail's preference to separate these items in the cost estimate. The elements were not added since the project leader was waiting for the approval of tunnels' project leader and tunnel designer.

6.3.3 Set Budget, Cost driving components, and their Target Costs

The team members discussed the budget setting in a meeting. The client did not specify the budget but provided a former estimate. The project leader and cost engineer noted the unclarity of the estimation in the document of the former estimate. Accordingly, the cost engineer determined points for modification. Based on these points, the cost engineer provided an estimate greater than that of the document. Having discussed these points with the project leader, the cost engineer's estimate was considered for the budget.

Since the object tree was based on an abstract level, the cost driving components were also considered at this level. The pinpointed cost driving components were the following objects of the tree.

- OBJ-00003 - Onderdoorgang snelverkeer
- OBJ-00002 - Onderdoorgang langzaamverkeer
- OBJ-00055 - Rotonde (noord)
- OBJ-00056 - Rotonde (zuid)
- Fietsenstalling (1000 st) bewaakt en overdekt (not added yet to the object tree)

For setting the target costs, the team proposed to allocate percentages of the direct cost to the cost driving components. Furthermore, the team members noted the consideration of the parameters which influence the costs of these cost driving components. These parameters can be characteristics or features of the cost driving component. To provide a target cost, the cost engineer mentioned the need for rough estimates based on which he applies expert judgement. Accordingly, the designer provided quantities for making a concept estimate. Then, the cost engineer applied his expert judgment to find the target costs for the cost driving components and the overall project cost. Based on the project's total direct costs, the percentages of costs of each cost driving component is derived. The results on cost driving components with their percentage from the direct costs are shown in figure 6.2. The cost driving components and their parameters are presented in table 6.3.

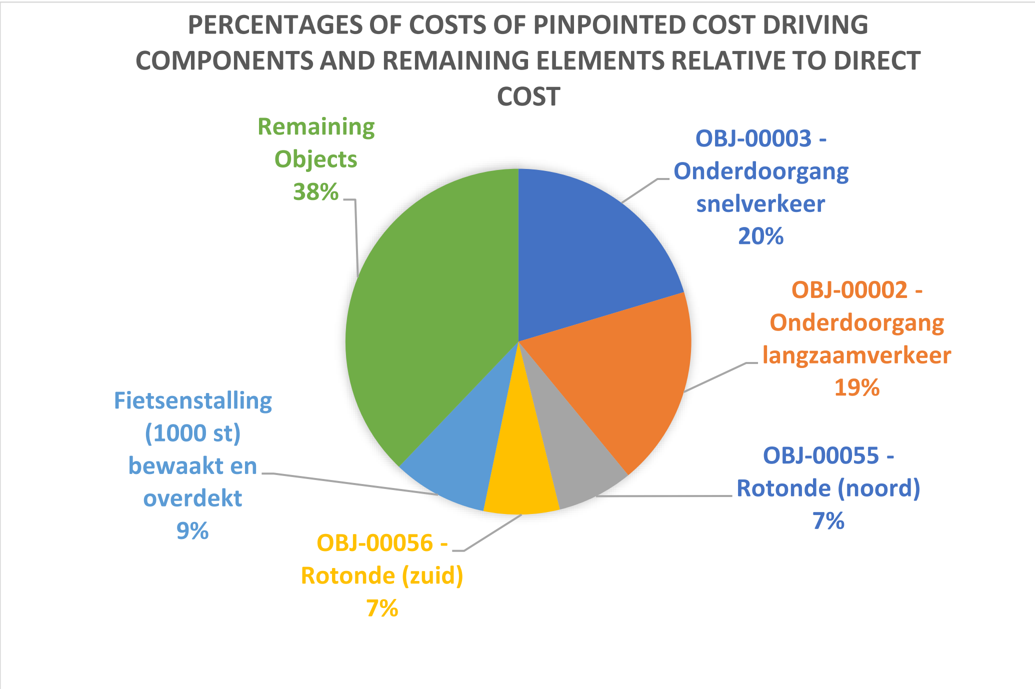

Figure 6.2 Percentages of Costs of cost driving components and remaining elements relative to direct costs

Table 6.3 Parameters set specifically for cost driving components to aid the design and controlling costs

Cost driving component	Parameter
OBJ-00003 - Onderdoorgang snelverkeer	dimension, concrete and steel composition
OBJ-00002 - Onderdoorgang langzaamverkeer	dimension, concrete and steel composition
OBJ-00055 - Rotonde (noord)	material and dimension
OBJ-00056 - Rotonde (zuid)	material and dimension
Fietsenstalling (1000 st) bewaakt en overdekt	location and capacity

During the discussions over these cost driving components, the project leader proposed the consideration of 2 more cost driving components, costs for purchasing land and phasing (years for execution, closing roads, displacing structures… etc). The real estate costs are influenced by the alignment of the tunnels and roads while phasing depends on the overall design. These are not design elements but can be considered as items influencing decision on the design option. Therefore, they are not identified as cost driving components for which designs are prepared. The project leader also discussed the addition of landscaping to the list of cost driving components. The architect proposed a greener area with high quality material. However, the idea was still too vague to discuss in terms of design.

6.3.4 Set Meeting Schedule based on Cost driving components

The team followed the meeting schedule already set for the project which is biweekly meetings with the client. The team preferred not to specify the time-table for meetings to discuss public space design and estimate.

The designer, project leader, and cost engineer were at the same location only once a week. At this time, the team members communicated or held meetings if necessary. Throughout the process, the team met twice in arranged meetings: in the start-up meeting and the meeting for discussing the cost driving components. The rest of the discussions occurred without arrangement. The important face-to-face discussions were: [1] the discussion between the cost engineer and project leader on the WBS and [2] the discussion between cost engineer and designer on the quantities to be extracted. Furthermore, communication via email and phone was intensive. This included [1] emails for exchanging information in word or Excel and [2] phone calls for questions related to the task being executed (such as questions from the designer to the cost engineer during quantity extraction). With the tunnel team, the project leader mentioned that the communication was very limited.

6.3.5 Discussion on BIM Execution Plan and Process Map

There was not a meeting specific for BIM execution plan and process map based on which the team members will work. In meetings, discussions, and email exchanges, some aspects related to the execution plan and process map were addressed.

Considering the input information on requirements and specifications necessary for the team members, no clear management was set. Later in the process, Relatics was prepared to manage this input information. It was further adopted for standardizing the representation of objects between the team members.

In a discussion with the project leader, the planning of the project was shared. The planning considered cost estimation to start after the completion of the design. In further discussions, the project leader and cost engineer considered studying costs throughout the design process. Accordingly, the team agreed to compute the estimate throughout the process. Furthermore, the designer and cost engineer agreed to communicate prior to quantity extraction and after estimation. For information exchange, it was agreed to be done via Excel and PDF drawing having the object codes from Relatics to enable traceability. The Excel having the different items for quantity extraction was prepared by the cost engineer and shared with the designer prior to the design.

At the beginning of the process, the team members discussed in a meeting the desire to reach automation such that the design was dynamic with changes directly reflected in the quantities. However, the designer noted that quantities were extracted manually from the previous design since most of the items were drawn in 2D. He also stressed on the point that making it 3D might not be possible since it would require more effort. Furthermore, the team noted that the client did not request a 3D model. Therefore, the team thought that drawing in 3D would not add value. However, the tunnels were designed in 3D, thus leading to a design with parts in 2D and others in 3D.

In further discussions, the team noted that they aimed for compatibility between design and cost estimation such that the designer does not perform unnecessary work to provide the cost engineer with information. Unnecessary work is having high details in 3D when the cost engineer can compute the estimate based on a simpler design. Finally, the project leader expressed the necessity to have the design traceable such that the design and cost estimate clearly show the representations of objects.

At later stages of the project, the designer changed from drawing in 2D to 3D to better consider the slope requirement added by the client. For this 3D model, the designer noted the ability to add information as metadata attributes to the model but the complication of extracting quantities. For this purpose, 3D modelers were consulted. From the consultations, it was found that the desired way for automatically extracting quantities is possible. However, all experts stressed on the need to agree beforehand with the cost engineer on the breakdown structure and requirements. Then, the design is made accordingly. Otherwise, the design has to undergo modifications prior to quantity extraction. Considering the latter points, the designer pinpointed that earlier preparations of the model should have been made. Furthermore, he estimated the time and effort to reconsider automated quantity extraction in 3D. Due to time limitations, the team adhered to manual quantity extraction that the designer is used to. This is done while considering the requirements of the cost engineer for quantity extraction.

For the tunnel design, the tunnel designer mentioned that the quantities are derived from Revit using a company-specific tool. Then, the cost engineer mentioned that the information on quantities from this tool does not meet his requirements. For instance, cubic meters for a complete structure are provided when he needs them to be separated per location. Therefore, the received quantities have to be filtered and adjusted to become applicable for cost estimation. For this purpose, the cost engineer specified information on the extraction of quantities.

6.3.6 Cost Information for the General Model Preparation

The discussion over cost information for the general model preparation was not considered separately. It was addressed by the cost engineer while specifying information on quantity extraction of cost driving components. The specifications were set in an Excel file including the division of elements. For instance, the Excel document showed the division of an alignment of the road into the footpath, bike-path, vehicle-path, and green area. For each of the paths, the cost engineer requested extracting quantities separately. This is general information for model preparation and design compiled in a document shared with the designer to clarify the cost information in general. After utilizing standard representation of objects from Relatics, another similar Excel file with object codes was prepared and shared with the designer.

Considering the format for extracting quantities, the cost engineer’s main concern was to extract information on length, area, and volume of a certain element. This helps him understand changes and easily adapt the estimate to these changes. However, he decided not to request this additional information for the overall design of the model since it requires extra effort from the designer. Therefore, information on the extraction of quantities for elements other than the cost driving components was not specified by the cost engineer and was left for the designer to decide.

6.3.7 Discussion on Cost driving components’ Requirements and Alternatives

Similar to the general model information, the cost engineer preferred to have quantities extracted based on the details provided in the Excel file. Furthermore, the cost engineer requested information on length, area, and volume for the cost driving components. As the design develops, more details would be considered. The required information was added to the Excel file and shared with the designer. Then, the cost engineer explained briefly the Excel and add a column for the designer to add his assumptions. Finally, the designer agreed to follow the Excel file.

Regarding alternatives, the team held a meeting for the discussion of alternatives. In the first meeting, the team members mentioned that almost 50% of the costs are related to fixed design options. For the remaining portion, the project leader mentioned that design considerations that influence costs or alternatives are minimal. However, as the team met further with the client, this perspective changed due to continuous changes in the design.

In another meeting on alternatives, the project leader mentioned that the client is not interested in reducing costs and considering the costs early in the design. The designer stated that the reason could be related to the contract type of the public space design. For the case of the tunnel designs, the tunnel designer mentioned that the client requests a conservative design without the consideration of alternatives. The client aims at leaving room for innovation and optimization for the contractor. For this purpose, the project leader considered to use the concept of cost driving components and their target costs to aid decision-making on evolving alternatives. The team agreed that this is important since stakeholders are continuously sketching without having basis for decision-making. Having the costs visible might trigger the stakeholders to study alternatives and make decisions to proceed with the project. Based on the latter, the alternatives considered for cost driving components were based on the alternatives investigated by the client.

Regarding the alternatives, there were discussions on the bikes parking **"Fietsenstalling"** which is also a cost driving component. The discussions were on the location and structure of the parking space. For the roundabouts, their number was still not agreed on. The cost driving component **"OBJ-00056 - Rotonde (zuid)"** might be disregarded. Furthermore, the type, size, material, and other important specifications for the roundabout were not specified. For the cost driving components **"OBJ-00002 - Onderdoorgang langzaamverkeer"** and **"OBJ-00003 - Onderdoorgang snelverkeer"** their location is fixed. However, alternatives in terms of dimensions of deck, floor, and wall for both tunnels were not studied yet. The designer and cost engineer mentioned that multiple options of the steel-concrete composition can be proposed by the tunnel designer. The tunnel designer stated that this is possible, and she can provide a cheaper design. Yet, this is not the client's desire.

6.3.8 Design of Cost driving components and Information in the Model

The design of cost driving components was not performed separately. The design process was based on the overall design and was performed in a short period of time. Referring to the alternatives discussed in section 6.3.7, the design considered only the alternatives of the cost driving component **"OBJ-00056 - Rotonde (zuid)"** along with other alternatives that are not related to cost driving components but are requested from the client. Accordingly, the result was 2 designs, having slightly different road alignment and considered **"OBJ-00056 - Rotonde (zuid)"** or replaced it with a junction. The design of the cost driving component **"Fietsenstalling"** was not prepared due to unfinalized discussions on this object. Furthermore, the designs of the cost driving components **"OBJ-00002 - Onderdoorgang langzaamverkeer"** and **"OBJ-00003 - Onderdoorgang snelverkeer"** were not completed. These were being designed in Revit and the resulting dimensions will be sent to the public space designer. The given dimensions were at an abstract level since they included the length without further details on the dimensions of walls, floor, and deck. The composition of concrete and steel was also unknown, thus the alternatives for these cost driving components were disregarded in the design.

During the design, the designer did not consider the information from the cost engineer in the design. The designer referred to the cost information for quantity extraction and added information to the design. The information added aimed for traceability, thus, the objects in the design were clarified with visible codes from Relatics. These were added to the PDF of the design which specified the boundaries of every object and had the object codes from Relatics with information on quantities. Figure 6.3 shows part of the design with boundaries and information. The values are in the figure are removed for confidentiality reasons.

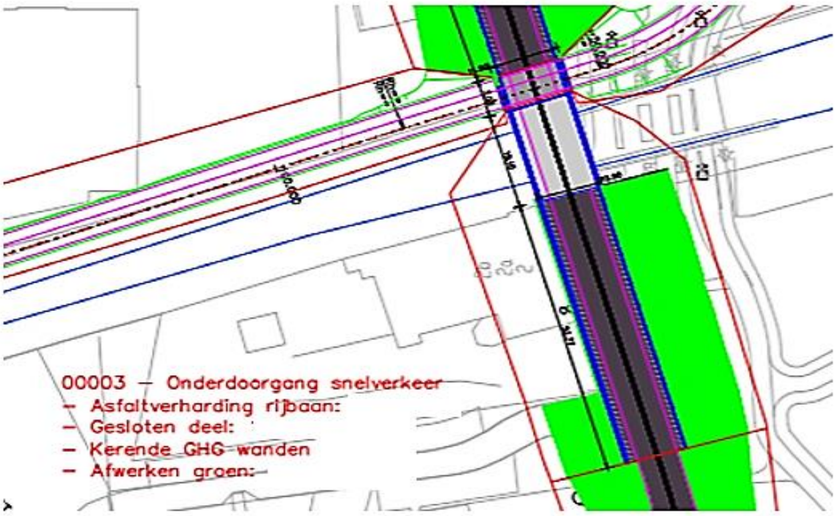

Figure 6.3 Example of the design of cost driving component with boundaries and tagged information

6.3.9 Group Elements based on WBS

In this case, the elements had to be split instead of grouped. Following the object tree from Relatics, the designer started to adapt the model to have the different objects. The designer also considered the requirements for quantity extraction. Accordingly, the designer modified the model by splitting the existing designed alignments. However, the designer noted that extra time and effort is required to match the model with the division of objects in Relatics and cost engineer's requirements. For this purpose, he stopped and contacted the cost engineer. The designer stated in an email, "using many objects means trimming and splitting the complete design and using a lot of hatches to extract those quantities". Raising the issue of effort and time, the cost engineer accepted that the designer proceeds with the design and quantity extraction in a method he finds suitable. Eventually, not all objects from Relatics were considered separately. The cost driving components were kept as separate objects but were not further divided for quantity extraction.

6.3.10 Check Compatibility of Level of Detail of Cost driving component Design with that of WBS

The breakdown structure used is at an abstract level as stated earlier. However, the design was at a deeper level of detail. The design considered the division of roads and roundabouts into vehicle-path, footpath, and green areas along the different roads. This division was not added to the breakdown structure.

6.3.11 Extract Quantities for Cost driving components

The method for extracting quantities was discussed with the team as mentioned in section 6.3.5. Since earlier preparation should have been done to have dynamic extraction, the quantities were extracted manually. Furthermore, the designer could not consider the requirements of the cost engineer due to time limitation and effort required. Therefore, quantities provided were limited to few requirements of the cost engineer and were extracted in terms of length and area without volumes.

The extracted quantities are presented in a PDF drawing (as shown in figure 6.3 in section 6.3.8) and new Excel files prepared by the designer. Instead of using the cost engineer's Excel file, the designer generated copies of this file for each of the objects. The designer did not mention this approach to the cost engineer. Once the cost engineer received the quantity information, he mentioned that he does not prefer this option since he works in a single file to compute the estimate of the overall design. Accordingly, the cost engineer mentioned that he has to compile the files and arrange a new Excel file to compute the estimate.

6.3.12 Estimate Cost for Cost driving components

The quantities provided to the cost engineer are considered good for a rough estimate. He used the quantities and applied expert judgement to reach the estimates. Further information is required to reach a better accuracy. The cost engineer mentioned that this is acceptable for this stage of the project. However, for later stages, he needs volumes and more quantities related to the information he requested.

The cost engineer is given the design, quantities on cost driving components, and quantities for the rest of the design elements. Based on this information, the cost engineer computed the estimate for cost driving components and that for the overall project. The estimate made is within the range of the budget estimate that the cost engineer judged in the beginning of the process.

At this point, the implementation is stopped due to time limitations. Therefore, the subsequent steps of the process are not considered.

6.4 Participants' Feedback

The participants reflection on the process is derived from semi-structured interviews with the designer, cost engineer, and project leader. The interviews are transcribed and provided in appendix H. The feedback is important to note the observations made by the participants and their assessment of the effectiveness of the integration. Furthermore, they provide future improvements. Further details on the feedback are provided below in terms of the main concepts of the process.

Alignment of design, cost estimate, and WBS: The feedback from the designer, cost engineer, and designer on this approach is provided in table 6.4.

Table 6.4 Summary of the feedback on alignment of design, cost estimation, and WBS

Subject	Project Leader	Designer	Cost Engineer
Suitability of Object tree	Suitable, the cost engineer also requested the addition of more items.	Suitable, but it requires effort to split the design based on the objects.	Suitable
Impact on integration	The approach would help in integration, but it is too early to note that. "I am convinced that this leads to effective integration, but you don't see the effect now."	It did not help in integration, but it is good to clarify the objects for the 2 parties and check the design. It is also helpful for communication.	It did not help in integration. The benefit is not noted now. For the future, it clarifies the updates. It should also reduce the mistakes between the designer and cost engineer.
Benefit from the Object tree	The object tree helped the designer and cost engineer understand one another.	It is not clear if the object tree would lead to time savings.	The best way is to work together. For the future, everyone gets used to it. Then, everyone benefits.
Limitations from the project	The focus of the team was on reaching a stable project scope, understand the client's desires and requirements, and integrate with the architect. Furthermore, the client is not familiar with big projects and how to act in such projects.	There was a problem in the planning since there was limited time. The time for quantity extraction is also not specified.	The problem is that it took time to reach a good structure. At first, the team was looking for that but now we reached a good structure.
Further considerations	The most important thing is to maintain the object tree dynamically and keep individuals aware that they are sharing the object tree. Therefore, further additions and changes happen after discussions in order to maintain it as a team.	It is important to clarify the objects, areas, and boundaries for everyone. Furthermore, changes can happen. "First split, then design."	It is helpful to set a process, clarify it to the team, work together, and be proactive by suggesting the process and structure to the client.

Budget, cost driving components, and target costs setting: The feedback from the designer, cost engineer, and designer on this concept is provided in table 6.5.

Table 6.5 Feedback on the concept budget, cost driving components and target cost setting

Subject	Project Leader	Designer	Cost engineer
Influence of the consideration of cost driving components	This approach was good since it led to having the cost engineer thinking earlier of the costs. It enabled him to share information on budget with the client and trigger the client to clarify the budget.	"The consideration of cost driving components clarified for me the expectations."	Not very influential since the team did not discuss it with the client.
Suitability of approach on cost driving components with the project	It is suitable for every project, but it depends on the client and project manager. The project was following a traditional way and it was hard to make a switch.	It is suitable for all projects, but in this project the team started too late. In big projects, it might be more suitable since time and space is given for innovation.	I think it was suitable for this project and it is suitable for complex and big projects.
Impact on integration	It gets the cost engineer more involved. Then, effective integration is reached.	The approach had to start earlier to have it impacting integration. If used from the beginning, it is good to be aware of the cost driving components and have the cost engineer giving the costs while changes are happening.	Not much. The team tried but the people have to be more open for changes.
Limitations noted	It is hard to implement this approach if the client is not aware of the process and the manager does not support it. Managers are afraid of integration by having parallel processes since they think of the hours and budget.	It started late in the project. In most cases, the project manager requires quick start with the design and does not want to do innovations. The managers focus on budget and time so when they see risk in delay from innovation they stop it.	The main issue is related to the hours being paid. This has to be clear in the planning from the beginning. Furthermore, the manager mentioned that the team can apply this concept but did not take any further action. The management focuses on budget and time, so it does not enable trying new ways.
Further considerations	It is important to agree on the concept earlier, make a process, and clarify the roles of client and project manager. It is helpful to have a visual and detailed processes (such as on weekly basis not months). The manager should also want this approach and adjust the process accordingly.	It is important to have it in the beginning. Furthermore, innovate in the design is necessary to have automatic quantity takeoff.	It is important to have a team willing to try new things from the beginning. The managers have to consider the process in the planning and workflow to easily implement it. It is also important to accept changes and undergo a cultural change.

<u>Meetings:</u> The project leader mentioned that meetings are very important to give awareness from the beginning. The cost engineer noted that the meetings held for discussions on cost driving components or other considerations were not effective since no one took action. However, he stated that meeting frequently is necessary for big changes in the design. The designer also supported this idea. Furthermore, the cost engineer noted that meetings are helpful, but the team members still think in a traditional way by focusing on time and budget. The project leader supported the latter point and stressed that BIM is a team effort not an individual effort. Understanding each other's work, talking with one another on changes, and helping one another are necessary points.

<u>BIM Execution plan and process:</u> Considering the extraction of quantities, the project leader and cost engineer mentioned that the designer stated this requires time. Furthermore, the designer mentioned that the dynamic quantity extraction requires preparation and time which were not given. The information on the quantities was added to Excel files and PDF drawings. The cost engineer mentioned that the PDF for the quantities is suitable, but the Excel file was missing information he requested. On the contrary, the designer finds the PDF and Excel files both suitable for the integration. Regarding the design model, the project leader stated that he would prefer to have the project in 3D sooner. The tunnel team was waiting for the public space design instead of going in parallel. Therefore, a lot of waiting happened.

Cost information and model design: The designer mentioned that the information provided by the cost engineer does not impact the design. Moreover, the cost engineer mentioned that the designer preferred to extract the quantities after fixing the design. The designer does not want to spend extra hours on the quantities due to changes. The project leader also mentioned this issue and stated that the designer is optimizing his individual process. The project leader added that the main consideration of going from traditional to a parallel process is to have the quantities extracted dynamically. For this purpose, a lot of awareness is needed. "It is not the techniques, it is the people." The people do not want to change their process. Individuals have to consider methods for extracting quantities efficiently. He also proposed developing the method before implementing them in running projects.

Cost driving component alternatives: The cost engineer mentioned that a lot of changes were happening in the design and the client did not think of changes with respect to the budget. Furthermore, the project leader mentioned that the client and project manager were not supportive of this idea. Despite this fact, the cost engineer mentioned that the discussions on cost driving component alternatives helped in the relation between the team members since the designer understood better the cost engineer's requirements.

Grouping of elements based on WBS and quantity extraction: The cost engineer mentioned that he did not receive enough information on quantities. Then, he stated that information on quantities provided as areas is not enough for good accuracy, but it is enough for this stage of the project.

6.5 Results of Embedded Case Study

The results show interpretations of the observations made by the researcher along with those made by the participants. Based on that, the effectiveness of the integration of design and cost estimation via 5D BIM is assessed to answer sub-question (6). The question is tackled by interpreting the observations in section 6.3 along with the feedback from the participants in section 6.4. This is performed while focusing on the definition of effective integration: [1] more interaction between design and cost estimation, [2] design made to cost, and [3] synchronized flow of relevant and desired information.

Considering the alignment of design, cost estimation, and WBS: Observations noted that the team struggled to setup the WBS or CBS due to the lack of information and support from the management. Despite that, the team was able to derive a unified abstract object tree with codes from Relatics. The objects and their codes were used in the design, quantity extraction, and requirements' management. However, at the time of the implementation, the designer did not have the time to modify the design by splitting it to consider all the objects. For this purpose, he focused on the cost driving components which is also the proposition of the designed process. Furthermore, the team members had discussions over the structure. This led to the consideration of important points to be raised to the client.

From the perspective of the project team, the object tree was suitable. At the time of the implementation, integration was not facilitated by this tree. However, the participants mentioned that it clarified the objects, helped in communication about objects, and enabled the designer and cost engineer to understand one another. Furthermore, the project leader and cost engineer agreed that its impact on integration will be regarded in the future. The participants expect that the unified object tree would lead to effective integration, reduce mistakes between designer and cost engineer, and enable the team to work together.

Accordingly, the points on synchronized flow of information and more interaction relating to the definition of effective integration are supported. The former is achieved due to having a single reference in Relatics where objects, their codes, and their information are available and used by all team members. The latter is attained as more interaction is made through discussions over the structure.

Budget, cost driving components, and target costs setting: The observations from the implementation show that the client did not set the budget and the accuracy of the estimate for the overall project. Raising these topics, the team started having discussions. The analysis and discussion over the estimate led to updating the overall estimate before its planned time and clarifying that a 15% accuracy is required for the overall design. Furthermore, the discussion over cost driving elements triggered the team to propose the consideration of characteristics influencing cost driving components. In this manner, the team members were analyzing the object to be designed while considering costs. Finally, the cost driving components set at an abstract level covered 62% of direct costs from the initial estimate. This conflicts with the expected 80% of costs covered by cost driving components. This is justified by the low accuracy of the quantities and estimate which the cost engineer mentioned earlier.

From the perspective of the team members, the project leader supports this concept as an approach getting the cost engineer involved in the project, having him thinking of the costs at an earlier stage, enabling him to share information on the budget with the client, and triggering the client to request an estimate. The designer noted that cost driving components clarified for him the expectations. However, he added that its earlier start might impact integration since awareness on cost driving objects is created.

Therefore, it is concluded that this concept enabled earlier and continuous involvement of the cost engineer in discussions. It also brought the analysis of costs with the different team members to an earlier stage. The team members benefited from this concept despite its limited impact on integration due to late application and support from the manager. Accordingly, the point on effective integration related to interaction is addressed.

Meetings: The observations showed that no specific meeting schedule is set but the team members were communicating via various means (face-to-face, email, and phone). Despite the latter considerations, the participants' feedback showed that meetings did not lead to action. Furthermore, the cost engineer and project leader noted that the team members focused on their own effort, time, and budget. This reduced the frequency of meetings. Therefore, this concept failed to enable effective integration via 5D BIM as few meetings were held. Furthermore, the meetings did not lead to action, meaning they were not effective.

BIM Execution plan and process: There was no specific discussion over the application of BIM and the workflow of the designer and cost engineer. The initial planning was fragmented which is not suitable for BIM application that relies on the integration of processes. The desire for dynamic quantities and ensuring compatibility of design with cost information to avoid unnecessary work were discussed. Furthermore, consultations with modelers were made to enable fast extraction of quantities and addition of metadata. However, the late consideration of dynamic extraction and time limitation, the quantities were extracted manually. Furthermore, the design was mostly in 2D then it shifted later in process to become mostly in 3D.

The feedback from the participants were also related to dynamic quantity extraction which was disregarded due to the time needed for preparation and execution. Furthermore, the designer noted that time was not allocated in the planning for this task. The information exchanged between the designer and cost engineer on the quantities was not complete and was only suitable in PDF as mentioned by the cost engineer. Regarding the model, the project leader preferred to have the design in 3D sooner.

The concept of preparation for BIM utilization and clarify the process for the different parties was not satisfactory. There were problems in planning, preparations, information and its exchange, and decisions on the modeling. These show that no agreements were made and that these agreements would have enabled the utilization of BIM and facilitated information exchange.

Cost information and model design: The cost information is added in Excel and the cost engineer understood the effort required to fulfill all his requirements. Therefore, he limited these requirements to cost driving components and left the rest for the designer to choose a suitable extraction method. The designer and cost engineer discussed and agreed on the latter. However, the designer did not consider the cost information in execution since it required time.

In the interview, the designer noted that the cost information does not influence the way he designs. He used it for quantity extraction. But he also did not use the information for quantity extraction as requested. The cost engineer mentioned that the designer does not want to spend hours on the quantities since the design is still changing. The project leader noted the same issue and added that the designer is optimizing his own process. Therefore, this concept failed to integrate the design with the cost information due to the lack of time for this task.

Cost driving component alternatives: The design of alternatives of cost driving components was limited. The client considered changes but did not think of the budget. The team members related that to the type of contract which provides room for the contractor to innovate. The designer noted in the interview that lots of changes were happening, but the client was not basing the decision on budget. Furthermore, the project leader noted that client and project manager were not supportive of the idea. Despite the failure of this concept to reach a design made to cost, the cost engineer mentioned that it helped in the relation between designer and cost engineer.

Grouping of elements and quantity extraction: The observations noted that the objects had to be split instead of grouped to consider the object tree. This required time which limited this to cost driving components. The extraction of quantities was done manually, and its result was the delivery of part of the requested information by the cost engineer. However, the cost engineer mentioned that the information was not suitable for the accuracy but is applicable for this stage of the project. Therefore, this concept failed to ensure integration by facilitating information flow since information was missing and manual extraction which requires time and effort is utilized. Despite that, this concept enabled the synchronization of relevant information between design and costs for the cost driving components.

Conclusion on the effective integration enabled by the designed process – sub-question (6):

The results show the limited successful integration of design and cost estimation via 5D BIM in the implementation. The challenges were mostly related to the lack of information from the client, lack of time, unsuitable planning, focus on individual effort, and lack of support from the management. Despite that, participants working closely with the different concepts of the process confirmed the ability of the process to attain effective integration by increasing interaction, designing to costs, and facilitating information flow. To reach the latter, the challenges have to be resolved.

From the process implementation, it is concluded that discussions ensure sharing relevant information which was limited to cost driving components in the pilot case. Furthermore, the consideration of alternatives to design to cost enables the designer and cost engineer to understand one another. Yet, the full benefit from this concept is achieved given that it is supported by the client with clear requirements, budget, and criteria for decision-making. In addition, participants noted that through the designed process, the information is synchronized by a common representation (object tree or WBS) which enhances communication. The process also introduces the cost engineer and cost analysis early to the project. With cost driving components and increased awareness of budget, the integration of design and cost is reached. The interaction between team members is improved by frequent discussions made in meetings. Furthermore, early discussions on BIM are essential to permit its implementation for design-cost integration. However, to reach the latter, the team members have to think of team effort instead of individual effort.

In general, the project leader mentioned that the process differs from previous practice since it requests parallel work and interaction. The main enabler for effective integration based on the process is the right planning with clear interactions between parallel design and cost estimation processes. Furthermore, the designer mentioned that time has to be allocated for model preparation considering dynamic quantity extraction. Otherwise, the lack of time leads to optimizing individual processes and disregarding cost information in the design as encountered in the embedded case study.

7 Validation, Discussion, and Reflection

The section validates the designed process based on the results from semi-structured interviews with experts. Then, the overall findings of the research are discussed. In the reflection, the focus is on the different steps of the research method.

7.1 Validation

The validation is based on semi-structured interviews with BIM experts. Interviewees 1V and 2V are professors at TU Delft and interviewee 3V works at a company specialized in digitalization. The details of the interviewees and the summaries of the interviews are provided in appendix I. Having BIM experts from academia and from practice provides a wider perspective for the validation of the designed process. The validation aims at confirming the applicability of the designed process to enable effective integration of design and cost estimation via BIM. Furthermore, the interviewees noted limitations of the process and provided recommendations for improvements.

In general, two of the interviewees (1V and 3V) supported the proposed design while the other interviewee (2V) diverged from the structure of the interview. Interviewee 2V rejected the notion of semi-automation, and he shifted the discussion to explain that through BIM the industry has to make a jump without a transition. He interviewee labels BIM is a game changer since it relies on symbolic representation for unique codes. He clarified that BIM enables tackling ambiguities and differences in interpretation. With respect to relating BIM to costs, the interviewee explained that his perspective is having an automated construction process based on which costs are derived. The construction packages would be decomposed, analyzed, and simulated in the model. Having the process, unit prices, quantities, and resources, the costs can be calculated without cost engineers. Additional considerations on inflation or other points can be performed by economists. For this purpose, cost engineers are not required. Construction expertise to model the construction process are needed instead. Furthermore, he stressed on the point of having a complete model by modeling all details and having the team work in a single model. The approach of this research seemed to the interviewee that it does not take advantage of BIM by having all team members developing a single model. The interviewee is against bringing BIM back to the traditional way of working. He believes that the methods in the construction industry are outdated and lead to cost overruns. Therefore, new processes have to be considered, people have to learn BIM, and work together on designing the model instead of relying on the designer to prepare the model. He added that "We need additional knowledge in designing" and "We don't have to make a transition plan, we need to find a way to educate the people" (interviewee 2V, 2019).

On the contrary, interviewees 1V and 3V, addressed the different concepts of the process and their impact on integration. They both noted that the focus on cost driving components for building the model is feasible. Interviewee 3V highly supported the idea. He noted that designers add too much details to the 3D model. These details require time and money and it is never the goal to add all this information to 3D, 4D, and 5D models. The aim is to have the necessary information to reduce the room for misinterpreting the design among the team members. Therefore, the focus on cost driving components is a good idea for cost computations via BIM (interviewee 3V, 2019). Furthermore, interviewee 1V mentioned the applicability of the idea and proposed considering main requirements rather than components. He believes that in this manner the information on costs is revealed. However, he noted that the focus on cost driving components is a good approach to increase integration (interviewee 1V, 2019). Similarly, interviewee 3V justified that integration is enhanced by the discussion over cost driving components and standardization between designers and cost engineers. He considers the latter idea is a big improvement since people will understand each other more. Usually, each member thinks from his own perspective which might not be suitable for the other. Discussions would reveal these problems. Furthermore, he added that the estimate is generally computed late in the project leading to redesign which is usually related to cost driving components (interviewee 3V, 2019).

Considering information management, interviewee 3V mentioned that focusing on cost driving components improves it. By focusing on cost driving components, the cost engineer is given the opportunity to think of his structure, monitor his information flow, and better handle received information. Furthermore, the team is thinking of the important components of the project at an earlier stage, looking at aspects related to the budget, and then going into the details. When looking into the details, the complexity of the model is reduced by identifying the details to be added and those excluded. This requires people sticking to the plan and accepting excluding details. Furthermore, the interviewee added that budgets are spent on designing unnecessary details while things that have to be designed are often absent (interviewee 3V, 2019). Interviewee 1V noted that the designed approach would help in information management, but this depends on the ability to pinpoint the cost driving components. It can also lead to a simpler model which might not be suitable for complex projects since information would be missed (interviewee 1V, 2019). On the contrary, interviewee 3V considered the focus on cost driving components suitable for complex projects due to the iterations considered in the process. The iterations are necessary for being agile to make changes and continuously updating the design instead of having it robust. Furthermore, the process enables a team spirit. Problems occur in complex projects, so the team should work together to handle them, minimize the impact, and think of future challenges (interviewee 3V, 2019).

Focusing on semi-automation, interviewee 1V noted that it helps in integration, and the approach might be fit for purpose. But it is also important to check available tools in the market. Furthermore, he mentioned that the agreement on a classification system helps in standardization, communication, and information exchange. Yet, practical problems and misunderstandings might still happen. To tackle the latter, the team shall not confuse the different breakdown structures and discuss occurring issues to agree on the solutions (interviewee 1V, 2019). Similarly, interviewee 3V mentioned that semi-automation is a good approach for the current case, yet it should not be the standard. It is suitable to avoid providing a new process and a new tool. Once the members are used to the process, the shift to automation can happen. Furthermore, he noted that the WBS is common for cost, time, risk, and other specialties. Therefore, the standardization and integration of the WBS leads to good information exchange, communication, and compatibility. However, the agreement on the overall WBS shall not be made at the start. It is better to start with a certain level of the WBS and then develop it through the process. Then, more detailed levels are added when necessary (interviewee 3V, 2019).

Regarding the drawn process map, it is considered good since it is kept simple by focusing on the relevant information to optimize the 5D BIM process for the designer and cost engineer. Later in the process, changes can happen (interviewee 3V, 2019). Furthermore, the reliance on the BPMN method is supported by interviewee 1V who also noted the necessity of definition and clarity of tasks and arrows to understand the process.

Finally, both interviewees 1V and 3V considered that the process in general leads to effective integration. Interviewee 1V noted that it leads to a cost-effective design but also proposed focusing on the main requirements for reaching more effective integration. He also noted that the effort of the people is essential. They have to get used to the new process and find a way to work with it. Thus, it might take more time in the beginning (interviewee 1V, 2019). Interviewee 3V added that the process leads to effective integration between designers and cost engineers. The main reason for effectiveness is that a good view is made from the beginning on what is important in the project for the designer and cost engineer. Furthermore, the relation between the two actors becomes smoother not only technically but also at the personal level by giving a team feeling. The designer and cost engineer understand one another's task, effort, and possible mistakes. However, the challenge is cultural since the designer has to accept not to add certain details and consider the cost engineer's perspective. The cost engineer has to get used to being involved early in the design process (interviewee 3V, 2019).

In brief, two of the interviewees validated that the designed process leads to effective integration of design and cost estimation via 5D BIM. The early consideration of estimation and study of cost driving components tackles the prevailing case of late estimation and redesign. With the designed process, the interaction is enhanced with frequent discussions revealing misinterpretations and leading to better understanding of team members' perspectives. Furthermore, the focus on cost driving components clarifies the details to be added/excluded in the model. In the model, the standardization of representation with classification systems improves information management and reduces the complexity of the model. The model's reliance on a semi-automated 5D BIM approach is supported given that it develops to full-automation after being familiar with the new process.

7.2 Discussion

The findings throughout the report are discussed to clarify their contribution to research and current literature. The first and second sub-sections discuss how the findings from the case study RHDHV on fragmentation between design and cost estimation and BIM/5D BIM application in practice contribute to research. The third sub-section focuses on the designed process "Integrated Design - Cost Estimation 5D BIM Process". The process is compared to other processes related to 5D BIM implementation. The fourth sub-section discusses the results from the implementation of the process in practice. Finally, the generalizability of the results is clearly identified in the last sub-section.

7.2.1 Fragmentation between Design and Cost Estimation

Upon interpreting the standards and literature on design and cost estimation processes, it is inferred that the design and cost estimation processes are integrated throughout the design process by different interactions stated in section 3.1.3. However, the study of a case from practice revealed that designers and cost engineers are not completely fragmented nor sufficiently integrated. The case of integration considers the cost engineer only in early discussions due to budget and time. Further integration is restricted to big projects. Furthermore, designs are not made to cost and optimization prevails at the end of the design process. The research provides a closer look into practice to assess the case of fragmentation noted in literature. Besides budget and time limitations, the major issues reflecting fragmentation are: **[Issue I]** the cost engineer is not involved continuously in the project and optimization prevails at the end of the design process and **[Issue II]** the cost engineer's influence on the design is limited.

Therefore, the research presented possible situations of a design-cost estimation relation in practice. The case confirms the problem of fragmentation noted in literature. Although the findings are based on a single case study and the problem is already mentioned in literature, the close exploration of practice decomposed the problem to underpin more specific points leading to fragmentation (noted in section 1.1). Furthermore, the root causes of fragmentation as expressed in the case are budget and time constraints. Thus, the research pinpointed the sources of fragmentation and the reasons for its occurrence.

7.2.2 BIM and 5D BIM Utilization

The comparison of the application of BIM and 5D BIM in literature and practice yielded to several issues: **[Issue III]** on model complexity upon adding too much information, **[Issue IV]** on the deficiency in information management, and **[Issue V]** on the lack of standardized approach for the WBS, cost plan, and model. These issues are similar to those discussed in section 1.1. Therefore, the influence of fragmentation as noted in literature on BIM application and interoperability is shown in practice. The derived issues are an elaboration on the problems noted in literature on: [1] the incompatibility of design models with cost estimation and [2] the lack of uniformity in building models and adding information. Furthermore, practice related the development of the model to budget and time.

Having budget and time as constraints to integration and BIM/5D BIM utilization, the research designed a process that considers these aspects and tackles the issues hindering integration via BIM. Even though budget and time constraints are derived from practice, they are generally distinguished as major constraints of project management. Therefore, it is important to also consider them in BIM processes followed to realize projects.

7.2.3 Designed Process: "Integrated Design- Cost Estimation 5D BIM Process"

The designed process aims at integrating design and cost estimation with BIM. It is based on the design process, cost estimation process, and BIM utilization concepts. This information is applied to reach a process tackling the issues noted in literature (section 1.1) and practice (section 4.4) on fragmentation and segregation of information in BIM. These are the major problems hampering interoperability as specified in section 1.1. Therefore, the integrated process with the focus on synchronized information management between designers and cost engineers leads to the contribution in the enhancement of interoperability. In specific, the designer and cost engineer interact to reach a design made to cost and coordinate the information to ease the workflow. The connection between the two disciplines is mainly through information management. This is reflected in the following ways: agreement on classification system to synchronize information, monitoring costs, discussions on the model information/details, compatibility checks, and frequent information exchange on the design and quantities. Covering these points, the proposed process fits with previously discussed literature. Literature recommends the alignment of project teams (Hartmann et al., 2012), integration of processes based on information management (Moses & Hampton, 2017), balancing information and details in the model (Stanley & Thurnell, 2014), and collaboration in building a model suitable for estimation (Sattineni & Bradford, 2011). The designed process relies on integration and collaboration with the focus on information and communication which are crucial. Integration and collaboration are key factors for long-term success of BIM as noted by Murphy (2014). Furthermore, the designed process provides flexibility to consider the 4^{th} dimension on time or other BIM uses. The entire project team follows the agreed breakdown structure to avoid conflicts and errors (Mattern, Scheffer, & König, 2018) and time information can be linked to the WBS and added to the third level of the WBS (Liu, Lu, & Al-Hussein, 2014).

Thinking beyond these points, the process is designed while considering time and budget constraints. For this purpose, the research proposes the focus on the cost driving components of the project for integration and model information. Through the consideration of cost driving components, the necessary information for costs is integrally studied and added to the model. Then, the integration between designers and cost engineers is based on specified influential interaction points. This specific interaction scheme clarifies the workflow to team members and relies on design portions that highly influence costs. Monitoring these design portions enables designing to cost. This is in line with PMBOK (2016) that briefly states the identification of cost driving components early in the design and their monitoring throughout the design. With the integration based on cost driving components, the cost engineer's perspective is added to the model without increasing the complexity. The focal areas for cost information addition are identified. Thus, the problem noted by Monteiro & Martins (2013) on increased time to add details for better estimates is addressed and the necessary information is added to the model.

Besides the concept of cost driving components in the designed process, semi-automation is adopted for applying 5D BIM. The semi-automated approach in the overall process enables the clear illustration of 5D BIM concepts (such as standardization and collaboration in building the model). Accordingly, it allows understanding BIM concepts and their incorporation into an integrated design-cost estimation process. This case is suitable to address the problems of 5D BIM implementation. The problems are related to information incompatibility and inconsistency along with continued fragmentation of design and cost estimation processes. Furthermore, it deals with the lack of understanding of BIM workflow and unclear participation which are challenges to implementing 5D BIM noted by Mayouf, Gerges, and Cox (2019). Therefore, the designed process joins tasks from design, cost estimation, and BIM application into a single process. This single process clarifies agreements, information flow, decision-making, iterations, and compatibility checks. The ideas in the process on compatibility checks, standardization using classification systems, and information flow are main achievements of the designed process. Mayouf, Gerges, & Cox (2019) underpinned the importance of analyzing the model information relative to the accuracy of the estimate. It is also necessary that designers do not add information freely and cost engineers clarify their requirements. Moreover, the authors stressed on the need for standardized codes to ensure the reliability of the data as it is transferred in different formats.

Furthermore, their study suggested the setup of information exchange and requirements for 5D BIM to reach effective integration. Accordingly, the designed process answers recent requests on 5D BIM.

The designed “Integrated Design - Cost Estimation 5D BIM Process” is distinguished from other processes available on the topic 5D BIM. Lu, Lai, and Tse (2018, p. 55) described a process for cost management throughout the different phases of the project. The process focuses on integration via software and databases without clarification of concepts of BIM for managing information to ensure the effective implementation. With the reliance on software for quantity extraction, parameters set by vendors are imposed. These parameters might not be suitable with the method of measurement. Besides this problem in the process relying on software, recent research on 5D BIM identified that the gap is in understanding the information flow (Mayouf, Gerges, & Cox, 2019). Furthermore, the process by Lu, Lai, and Tse (2018, p.55) disregards the problems noted in literature on model complexity and standardization. On the contrary, the “Integrated Design - Cost Estimation 5D BIM Process” focuses on incorporating the concepts of BIM into the integrated design and cost estimation process. It also proposes solutions to the issues described earlier. Therefore, the proposed process lags in technological aspects but clarifies the information flow. The consideration of software and databases is assumed to be the next step after understanding the underlying concepts of BIM. Otherwise, the noted problems in literature will continue to occur. In this manner, the “Integrated Design - Cost Estimation 5D BIM Process” is the stepping stone towards full-automation. It integrates design and cost estimation processes based on BIM concepts without the introduction of further variables (software and databases). This idea is supported by interviewee 3V who mentioned the strength of the process is its focus on a single change in the process before having the change in process and tools.

Another process on 5D BIM is investigated. The study provided a process which starts with the preparation of a historical database. From this database, an estimation model having information on quantities, costs, and schedule from similar projects is derived. Based on this model, costs are computed from the design. In the different design phases, the design is completed then the estimate is checked with the budget. Thus, exceeding the limit leads to the optimization of the design (Li, Yuan, Han, & Li, 2019). Although this process relies on real-time cost computation based on the estimation model, the design and cost estimation processes are still fragmented. Furthermore, the process does not consider the management of information to be compatible for design and cost estimation nor its standardization to enhance interoperability. Accordingly, the “Integrated Design - Cost Estimation 5D BIM Process” has a less advanced 5D BIM approach compared to this process, but it focuses on issues noted in literature and practice.

An alternative 5D BIM process proposed in literature is based on the level of development and level of details. The aim of this approach is to enable understanding the required details and information. Furthermore, it focuses on high-level elements for cost estimation to avoid heavy models and faster cost analysis. During the design stage with frequent changes, the cost analysis is based on high-level elements. In the overall process, standardization is done based on the New Rules of Measurement or classification systems. This approach claims to enable effective 5D BIM implementation (Mayouf, Gerges, & Cox, 2019). This approach is similar to the “Integrated Design - Cost Estimation 5D BIM Process” in terms of focusing on certain elements, incorporating the cost engineer earlier, and standardizing information representation. However, it does not clarify the selection of high-level elements based on which the integration is occurring. On the contrary, the “Integrated Design - Cost Estimation 5D BIM Process” adopts the concept of cost driving components to integrate the processes.

In brief, the “Integrated Design - Cost Estimation 5D BIM Process” focused on the change in workflow while the discussed processes focused on technology. The designed process and those noted from literature are relevant yet not holistic approaches for the implementation of BIM. The implementation of BIM requires the investment in technology, education, and change. The latter depicts the development of internal BIM workflow and procedures which rely on collaboration (Rokooei, 2015). Therefore, the designed process contributes to research as it adopts an approach that aims at addressing the issues from literature and practice. It clearly shows the workflow of design and cost estimation and integrates them using 5D BIM while considering budget and time. The process also enables agility due to the added iterations for discussions and changes in the design (interviewee 3V, 2019). In terms of 5D BIM approach, the process follows semi-automation to enable understanding BIM concepts and workflow. Therefore, it can be noted as the path towards automation which relies on databases and estimating software described in other 5D BIM processes.

This mid-way solution that the process provides is also important for practice. In the studied case, fragmentation between design and cost estimation was regarded. Furthermore, the application of 5D BIM from explored strategies is developing. Therefore, the case from practice suggested the setup of a process based on integration and 5D BIM utilization. The designed process can answer this request especially that it tackled the issues and the major disruptions of integration: budget and time. Furthermore, the designed process focuses on the concepts and does not require databases or specialized software for implementation. In this manner, the process can be directly applied in practice. For future considerations, developments and trainings has to be made to change to full-automation.

7.2.4 Designed Process Implementation in Practice

The designed process is implemented in a running project. The aim was to check the ability of the designed process to reach effective integration between design and cost estimation via 5D BIM. The general finding was that the implementation did not show effective integration. The unsatisfactory result of the implementation is justified with the research by Elmualim and Gilder (2014). The authors identified "effective implementation of a new process and understanding BIM to apply the process" among the challenges to BIM utilization. Despite the unsuccessful implementation, the involved participants supported the ability to reach effective integration through the "Integrated Design - Cost Estimation 5D BIM Process". The team members understood one another's tasks, thought of costs earlier as the cost engineer was continuously involved, enhanced their communication, and initiated discussions that clarify points influencing the budget of the project.

Further integration and 5D BIM application were not achieved due to several reasons. First, the planning of design and cost estimation was based on fragmented processes and did not allocate time for quantity extraction. Second, the client and project manager were not supportive of the process. The client was not aware of it and the project manager accepted its implementation but did not adjust the planning accordingly. The focus was on budget and time. Furthermore, the project manager sees risk of delay from innovation and budget exceedance from integrated processes. Third, time was not given from the management for the preparations for automatic quantity extraction. Fourth, meetings were made but no actions were taken. Members focused on their own effort and optimizing their individual processes. Therefore, the transition from individual to team effort was not made. Furthermore, meetings led to agreements which changed upon noticing the effort required during execution. It is inferred that the team members underestimate the tasks required or are not fully aware of the tasks discussed during the meetings. Finally, the team composition and the unwillingness of the members to change were noted by participants as barriers to the implementation of the designed process. Therefore, the obstacles hampering integration and implementation of 5D BIM are related to people and management. The team members influence the implementation of BIM, especially the project manager who is the center for communication channels. The knowledge of BIM enables the application of BIM to integrate and coordinate project members (Rokooei, 2015). Furthermore, the focus on budget of projects leads to avoiding innovation and collaborative integrated processes which form complex interfaces and require investment in new skills (Babič & Rebolj, 2016).

A crucial point concluded from the research is that the management's distribution of budget and time into working hours for each member is a major problem. It is triggering individuals to avoid meetings or work that is not counted within these hours. In this manner, the focus is on individual effort rather than team effort. To easily control budget and time, fragmented planning is followed, and innovation is avoided to reduce the risk of delay. Furthermore, the plan lacks details on tasks relating to preparations and quantity extraction. Therefore, fragmented planning, lack of details in the plan, and the focus on individual hours complicate the implementation of BIM. From these results, it is derived that the role of the project manager has a major influence on BIM implementation. Earlier research has noted that if the project manager is not acquainted with BIM, it is difficult to successfully relate the design scope and modeling details with the time required for the development of the model (Tauriainen, Marttinen, Dave, & Koskela, 2016). The results from the implemented process show that not only the time for the model is underestimated, but also the periods for preparation and collaboration are missed in the planning. The latter situation was a barrier to the implementation. This is in line with the research by de Almeida and de Brito Mello (2017) who specified the lack of planning and time as an issue hampering the implementation of BIM.

Another point regarded in the research is the importance of the change in culture which is identified as one of the difficulties of BIM. Individuals are used to the company's workflow relying on the distribution of hours among the team members. This triggers the members to associate their own effort to the allocated working hours. Their focus is on individual rather than team effort. This is justified with the study by Babič and Rebolj (2016). The authors note that the hierarchy in projects clarifying responsibilities results in members who try to ignore additional work and innovative approaches that add benefits to the overall project but are not directly related to their specific work. The change in culture from individualism to team effort may lead to an obstacle towards BIM implementation. This depicts the difficulties in changing a company's workflow and culture to apply BIM (Murphy, 2014). Cultural transformation is considered a stronger threat than technology (Stanley & Thurnell, 2014). The designed process and its implementation did not consider the cultural change. Yet, it was regarded in the pilot case. Therefore, BIM is not only a technological or digital development, culture has a major influence. Furthermore, Murphy (2014) stated that BIM's requirement for extensive collaboration and interaction is a challenge for the construction industry. He also denoted that organizational culture capabilities in firms and projects will postpone the application of BIM. Therefore, it cannot be expected that the change to BIM could be a jump as considered by interviewee 2V.

The findings from this part of the research are related to Issue VI on the resistance of client and practitioners or their inexperience in BIM. The test of the "Integrated Design - Cost Estimation 5D BIM Process" was not successful but it showed the resistance in the construction industry to apply innovation in technologies and processes that lead to collaboration as noted by Murphy (2014). The illustration of a case in practice is an added value to research as Murphy (2014) calls for practical studies and case-based studies for the implementation of BIM. Furthermore, the findings clarify reasons yielding to inappropriate BIM application. These include: difficulty in cultural and workflow change (lack of collaboration and team effort), lack of management and client support, unsuitable planning, and unawareness of BIM preparations and methods.

7.2.5 Generalization

Despite the reliance on a single case to explore fragmentation and BIM application in practice, the results are explanatory to regular cases similar to RHDHV. These are cases that are typical in their experience in BIM and are developing towards further advancement. Therefore, the presence of fragmentation along with the derived issues leading to fragmentation and hindering BIM application are considered to occur in other average cases.

Since the designed process relies on derived issues from the single case study, it becomes applicable to cases similar to RHDHV. Furthermore, the issues based on which the process is designed are supported from literature. Therefore, the designed process can be applied in other cases too. Based on experts' judgement, the application of the designed process is related to specific projects. Interviewee 3V mentioned that it suits complex projects as it enables team spirit, involves the cost engineer to think of upcoming challenges, and has iterations to adapt to changes. On the contrary, interviewee 1V noted that the designed process is suitable for standard projects. It is not applicable to complex projects since information will be missed due to focusing on cost driving components. Yet, it is important to be aware that the process is for the integration of design and cost estimation along with their information. Further information is added to the model depending on requirements from other specializations. In this manner, information is not missed. Instead, it is balanced among disciplines as necessary information is added to the model. Then, the point raised by interviewee 1V is addressed. Therefore, the designed process is considered suitable for various projects, standard or complex.

The research also shared findings that resulted from the implementation of the process in an embedded case study which is a single case. The results determine cultural change as a challenge to BIM application. The problem in general is noted in literature and further illustration is provided in this research. Furthermore, other reasons (lack of support from the management and client, unfit planning, and unfamiliarity with BIM preparations and methods) disrupting the implementation of BIM were pinpointed. The provided barriers can be observed in projects having the client, project manager, or project participants have not yet evolved to the culture of team work and collaboration that is required for BIM. The results are also generalizable to standard projects in terms of complexity and dynamic aspects similar to those of studied pilot case. Furthermore, these findings shall be used to improve the designed process in future research.

7.3 Reflection

Throughout the research process, different approaches were adopted to answer the research questions which created the areas of focus and steered the research. The overall methodology covering various steps and suggesting their continuity for further improvements is a unique approach used in this research. Such an approach can be adopted in other studies considering dynamics and aiming for continuous development.

The different steps of the research method are addressed in the reflection. These includes the following: desk research, single case study, process design, embedded single case study, and validation interviews.

7.3.1 Desk Research

Instead of focusing only on 5D BIM which is the main topic of the research, the topic is decomposed to the main aspects (design, cost estimation, and BIM/5D BIM application) which are studied thoroughly. Literature on 5D BIM process in specific was not abundant. Yet, throughout the process the researcher came across new publications on a similar topic. This aided the discussion of the findings in comparison with literature.

The choice of having a deep study of the different topics helped the researcher in comparing literature with practice and designing the process. However, it led to an overload of information that required time to restructure while preserving the relevant details for the reader. An earlier clear plan would have created more focus to aid the desk research process and reduce the time for modification.

7.3.2 Single Case Study: RHDHV

The single case study on design, cost estimation, their interaction, and BIM/5D BIM application provided a perspective of the situation in practice. The aim of conducting this study is to have a closer look into practice. Literature claims the presence of fragmentation with general reasons to support it. However, the researcher believes that a view from practice in its most recent cases enriches the research. In this manner, the designed process is based on up-to-date occurring problems. Multiple cases would have given a better description of the case in practice. However, the time for the completion of the research is limited to 6 months which cannot be distributed among various firms.

The information from the case was collected from accessible documents and semi-structured interviews. The documents did not give details since they were brief presentations or Excel files. On the contrary, the semi-structured interviews with a large number of experts provided information that was sufficient to map the current processes. The choice of having interviews aimed to reach individuals' view of the process and encountered issues. Such information is not readily available in documents. Despite the benefit of collecting and documenting the information from interviews, it was a challenge to create with it a whole picture of the processes. When performing the interviews, it was a main concern to have the interviewees answer the questions based on the process as it occurs rather than the ideal case from standards. This was mainly with the designers who did not note problems with cost engineers till questions were specifically directed to communication and reasons for it. Furthermore, interviewees on BIM had expertise related to BIM processes rather than 5D BIM. However, they were the only available respondents within the suggested timeframe. Earlier invitations for interviews should have been sent or more time should have been given to interviews.

7.3.3 Process Design

The design of the process initiated with issues leading to fragmentation and hampering BIM/5D BIM application. Although the issues were derived from practice, they are related to general problems noted in literature. Then, the issues are countered based on literature. Accordingly, the designed process is based on literature along with practice. Finally, the steps of the process are translated to a BPMN process map with information exchanges.

The approach of the process design was selected to focus on occurring problems with the intention to have a 5D BIM process from a different perspective. Literature provides 5D BIM processes with advanced technologies but does not clearly indicate the workflow of the individuals. However, the problems hindering the application of 5D BIM are not related to the technology but are related to the people, their interaction, and culture. Therefore, the researcher decided to go a step backward. The decision was not to focus on the tools, but on the integration of the disciplines in a workflow that clarifies the concepts of BIM. Furthermore, the researcher meant to deeply look into the way for integration and create links between the disciplines rather than proposing parallel processes without a comprehensive plan. The link was based on the concept of cost driving components that originated mainly from practice. It was appealing to adopt this concept since the driving components cover a big percent of the cost but form a small portion of the components that would be modeled. For this purpose, it was chosen as the means to focus on necessary information for cost engineers in the model. Since the problems occur in practice, the perspective of practice on improvements was considered knowing that they are supported from literature. To have a solid base to the process, literature was mainly relied on in the design.

After setting the steps of the process, BPMN was used to form the process map with the information flow. The decision to reach this map was to incorporate the information into the process since it is the key in BIM. Focusing on BIM and information, the researcher was triggered to follow the notation that is generally used to present BIM processes. However, the decision points were specified to the designer or cost engineer when it is preferable to have the decision made by both actors. Therefore, another process map could be prepared to show the common decision-making points.

7.3.4 Embedded Case Study: Process Implementation

First, the case is selected based on criteria identified in section 6.1 such that it enables implementation and generalization to standard projects. It was especially important to have a project whose members are willing to have the researcher in the team and speak in English in some meetings. Despite the suitability of the team for the implementation, the project manager and client were not aware of the process to be implemented. The top management agreed to the implementation of the process in the selected project. The involved project manager accepted without further clarifications on the process. This led to struggles during the implementation as the project manager had to be contacted to confirm the execution of tasks. Individuals who have the authority to impact the project manager or client provided support, yet it was not sufficient to facilitate the implementation. Delays occurred since the project manager did not respond fast to their requests. Perhaps the flow of events would have been easier if the project manager is reachable and responsive. The researcher did not set a criterion in the project selection for the project manager in specific. However, after encountering the problems in the implementation and noting the importance of the project manager's role, such a criterion seems crucial.

For the implementation, a protocol was set. It guided the researcher during the 2 months implementation. Although the protocol was detailed and covered the different steps of the process, it was not strictly followed. Some tasks were delayed till the project manager approved the execution and some tasks were postponed till the requirements were clarified by the client. The 2 months duration of the implementation is short for a running project. The involvement in a running project was interesting for the process especially in relation to real and direct interactions that provided results on the cultural challenge of BIM. However, it was a major struggle of the research period. Lots of effort had to be made to get tasks done. In some cases, the tasks were not executed as communicated. The participants showed enthusiasm in discussions over tasks but focused on individual effort and paid hours during execution. The members took the process implementation seriously, but they were limited by the management. When the researcher requested tasks to be performed differently, there was not enough support to motivate the team members to change and invest time now to gain later from the benefits. Therefore, the implementation of the process was about to be reached in several occasions. With more support, better implementation and results would have been observed. Support is needed since the team members of the selected project did not want to take the initiative to perform a job not requested or accepted by the manager. Furthermore, providing support would have helped in managing the change in workflow.

The results of this case study were collected from direct observations and participants' feedback. The researcher tried to narrate the details of all meetings directly after each session. However, some points might be missed. The researcher avoided recording the meetings in order not to influence the members' interactions. Despite that, the presence of the researcher might have influenced the discussion. It was noted that during meetings, the team members showed engagement and encouragement to consider the tasks of the process. However, the execution of the tasks did not reflect the latter. This issue is tackled by interviews with the participants who revealed that the main struggle was with the project's plan and the manager's confirmation of the extra hours required for some of the tasks. Furthermore, the semi-structured interviews with the participants supported many of the observations made by the researcher. The interviews also helped in assessing the effectiveness of the process especially that the implementation was not complete and sufficient integration was not reached.

7.3.5 Validation Interviews

The validation interviews were made at the end of the research since they were not part of the plan. However, with the limited time for a comparative case study and further implementation, the researcher decided to validate the design of the process to improve the results of the research. The interviews were conducted shortly before the submission of the report. This reduced the options of interviewees to those who were directly available. If this task was planned earlier, more interviews would have been made with 5D BIM specialist, designer, and cost engineer. This would have provided the judgement of the process from all disciplines covered in the research. Furthermore, one of the interviews was not performed as planned since interviewee 2V focused on his idea of full-automation with a fast transition and rejected the research's proposition when presented. It was interesting to have this view, yet, it negated the role of cost engineers which was still clearly present in the other studies discussed earlier on full-automated processes. His view on the fast transition ignores the reality depicted by numerous studies on the barriers to BIM implementation in the construction industry (one of which is cultural change). Furthermore, the necessity of a process for 5D BIM implementation that clarifies concepts and acts as a stepping stone to full automation is supported from literature. Interviewee 2V was limited to his own vision without considering the issues and propositions in literature and practice that triggered the design of the process. Therefore, another interview covering the planned questions should have been done to enhance the validation.

8 Conclusion and Recommendations

This section concludes with brief implicit answers to the sub-questions to reach the answer to the main research question. Then, recommendations for the improvement of the designed process and future research on the integration of design and cost estimation via 5D BIM are provided.

8.1 Conclusion

Throughout the research, the sub-questions are resolved and utilized to develop the conclusion of the research with an answer to the main research question:

How can design and cost estimation be effectively integrated using 5D BIM?

For the effective integration via 5D BIM, the design and cost estimation processes are combined in a single "Integrated Design – Cost Estimation 5D BIM Process". The process tackles the issues derived from the study of practice in a single case study RHDHV. Practice encounters problems that lead to fragmentation and challenge 5D BIM application. The issues related to fragmentation are: [1] costs do not guide the design as the cost engineer is not continuously involved in the design process and [2] the cost engineer does not always aid decision-making on design options. In relation to 5D BIM, the following issues are noted: [3] engineers include lots of details to the model leading to complexity and hampered design-cost connection, [4] the information, its format, and exchange are not appropriately managed, [5] inconsistent representation of information via codes is used to align design, cost estimation, and the model, and [6] clients and practitioners resist to the application of BIM.

Countering the 6 issues from literature and practice along with incorporating 5D BIM into the process, the "Integrated Design – Cost Estimation 5D BIM Process" is finalized in figure 5.8 of section 5.3. Then, it is translated to a process map clarifying the information flow as presented in figure 5.9 of section 5.3. The process is designed such that the processes move in parallel with specific points of close interaction. Primarily, the integration considered in the designed process is regulated by cost driving components whose costs are monitored. Various points of interaction between disciplines are added to the process to ensure integration. The designer and cost engineer share their understanding of the project, pinpoint cost driving components, plan the workflow with the focus on cost driving components, ensure compatibility between design and cost estimation, and discuss the development of the design to reach a design made to cost.

To facilitate the interaction, the integration of design and cost estimation is done via 5D BIM such that the disciplines collaborate to build a model suitable for estimation. The necessary information for estimation that is added to the model is limited to the cost driving components. This enables balancing the information in the model and reducing its complexity. Furthermore, a standard classification system is used for the WBS, CBS, and other disciplines. Accordingly, the information is structured and standardized for the project in general and used for clear connection between design-cost estimation. Since a semi-automated approach of 5D BIM is selected, design objects are grouped for quantity extraction based on the system followed in the WBS and CBS. Then, the extracted quantities and information added to the model are exported to Excel for computations.

The "Integrated Design – Cost Estimation 5D BIM Process" is implemented in a pilot case which is a running project at RHDHV. Based on the embedded case study research, the effectiveness of the integration specified in the research question is studied. The successful integration was limited due to obstacles related to the client and management of the project. Not enough support nor suitable planning were given to encourage participants to prepare for BIM and perform new tasks. The team members also focused on their individual effort rather than team effort. The participants of the project reflected these challenges and ensured that the process leads to effective integration given the following conditions: [1] The client is aware of the process, [2] the management supports it, and [3] the project planning provides room for innovation with clarification of the integration points. Furthermore, the participants view that the process enables effective integration due to having parallel processes with clarification of integration points, standardizing the information used by participants, and thinking earlier of costs within the team.

Therefore, the "Integrated Design – Cost Estimation 5D BIM Process" leads to the effective integration after addressing the barriers to BIM implementation concluded from the pilot case. These include: the lack of support from the client and management, unsuitability of the set planning, lack of awareness of BIM application, and the difficulty of cultural change from independency to collaboration and integration. Furthermore, recommendations for practice and research are provided below to further develop the "Integrated Design – Cost Estimation 5D BIM Process".

8.2 Recommendations

The implementation of the "Integrated Design - Cost Estimation 5D BIM Process" was not successful in assessing the different steps and the effectiveness of the integration. Another implementation in a project has to be performed to test the designed process and propose further improvements. Despite the limited observations made in the implementation, few recommendations for the improvement of the process are based on observations and participant's feedback. Furthermore, BIM experts interviewed for the validation of the process proposed future considerations.

For future implementation, the application of the process in a project has to be made earlier in order to consider the management of changes and set a suitable plan. Throughout the process, its continuous monitoring and updating is advised to ensure the flexibility of the process. Regarding the involved parties, the top management and the client shall provide support. Furthermore, the selection of the team members who will work together is important. The selection shall consider common location and synchronized timing. Working at the same location and having common hours facilitate meetings and discussions. It is recommended to document the outcome of meetings and discussions to ensure that agreements and the reasoning behind each remains clear for all members. For model preparation and information addition, it is suggested to perform trials in order to reduce the risk of agreeing to tasks and discovering during execution that they are inappropriate. Furthermore, training is necessary to develop skills for the automation of quantity extraction and application of 5D BIM process.

Participants suggested earlier consideration of the process in the project and its introduction to the team and client. The planning of the project has to be coordinated with the flow of the process. Furthermore, the roles of the client and project manager need to be clarified. It is advised to be proactive by suggesting the process and proposed breakdown structure to the client. The process and detailed planning have to be visually illustrated for the team members. Furthermore, the breakdown structure of the project has to be maintained dynamically by the members who share this structure. In this manner, further additions and changes to the structure are performed after discussions. For quantity extraction, experts have to cooperate to reach efficient methods for automation. These methods have to be developed first in closed cases. Then, they can be considered in running projects to reduce the risks which designers and project managers worry about in quantity extraction.

From the validation interviews, the following recommendations for future research are suggested. Interviewee 1V proposed starting with the main requirements instead of the main components. For further improvements of the process, it is recommended to study the consideration of cost driving components along with main requirements relevant for costs in a process. The integration focuses on design and cost estimation; thus, the requirements shall also be fit for this purpose. Considering 5D BIM, semi-automation with Excel has to be changed. Excel is not suitable for data storage and management. It is important to check available tools on 5D BIM in the market to shift to full-automation. With full-automation, the risk of human error is eliminated (interviewee 1V, 2019). As mentioned earlier in the discussion, the designed process is the stepping stone to full-automation. After the clarification of the workflow and successful integration in a new process, the next step is to study the addition of suitable tools to the process to reach full-automation. Furthermore, the addition of the planner to the process is important for the different discussions and agreements (Interviewee 3V, 2019).

Other recommendations consider future research which studies the "Integrated Design – Cost Estimation 5D BIM Process" in relation to other processes and members of the project. The research in this thesis isolated the designer and cost engineer in a single process to reach 5D BIM. Yet, other processes that relate the designer with the planner to reach 4D BIM and the cost engineer with the planner to get information (time and risk) interfere with the designed process. Furthermore, future research on BIM has to investigate the cultural challenge and means to ease it. Studies shall look into the management of cultural change and its incorporation in BIM processes or workflows. BIM workflows or processes will be based on integration and collaboration. Therefore, approaches to enhance the collaboration and integration between the participants in the workflows shall be studied, considered in designed processes, and tested in practice.

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Appendix A: Interviewees' Details in the Case Study RHDHV

The appendix provides the details of the interviewees from the case study RHDHV.

Table A.1 List of interviewees with their experience and specialization

Name	Role	Experience and specialization
1D	Designer	1.5 years' experience in road design
2D	Designer	9 years' experience in infrastructure projects
3D	Designer	11 years' experience in road design
4D	Designer	28 years' experience
5D	Designer	11 years' experience in railway, highways, and other big projects
6D	Designer	12 years' experience as structural engineer and 2 years' experience as designer on Revit for bridges and tunnels
7D	Design leader	20 years' experience, going from draftsman, 3D designer, design leader, to design manager
8D	Design leader	12 years' experience at consultancy firm, going from designer to design leader/design manager And 4 years' experience at a contracting company
1C	Cost Engineer	19 years' experience, 10 of which are experience in cost engineering
2C	Cost Engineer	29 years' experience in cost engineering at a contracting company and 6 months at the consultancy firm
3C	Cost Engineer	Senior cost engineer for infrastructure, industry projects, and buildings
4C	Cost Engineer	12 years' experience in cost engineering for infrastructure projects at the company and 8 years of experience at 2 other companies
5C	Cost Engineer	27 years' experience in cost engineering for infrastructure and water-related projects, could also take the role of coordinator in case of big projects
6C*	Cost Engineer	40 years of work, 10 of which are in cost engineering
1B	BIM expert	4 years' experience with BIM, few months BIM coordinator at the firm
2B	BIM expert	20 years' experience as project manager, BIM manager
3B	BIM expert	5 years' experience at a contracting company and 2 years at the consultancy firm, BIM coordinator/Manager
4B	BIM expert	1-year experience at the consultancy firm and 4 years' experience at another company
5B	BIM expert	6years' experience as 3D engineer at the consultancy firm, BIM modeling

Note: * Interview did not follow exactly the questions due to the experience of the interviewee in BIM, so the focus of the interview shifted

Appendix B: BPMN Annotation

The appendix clarifies the annotation used to draw the process map.

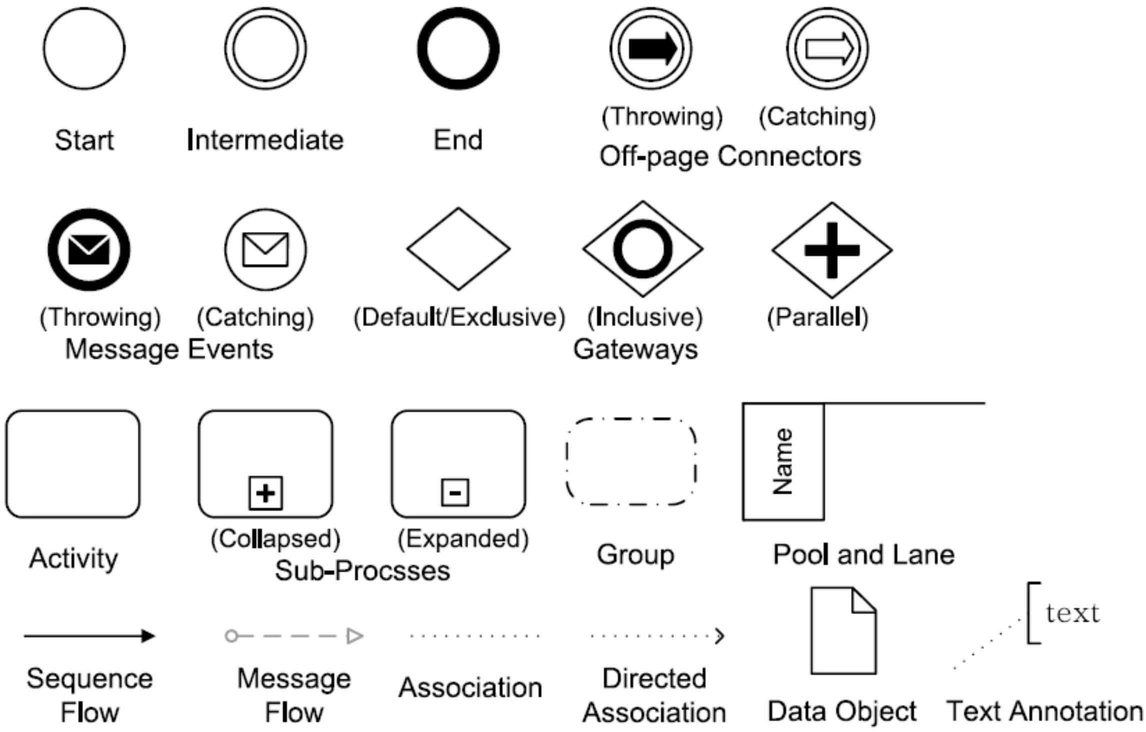

Figure B.1 BPMN Annotation. Reference: (ISO, 2017)

Table B.1 BPMN Annotation. Reference: (ISO, 2017b)

Element	Definition
Activity (Task)	A task is an atomic activity that is included within a process. A task is used when the work in the process is not broken down to a finer level of process detail.
Sub-process	A sub-process is a compound activity that is included within a process or choreography. It is compound in that it can be broken down into a finer level of detail (a process or choreography) through a set of sub-activities.
Sub-Process (Expanded)	The boundary of the sub-process is expanded and the details (a process) are visible within its boundary. Note that sequence flows cannot cross the boundary of a sub-process.
Sub-Process (Collapsed)	The details of the sub-process are not visible in the diagram. A "plus" sign in the lower-centre of the shape indicates that the activity is a sub-process and has a lower-level of detail.
Start Event	A start event indicates where a process will start. Start events can only react to "catch" a trigger.
Intermediate Event	An intermediate event indicates where something happens somewhere between the start and end of a process. Intermediate events can "catch" or "throw" triggers.
End Event	An end event indicates where a path of a process will end. End events can only create "throw" a result.
Start Event(Message)	A message arrives from a participant and triggers the start of the process. The actual participant from which the message is received can be identified by connecting the event to a participant using a message flow within the definitional collaboration of the process
Intermediate Event (Message/Catching)	A message intermediate event can be used to either send a message or receive a message. When used to "catch" the message, then the event marker shall be unfilled. This causes the process to continue if it was waiting for the message, or changes the flow for exception handling.
Intermediate Event (Message/Throwing)	A message intermediate event can be used to either send a message or receive a message. When used to "throw" the message, the event marker shall be filled (see the upper figure on the right). This causes the process to continue if it was waiting for the message, or changes the flow for exception handling.
End Event (Message)	This type of end indicates that a message is sent to a participant at the conclusion of the process. See page 91 for more details on messages.
Intermediate Event (Link/Catching)	Paired link events can also be used as "off-page connectors" for printing a process across multiple pages. They can also be used as generic "go to" objects within the process level. There can only be one target link event. When used to "catch" from the source link, the event marker will be unfilled. When used to "throw" to the target link, the event marker will be filled.
Intermediate Event (Link/Throwing)	
Gateway	A gateway is used to control the divergence and convergence of sequence flows in a process and in a choreography. Thus, it will determine branching, forking, merging, and joining of paths. Internal markers will indicate the type of behaviour control.
Gateway (Exclusive)	[XOR] when splitting, it routes the sequence flow to exactly one of the outgoing branches. When merging, it awaits one incoming branch to complete before triggering the outgoing flow.
Gateway (Parallel)	[And] when used to split the sequence flow, all outgoing branches are activated simultaneously. When merging parallel branches, it waits for all incoming branches to complete before triggering the outgoing flow.
Gateway (Inclusive)	[Or] when splitting, one or more branches are activated. All active incoming branches shall complete before merging.
Sequence Flow (Normal or Uncontrolled)	A sequence flow is used to show the order that activities will be performed in a process and in a choreography.

Element	Definition
Message Flow	A message flow is used to show the flow of messages between two participants that are prepared to send and receive them. A message flow shall connect two separate pools. They connect either to the pool boundary or to flow objects within the pool boundary. They shall not connect two objects within the same pool.
Association	An association is used to associate information and artefacts with flow objects. Text and graphical non-flow objects can be associated with the flow objects and flow.
Data Association	A data association is used to move data between data objects, properties, and inputs and outputs of activities and processes. Data associations can be visually represented in the diagram by using the association connector style.
Pool	A pool is the graphical representation of a participant in a collaboration. A pool acts as the container for the sequence flows between activities (of a contained process). The sequence flows can cross the boundaries between lanes of a pool, but cannot cross the boundaries of a pool. That is, a process is fully contained within the pool. The interaction between pools is shown through message flows.
Lane	A lane is a sub-partition within a process (often within a pool) and will extend the entire length of the process level, either vertically or horizontally. Lanes are often used for such things as internal roles (e.g. manager, associate), systems (e.g. an enterprise application), an internal department (e.g. shipping, finance), etc.
Data Object	Data objects provide information about what activities require to be performed and/or what they produce. Data object elements shall be contained within process or sub-process elements. Data objects cannot specify states.
Group	A group is not an activity or any flow object, and, therefore, cannot connect to sequence flows or message flows. In addition, groups are not constrained by restrictions of pools and lanes.
Text Annotation	Text annotations are a mechanism for a modeller to provide additional information for the reader of a BPMN diagram. The text annotation object can be connected to a specific object on the diagram with an association, but does not affect the flow of the process.

The following sections are collections of the general principles and rules from the OMG's *BPMN Specification* below. The references below may be consulted for examples and details.

— Business Process Modelling Notation (BPMN), OMG, 2013, available at: < http://www.omg.org/bpmn/>.

— Silver, B., BPMN Method and Style: A levels-based methodology for BPM process modelling and improvement using BPMN 2.0, 2011, Cody-Cassidy Press.

D.2 Specification of processes and flows

In a process map, all of the diagrams and sub-diagrams created for describing the process shall be included. All processes within the process map have a unique identity and name.

Each process within the process map is described in such detail as required. The aim is to describe the purpose of the process to a reader. The followings are the rules specified in the BPMN specification associated with process flows and events.

Process flow

— It is best to pick a direction of sequence flows, either left to right or top to bottom, and then direct the message flows at a 90° angle to the sequence flows.

— The process flow is contained within the pool and cannot cross the boundaries of the pool.

— The interaction between pools is shown through message flows.

— If a sub-process has been expanded within a diagram, the objects within the sub-process cannot be connected to objects outside of the sub-process.

Sequence flow connections

— A connecting object that shows the order in which activities are performed in a process and is represented with a solid graphical line.

— Each flow has only one source and only one target.

— A sequence flow can cross the boundaries between lanes of a pool but cannot cross the boundaries of a pool.

— Only activities, gateways, and events can be the source and the target. And an artefact shall not be either a target or a source for a sequence flow.

Message Flow Connection

— A message flow shall connect two separate pools. They connect either to the pool boundary or to flow objects within the pool boundary.

— A message shall not connect two objects within the same pool.

— Message flows cannot connect to objects that are within the same pool.

— The interaction between pools is shown through message flows.

— Only pools/participants, activities, and events can be the source or target of a message flow. And an artefact shall not be either a target or a source for a message flow.

Association and data association

— Text and graphical non-flow objects can be associated with the flow objects and flow.

— An association is used to connect user-defined text (an annotation) with a flow object.

— A data association uses the same notation as a directed association.

— Data associations are used to move data between data objects, properties, and inputs and outputs of activities, processes.

— Data objects may be directly associated with a sequence flow connector.

— Activities define two sets of data associations, while events define only one.

D.3 Specification of events

An event indicates the state of an activity. The three basic events are start, intermediate and end events.

Start and end events

— A process is instantiated when one of its start events occurs.

— For a process instance to become completed, all tokens in that instance shall reach an end node, i.e. a node without outgoing sequence flows. If a token reaches a terminate end event, the entire process is abnormally terminated.

— The use of start and end events is independent for each level of the diagram.

— If there is a start event, then there shall be at least one end event. And if there is an end event, then there shall be at least one start event.

— If a start event is not used, then the implicit start event for the process shall not have a trigger.

- If a process is complex and/or the starting conditions are not obvious, then it is recommended that a start event be used.
- If an end event is not used, then the implicit end event for the process shall not have a result.
- The process shall not end until all parallel paths have completed.

D.4 Specification of data objects

A data object is a named collection of data. It may be a collection of data that is available from an external source (e.g. library data) or it may be data that is exported from an activity to enable other activities to occur (e.g. exchange requirement).

Data objects that are not exchange requirements shall have a name that is indicative of their purpose and a description that outlines their purpose and content. The followings are the rules specified in the BPMN specification associated with data objects.

Data objects

- Data object elements shall be contained within process or sub-process elements.
- Data associations are always contained within another element that defines when these data associations are going to be executed.
- A data object may not be either source or target of sequence flows and message flows.
- Data objects may be directly associated with a sequence flow connector.

D.5 Specification of exchange requirements within a process map

In BPMN models, an exchange requirement is represented using a data object within a process map.

Exchange requirements shall have

- a name that is indicative of their purpose following the IDM naming rules, and
- a description that outlines the purpose and content in a separate exchange requirement document.

Appendix C: Table on cost computation methods

Table C.1 summarizes the different methods for cost estimation. Each of the methods is briefly described.

Table C.1 The different cost estimation methods. Based on (Project Management Institute, 2017), (Project Management Institute, 2008), (Project Management Institute, 2016), (Abanda, Kamsu-Foguem, & Tah, 2017), and (Milošević, 2003)

Method or Tool	Description
Expert Judgment	• Relies on individuals' information from specialized knowledge on previous similar projects to understand the situation and determine the methods for estimate computations
Analogous Estimating	• Uses parameters (such as scope, cost, budget…etc.) and measures (such as size, weight, complexity…etc.) from previous projects • Adjusts the values according to the features of the project at hand and estimates the cost • Employs historical data and expert judgment • Suits calculations on the total project or segments of it • Applies to early phases with limited level of detail
Parametric Estimating	• Applies statistical analysis on variables according to historical data to estimate activity parameters (such as cost and duration) • Adjusts the costs to consider the difference between the new project and the database • Organizes cost data to build a model having equation type fit to the available database • Fits the cost data empirically using linear, power, exponential, or logarithmic curves • Calculates the estimate for the new project based on the derived model • Uses software applications having cost database and information from specialized publications • Enables estimating the total project or segments of it • Runs comparative analysis of alternatives
Bottom-Up Estimating (Detailed Estimating/Engineering Estimate)	• Provides estimates based detailed project design • Requires defined and detailed scope definition supported with documents (drawings, WBS) • Computes estimates for single components of work • Sums the costs of individual work packages or activities to reach estimates at higher levels • Leads to a structured, reliable, and accurate estimate
Three-Point Estimating	• Considers uncertainty and risk • Uses 3 estimates: Most likely (realistic-case scenario), Optimistic (best-case scenario), Pessimistic (worst-case scenario) • Calculates the expected estimate from the 3 cases • Provides a range for uncertainty • May use a project simulation model to study the impact of costs uncertainties on project objectives
Monte Carlo Simulation	• Models construction costs based on beta, triangular, or lognormal distributions
Estimating Software	• Includes computerized spreadsheets, simulation, and statistical tools • Could follow standards and work breakdown structure
Project Management Information System	• Includes spreadsheets, simulations, and statistical analysis tools to assist the processes

Appendix D: Case Study RHDHV Interview

The appendix covers the questions and transcripts of the interviews with designers, cost engineers, and BIM experts.

Appendix D.1:

The appendix covers the interview questions with the designs and the summaries of the interviews.

Interview Questions- Designers

The interviewees are asked about their experience and kind of jobs performed at the company. Then, questions related to the research are asked as follows.

Design process followed:

1. Once you receive a new project, how does the design process start?
2. What standards do you follow to proceed with the design? (national, international, organizational?)
3. Is the design process common for all projects?
4. Could you describe the regular process and another unique design process followed?

Design process management:

5. How do you manage the design process?
6. What are the different aspects considered in the management plan?
7. How do you consider other disciplines, such as the cost estimation, in the management of the design?
8. Based on what criteria do you select the software to be used to prepare the design?

Design representation:

9. On which software is the design regularly made and to which level of detail is it made?
10. Based on what do you specify the level of detail required?
11. Do you have specific templates for the representation of components within the design?
12. If yes, based on what aspects are these templates developed? If not, is the current process without unified representation efficient for the design and other teams?

Changes in the design:

13. How often does the design undergo changes?
14. During which phase are the changes maximum?
15. How do you handle value engineering/design iterations happening during design process?
16. Could you describe an experience of design change that was followed by chaotic responses from other disciplines such as cost estimation?

Relation with cost:

17. How is cost derived in the different phases of the design?
18. How do you consider the cost in your design?
19. To what extent does the cost influence the designers decision-making of the various design alternatives?

20. Do you consider that cost is an important aspect that shall be directly updated as changes occur?
21. Are the design and cost teams integrated in terms of information and pace of work?
22. How are they integrated?
23. Is there a standard approach for the connection of the design and cost teams?

Communication:

24. How do you communicate the information in general and the changes in specific?
25. How is the communication between design and cost teams happening? (verbal, meetings, software synchronization…etc)
26. How often do you get questions from cost experts to clarify components and changes?
27. How do you or would you communicate to ensure an integral design with the cost?
28. How would you define an efficient and sufficient communication process with the cost team?
29. What would you suggest for the improved integration between the two design and cost estimation?
30. Can you describe a project where there was an attempt to improve the communication between designers and cost experts?

Interviews' Summaries – Designers

The summaries of the interviews are provided in the following sub-sections.

Interviewee – 1D

- Worked a structural designer for 1.5 years at the company
- Worked on road design projects, small projects in Civil 3D
- Focused on the Bill of Quantities for the Mexico Airport project

Focusing on the management of the project, the selection of the software for the design depends on the project and client, for roads it is usually Civil 3D and for structural designs it is Revit. To initiate the project, templates and BIM execution plan are prepared in some cases. If templates are not available, then the designer has to invest time to prepare one himself. Furthermore, the preparation of the model requires looking ahead to consider later stages and information extraction. In other cases, the project follows standards specifying naming and aspects which will be used later for the quantities.

(During the design process, changes happen a lot, so the process would be facilitated with standardization to easily track the changes.[BDU]) Such a case is project specific and it has been done on one project. (The communication of changes is best done verbally accompanied with an email with clarifications.[DA]) (Therefore, even if design and cost estimation are linked through software to immediately reflect the design changes, the human judgment is still required.[BDU])

The communication between the designer and the cost engineer is based on sharing extracted quantities and providing explanations. First, the designer prepares a list for himself to extract the quantities accordingly. If necessary, the calculation of the quantities is verified by applying different methods. (Then, the values with explanations are shared to the cost engineer at the agreed moment. The means of communication vary, could be face to face, through phone, or email.[DC]) (However, an efficient way of working would be working more closely and understanding each's task. The cost engineer would know the means to extract quantities and the designer would be familiar with the tasks and software of the cost engineer so that he knows which cost aspects to consider and what their impact is.[DCI])

Interviewee – 2D

- Project engineer for the department infrastructure, transport and planning
- 9 years' experience

The design process depends on the project, customer, and phase of the project. (Generally, after meeting the client and preparing a report according to the project information, the customer is consulted to get feedback and make the necessary changes. The management of the process differs according to the size of the project. For small projects, the design leader with technical knowledge works closely with a draftsman. For big projects, there is a project manager on top of the hierarchy, then there are different leaders and finally the teams of the different disciplines. [DA])

The design is produced using the software adopted by the company. But, this also depends on the request of the client and the output he wants. The level of detail of the design is also dependent on the client. After identifying the latter, the design is initiated based on unstandardized templates. The templates are self-prepared depending on the output and client requirements. During the design, changes are communicated as agreed upon in the BIM execution plan. In the BIM execution plan, the output is thought of, the information exchange is identified, and the software connection is considered.

(Regarding the relation with the cost engineers, their input which is the designer's output is considered earlier since the design differs and cost properties are added. The project leader derives the criteria to deliver the input for the cost engineers and clarifies the use of the information. If the cost engineer's input is ignored in the beginning, the design representation will undergo changes later. There are cases when the importance of the cost engineer is noted late in the project. Thus, rework had to be done to adapt the design representation to the cost estimation aspects. As the design develops, the design and cost teams do not work closely. They only communicate verbally to answer questions. When the design is complete, the cost engineer does the estimations and works with designers for optimizations of the design.[DC]) (Since the cost estimations aid the designers to meet the client's requirements, the company strives to have the teams working closely from the beginning. With the teams integrated, the processes become more efficient with the design fit to the standards of the cost engineer.[DCI])

Interviewee – 3D

- Almost 11 years of experience as a road designer
- Worked at RHDHV for almost 2 years

The design process in general is not standardized, yet there are intentions to form an internal standard process. The start of the design process depends on the stage in which the company is involved in. In the preliminary phase the client's question is interpreted. If a basic design is provided, the team analyzes it, makes remarks, then communicates on it with the client. Therefore, the general case is to get information, analyze it, then start designing. When the design begins, the technical standard is followed to make sure the design complies with the guidelines. (During the design, the models are prepared to a level of detail required by the client and the design stage.[DA]) Furthermore, the drawings follow a template with 4 characters, 2 of which are set by the Dutch standard. This makes it difficult to add further aspects that are necessary for other disciplines. However, in civil 3D enough information can be added in surface assembly exposure in the cross-section.

(Changes in the design vary between stages. In the preliminary design, different alternatives and their costs are studied and major changes to the design are made to meet the client's desire. In later stages, smaller changes and optimizations are made yet their impact could be large. When such changes happen, the process is not definitive. Usually, the designer analyzes the change and its impact to know which party to consult.[DA])

(The design process does not consider the cost in all stages. The cost is introduced at the end of the preliminary phase to study multiple options. During the design, the cost is neglected, and the focus is on the guideline and safety. [DC]) The approach is to have first the safest design to share with the client who can then notice that the option is costly. It is important to share this case with the client before designing while considering the cost. (When the design exceeds the budget, optimization is initiated.[DC])

(To manage the process, the management plan is prepared at a higher level of the company. The approach of the management could sometimes be systems engineering, but in all cases, it is written down and communicated. Ideally, all the disciplines meet to clarify the description of the project, set the requirements, request input information, and identify the procedure to reach the specific outcome.[DA]) (Focusing on the relation with the cost engineer, the communication procedure is not a specific way followed by everyone. Yet, the interviewee's way is to sit with the cost engineer in the preliminary stage to clarify the information needed (drawings, excel with quantities, bill of quantities). This is not always the case. For small projects, the information is passed to the cost engineer upon completion of the design. It could also be the case that time limitations prohibit the early communication with the cost engineer. Thus, the cost engineer frequently asks questions on the design. [DC])

(The communication is best done face-to-face with the disciplines sitting close to each other on daily basis. In this manner, the disciplines are not departed to different levels. [DCI]) It is important in the first stages to talk about the project and interact without solely relying on software to synchronize the tasks (such as direct extraction of required quantities). The communication and interaction are always improved by considering lessons learned. Thus, big projects lasting years shall not fix the communication and interaction strategies so that improvements can be made.

Interviewee – 4D

- Road designer with experience of 28 years at Royal HaskoningDHV
- Works internally with other designers
- Communicates with the client
- Leads some projects

(As a start, the project leader and client meet to clarify the information on the project. With the information from the client and basic information from standards, the design is initiated and put in the right direction.[DA]) (The design is developed in 2D or 3D software, depending on the size of the project.[BU]) In case of 3D utilization, the models are done at a global level with limited details or are not finalized. (During the design process, the design team of the numerous units meets at design moments to communicate the designs. Furthermore, the communication with the client resumes to approve the design and continue forward or disapprove and make changes. Changes mostly occur during the detailed design stage as elements are further clarified. The changes are rarely done for the sake of value engineering.[DA])

(In relation to cost estimation, the design and cost processes are not always integrated to enable the teams to work at the same level. Regularly and especially for small projects, the cost expert prepares a list of requirements for his calculation before the initiation of the design. With the list available, the design and cost processes move in parallel with direct verbal communication of changes. [DC]) Therefore, the design and cost teams are not detached but are not lively connected with real time communication through BIM. For large projects, the management of the design and communication becomes more intensive. (Therefore, such projects benefit from the live and real time process whose prerequisites are:

1. The availability to invest in time to prepare for the live integral process
2. The formation of a credible 3D model
3. The early development of a list of the required information for the computation of the estimates
4. The preparation of good standardized templates to link to the Bill of Quantities [BU])

During the live process, the designers do not have to analyze the possible cost changes anymore but shall still communicate verbally with cost experts to clarify problems and changes. The accurate costs are computed in a timely manner since values are derived from the 3D model according to the prepared templates and are regularly reviewed by cost experts. In case of irregular elements of the design such as those having curves, the template is modified to consider these elements and 2D modelling is used for fast and easy cost computations. (Therefore, the integral model is guaranteed with proper communication that is verbal with frequent questioning and electronic through BIM. [BU])

Interviewee – 5D

- Designer for 11 year for big projects, railway, highways

(At the beginning of a project, the team members meet in a kick-off meeting where the goal is defined, and the planning is set. The project leader makes parts of the process and assigns to everybody their task. For big projects, the different designs are managed in one model. It could be the case that there is one person responsible for BIM, thus, he receives the models from the different design units and merges them into one. The management of the process and information is considered costly for small projects. Therefore, for small projects, the process is more practical such that comments and questions are provided by email. [DA])

(The design is performed on a software selected by the client.[BU]) (To perform the design, the technical standards and guidelines are followed, and templates based on drawing Dutch standards are used. The level of detail of the design depends on the project since having too much details could be costly. During the design, a lot of changes occur, especially in the beginning when alternatives are made till the client's wish is met. Changes are discussed in weekly or biweekly project meetings to consider clashes and clarify the proceeding steps. Furthermore, clashes could be communicated via email. If the clash is major, the designer makes a screenshot and sends an email for everyone to stop designing till the project manager decides on the solution to the problem. It is important to report the choices made with justification from the guidelines. Everything has to be reported and made visible.[DA])

(The designer focuses on safety with little notice of the cost. But the client could stop the design if it is too costly. Then, the design team forms a baseline and redesigns to reach another alternative. Therefore, the integration with the cost team is important. The designer meets with the cost engineer who clarifies the information required for his job and its format. In every phase, the designer delivers an output to the cost team,[DC]) (thus the teams are trying to work in parallel.[DCI]) (However, the cost engineers are usually not involved from the beginning of the process.[DC])Questions from cost engineers arise and they are discussed with the help of the model. For example, questions on the volume report are handled by meeting to extract the unclear volume from the model. (Through the model, it could be possible to connect the design and cost such as in Civil 3D, yet this is not an easy process.[BDU]) (There was an attempt to integrate the design and cost teams by the connection of the cost excel file with the design model, but it was not completely successful.[BU])

Interviewee – 6D

- Worked as structural engineer at the company for 12 years
- Worked now for 2 years as designer
- Uses Revit for bridges and tunnels

(The teams working on big projects consists of different design teams each of which have a design leader. All the teams are guided by an overall leader and a BIM coordinator. The teams communicate mostly via the leaders who prioritize the work according to time. The individuals from different teams sometimes communicate to align inputs and outputs of their tasks. [DA])

The design in Revit follows a detail book, BIM protocol, and BIM/Revit standards. Drawings follow the Dutch standard for the representation of components (such as line parts). In Revit, there is a project template with loaded families that is unified among teams. The template focuses on the design without considering other aspects (such as time and cost). In some cases, the schedule and quantities are prepared. Since the project is big, the different parts are prepared separately with models of the different parts later integrated in Navisworks. (Drawings are also made in Autocad to simplify some components.[BU])

(During the design, a lot of changes happen. These changes are directly reflected in the linked models.[BU]) (When the change is related to safety, the change is made, and other teams adapt to the change. The design leader takes the decision to make the change. If necessary, the design leader also discusses the impact of the change on cost with other teams to allocate the additional costs to one of the teams.[DA])

Designing while considering costs is sometime difficult since costs and efficiency of sitework are both important factors for the designer. Therefore, (discussions are made on the latter matter to improve the design, increase the efficiency of sitework, and reduce costs. Accordingly, the cost team is consulted to make changes that reduce the cost of the project.[DA]) The relation with cost team is not through software integration, it is based on verbal communication which is considered the best way for clarifications and discussions on options. [DCI])

Interviewee – 7D

- Design manager or project manager depending on the project
- Experience of 20 years at the company, started as a draftsman, then 3D designer, then design leader, and now design manager

(The design process followed is based on the system engineering approach. This approach follows the international guideline for system engineering which entails 3 steps: Requirements, Design, Check. The client's requirements are defined and evaluated relative to scope and budget. Based on the client's requirement and a fixed set of design requirements, the design process starts. As the design proceeds, approval and justification ensure the design's traceability. This process is common among most of the projects, but with different clients, contractor or government, the role differs.[DA])

(Regarding the management of the design process, the first step is the kick-off meeting with the whole team. The manager forms a scheme with the steps followed to complete the project and the tasks divided among the members. [DA]) Therefore, a lot of communication happens with little documentation which leads to difficulties. The documentation and detailing are looked at from a risk point of view due to the time and cost invested to write the management guidelines. The higher the risk, the better to go into more details. For big projects, documentation is done in terms of project management plan, design management plan, and system engineering plan. For small projects, the proposal is mostly adapted as the plan.

(The software to be used is not usually an aspect in the management plan. For roads, it is usually modelled in 3D, yet the level of detail is not defined. To consider details in the design, a backward thinking approach is used. First, think of the usage of the information which is mostly decision-making. From that point, think of the necessary information to be presented to enable others to take decisions. This is done without following specific templates or libraries with defined components. [BU])

(Design changes happen most at the end due to the difficulty to judge the design when it is in a global state. Although the designer can see and judge better at the detailed level, the design is actually less flexible at this stage.[DA]) Furthermore, changes are encountered upon using value engineering in cases of costs exceeding the budget. (The budget could be exceeded in the design since the designer does not have the project context which helps him judge costs. The design manager or leader with the project context can judge the design with respect to costs. Thus, the cost aspect is neglected by designers who focus on the design guidelines.[DC]) To consider costs from the beginning by the team members, it is better to consider value engineering in the early phases, yet difficulties with this approach are encountered with the client. The client misunderstands the communication on the budget from the beginning and considers it too early to speak of costs.

(The communication of design changes differs depending on the size of the project. For large project, there is an information manager and design meetings. For small projects, the design manager tracks the design by being fully informed with everyone's task. Then, he can analyze the change and understand its influence on other teams. For that, a combination of mailing and calling is followed to make decisions instead of meetings which are considered to be expensive for small projects.[DA])

(The cost estimation accuracy and design detail are not always compatible. This happens due to the absence of guidelines to specify the information required for a certain level of accuracy [DC]) or due to the incompatible requirements set by the client. The latter would not be a problem if the project manager had noticed it from the beginning. Therefore, it is advised that the project manager communicates with others to become aware of such cases. He could also consider studying the risk from the perspective of the company. This is crucial especially that the project is split from the beginning, thus leading to a dangerous situation with leaders and members not fully introduced to the overall context of the project.

(Dealing with the design and cost estimation teams integration, a standard process of the two disciplines is required. Then, the inputs and outputs can be standardized. The standards made could be adapted to the different project sizes. [DCI])(Even if the processes are standardized and the cost estimation is automated, the numbers have to be traceable by being able to explain and prove the value of a certain quantity at a certain location. [BDU])(However, it is not efficient to perform automatic and manual calculations for judging or proving. Therefore, it is better to find a way to make it automatic but also checkable. [BDU])

Interviewee – 8D

- Worked at the company for 12 years as designer and design leader/project manager
- Worked as designer for 4 years for infrastructure projects
- Worked before in a contracting company for 4 years

(The initiation of the project focuses on the scope of the project. The client provides an assignment which is completed by proposing a solution. Based on that, discussions are made to understand the client's needs and clarify the scope. Then, the budget is derived based the needs and experience with such projects. [DA]) Having this set, the process gets simple as it takes input that is processed to reach a certain output.

(The management of the project follows system engineering. The project is decomposed into work breakdown structure, product breakdown structure, and system breakdown structure. These are structured into clear workloads and packages that are discussed with the client.[DA]) The management of the teams starts with the assumption that they do not communicate. Then, the manager noticed the communication happening and try to influence it. (The communication between the teams is best done verbally [DCI]), yet it is mostly done via email which leads to different interpretations of the content.

(Focusing on the collaboration and communication between the teams, other aspects such as software are considered tools. The tool is not enough to make the integration and communication possible. For example, on one of the BIM projects, the people's collaboration and the communication were missed, thus leading to an inadequate model having uncoordinated information. Therefore, the focus of the model cannot be on the technical aspects.[BU]) (The BIM coordinator and design coordinator shall connect the people.[BDU]) (At the start of the project, the team members meet to discuss the way for collaboration and coordination such that rework is prevented. In the BIM execution plan, the process to complete the project and the collaboration between the teams are clarified. Accordingly, the BIM coordinator selects the appropriate software. However, there are no templates for the design that are based on input and output information. [BU])

During the design, changes occur with major ones happening in the beginning of projects with unclear scope. When big changes happen, a new baseline is set and is communicated to the team in a meeting. (After the completion of the design, the cost engineer does the estimations, thus he reacts but does not interact in the process. Therefore, if the estimations note the exceedance of the budget, design optimization and rework dominate till the budget is met.[DC]) (If the cost engineer is involved from the beginning, the cost driving elements are identified to facilitate decision-making on the design in early stages. To reach the latter, the model has to consider the cost properties and the teams have to understand each other's process. Then, the processes can be integrated and automated. Furthermore, the focus of the teams shall not be on their individual goals, rather on the context of the project at a higher level with the whole scope in mind. [DCI])

Appendix D.2:

The appendix covers the interview questions with the cost engineers and the summaries of the interviews.

Interview Questions – Cost engineers

The interviewees are asked about their experience and kind of jobs performed at the company. Then, questions related to the research are asked as follows.

Cost Process and Management:

1. How are you usually introduced to a new project? Are you provided with the whole context in detail?
2. How would you describe the cost process from initiation to delivery?
3. Who is responsible for the management of the cost process (planning and estimating)?
4. Based on what aspects is the cost process defined and managed?
5. At which point of the project does the cost estimation start?
6. How is the cost process connected to the design process? Is this considered efficient especially considering design changes?
7. Are the cost and design processes moving in parallel? If not, what are the reasons for the lagging of these processes?

Cost Methods:

8. What are the methods used for the computation of cost estimates at different phases of the project?
9. Are there cost databases which you rely on? If so, is it structured?
10. How is experience and tacit knowledge used for cost estimation? Is it documented?
11. Which cost estimate method would you consider to be most suitable for standardization and automation?
12. How do you keep track of your estimations in order to make changes when design changes occur?
13. Do you use any software to compute costs?

Cost accuracy/Level of design:

14. What are the different accuracies of the cost estimations computed?
15. Is the accuracy required compatible with the information provided from other teams?
16. Do you specify the information input you need and provide it to other teams? If so, how are these requirements structured? (based on accuracy, phase…)
17. Do you follow a guideline to clarify the process and point out the inputs required to other teams?

Information extraction:

18. In what form is the information provided to the cost engineer?
19. How would you assess the information provided relative the information required?
20. How often do you go back to other teams to get the input information or adjust the one provided to meet your requirements?
21. Is there an integrated representation of information between the cost and design teams?

22. What would be the best way to handle the integration of the output information from others with the input information required?

Value engineering and involvement of cost estimation:

23. How often do you make value engineering?
24. When is value engineering usually made? At the beginning or when the costs exceed budget?
25. Do you consider being involved from the beginning to have value engineering done early on?
26. To what extent do you think that the cost engineer's involvement would improve the design and decision-making?
27. Do you consider that you are able to influence the design with the current situation?
28. What would further enhance the involvement of the cost engineer?

Design-cost communication:

29. How is the communication made between the cost and design teams?
30. For what main reasons is the communication made?
31. How are design changes communicated to you?
32. What would you recommend for better integrated and collaborative design-cost process?

Interviews' Summaries – Cost Engineers

The summaries of the interviews are provided in the following sub-sections.

Interviewee – 1C

- 19 years at the company with 10 years of experience in cost engineering
- Works on construction projects bridges, dykes, and noise barriers

The introduction to a new project differs depending on the manager who is responsible for the cost and its planning. (The cost engineer could be invited to the project start-up meeting to think of the quantities and their derivation. It could also be the case that the cost engineer is introduced to the project at the end of the stages. Although such cases happen, there is a single page process with checklist built by the company to aid the cost engineer process and interaction with the manager and designer.[DC])

(The cost engineer starts his process by interpreting the scope, requirements, input, estimation methods, and output. Further information could be requested from the project manager, especially information on the planning. The planning is crucial in order to inform the cost engineer about the availability of his input. Based on the estimate required from the client and tools used, the cost process proceeds.[CA]) For instance, (in case of 3D models, BIM discussions are made with the designers from the initial phases in order to clarify the design methodology to facilitates quantity extraction.[BU]) It is advised that the cost engineer extracts quantities early during the design process. In this manner, the process is expected to become efficient since the design process is not leading anymore nor is it limiting the time for computing estimates.

(The cost team follows the SSK format which is a simple excel format,[CA]) yet it can be easily connected with other software such as planning and BIM. This is work in progress. The team rarely uses an estimation software since it is used for contract estimates for specific Dutch contracts. For the cost information, there is a database that allows knowledge sharing and structuring of cost information based on categories. Accordingly, experience and tacit knowledge are preserved as reflections on previous experienced are discussed and added to the company's repository. (From the different sources, information is used to make estimates. These sources shall be provided in the estimate document.[CA])

(In general cases, the cost engineer does his own coding and grouping to facilitate his own job and track changes.[CA]) The design team extracts quantities from 3D model following the NLCS layer material-based coding and OTL which are set by law. However, (Uniclass is preferred for the BIM environment since coding is done per object. Therefore, the coding used by the cost engineer is not similar to that of the design team since synchronization of codes requires early agreements. [BDU])

(Based on the project phase and client, the accuracy of the estimate is defined with a bandwidth. The SSK model considers the bandwidth along with the estimate. The bandwidth starts wide with few information, then it is reduced as more information is available. Discussions are made in the early phases to pinpoint the information required for the different accuracies, thus making decisions on the input and enabling integration.[CA]) (Focusing on quantities, the cost engineer agrees with the designer on the detailing of objects to aid the estimation process. Furthermore, the format for exporting quantities to excel files is also agreed upon earlier. [DC])

(The cost engineer's input information is comprised on drawings, quantities, risks, geotechnical reports, and other necessary report. It could be the case that information submitted is insufficient. For this purpose, teams responsible for the information are contacted. If the information is still missing, the cost engineer makes his own assumptions, adds a risk for this value, and communicates it. [CA])

(During the design process, alternatives considered are estimate without usually considering the concept value engineering. If the cost engineer is involved from the start and in the different phases, it is expected that he uses his experience to influence the design. [DCI]) However, the management should also enable such a process.

The communication within the team depends on the project scale, project manager approach, and location of team members. (Yet, it is crucial to meet face-to-face at least once.[DCI]) (In big projects, such meetings are more frequent. With the design team, communication is also done digitally as drawings with explanations and specification of versions are shared, especially in the case of design changes. The prevailing communication between the design and cost engineer is on discussing input/output information, requesting measurements, asking for reviewed calculations, and checking values in 3D models.[DC])

Interviewee – 2C

- 29 years of experience as cost engineer for contractors
- 6 months cost engineer at the company, cost engineer for consultants

(Once a project is initiated, the cost engineer is introduced to his task with specific information. This is considered a good approach by the interviewee who states that the cost estimate is done at the end. Then, he does not have to look at all the information but focus on specific information necessary for his job. The cost engineer reads the project and design to select the scope of the project and identify the methodology for computing the costs. Therefore, the first step to cost estimation is the analysis of the project to answer the question: How it will be constructed, is it possible, and are there alternatives to check? These points are discussed with the whole team who is reached again for further clarification as the project progresses. [CA])

(The current case at the company considers the cost engineer and his task late in the project process. [DC]) (The interviewee believes that the project start-up shall consider the cost engineer since he can think out of the box while designers usually provide similar designs. He also thinks that the cost engineer is a good reviewer since he asks critical questions as he has knowledge of products, suppliers, and methods. Currently, value engineering is not applied. However, being involved from the start, the cost engineer can influence the design and apply value engineering in the early stages. In this manner, the project team as an advisor to the client becomes proactive by offering more than just designing to requirements. [DCI])

(It is good to be present in the first few meetings to check the milestones of designers and be informed of the delivery of the outputs necessary for the cost engineer. For proceeding meetings, it is not important to be present at all meetings. Thus, it is beneficial to have the process put on paper with involvement in project start-up and follow-up meetings. Through the phases, the same cost engineer shall be involved in order to avoid the loss of information happening at every transfer. The cost engineer has to sit with other team members instead of relying only on communication through email to discuss the design or report failures noted. The latter point reflects the responsibility of the cost engineer for the whole project. [DCI])

The cost engineer manages his own task and the necessary input. (After reading the project information, the type of cost estimate, its purpose, and its required level of detail are clarified. Then, the relevant input information is derived.[CA]) (The cost engineer is responsible for identifying the information required and discussing frequently with the designer the project inputs and outputs. Accordingly, the designer is also responsible for knowing and providing the relevant information. [DC])

(The cost group have decided earlier to follow the SSK model in excel as suitable approach for their end product. The values added to the model are derived from a database and price list shared within the company. Furthermore, values from experience are utilized. The SSK model used is not integrated with the list of quantities prepared by designers nor does it inform them of the cost-input information. SSK is just a format that shall be filled by the engineer with quantities and prices. Furthermore, the quantities extracted by the designer are not complete since they are based on 2D drawings. The cost engineer proceeds to split the drawing into objects and find volumes. [CA]) (The items of the SSK model could be coded and unified among teams for practical use if the right people worked together from the beginning. They would discuss the end product and make the breakdown structures accordingly. [BDU])

(The accuracy of cost estimates depends on the level of information provided. If the latter is not compatible with the requested accuracy, the client is contacted. The information is derived from drawings, quantities, and reports. The cost engineer analyzes the available information and reviews summaries of other documents to know if further information is helpful.[CA]) (In case information is not available, the cost engineer asks other teams to provide the information or the reference in the company's repository. [DC]) It is faster for people who have been involved from the beginning to find the relevant document than the cost engineer who is not familiar with all the documents shared.

Interviewee – 3C

- Senior cost engineer with experience in different cost engineering roles
- Past 4 years cost engineer for infrastructure projects
- The years before, had experience in the industry and buildings

Depending on the project scale, (the cost engineer is asked to make an estimate, or he is involved but not continuously in the project. In the latter case, the cost engineer becomes familiar with the input and output of the project.[DC]) For the general process, the cost team is trying to follow a single process sheet prepared by the company. (The project manager guides the costing process and decides if the cost engineer is an advisor involved from the start or an estimator approached at the end of the project. Either way, the cost engineer himself have responsibility to estimate and review his results with others. The cost engineer relies mainly on the input and defines the process to reach the estimate. The input differs based on 2 aspects, the project type and phase. In the early phases, there is merely any input and in later stages drawings are available. Information for the input data is also collected from the experience and knowledge other colleagues, from previous projects, and price information in the directory. These directories are available for all cost engineers to use and add information to. Having the input, the estimate is computed in an excel SSK model which is a post book with items to be fed with quantities and prices. It is important to note that 80% of the cost is derived from only 20% of the items. After the estimate is made, clarifications are also attached along with reports if requested from the client.[CA])

(The designer finalizes the design and sends it to the cost engineer to make the estimate in case of small projects. In other cases, the cost engineer is involved and consulted earlier to assist in decision-making. Therefore, in some cases, the information is shared within the process while in other cases, the information is provided at the end to make the estimate. In case of design changes, the information is sometimes communicated and in other cases not. It is also possible that the cost engineer advices over the changes. [DC]) Currently, (the company is experimenting with BIM to have the processes going in parallel.[BDU and DCI]) Furthermore, (there was a trial in one of the projects to integrate design and cost processes and improve the efficiency that is now considered low. During this trail, complexity increased as the project progressed. This led to complications in keeping the codes of the 2 teams consistent.[BU]) (To have such synchronization, designers and cost engineers shall communicate on the coding and coordination from the start. [DCI]) The interviewee himself takes the initiative to sit with the designer and agree on the input required and its format.

(The cost engineer tries to identify the input information needed for his estimate, yet this is not done for small projects. Furthermore, the clarification of the input depends on the management approach followed. The input list shared is not standardized among projects but the preparation of such a list is not hard. If the list is not prepared, the cost engineer is provided with the available information. This information dictates the accuracy of the estimate. In case the information from other teams is not enough, we undergo further discussions. There is also a problem of having a lot of information for the large number of involved components. Then, it becomes hard for the cost engineer to find the needed information. [CA])

(Communication and meetings depend on the size of the project and the budget. For big projects, they are more frequent than in small projects. It is preferred by the interviewee to be involved from the beginning, but he understands the limited budget of the project. [DC]) Furthermore, the interviewee advises that the design and cost models are linked to have an efficient and fast process. Trials shall be made in order to learn and improve.

Interviewee – 4C

- Senior cost engineer with 12 years of experience at the company and 8 years of experience at 2 other companies
- Involved in small and big complex infrastructure projects

(The way the cost engineer is introduced to a project differs depending on the stage and the estimate requested. Following the Dutch division of design phases, each of the phases has different information on the scope, thus leading to different accuracy of estimates. During each stage, the scope and its realization are analyzed while considering the complete image of the project with the information available and the associated risk. Considering the latter, the cost engineer proceeds with the estimate taking responsible for his own procedure and product without following any specific cost plan. [CA])

In the early phases of the project, the model or sketch of the project are not needed. (The work breakdown structure which is unified among the different teams is considered a good start. Looking at the objects of the work breakdown structure, the cost engineer identifies the most important components for which alternatives and details are considered. These items make up 20% of the project but cover 80% of the costs. Accordingly, the information required is identified in reference to the work breakdown structure and stage for which the estimate is being made. [CA])

(The cost estimation method depends on the stage and client requirements on accuracy and methodology. In the early phases, expert judgement is utilized to look into the budget. In later stages, quantities and unit prices accompanied with experience are analyzed together to reach an estimate. Probabilistic methods are limited to the client's requirements and project characteristics. The quantities are prepared in excel files following the SSK format. It is a common format for the cost group, yet the coding it follows is not linked to other input information. In general, the cost engineer decides with the project manager at the beginning of the project on the organization of the information. For example, they agree on using numbers 1 to 10 for the sub-structure. When design changes occur, new version of the excel file used for the computation is prepared with a clarification of the information used to compute the new estimate. Since the information is not generally coded to easily make changes, the cost engineer takes the initiative organizes his own coding. [CA]) This is especially helpful with clients who have moments for checking the quantities.

(The cost engineer shares information with the designer on the input and clarifies it in discussions.[DC]) The input for the project is structured by the engineer himself to facilitate his own work, but it is not a standard available for the cost team. The information on the input required is not inferred from guidelines, rather it is derived from experience in the project location or other similar projects. (Information could also be derived from google Earth or google maps.[CA])

(The accuracy of the estimate depends on the input information and price. Depending on the project phase, the information could be provided in terms of drawings, quantities, construction information, and available reports. This input information is affected by the deliverables from other teams especially the design team who does not always provide the sufficient level of information.[CA]) (Furthermore, the information on the design could have changed but not communicated to the cost engineer.[DC]) (Considering the prices, they are influenced by factors such as location, quantities, and market conditions. These prices are derived from the company's cost database, the company's pricelist, the market, and one's own experiences. The information used from experiences is not documented to be preserved and shared.[CA])

(The design and cost estimation processes are not integrated. It is mostly the case that the designer finalizes a certain task and sends it to the cost engineer. For big projects, more collaboration is noted especially in meetings in the early phases to discuss alternatives. Therefore, there is not a standard process, but the company is working towards that.[DC]) (Both design and cost teams shall cooperate to improve the integration. It is important to work closely as a team and meet frequently to be involved in the project and exposed to updates. Furthermore, the cost engineer interacts with the project manager, designer, and client in meetings. In this manner, there is consensus on the product and the process to reach it. The cost engineer does not have to attend all meetings. He shall be on board from the start and attend meetings at certain moments. When involved from the beginning, it is possible for the cost engineer to influence decisions made on the design. Designers usually do not have the sense of cost. Therefore, with discussion between the cost engineer and the designer, the designer might be triggered to think in another way. In the beginning, you can also give advice, feel that you are part of the team, and perform value engineering even before the design is made.[DCI]) (Currently, value engineering is made later in process and aims at reducing costs to meet the budget.[DC]) (The early involvement and close working are crucial for integration and collaboration. However, time and money shall be invested for this purpose. (The culture within the company is also restricting the integration and cooperation. There is freedom for everyone to work in their own way without specifications of standard processes. [DCI]) Moreover, individuals shall think of the whole project process and not be limited to their own tasks in order to reach cooperation. [DCI])

Interviewee – 5C

- Cost engineer for 27 years on infrastructure projects and water-related projects, focusing mainly on the early phase
- For big projects with large number of engineers, the interviewee takes the role of the coordinator

(The start of the project depends on the client and his request. However, cost engineers prefer being involved from the beginning of the project and attend the first meetings. This enables them to be familiar with the project and think of risks and cost drivers. Furthermore, the cost engineers will be involved in decision-making. [DCI])

(The cost management is led by the project manager who is responsible for cost, time, and resources. This is the case for big projects, otherwise the cost engineer is responsible for managing his work. The process follows the one sheet prepared by the company. This sheet describes the process along with a list of input, checks, and questions to be considered. This approach is considered the ideal approach which cost engineers strive to reach. In the initial phases, there is not much information, so the cost engineers have to collect from what is available the needed information. At this stage, it is crucial to understand the question, scope, cost drivers, and other considerations. During the process, the quantities provided are checked even if they are extracted automatically. The checking is based on samples from cost driving items to reassure that the quantities are right. There is also information that the engineer adds himself such as finding the volume. For the computations, SSK model is followed and excel is used for the different methods. Mainly the bottom-up method is followed for the different phases even if the estimate is not based on detailed design. If we use the top-bottom approach, we look at previous projects and perform adjustments. Furthermore, the probabilistic approach is done for most projects and for any method followed. After the probabilistic values, monte carlo simulation is made.[CA]) (Currently, engineers are working on automating the system based on bottom-up approach and representative costs of average cases.[BU])

(The information from past projects is not preserved in an official data since such databases rely on actual values which are stored in different systems. The cost engineer looks into past projects to check previously used factors and use it as a reference. Therefore, tacit knowledge is not preserved.[CA])

(The design and cost processes could be parallel or fragmented depending on the project and client. [DC]) But in general, the cost engineers are well-informed and in a timely manner of the estimate to be computed. When the design changes, it is the cost engineer's task to track changes, update the estimate, and note the change made. Some cost engineers do the latter job better than others, so this would be shared for everyone to learn from one another.

The accuracy is calculated for each estimate. It is judged by checking if the risk and uncertainty are right and aligned. In some cases, the estimate can be very accurate from the first phases due to the clarity of the scope and the independence of the prices on the level of detail. In other cases, the estimate might remain with low accuracy in the realization phase. There are cases when the requested accuracy cannot be reached. For such cases, the cost engineer explains the reasons for the client.

(During the project start-up, the input and output information is discussed and agreed on. The coding of the items is also considered in the meetings. [DC]) However, some teams are doing the coding better than others. Information used by the cost engineer involves drawings, quantities, information on the phases, schedule, and risk. (This information is filtered to be used by the cost engineer and assessed in discussions. When the information is not clear, questions are asked and discussion with geotechnical engineers are made. If the quantities are missing, the cost engineers search for them in the available information. [CA]) If it is still not found, the designer is asked to find it. For tight scheduled estimates, daily or weekly contact with designers take place to understand the deliverables. Communication is made face to face and through emails to discuss questions and provide advice.

(Value engineering is not practiced a lot. Value engineering has different approaches and requires the involvement of the team. The cost engineer would be considered to facilitate the process of value engineering. Apart from value engineering, the cost engineer has influence on the design since he looks at the design while thinking of the construction methods. Then, he starts asking questions that trigger ideas for the designer. This can be done when the cost engineer is involved. To enhance the involvement of the cost engineer, information has to be shared on the project and understanding of the project and the process has to be communicated with the team. Furthermore, by following the one sheet process mentioned before along with the specification of roles, the design and cost processes relation is improved.[DCI])

Interviewee – 6C

- 40 years of work, 10 of which are experience in cost engineering

NOTE: This interview does not follow the questions prepared. It focuses on the interviewees experience in integrating design and cost processes. Furthermore, the interview mentioned points which are already considered by the researcher. Then this interview can support some of the ideas.

- The interviewee developed a program for value engineering. The program looks at the functionality of the item and the corresponding cost.
- (The interviewee had the experience in integrating the design and cost processes in one of the projects. It was a trail and the company learned from it. Complications were noticed when the project became complex and the engineers tried to catch all the details. This strategy leads to lots of work and high risk of making mistakes.[BU]) (Therefore, it is recommended for future work to select important items and perform the links for these. [BDU])
- (The interviewee states that the pitfall is to integrate too much data when you are aware that 80% of the costs are deduced from 20% of the items.[CA]) (The focus has to be on these cost drivers and form the connections for these. These items have to be 100% BIM but for the rest it does not matter. This is also the way contractors work. [BDU])
- The department working on dikes has better experience in standardization.
- (The SSK is a model in Excel. This facilitates the export of information from other software in Excel format and use it in the SSK model. Then, the section on the quantities can be linked to the model. [BDU])
- (In the SSK model, variations of price and quantities are considered. These variations can also be connected to the model. [BDU])
- (There is not a database for costs. The cost estimating process requires the analysis of the engineer even if quantities are automatically computed. Furthermore, cost engineers are becoming specialists in roads or tunneling…etc so that they can interpret the process, necessary items, and risks. [CA])
- (The cost engineer thinks of a model in a different way from the designer. Therefore, the cost engineer has to be involved in modeling to point the interesting items to be considered in the model. The integrated model can be reached if the cost engineer's perspective is considered from the beginning. [BDU])
- (Value engineering is done for few projects, but it should be part of the design process. When the design and cost teams work together, they can apply value engineering since the cost implications would be analyzed. In such cases, the first few steps are to model the project, decide on data sharing method, and identify the relevant data. [DCI])
- The cost drivers and value engineering components are the same. The value engineering components are also thought of as the items making the project costly.
- The cost engineer at the company is usually the one applying value engineering. However, this is a different case for other companies.
- (As consultants, the teams follow the client's rules, so it is hard to make changes that do not fit their rules. With that, the clients are not giving room for innovation and value engineering. Furthermore, big design teams do not easily grasp changes. Changes to the process can be made for small municipalities and small design groups.[BU])

- (The client has to be open-minded to accept different processes. There are some clients who are willing to practice new ideas such as applying value engineering. In such cases, the teams work with the client to find the best solution and complete the design. Thus, the processes have to be flexible. [BDU])
- The interviewee had an experience with a project were value engineering was applied and costs were saved. The saved costs were used to accomplish other requests from stakeholders.
- (Full automation yielding to a black box is not trusted. The cost engineer has to understand what is happening. [BDU])
- (If the model considers the cost engineer's perspective, it can be used for future projects.[BDU])
- (To reach new processes, the experience of the old generation is needed since they know best about expected results. Furthermore, the new generation thinks of new ways and styles to do the same process which is then checked by the older generation.[BDU])

Appendix D.3:

The appendix covers the interview questions with the BIM experts and the summaries of the interviews.

Interview Questions – BIM Experts

The interviewees are asked about their experience and kind of jobs performed at the company. Then, questions related to the research are asked as follows.

BIM execution plan and process:

1. Who is usually involved in the BIM execution plan?
2. What are the important aspects considered in the execution plan?
3. Who forms the process map?
4. What does the process map usually cover?
5. Are there templates for process maps? Or are they always changing from one project to another?
6. From your experience, is the process map followed to a certain extent? Does it get too hard to follow as the project becomes more complex?
7. Who is managing the integration between processes?
8. How is the utilization of BIM managed over the project phases considering the different disciplines?
9. How the input information and output deliverables from BIM identified and managed?

BIM modeling:

10. How the different features to be included in the model identified and delivered to modelers?
11. Are specialists from different disciplines involved in the preparation of the model?
12. Is BIM used in the early phases of the design such that schematic models are prepared?
13. Are the models fully prepared with information or is there focus on special items?
14. Do you think it is sufficient to detail the model for special features only?
15. Based on what aspects do you select the dimension to which BIM will be applied?
16. How is the cost-related data considered in BIM?
17. Have you done 4D or 5D BIM? If so, can you explain more based on your experience (the tools used, success factors, complications…)
18. What steps would be followed to reach 5D efficiently?
19. How are the connections between tools ensured? (following IFC or others?)
20. What are some ways that you have noted that could enhance the model? (such as color coding, feature-based model, queries, object-oriented approach, standard coding with external files)

BIM and people:

21. How is human intervention still considered in the automation of processes?
22. Is BIM enhancing integration and collaboration between the different teams? If so in what ways, if not, what shall be done to improve the integration and collaboration through BIM?
23. Do you notice resistance from engineers or managers to the utilization of BIM? Can you mention an example?
24. How is the communication and exchanges happening between the teams? Is it enough for the BIM way of working or what should be done?
25. How are the updates in the model communicated to other teams (those who have access to the model and those not)?

BIM add-value/complications:

26. Is BIM enabling structuring of information? If so, how is it structured and preserved?
27. What are some positive aspects resulting from the utilization of BIM noted from projects at the company?
28. As the project progresses and gets complex, Does this lead to complications in BIM?
29. What are the drawbacks of having a detailed model with lots of information tagged to objects?
30. How do you notice or judge that BIM modeling is getting extensive and costly with respect to the overall project?
31. What is the main target for using BIM in projects?

Interviews' Summaries – BIM Experts

The summaries of the interviews are provided in the following sub-sections.

Interviewee 1B – BIM Expert

- BIM coordinator to help others and give advice on BIM and 3D
- Worked earlier in Finland
- Started working at the company few months ago

(The BIM execution plan is prepared from the beginning by the BIM manager. The plan develops with the process, so it is never ready. Lots of discussions are made with the client to agree on the roles, format, software, process/workflow, and delivery procedure. [BU]) The latter is important to select software that can be integrated and coded. The process maps are prepared by the BIM manager and BIM coordinator who think together of the process and present it to the client. The client has to agree to the proposed process. (It is also important to show the client new ideas since they might not be aware of other or new options. The client decides if he wants 3D model or BIM model. The BIM model considers standards, regulations, properties, and much more information. But the client might request 3D model, and he actually wants a BIM model. Therefore, it is important to ask from the beginning about the information he wants. [BU])

(The process map focuses on bringing everything together and it considers the input, output, software, and integration of models. The model outputs have to be discussed with the modeler before including them in the process. The modeler checks if the desired output can be reached using a certain software. [BU]) The preparation of the process map is initiated from a self-prepared mind map, then brainstorming sessions and discussions are conducted to reach the process map. The process map is followed during the project, but it can also change throughout the project.

BIM manager works a lot with the client and contracts while the BIM coordinator works with the models and their integration. Other aspects such as time management, another person would be responsible. For example, for one of the big projects, one person had a full-time responsibility for 4D. (BIM manager, BIM coordinator, and project manager have discussions to identify the aspects to be considered in the model. Then, the modeler builds it accordingly. [BU])

(In the beginning, the team with different disciplines meet to specify the standard and other items to be used. Having agreed on that, the BIM modeler considers these in the model. [BDU]) (However, now it is happening the other way around. The BIM modelers understand well the model and innovate in the ways to use. Therefore, the BIM modeler is consulted to know what can be considered in the model. Furthermore, they give insight for integrating information and reaching faster processes. [BU])

For schematic design, Infraworks is used to consider different proposals with the prices. There are tests in automating this process. In other phases, the model becomes more detailed. (The level of detail for the different stages is defined in standards on BIM. However, due to miscommunication, lots of unnecessary work is done. [BU]) For example, a box would be enough to answer the client's question at the first stage, but the delivered model considers much more aspects. For the end of the project, it is good to have a high level of detail since it helps in the life cycle of the project (operation and maintenance).

There is an online toolkit explaining the aspects to consider and procedures for drawings for the different phases of the design. Following this tool, problems are reduced, the requirements from different disciplines are considered, and the design is prepared for the different phases. The interviewee is introducing this tool to people in the company. (However, there are also restrictions on the level of detail. Based on time and money, the level of detail is derived and communicated with the client. [BU]) Furthermore, the experience of the people who work with BIM has an influence since for fresh engineers they need more time to execute the job. Therefore, we usually request more hours. (For the cost component, the quantities can be extracted easily but the pricing varies depending on suppliers or other conditions. This complicates the addition of prices to the model especially that there are lots of details that the cost engineer thinks about to find the cost. These details might not be in the model or their addition might require lots of work. [BU])

Using IFC, the export is useful since it can be added to any software and most software read it. (But now it is developing. In some cases, IFC failing such that it is read differently by different software.[BU]) Navisworks and Navisworks freedom can read different models even 2D drawings. Codes for buildings are used such as NLCS but this is for 2D. For infrastructure, there is not much coding systems. IFC works well in Revit for buildings but not in Civil 3D for infrastructure. (Furthermore, there are standard coding such as UniClass that facilitate collaboration since everyone would have the items coded in the same way. [BDU])

Currently, the company is also using BIM 360 as an online browser to get access to the model and details. In BIM 360, the engineers can communicate, and the changes are notified by email. Moreover, connections between the model and Relatics is helpful to preserve and code the requirements and regulations. (For semi-automation, keep the price for example as a property and every time it has to be plugged in. If color coding is considered in the model, there has to be a standard for that for everyone to follow. For other objects, it is helpful to have a library that provides a standard for everyone to use instead of developing the same object many times by different engineers. [BDU])

Collaboration happens already, but BIM triggers people to collaborate due to standards and single workflows. (However, the older generation and clients have some resistance to BIM since they are used to certain processes or are not aware of the benefits of the technology and think it requires too much work. [BU]) Usually after seeing the results from BIM, the managers and client are satisfied. There is a lot of work, trainings, and investment in the beginning, but it pays off later with easier processes. (Furthermore, it is nice to work together and view the model to check for details and mistakes. BIM is about information management, using standards, working together faster, and avoiding double work. Technology is growing fast, and it is enabling the execution of various tasks. [BDU]) The problem is not with the technology but with the standards and people's mind-set.

Interviewee 2B – BIM Expert

- Project manager for 20 years at the company
- Have been using BIM since 1993, the idea behind BIM "information management" existed but the naming was different

(The BIM execution plan is prepared by the project manager, BIM experts, and BIM champions. The BIM champions are experts and engineers who give advice on BIM utilization and its process. The team meets to discuss the conditions and process. The agreed process and management of information are set in the execution plan. The execution plan considers details in order to clarify the workflow. Furthermore, the execution plan considers the level of development and its specific moment in the project lifecycle. The process maps are prepared with the team and BIM champion. The different disciplines in the team provide information on their tasks and the project manager agrees on the deliverables from the process. [BU])Since the process map is prepared by the engineers doing the work, the process map will be followed without problems. There are standards for the preparation of BIM plans and process maps found in BIM22 toolkit. Besides the execution plan and process map, the interviewee prepares an information flow chart which shows the dependency between information and software. The process schemas are drawn in Visio, EnterpriseArchitect, or Modelbased.

The information is managed using databases which are linked to the model. The interviewee uses systems engineering for the latter purpose. The databases are available for everyone at the company. They cover information on specifications, technical requirements, project management data, and risk. (However, the cost information is not compiled in databases yet. The process towards preparing cost data bases and 5D BIM are work in progress. For cost information, the quantities have to be found and classified according to UniClass or other classification system. UniClass is the suitable classification system from the perspective of the Netherlands and the cost engineers at the company. It is flexible for national codes NEN and SfB. Therefore, the interviewee among others are developing a company-specific Dutch version of UniClass. This version is based on UniClass along with the element book used in the Netherlands. The use of UniClass has the advantage of having an open standard which is known by various countries. Furthermore, costs need meta-data which identifies the aspects influencing the cost. These aspects provide information helpful for the generation Bill of Quantities, but they are not the complete required information for cost estimation. For example, in Revit, the meta-data on cost aspects are the tagged attributes. Other important considerations on cost information is related to value engineering. Value engineering is important since the value is the focus, not the cost. Based on the functional needs of the client, the value is defined. [BDU])FAST is used for the functional analysis. FAST helps describe the objectives and needs of the project to find the value based on which value engineering is made.

(The features added to the model depend on the client needs and deliverables. [BU]) Further discussions on the needs are made with the client to clarify and derive the intended needs. Having the needs understood by the team, the work to meet the needs is defined. The dimension to which BIM is prepared is decided by the project manager who agrees on it with the client. To reach a certain dimension such as 5D, (the engineers whose work aids the production of the model are consulted. The consultations lead to the preparation of a model with suitable characteristics such as attributes, classification system, and level of detail. [BU]) Along with the engineers, the people involved in the preparation of the BIM execution plan and process map are involved to make the process towards 5D BIM and the corresponding information flowchart. (The interviewee has experience in using 5D in terms of extracting quantities from a 3D-GIS model. The model can be enhanced using semantic aspects, meta-data, and links. For this purpose, the tool grasshopper is utilized to create links and identify relationships between the items. [BDU])

The connection between several open standards is through semantic web using Object Type Libraries (OTL). These libraries define the type of objects for the asset, thus, such libraries are being developed for asset owners. (Connections through IFC are not made currently since they are not used in the Netherlands. IFC is also not the only way for exchange. [BU]) Currently, the exchange is done via software and open standards such as COINS.

Systems engineering facilitates the management of problems and risks occurring at the interfaces. (The teams and the dependencies between them have to be managed such that the people have enough knowledge on the project and are provided with the right circumstances. The right combination of people is important since they think together of the execution plan, information flow, and model. Furthermore, the project manager shall be the BIM coach who introduces BIM and the model to the different individuals. [BDU])

(Through BIM, the information is structured and preserved as described in the BIM execution plan. Since BIM manages the information, it helps aligning the information and dealing with complexity of projects. BIM is all about the information management. Furthermore, the communication and common data environment with a network of linked datasets are important for the information management of the requirements of the team. [BU]) This can be achieved through BIM360, however, BIM360 leads to dependency on Autodesk. It is better to use cloud from various companies. For the changes that occur in the model, they are not always communicated but it is important to inform the project manager of the change.

(Despite the introduction of BIM and its benefits, there are cases were resistance against BIM is noted from individuals and clients. Another disadvantage of BIM would be related to reduced efficiency, time loss, and extensive costs from overloading the model with information. Working with high details from the beginning is not necessary since it gets too complicated and unhelpful. [BU]) This is the risk of BIM. To avoid such cases and enhance the efficiency, the level of detail is discussed in the BIM execution plan and with client.

Interviewee 3B – BIM Expert

- Has different roles as project manager, BIM coordinator/manager, and Design manager
- Work experience of 5 years with contractors and 2 years at the consultant company

(The BIM execution plan is prepared by the BIM manager, BIM coordinator, project manager, and other engineers involved in the project. The engineers allow the clarification of information and deliverables necessary for their tasks and project. The BIM execution plan progresses with the project and is constantly communicated with involved engineers. [BU]) The BIM execution plan identifies the general aspects (such as cost) to be considered. Furthermore, it explains the agreements which shall be followed throughout the process. Failing to do so, it is beneficial to show the engineers the difference between their work and that of the plan.

The BIM goals and BIM uses have to be defined to derive the tasks, roles, input, and deliverables. (Then, the process maps can be prepared by the BIM coordinator along with other engineers performing the tasks. Then, the BIM coordinator manages the integration and connection between the various processes and models. [BU]) During these preparations, the information to be exchanged and software used are stated. At different points of the process, the goals and processes are reviewed based on Plan-Do-Check-Act cycle to ensure their realization. (There are no templates to produce process maps, but it is good to have examples that would be a reference for future work. [BDU]) However, there are general standards for considerations of the different design phases.

BIM models are prepared for the different design phases depending on the size of the project. For example, BIM is used for the schematic design of large projects. The level of details of the model has to be made for the different stages according to the BIM plan and agreed needs and uses. If the level of detail is not reached, the uses are changed, and the BIM plan is reviewed. (Furthermore, the progress in terms of detailing the model has to be monitored to ensure that the allocated time and effort are synchronized. If this is not the case, the causes for getting out of plan are investigated. [BU])

Human intervention through BIM modeling is made through verification of the results from automated processes. The dimension to which BIM is prepared are depicted from the BIM uses clarified in the BIM execution plan. This is the case of working with clients who specify the need but not the way to achieve it. However, when working with contractors, the team has to follow their way. Thus, if the contractor is using 5D BIM, it will be the same case for the consultant team. (In case a 5D BIM model has to be prepared, the design manager, design engineer, cost engineer, project manager, and BIM coordinator work together to form it. [BDU])

BIM enhances the integration and collaboration of the teams through the use a single integrated model. Through BIM and common data environment, the information is structured, the processes are made explicit, and the agreements are clarified. (Despite these advantages, there is resistance to BIM from individuals who want to stick to their way of working as derived from their experience. This decreases the potential to cooperate and work together in a similar environment. [BU]) (Cooperation is needed in terms of agreements on formats and deliverables that fit together. Furthermore, BIM deals with the complexity of projects due to the structured information. [BDU])

(Communication is usually made through email or through meetings, the latter is especially important for multi-disciplinary projects. Communication between different actors is important for designing the complex model such that their information is added and linked. However, the addition of too much information leads to a big model that cannot be well structured or easily understood. [BU])

Interviewee 4B – BIM Expert

- Junior project manager for 1 year at the company and 4 years at another company
- Works on inner city projects and management of a new platform for the company

After the discussions over the client and stakeholders' demand, the requirements are set and integrated to Relatics which is connected to Asite, a new cloud-based platform. These demands along with the input requested from the different disciplines are the input to the process and the model. For the different projects, the 3D model is prepared. The model is prepared according to the NLCS standard along with attribute information tagged to the drawing. Furthermore, NLCS provides line and color codings which are helpful for the information management. (For the different phases, the model is prepared with information and exchanged with others. The detailing of the model depends on the client. In case he wants to check for alternatives for some parts, then these only are studied. Otherwise, the whole project is designed while adding information. [BU])

(For the case of costs, the model cannot have strict price definitions since the prices fluctuates. Such prices require continuous update, but prices of other components can be fixed in a pricelist (such as prefabricated items of supplier price). Accordingly, human intervention is always important, and it can be considered through the use of Excel. [BDU])

BIM is enhancing the collaboration and integration between the teams especially when Asite is also used. BIM provides an integrated view of the whole model, trace demands, and facilitates the management of complexity. Furthermore, BIM structures, presents, and transfers the information for all parties. Through Asite, the comments and changes can be directly communicated in the model. It is possible to send notifications on changes and reviews. (The information in Asite is traceable since the user can see the source (email, report? And from who?) of the request or demand. This leads to transparency since versions, users, and remarks are all clarified in the model. Further communication is done via email and in meetings. [BU]) Besides these advantages, resistance is faced with the older generation who prefers to stick to their own processes. Another disadvantage of BIM is related to the (intensive project administration of the remarks, demand, and other information added to the model. Otherwise, the team will lose track of the demands and the information will not be specific. [BDU])

Interviewee 5B – BIM Expert

- 6 years of work experience in 3D engineering at the company
- Work focuses on Civil 3D and GIS

The BIM execution plan is prepared by the team who decides on the way the work will be performed. The plan covers the codings, namings, inputs, and outputs. The process map is produced by the engineer himself since there is not a standard on guidelines for the work of 3D engineering. (The integration between processes is managed by the design leader, engineer himself, or information manager. The interviewee has prepared a standard process relying on codings to describe the elements in the model. Furthermore, mapping between elements and attributes are made to aid the cost estimation calculations. The interviewee also provided guidelines and a manual which the dike team can rely on to follow the process and reach the desirable results. This BIM approach is applicable to the different phases of the design. Yet, as the design gets more detailed the codes are extended. [BU])

(The input is derived from the manual or from the quantity sheet prepared by the engineer. The latter sheet has to be compatible with the codings prepared and identified in the manual. [BU]) The manual covers all requirements and enables the revision of products. (For each project, the necessary requirements and their representation are further discussed. There are checklist documents for appointments to be done before the project. The appointments consider the aspects to be added to the model, their codings, and standards. In case there are no standards available for the aspects, an Excel sheet is used and trails for standardizing and automating are made. As the process proceeds, quantities extracted are checked based on a developed review sheet. These strategies enable considering the human intervention in the automated processes. [BU])

(For the preparation of the 3D model, specific objects are detailed more than others. Detailing the whole model is time-consuming, so the 3D engineer tries to make a model fit for purpose. [BU]) 4D and 5D BIM models are not prepared in the interviewee's domain of work. However, the approach prepared by the interviewee covers the cost component aligned with the quantities. Neither the time component for cost estimation nor the integration in one model is made. (The cost related data is added as attributes as pointed from the cost engineer for the specific project. The attributes and codings are mapped to the quantities which are extracted from Navisworks. Then, an Excel sheet is exported to proceed with the calculations. This is considered an efficient process compared to earlier approaches. [BU]) IFC is not used for the exchange, yet it would be suitable for this approach. The model is enhanced in terms of mapping the prepared codings with those of Dutch drafting Standard. Furthermore, add-ons are customized for Civil 3D to find areas and make the design process faster. Even though BIM provides lots of information, the engineers have to be aware that the model looks complete, but it is not the case. There is still information to be considered apart from the model.

BIM is enhancing the collaboration and integration since all information is stored, checked, and compared. Furthermore, BIM structures the information which can later be preserved in databases in cloud. BIM also enables viewing designs, sharing them, checking relationships between components, and comparing alternatives. With such benefits of standardized and improved information management, (the efficiency is improved as the process and information to be used and delivered are clarified. [BDU]) (Despite the benefits of BIM, not all engineers are encouraged to use since they continue to use their own coding list. [BU])

The communication throughout the process is based on emails, meetings, and report meetings in cloud. When updates are made to the model, there is not a standardized way for communicating changes. In most cases, the design leader informs others of design changes.

Appendix E: Table on BIM suggestions for improvement from interviewees

Table E.1 provides more details on the improvements for BIM utilization mention.

Table E.1 BIM Considerations for improvement from interviewees

BIM Suggestions for Improvements		Interviewee
Semi-automation: Connection of Excel with Civil 3D	The SSK Excel covering variations of price and quantities can be connected to the BIM model.	6C
	The design model in Civil 3D can be connected to costs.	5D
	Even if design and cost estimation are linked through software to immediately reflect the design changes, the human judgment is still required.	1D, 4B, 6C
	The price is kept as a property to be added by the cost engineer.	1B, 4B
Standardization	Synchronization of codes requires early agreements.	1C
	With lots of changes happening, standardization can facilitate tracking changes.	1D
	UniClass is preferred for the BIM environment since the codes are done per object and it would be used by everyone in the same way.	1C, 1B, 2B
	A library with standard objects for everyone to use is necessary in order not to develop the same object several times by different engineers.	1B
	The right people have to work together from the start to unite the use of codes. They discuss the end product and make the breakdown structure accordingly.	2C, 2B
	The team with different disciplines meets to specify the standard and other items to be used.	1B, 3B
Connect people	The BIM coordinator and design coordinator shall connect the people.	8D
	The client has to be open-minded to accept different processes and new ideas.	6C
	The project manager shall be the BIM coach who introduces BIM and the model to the different individuals.	2B
	The design manager, design engineer, cost engineer, project manager, and BIM coordinator shall work together to form 5D BIM.	3B
	The team works together and views the model together to check details and mistakes.	1B
	The design and cost estimation processes would go in parallel via BIM.	3C
	The experience of the old generation is needed since they know best about expected results. The innovation from the new generation is essential to think of new ways and styles to do the same process.	6C
	The efficiency of the process is improved upon clarifying the process and the information used.	4B
Consider the cost engineer's perspective	The cost engineer thinks of a model in a different way from the designer. The cost engineer has to be involved in modeling to point the interesting items to be considered in the model.	6C
Focus on cost driving components and specified items	The focus has to be on the cost driving components for which details and connections are made.	6C
Model enhancement	The model can be enhanced using semantic aspects, meta-data, and links.	2B

	Metadata on cost information can consider information helpful for the generation of Bill of Quantities.	2B
	Consider in the model cost information relating to value engineering. This includes functional needs of the client to reach the value.	2B
	The tool grasshopper can be utilized to create links and identify relationships between the items.	2B
Prepare templates	Good examples of BIM utilization shall be preserved for future reference.	3B
Intensive project administration	The team has to keep track of the demands and information by monitor the addition of information.	4B
Checkable process	It is not efficient to perform automatic and manual calculations for judging or proving. Therefore, it is better to find a way to make it automatic but also checkable.	7D

Appendix F: Embedded Case Study Protocol: Case Study Questions and Field Procedures

The appendix provides the questions of the embedded case study along with the details of the field procedures.

Case Study Questions

The case study investigates the implementation and effectiveness of the designed process. The major question to be answered sub-question (6) as mentioned earlier. However, to guide data collection yielding to the answer sub-question (6), case study questions are set as follows.

Integration based on cost driving components:

- Which members of the team are actively involved in the selection of cost driving components and setting their target costs? How do they influence the selection?
- How is the communication between the designer and cost engineer on cost driving components happening and how frequent is it?
- In which discussions is the cost engineer required (besides discussions over cost driving components)?
- What are the ideas that evolved during the discussions on cost driving components? Do these ideas trigger important considerations for the design?
- In what way is the cost engineer influencing the design of cost driving components?
- How frequent are the estimates computed and did they influence the design?

BIM utilization:

- How is the discussion over the preparation of BIM made? What are the agreements made in relation to cost estimation?
- What is the information added to the model to consider the cost engineer's perspective? Does it require extensive effort?
- How does the designer and cost engineer standardize the representation of objects?
- How is the WBS, CBS, and model linked?
- How is the information flow between the designer and cost engineer coordinated (in terms of time and structure)? Is it satisfactory for the designer and cost engineer (in terms of time and effort)?
- How is the design level of detail and estimate's accuracy coordinated? Is the compatibility successfully met?
- How is the design level of detail and WBS for quantity extraction coordinated? Is the compatibility successfully met?
- How are design changes communicated?
- In what ways does the utilization of 5D BIM semi-automated method facilitate the integration between design and cost estimation?

- Does the cost engineer receive the quantities and cost information as required?
- Does this 5D BIM method facilitate the frequent extraction of quantities to enable monitoring the cost of the design?

Field Procedure

To prepare for the pilot case study, the data collection approach is set before the implementation. The data collection approach is described as follows.

Data is collected from different sources, which generally are: project information, observations in meetings, and interviews with team members. The documentation source enables the extraction of relevant information on the project. Observations made are direct and participant observations in meetings focus on discussions on implementation, task execution, and feedbacks. Through direct observations, the accomplishment of certain tasks over time is assessed. Participant observations are considered in situations where the researcher takes an active role as she participates in the events being studied. One of the opportunities of participant observations is the ability to manipulate minor events such as calling for meetings. (Yin, 2009) Accordingly, participant observations have a major role in data collection for several reasons. Firstly, the researcher is considered part of the team and is arranging meetings during which ideas for implementation are introduced. Secondly, the researcher is guiding the implementation of certain tasks by working closely with professionals. During meetings, the researcher is also collecting information by posing questions on certain topics. Thus, informal and unstructured interviews are conducted to provide flexibility by addressing general concepts without following categorized questions (Chism, Douglas, & Hilson, 2008). Furthermore, the team members are interviewed at the end of the case study to get general feedback on the process, the efficiency of the collaboration, and the effectiveness of 5D BIM.

Table F.1 clarifies the data collection approach in relation to the different steps of the designed process. The data collection approach includes the activities, preparations, involved individuals, resources, and points of focus. These are points that guide the researcher throughout the case.

Table F.1 Data collection approach at the different process steps and detailed tasks

Process Step	Tasks to complete the process step	Data Collection Approach					
		Data Collection Activities	Preparations	Involved professionals	Resources	Assistance	Points of focus
Define scope and requirements	Scope and requirements are already defined		Get access to the project's folder and identify necessary documents		Project information	All team members: guidance to find necessary documents	Read the documents and investigate the available design
	Meet team members, introduce the project, brainstorm for the process	Attend meeting on process discussion	Arrange a meeting and prepare a presentation of the proposed process and plan	All team members	Personal computer, *Project information		Note the limitations and recommendations discussed in the meeting

Agree on classification system, WBS, and CBS	Adopt a standard breakdown structure and codes to be used by all members	Attend meeting on breakdown structure discussion	Arrange a meeting with the team	All team members	Personal computer, Project information	Project leader: guidance to understand the division and the different structures	Note the agreed structure and codes and the satisfaction of the members
Set budget, cost driving components, and their target costs	Set budget	Attend meeting on budget setting discussion	Check documents to be introduced to the case	All team members	Personal computer, Project information	Cost engineer: guidance to understand the document used to set the target cost	Note the agreed budget and the reasoning leading to the value
	Prepare a proposal on cost driving components with their target costs	Meet with the cost engineer for the preparation of proposal	Arrange a meeting with the cost engineer	Cost engineer	Project information personal computer		Note the identified cost driving components with their target costs
	Agree on the proposal	Attend the team discussion on the proposal	Review proposal	All team members	Personal computer, Proposal		Note the changes made on the proposition of the cost engineer
Prepare BIM execution plan and process	Prepare BIM execution plan and process focusing on the connection between design and cost engineer based on cost driving components	Attend discussion on the BIM execution and process	Check the identified cost driving components	All team members	Cost driving components list and personal computer		Note the agreed workflow, the way for integrating the processes, and information exchange
Identify cost information	Cost engineer clarifies the information needed, its format, and delivery	Talk with cost engineer on the cost information noted	Arrange a meeting with the cost engineer	Cost engineer	Personal computer, list of cost information	Cost engineer: guidance to understand the list made	Note the list of cost information made with justification
Consider alternatives of cost driving components	Discuss and agree on alternatives of cost driving components to be designed	Attend the team discussion on alternatives	Review proposal	All team members	Personal computer, proposal		Note the alternatives discussed and the owner of the idea
Prepare BIM	Prepare metadata	Get information on the metadata to be added	Request the description on metadata from the designer	Designer	Personal computer, drawing		Note the ability to represent the requested information in metadata
	Add information to the model	Observe the addition of metadata to the design	Arrange a meeting with the designer	Designer	Personal computer, drawing		Note the ease of information addition to the model

Design of cost driving components' alternatives	Design alternatives of cost driving components	Get drawings	Request the drawings from the designer	Designer	Personal computer, drawing		Note the information added to the alternative drawings in the model
	Extract quantities and metadata	Get the extracted information and talk with cost engineer	Arrange meeting with cost engineer	Designer and cost engineer	Personal computer, drawing, Excel		Note the compatibility of the information with estimate to be computed
	Compute estimate and compare to target cost	Get the estimate from the cost engineer and talk with cost engineer	Request the estimation information from the cost engineer	Cost engineer	Personal computer, Excel		Note the effectiveness of model for estimation
	Adjust design(s) to meet target cost (if possible or necessary)	Attend discussions to adjust the design		All team members	Personal computer, alternatives and their costs		Note the ideas made to change the design to reach target costs
	Compare the different cost driving components' alternatives	Attend discussions on the comparison of cost driving component s	Review the criteria	All team members	Personal computer, list of alternatives and criteria for comparison		Note the comparison and the justification made to support selection of a smaller list of cost driving components
Complete the design	Design the rest of the project (not cost driving components)	Get drawings	Request the drawings from the designer	Designer	Personal computer, drawing		Note the information added to the design
	Discuss the compatibility between the design and estimate	Attend discussions on compatibility of design with estimate's accuracy		All team members			Note the analysis and discussion on compatibility
	Extract quantities for the rest of the design components	Get the extracted quantities	Arrange meeting with cost engineer	Cost engineer	Personal computer, drawing, Excel		Note the suitability of the extracted quantities based on general information from the cost engineer
-	Compute estimate and compare to target cost	Get the estimate from the cost engineer	Request the estimation information from the cost engineer	Cost engineer	Personal computer, Excel		Note the effectiveness of model for estimation of the rest of the components

-	-	Attend meetings	Follow-up with the case	All team members	Personal computer, drawings, estimate	Project leader and cost engineer	Note updates in the case to extract results relevant for the process testing

Note: * Project information includes the presentations made, contracts, reports describing the project, drawings, models, and cost estimation Excel

Appendix G: Object Tree of Embedded Case Project

The appendix shows the object tree used in the embedded case study by the participants but with vague object naming due to confidentiality reasons.

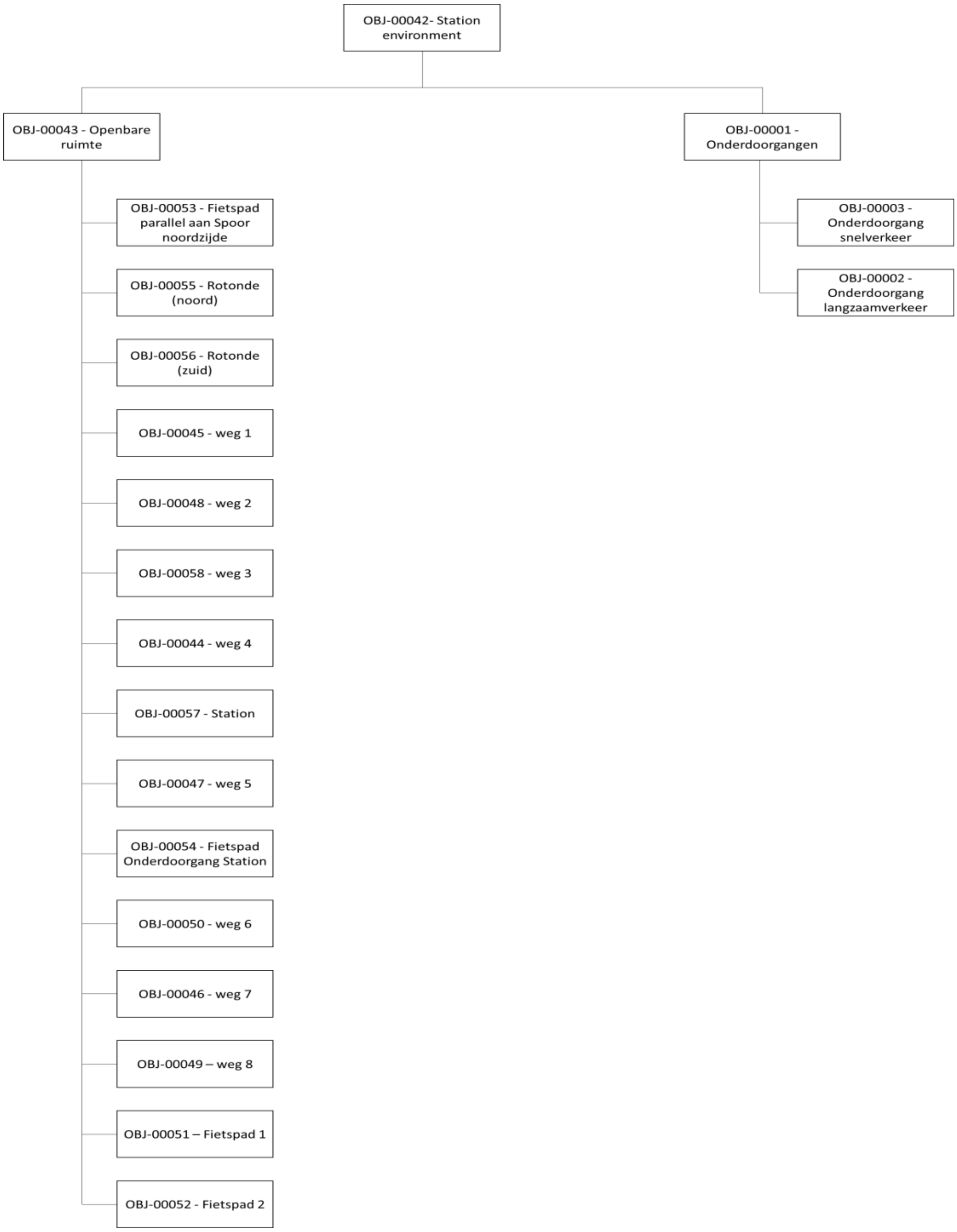

Figure G.1 Object tree of project

Appendix H: Interviews with Project Team – Feedback

The appendix covers the transcripts of the interviews with the project leader, designer, and cost engineer.

Interview with Project Leader

Alignment of design, cost estimate, and WBS:

1. Why do you regard the object tree derived was suitable or unsuitable for aligning design and cost estimation?

I think it is suitable, I saw that the cost engineer had some extra wishes and we can add them.

2. In what way did it help design-cost estimation integration or how did it fail to do so?

I think it will help but it is too early right now. We had a meeting this week with the client. It is a bit early to see the results, but it already helped the designer and cost engineer to understand each other more. We will see it, but it is bit too early.

3. What are the issues in the project we are working on that limited the preparation of a breakdown structure that can be followed by the designer and cost engineer?

I think the major issue was to get the project scope stable and to understand what the client wants. The client keeps on changing the requirements and question. He is also not giving response on requirements sent for the design. They are not used to this kind of big projects and they do not understand how to act in it.

I think at the company our focus has been too much on the construction work for the tunnels. We put a lot of effort to place the tunnels but the other scope around is not regarded in the same way.

Now, more integration is happening between the public space and tunnels designs. However, the architect is still sketching, and it is hard to get the synchronization with the architect.

4. What shall be done to ensure that the set WBS or object tree is applicable for design and cost estimation?

I think the most important thing is to maintain it dynamically and keep people aware that they are sharing the object tree. You can request changes, but you have to discuss it. So, a lot of awareness is needed. It will dynamic and new objects will be added but you need to maintain it as a project team.

5. Do you think this approach of following a unified description and division enables effective integration of the information between design and cost estimation? Can you explain in what ways?

I am convinced that this leads to effective integration, but you don't see the effect now.

Budget, cost driving components, and target costs setting:

6. Was the consideration of cost driving components influential? In what way?

I still think it is good. But it is a shame that we cannot show it to the client. It was good for the cost engineer to start thinking of the costs. This also enabled him to share the information on the budget with the client. Now, the client wants the estimate of the costs after the discussion and information the cost engineer gave on the costs.

7. Was it a suitable approach for the selected project? In which projects would it be better applied?

I think it is suitable for every project. It depends on the client. The client needs to know of the process, be aware of it, and learn to appreciate it. And the project manager needs to sell it. These are not happening, so it is hard to implement it. If it is agreed earlier, then you make a process and know the role of client and project manager. The project we were working on is old fashioned so it was hard to make the switch. It would have been helpful to use the method and helped the client since he has been working on this project for 10 years.

You also need a project manager who really wants this and adjusts the process accordingly.

8. Did it allow for effective integration between design and cost estimation? How or why not?

I would say yes. It does get the cost engineer more involved.

9. What considerations can improve the utilization of the approach?

I would say start with presenting a visual process of the project and make it visible in time. Now it is going traditional. To make it integrated, we need to make it in parallel. It is also good to have detailed planning on weekly basis. The key issue is that you plan resources (your team) since in this process it is different from the traditional way. For instance, to have the cost engineer in the beginning, it has to set in the planning. However, the managers are afraid of that since they think if he started then he will start booking more hours. They think in a traditional way to keep the hours safe. For BIM projects, the planning is different, and it should be clarified and detailed for everyone.

Meetings

10. What is the importance of frequent meetings?

The meetings are very important, and they give awareness in the beginning. The managers and team members are traditional. Some people are annoyed with meetings instead of understanding what the other team members are doing. It is a team sport not individual, BIM it is team sport. We need to know how to help each other. Instead of making the change alone and sending it to the cost engineer, talk about it and help each other.

BIM Execution plan and process

11. What are reasons for disregarding the dynamic quantity extraction in the design?

The designer does not want to spend time on making changes to have this method. It could also be that he would prefer to try this method outside the project.

12. Why was the adoption of 3D modeling and automation late in the process? How would the earlier consideration helpful?

I tried to do the whole project in 3D. I think now it is all in 3D. But the tunnels are still in development. For the next project I prefer to have this sooner. This should be a parallel track, but tunnel designers are waiting for the road. Then a lot of waiting is happening.

Cost information and model design

13. What are reasons for disregarding the cost information in the cost engineer's Excel in the design?

This is a general problem. The designer is optimizing his process individually and he does not think of the process of the cost engineer. He is thinking of being efficient. The individuals work on optimizing their own process. He is not starting with the quantities since the design is changing. We talked on this issue and suggested that even if changes happen, we will have a baseline. But he does not want that. He is looking for his own work load, he does not see the effort for the project.

14. Would the consideration of the cost information enable integration in other cases? What are the prerequisites to prepare a model considering the details of the cost engineer?

The main discussion is to change from traditional to a parallel process, then you need the quantities to be dynamic. I understand the designer's argument that he is going to do it 5 times. But if you make it dynamic, you make it once and later changes will require less effort.

A lot of awareness is needed. It is not the techniques, it is the people. The people do not want to change their process. It does not help now since if it is manually done more hours are made and higher costs. So, we need to find an efficient way to have quantities at the beginning. Maybe we have to develop the method outside the project first.

Cost driving component alternatives

15. Would the consideration of cost driving components and alternatives help?

It would help but the client and project manager are not supporting this idea.

Grouping of elements based on WBS and quantity extraction

16. How would it help quantity extraction, estimation, and management relative to the effort put in the design?

I think it will help as a team effort, it will not help the individual but the project and the team. For the project it does not help since there is not a method to do that. We are developing the method in the project and the managers see this as a risk.

General

17. What was considered in this process as an enabler for effective integration?

I think the main enabler will be to have the right planning. Make the planning integrated not sequentially. Make it in parallel tracks and make it visible that people must interact. Having them one in May and another in June shows that they don't interact. The planning has to be at the higher detail level. The risk of parallel planning is that you see 1 box in May for the designer and another for the cost engineer. So, we need a higher detail level to specify were each is happening (such as showing tasks in a time frame of 2 weeks). It is also important to make it visual. Then people understand what they are doing. If you don't do that everyone is going to wait. And the main issue is that decisions are not made.

18. What were the major limitations hindering the integration?

I think the major obstacles are the people, process, and their combination. People with experience in the BIM way of working that are given a traditional process will never lead to a BIM way of working even if you have the tools. The main signal is that we have to think in team effort instead of individual effort. We have to think of how we can help each other.

19. How does the process differ from previous practice?

I think the change is from traditional tasks to parallel processes with interaction.

Interview with Designer

Alignment of design, cost estimate, and WBS:

1. Why do you regard the object tree derived was suitable or unsuitable for aligning design and cost estimation?

It is suitable, but it takes a lot of work to get the quantities from the little spots. I had to cut the design in pieces.

2. In what way did it help design-cost estimation integration or how did it fail to do so?

No, the objects did not help. However, it is necessary to have the objects clear for the designer and the cost engineer to check while designing. But I don't know if it is going to be quicker or saves time.

3. What are the issues in the project we are working on that limited the preparation of a breakdown structure that can be followed by the designer and cost engineer?

You just need time to do these things, so maybe we need to specify time for quantities. The problem was in the planning not the management. There was limited time to do certain things.

4. What shall be done to ensure that the set WBS or object tree applicable for design and cost estimation?

It is important to clarify the objects, areas, and boundaries for everyone. But this does not mean that they are fixed. Boundaries can change in the process. So, first split, then pick up the design.

5. Do you think this approach of following a unified description and division enables effective integration of the information between design and cost estimation? Can you explain in what ways?

Unified description can be helpful. The communication gets easier, everyone would be speaking about the same object.

Budget, cost driving components, and target costs setting:

6. Was the consideration of cost driving components influential? In what way?

The consideration of cost driving components clarified for me the expectations. I usually talk to the cost engineer when I have already started. Then, we have a conversation about it. So, it is always helpful.

7. Was it a suitable approach for project we were working on? In which projects would it be better applied?

It is suitable for all projects, maybe in this project we started too late. You were looking at cost driving components and we have already started the project long time ago. If it were in the beginning it would be good to be aware of the cost driving components. And maybe have from the beginning the cost engineer giving the costs then while changes are happening, we can see the changes in costs.

It works in big projects since more time is given to setup things and make it easier. So you can innovate.

8. What considerations can improve the utilization of the approach?

Cost engineering should start with the designer. We should invest more in innovation to reach automation and have costs dynamic.

Innovate in the design to have automatic quantity takeoff. We should do more of this, or design in a specific way to make it standard then dynamic. In most cases, the project manager says to start designing directly and doesn't want to do innovations. The managers focus on budget and time so when they see risk on delay, they say it is not going to be done.

Meetings

9. Were the meetings made with the designer and cost engineer on cost driving components or other considerations beneficial? How or why not?

Yes, meetings were very important. There were also weekly scrum sessions on skype or at the office. Also, once in 2 weeks the client is there, then we discuss alternatives.

10. What are the reasons for not meetings to discuss the design of a specific cost driving component?

The delay happening was related to the architect since he had a lot of variances. Lots of changes were happening. There is continuous change when the architect is there.

11. Would the discussion over the design of a specific cost driving component enable effective integration?

Meeting on one object is necessary if lots of changes happened. Otherwise, there is not needed to meet. We can have small discussions.

BIM Execution plan and process

12. What are reasons for disregarding the dynamic quantity extraction in the design?

This requires earlier preparations and it takes time to perform it. No time was given for this task.

13. Was the exchange of Excel files and PDF drawing suitable or unsuitable for the integration between design and cost estimation? Why?

Yes, the integration using excel and pdf is good.

14. Why was the adoption of 3D modeling and automation late in the process? How would the earlier consideration helpful?

The parts which are going to take a lot of groundwork were designed in 3D. But for little improvement or junction it is done in 2D. The client didn't specify, it is our choice to use 3D or 2D.

Cost information and model design

15. Was the cost information in the cost engineer's Excel complete?

It was complete and when I see something missing, I add it and discuss it with the cost engineer.

16. Would the consideration of the cost information enable integration in other cases? What are the prerequisites to prepare a model considering the details of the cost engineer?

The cost information does not impact the design. I don't need the cost information to design. I work the same way. But it can influence at a higher level such as requiring volumes which can be done in 3D not in 2D. So then we have to design in 3D.

Cost driving component alternatives

17. Was the consideration of alternatives of cost driving components and their analysis helpful for the design of the project? If not, what were the limitations?

Alternatives should be done more in the early stages of the project.

18. In what way did this approach improve the integration of design and cost estimation?

With the investment in innovation, we can get integration.

General

19. What was considered in this process as an enabler for effective integration?

Integration is helpful. Cost driving components and thinking of the budget are good considerations.

20. What were the major limitations hindering the integration?

Designing in a way to get quantities easily is possible but takes time. So, we need to decide earlier on time allocate for this task and the manager should see positive things in it. It also depends on the project maybe it is not necessary to make it complex.

21. How does the process differ from previous practice?

There was not much difference except for the awareness of cost driving components and objects in Relatics.

Interview with the Cost Engineer

Alignment of design, cost estimate, and WBS:

1. Why do you regard the object tree derived was suitable or unsuitable for aligning design and cost estimation?

The object tree was good, but the designer mentioned that it is a lot of work for him to consider these objects. But for me, it was good.

2. In what way did it help design-cost estimation integration or how did it fail to do so?

It did not lead to integration since they do not see the benefit now. But working together from the beginning is the best option. People have to get used to it and for the future I think it is better for all of us.

3. What are the issues in the project we were working on that limited the preparation of a breakdown structure that can be followed by the designer and cost engineer?

The problem is that now we are getting good structure in the project. In the beginning, everyone was searching for the structure. Next week, I will have the meeting on the structure and the boundaries.

For the meeting next week, I suggested to have the team members involved to set the structure with the client.

4. <u>What shall be done to ensure that the set WBS or object tree applicable for design and cost estimation?</u>

The best way is to meet all together. You have to be proactive to get these things done. We have to suggest this to the client. Also, not all designers work this way, so we need a process on this.

5. <u>Do you think this approach of following a unified description and division enables effective integration of the information between design and cost estimation? Can you explain in what ways?</u>

It would help when we use Relatics and it clarifies the updates. It should reduce the mistakes between the designer and cost engineer.

<u>Budget, cost driving components, and target costs setting:</u>

6. <u>Was the consideration of cost driving components influential? In what way?</u>

The cost driving components are specified but we did not discuss it with the client.

7. <u>Was it a suitable approach for the project we were working on? In which projects would it be better applied?</u>

I think it was suitable for this project and it is suitable for complex and big projects. You need to think about cost driving components.

8. <u>Did it allow for effective integration between design and cost estimation? How or why not?</u>

Not much. We were trying to have cost driving components but what I noticed is that we need to have people open for changes.

9. <u>What was hindering the integration based on cost driving components?</u>

The main issue is related to the hours, if they will be paid or not. These has to be clear in the beginning. The manager mentioned that we can do it, but he did not do anything extra.

10. <u>What considerations can improve the utilization of the approach?</u>

We need to try to find a team that wants to try something new from the beginning. It would be helpful. If the managers mention from the beginning that we have to do it, then it would be part of the planning and way of working so it will be easier to implement. The managers have to know that if we do it differently it could be more efficient, and we would not know if we didn't try. We need to solve it within the company not with the client. Focus on the people and give them space to do something new instead of thinking of budget and time. We need flexibility in this.

It is also important to accept changes and undergo a cultural change.

<u>Meetings</u>

11. <u>Were the meetings made with the designer and cost engineer on cost driving components or other considerations beneficial? How or why not?</u>

Not really because we talked but no one took action. But it is important to meet frequently if big changes happen.

12. <u>Would the discussion over the design of a specific cost driving component enable effective integration?</u>

It would be helpful, but we are still working in the traditional way thinking of budget and time.

BIM Execution plan and process

13. What are reasons for disregarding the dynamic quantity extraction in the design?

The designer mentioned that this requires time.

14. Was the exchange of Excel files and PDF drawing suitable or unsuitable for the integration between design and cost estimation? Why?

We are still searching for the best way to extract quantities. It is much better than other projects. PDF is okay but in the Excel I need more information. I didn't get the information I asked for.

Cost information and model design

15. What are reasons for disregarding the cost information in the cost engineer's Excel in the design?

The designer was thinking in a traditional way so thinking of doing the quantities at once when the design is fixed. He does not want to spend time on it now since the design is still not stable. If he does it now and later he had to do it again because of changes, it is not clear if the work before is considered within the budget of the project (being paid for these hours).

16. Would the consideration of the cost information enable integration in other cases? What are the prerequisites to prepare a model considering the details of the cost engineer?

Then, I would make a good estimate. For the future, it is better to meet with the designer and project leader too to clarify my requirements.

Cost driving component alternatives

17. Was the consideration of alternatives of cost driving components and their analysis helpful for the design of the project? If not, what were the limitations?

A lot of changes were happening without thinking of the budget. The client does not have a lot of experience. The client wants to do what he wants and then check its budget.

18. In what way did this approach improve the integration of design and cost estimation?

If we work like this, we are a team and the relation is better. The designer understood also why I need these quantities and assumptions.

Grouping of elements based on WBS and quantity extraction

19. How would it help quantity extraction, estimation, and management relative to the effort put in the design?

If we clarify from the beginning what everyone will deliver, then this is the best way. It is useful in the future. If changes happen, you look into this specific object.

20. Was the presentation of quantities problematic? Why?

I did not get enough information.

21. Compared to the delivered quantities, how would their accuracy be improved if the object tree was followed? Would it be beneficial in other ways?

Information on quantities provided as area is not enough for good accuracy. This is especially important for cut and fill. So, this is important to do in 3D. Other quantities I will get in 2D. This affects accuracy, but it is enough for this stage of the project.

<u>General</u>

22. <u>How does the process differ from previous practice?</u>

This is not exactly the same. We were talking about cost estimation, but nothing happened. So, we did more talking but still there is no action.

Appendix I: Interviews for Validation

The appendix covers the transcripts of the interviews with BIM experts. Interviewees 1V and 2V are professors at TU Delft while interviewee 3V is a BIM expert in a company specialized in digitalization.

Interviewee 1V:

The interviewee is an assistant professor for the studies in integral design and management at TU Delft. The professor's focus is on information systems for construction. These include research on the incorporation of artificial intelligence technology in design and decision processes. Furthermore, the professor has research related to data technology for the collection and connection of asset information.

Cost driving components:

1. How would you assess the feasibility of building a model with the focus on cost driving components which make 20% of the components?

It can be done, but the main characteristics can be considered instead of the cost driving components. These characteristics are requirements and dimensions. With main requirements, you can tell a lot about costs.

2. How would you assess the influence of this case on the integration of design and cost estimation via BIM?

Such an approach can increase integration. I think this is a good approach.

3. How would you assess the influence of this case on information management (in terms of information preparation, compatibility, exchange)?

In principle it would help, but it depends if you are able to identify the cost driving components. Then, it can help.

4. When is it best to adopt such a case?

The project cannot be too complicated because there are too many elements that play a role.

5. What are the advantages of such a case?

You can have better and cost-effective design.

6. Does this case reduce the complexity of the model? Are there any other arising complexities from this adoption?

In such a case you simplify the model yourself. It is made simpler. However, in complex projects it won't help since you miss information.

7. What do you recommend for improving this concept?

I think it is more effective if you start from the main requirements not the main components. The intensity of the interaction is important. If no communication happens, then it won't work. The team should also agree on decomposition, tools, and classification systems. A good tool can make a lot of difference.

8. What problems would arise from this case?

If you have a good method, but do not communicate then it will not work. This leads to going back to the problem of designing then sending it for cost estimation. Other problems could happen in classification if systems are not used because the names could be different.

9. What other recommendations can help reduce the complexity of the model?

It is important to use systems engineering for decomposition and the V model also helps.

Semi-automation:

10. How would you assess the feasibility of adopting the method of semi-automation given the current technology?

I think it can work but it is important to look into available tools in the market. But this could also be fit for purpose.

11. To what extent is the reliance on classification systems for WBS, cost plan, and schedule helpful for standardization, communication, and information exchange?

The agreement should help but all kind of practical issues and misunderstandings can happen. So, it does not go right automatically. Misunderstandings can still happen so discussions are necessary. You have to discuss and agree on solutions for the different occurring issues.

12. To what extent does the WBS of classification systems improve the compatibility between the model and cost engineer's requirements on quantity extraction?

I think you should not confuse the system breakdown structure with the work breakdown structure. The WBS is for packages and activities while the SBS is for the objects. So, if these are messed up it will lead to problems.

13. Does this method enable the integration of design and cost estimation?

Potentially it can help.

14. What would you suggest for improvement of this method that aims at integrating design and cost using 5D BIM?

The semi-automated method can be improved by having a lot of interaction. I am concerned with systems like Excel. Excel is not good for data storage and data management. Full automation can be considered to eliminate the risk of human error. To have it semi-automated, there must be an important reason for that. It is difficult to check implicit knowledge that is used in cost estimation. Maybe try to find a way to transform the implicit knowledge to explicit knowledge. If it is dependent on humans, then the answer is also dependent on humans. This is not what you want. It would be interesting to look into the reasons for not having it fully automated.

15. What problems would evolve from semi-automation?

Excel has problems with data management.

16. What are other recommendations for integrating design and cost estimation while utilizing BIM?

It is important to look at what is available in the market on 5D BIM. There are a lot of tools in this area and that can be very useful.

Process map:

17. How would you assess the sequence of tasks forming the process?

I have not checked it thoroughly but makes sense.

18. Does the division of the process and its iteration to cover the design process feasible?

It makes sense, but it would be helpful to check it with designers.

19. How would you assess the information flow throughout the process?

The BPMN is a helpful method. When you make such a map, you can check if all the tasks and arrows are clear and defined. However, it is not enough to draw the map. It is important to know what is going on between the tasks and arrows.

Effectiveness:

20. How would you assess the effectiveness of the process focusing on cost driving components for integration and modeling?

Yes, it does but I think it is more effective to look at main requirements.

21. How would you assess the effectiveness of the semi-automated 5D BIM method for integration and modeling?

I think it can work.

22. Would the proposed process work effectively in practice?

I think it can work but it will require effort from the people who will first use it. They will find a way to use it. Maybe it is more work in the beginning till it works.

23. Does this approach fit literature's perspective on BIM while adding value to research on BIM?

Yes, it is in line with literature on BIM but for adding value I am not sure. I am not sure if it is new enough to call it a contribution.

Interviewee 2V:

The interviewee is a professor for studies in the management in the built environment and for design and construction management. The professor focuses on design analysis and information management among other topics. Furthermore, the interviewee has publications on BIM.

The interview did not proceed with the set questions. The interviewee showed complete rejection of the idea since he insists on using BIM for automatic estimation without the expertise of cost engineers. The conversation used to support his idea is summarized below.

- You interpret designs based on your own discipline. So, there is a clash. We need to find common ground. Then, BIM comes. BIM is far from perfect, but it provides advantages in relation to interpretation. BIM relies on symbolic representation placed in the design, thus it became a game changer. Instead of having differences in interpretation, we have unique codes in the computer. Accordingly, everything in BIM can be complete and unambiguously interpreted. Then, we do not need common ground.
- You do not need the cost expert to get the costs. In the same way that the door sticks to the wall, BIM can demand scaffolding for this wall. This is a symbol in BIM. With BIM big changes happen, so there is no reason for not modeling properly in BIM. It is more precise. There are problems in BIM,

but it is the future by working with symbols to avoid misinterpretations. With BIM we have economical means to do simulations for energy and construction processes in one model without misinterpretation.

- I have worked through the digital evolution. But in buildings, it is not fast. The start point is that everyone wants to economize in BIM. It is important to have all the details in BIM, even the screws and nails. When you reach the level of thinking of screws and nails, you will need them. At certain points in the life of the building you might need information on the screws. Then you can have direct access if you have it there. In one information system, the information is growing. For example, when you want to repair something, you do it and add it to the model.
- BIM requires a single model. One information system in the middle and everyone can access it. You can work together with a resent version. But in the current state, everyone wants to stick to the old way of working. With this approach you are also not taking advantage of BIM.
- BIM replaces quantity surveyors or cost engineers. We know all the things and we don't need cost expertise. The cost engineers are implicitly thinking of the construction process. So, we need construction expertise to model the construction process and map it to the model. We cannot tag cost to a symbol in BIM. We have to break everything down to construction packages and analyze the packages (do I need a crane, scaffolding…). Then, you don't have anything missing to get costs. You have the construction process, you also have the unit prices, and you can calculate quantities, labor, and equipment.
- Bad timing can increase the cost, how to factor this in. Everything can be a cost driving component.
- The correct way is to push construction to be considered first then get the costs. This is instead of having costs then planning for construction. When there is an idea, you think of how you will construct it not of how much it will cost. Then, you conclude with the cost. This is simulation of reality. Having the design and cost to bid and then construct is old fashion. Having design bid and build doesn't make sense anymore. We used to cut it down to manageable pieces. But now you don't have to do that.
- Companies need new processes and nee to make things transparent. It is not necessary to reduce costs, but it is required to control it. Ending over budget is a main issue. Cost overruns are happening with the methods followed, so we need new processes to fix this issue.
- Budget is also in the old way. Now we pay attention to use costs which make 70% of the costs. Now, buildings cost more, and production cannot keep up. There is something fundamentally wrong and professionals rely on outdated methods. Then BIM comes along, and it is fundamentally different. And they want to bring it back to the way they work.
- There is no transition in technology such as computers. It is a jump. You do not need to have a transition. We don't have to make a transition plan, we need to find a way to educate the people. You learn by spending time learning BIM. Why don't we want to change? We have to change. We need to adapt to the new world.
- By having a model in the middle, everyone can work on designing and not have only designers working on the whole design. We need additional knowledge in designing.
- Whatever affects costs is not in the domain of the cost expert, it is the domain of someone else that contributes to costs. So, if everything is done properly, you don't need cost expertise. Everything is quantifiable. Then, I need economists to consider other points such as inflation.
- Information has to be complete and meaningful. It is important to have everything as complete as possible also for construction processes.

Interviewee 3V:

The interviewee works with 4D BIM for more than 2 years. The interviewee prepares the project management plan, works with 4D planning, and works with visualizations of the design in time. The interviewee mentioned that the challenge in their work is to define the right level of detail and minimizing the room for misinterpretation.

Cost driving components:

24. How would you assess the feasibility of building a model with the focus on cost driving components which make 20% of the components?

I think it is a really good way to actually work because what you see in a lot of projects is that designers are designing everything in 3D with a huge level of detail just because they can do it. This costs a lot of time and money. It is never the goal to design everything in 3D, 4D and 5D. It is about having the right information to successfully lead the project and enable decision making. The goal is always to deliver within time and budget. It is about making sure that you can build it, so if the level of detail is necessary for that then you should design in detail. Also depending on the project, the level of detail differs.

It is not about how deep you go in modeling. It is about reducing the room for misinterpretation of the design by the different engineers. Based on that, we add the details. This is also the case for costs for which I think focusing on cost driving components is a really good way.

25. How would you assess the influence of this case on the integration of design and cost estimation via BIM?

I think it would influence the integration because you already mentioned in many projects, the design is completed then a lot of time is needed to review it and estimate costs. If it is expensive, you need to fix the design. Then you might run into problems. Maybe the designer has a new project, or he left. So, any problem could happen, and you will need a lot of time to redesign especially these cost driving components. In many cases, the design is over budget not due to minor details. It is related to these cost driving components which require time and effort to change. Therefore, having the cost engineers discussing the cost driving components with the designers can make a big improvement. The discussions in the beginning on classification system or others is important since the cost engineer thinks from his perspective. His requirement to calculate the cost easily might not be suitable for the designer. So, having discussions early on is a big improvement. People start understanding one another.

26. How would you assess the influence of this case on information management (in terms of information preparation, compatibility, exchange)?

The focus on cost driving components does help in information management since we want to focus on important aspects instead of having lots of information with high level of detail of the overall design. By focusing on cost driving components, we are focusing on important aspects when it comes to budget. In this approach you also think early on about what is important and then you go into the details.

With the cost engineer involved from the beginning, he is given the opportunity to think of his structure. He also knows what information is coming next and enables him to understand what is important in the project. Accordingly, this helps the cost engineer in handling the information he receives. I think this is a big improvement and it is important to have a plan in the beginning as you are doing here in this process.

27. When is it best to adopt such a case?

I think it is suitable for complex projects because for the standard projects you could follow standards for designing and later providing the information for the cost engineer to perform the estimate.

The iteration is very important since there are always changes and we make mistakes. So, we are continuously updating instead of making it robust. I think the major power of this process is for complex projects since you do not know what will happen, so you need action to change by doing iterations and changing directions. Due to high uncertainty we need to be agile and I think this process makes it more agile. Also, for the cost engineer, he can think with the team of challenges that are coming next. Moreover, things go wrong in complex projects, so we have to be a team to handle it and minimize the impact.

28. What are the advantages of such a case?

The understanding between the designer and cost engineer is important not only for the calculation but to think of the time and effort others are putting in. With early involvement, the individuals know what each is doing and understand what is possible to do, what mistakes could arise, and why these mistakes happen. Furthermore, the relation between the 2 actors also becomes smoother. It is not only the technical side, but also it important at the personal side. It gives a team feeling.

29. Does this case reduce the complexity of the model? Are there any other arising complexities from this adoption?

This approach does not necessarily minimize complexity but if handled properly it should. By focusing on drivers and having discussions, you are making decisions on what is going into more details and what is not. It is very important to specify what is not going to be designed. Then, the complexity should be low, but this depends on sticking to the plan. So, we think about what we will design, what are the costs, and what we will focus on. We should accept not doing things and I think this is an important factor since usually we agree on what we are going to do but not on what not to do. You would have people who stick to what they do and design things that are not required. This would frustrate the whole project.

30. What do you recommend for improving this concept?

I see that a lot of steps are being done by the designer and agreed on by another, but I think it would be helpful to have both parties discussing and making decisions instead of one.

I also think that planning has to be considered. So, the planner shall be in early discussions too because there are some consequences for him. The data has to be checked for compatibility with him too. For cost estimation, it is a good process, but it is not ending here. I think more people are involved in the beginning.

31. What problems would arise from this case?

I think the problems are cultural because cost engineers are not used to being involved from the early stages. Maybe more importantly, the designers are not used to having discussions with the cost engineer to tell them what to do. But I think it is manageable. The challenge is also accepting not to do stuff.

Semi-automation:

32. How would you assess the feasibility of adopting the method of semi-automation given the current technology?

Semi-automation is possible, but it should not be the standard. There should be a point of change. But it is good for now since it is not possible to provide a new process and new tools. So, I agree in keeping it simple in the beginning, they get used to the process. Then, a shift for automation can be made.

33. To what extent is the reliance on classification systems for WBS, cost plan, and schedule helpful for standardization, communication, and information exchange?

The WBS is very important since it is standard between cost and planning. It is also the standard for most information and communication within the project. For example, we assign risks and link it to the package. With all information linked to the package, better estimates are made. We can also add documents or any other relevant information to the work packages and regular objects. Then, we are integrating it all together. With a standard we have good communication and information exchange.

34. To what extent does the WBS of classification systems improve the compatibility between the model and cost engineer's requirements on quantity extraction?

I think it helps in compatibility, but I do not think we should decide from the beginning on the overall WBS levels. We start at a certain level and later the WBS might become more detailed and complex. We go to deeper levels only when it is necessary. So, yes, it is a good way since it is a standard which different specialists use.

35. What would you suggest for improvement of this method that aims at integrating design and cost using 5D BIM?

I think it is important to add the planner as mentioned before. The relation between the planner and the cost engineer is important also in relation to the breakdown structure each is following. So, it is very important to make sure that the breakdown structure works for everyone.

Process Map:

36. How would you assess the sequence of tasks, information flow, and decision points forming the process?

It is good that the information exchange is kept simple and focusing on the relevant information. It looks like there are a lot of documents, but they are the same. So, these are updates. I also think these are the most relevant documents. This is important since the goal is not to have it complete with everything but to optimize the process for 5D for the designer and cost engineer. Later in the process changes could happen.

37. What would you suggest for modification?

I think the decision points have to be shared and not done by one party in order to mitigate the danger of misinterpretation. A single individual would make the decision based on what he thinks only. So, you need others in the decision-making.

Effectiveness:

38. How would you assess the effectiveness of the overall process to integrate design and cost estimation via BIM?

I think it would lead to effective integration between designers and cost engineers. The main reason for effectiveness is because a good view is made from the beginning on what is important in the project for the designer and cost engineer. So, a lot of discussions can be held already in the beginning.

The End