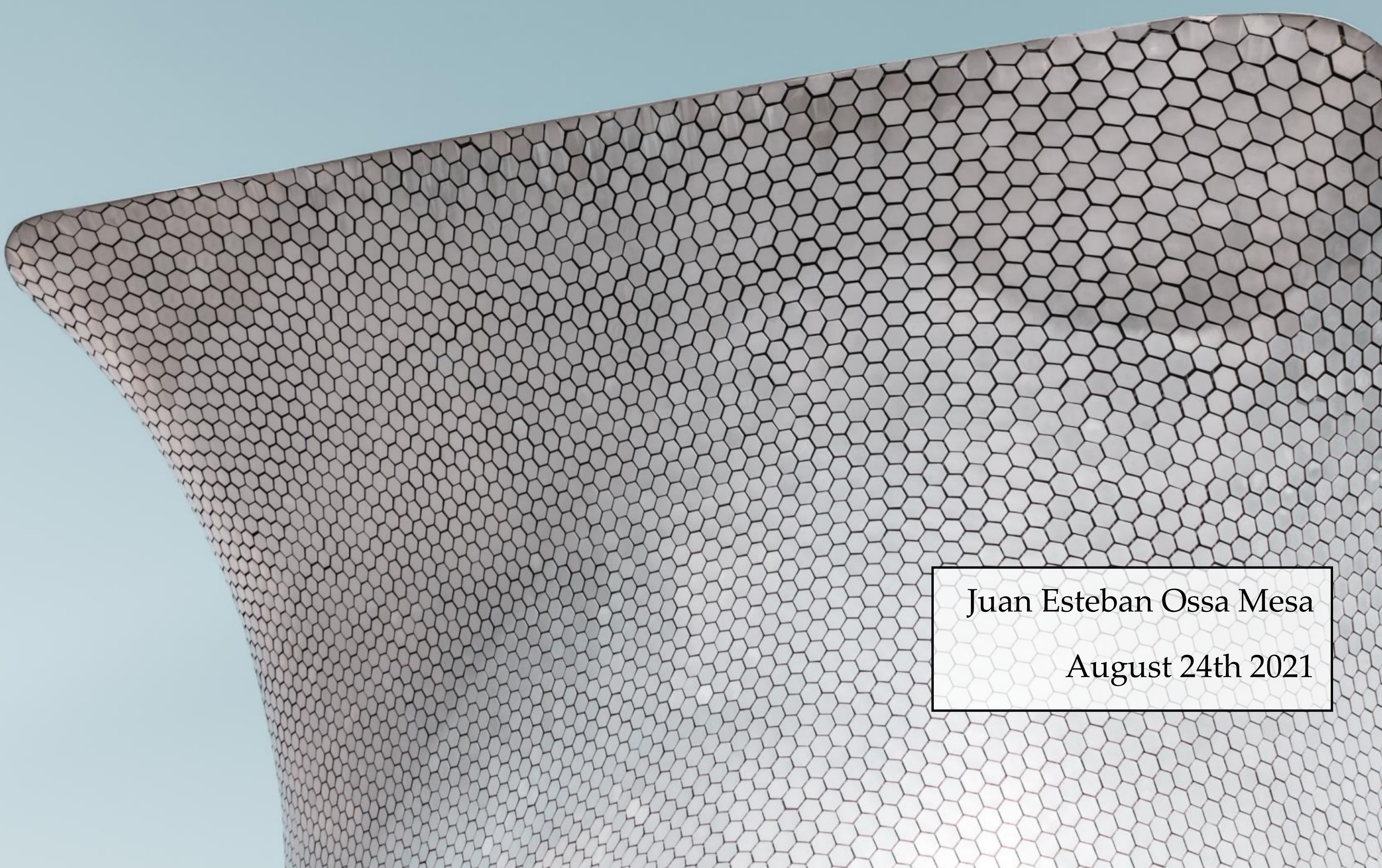
Master Thesis

Cost Estimation of Construction Projects Using 5D BIM:

Integrating the cost engineer in BIM-based processes through activity theory.



Juan Esteban Ossa Mesa

August 24th 2021

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Cost Estimation of Construction Projects Using 5D BIM:

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By

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Master of Science in Construction Management and Engineering

Delft University of Technology

August 24th 2021

Colophon

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Preface

Dear reader. Before you lies the graduation thesis titled "Cost Estimation of Construction Projects Using 5D BIM: Integrating the cost engineer in BIM-based processes through activity theory." The end result of a research undertaken as part of the requirements of the MSc Construction Management and Engineering and Delft University of Technology. This report is the result of six months of preparation, research work, and writing.

The research was carried out at Witteveen+Bos, under the BIM – Project Information Management group. The group has shown strong interests in the area of BIM implementation, and through their enthusiasm it was possible to design the research project, which aims at further pushing the boundaries of BIM, and keep developing it, in this case, by analysing and designing a better integration of the cost engineer in BIM-based project development, with aims towards reaching 5D BIM.

The research would not have been possible without the support of a number of persons, who I would like to take the time to thank. First of all, my university graduation committee. Chairman Hans Bakker, whose precise feedback helped focus the research into something meaningful, and who believed in my research subject. First supervisor Yan Liu, whose constant feedback was invaluable for the research development, especially when I was losing focus, and was doubtful. Your eagerness to help and guide others is a matter of inspiration and helped bring the research to a higher level. Second supervisor Bauke Steenhuisen, whose input from a management perspective helped me to critically analyse the research from a different viewpoint. From the company, I would like to thank Maarten Visser, for seeing potential in my research ideas and supporting the development of them, without you, this research would not have been possible. Beatriz Braga, whose constant help and feedback was invaluable to carry out the research at the company. On the same line, I would like to thank all the respondents from the company, and especially Erick Schulte and Ilja de Jong, whose support was invaluable for carrying out the research.

On a personal note, I would like to thank my family, mom, Gilma, dad, Alvaro, brother, Mateo, cousins, uncles and aunts for supporting me in my dream of carrying out a master's programme abroad to help me keep developing as an excellent professional. It would not have been possible without you. I would like to thank all my friends in the Netherlands for making this experience an unforgettable one, for being my family here, and overall, for motivating me to give my best. You all are the proof that good people bring out the best of anyone. Lastly, a mention to my friends from Colombia, who have never stopped supporting me, and are living proof that good friendships are undeterred by distance.

Delft, 04 August 2021

Executive Summary

Cost estimation is a process that is still being done following traditional practices, and is lagging behind the rest of the project development process. Currently, the cost engineer and the tasks they carry is detached from the work performed by other actors such as designers and modelers. One of the reasons for the detachment, is that projects are being increasingly developed through more innovative BIM-based processes, and leave the more traditional cost engineer on the margin. At the same time BIM and specifically 5D BIM offers a potential solution to integrate the cost engineers in projects, and to improve the cost estimation process. The end goal of the research is to develop a framework that allows integration of cost engineer in a BIM-based project development, in order to achieve at least a basic 5D BIM project development, and some benefits attached to it.

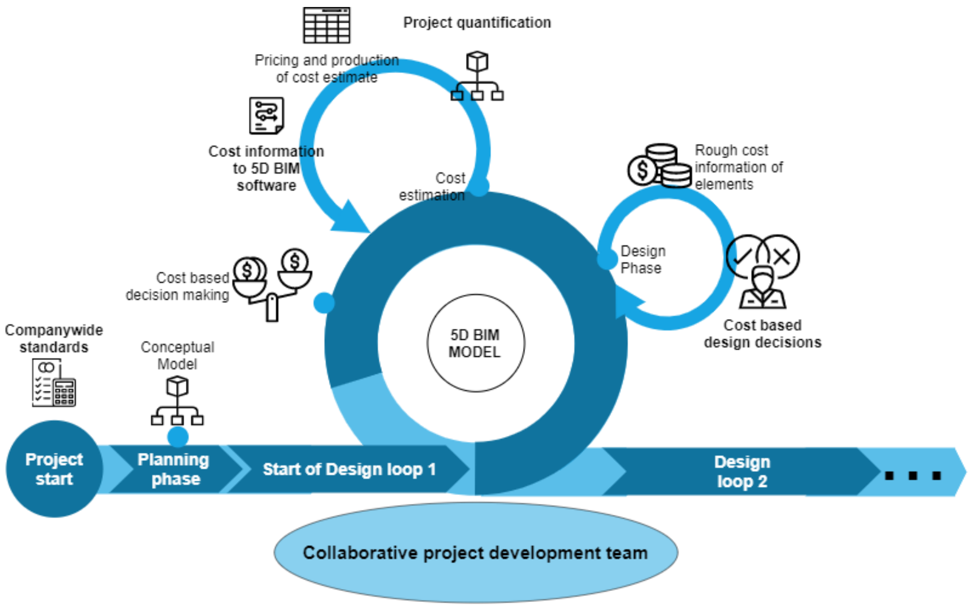
In order to develop the research, activity theory was used as an analysis framework to analyse the results obtained from literature and a case study, which in this case was the engineering consultancy company Witteveen+Bos. While activity theory is not new, it has not yet been widely used in this field, and it proposes an interesting holistic framework for the analysis and redesign of work. Through activity theory it was not only possible to make an analysis of cost estimation, but also of other identified associated processes, providing an innovative viewpoint at the topic of BIM implementation for specific users, such as cost engineers. Through the case study results it was identified that the activities associated with production of cost estimates are a) cost estimation itself, but also b) project development and management, and c) project design and modelling. It is proposed that to achieve integration of cost engineer in a BIM-based project development, adjustments must be made to all identified activities.

Activity theory was used to in the following manner. First, contradictions, which prevent reaching the object of an activity were identified. These fell in the categories of lack of integration of the cost engineer, lack of standards, lack of defined guidelines, and lack of use of technological instruments. Second, a discussion was carried out analysing the contractions in the group of activities identified. Third, with analysis and discussion in place, some recommendations were proposed. These are namely:

i. Acquisition, implementation, and specialized training of 5D BIM software.
ii. Well timed and more extensive integration of cost engineer and systems engineer in the project development process.
iii. Adoption of companywide standards and guidelines for conceptual model development and use, BIM modelling and use of models, and management of cost information.

Fourth, activity systems based on the recommendations and aimed at solving the contradictions were developed. From these. Some potential outcomes were identified such as earlier production of cost information, improved end product cost-benefit quality through cost-based design decisions and increased involvement of cost engineers in projects. Fourth, a framework for project

development based on 5D BIM elements was proposed as shown in the figure. The framework makes use of the current project management at the company and further enhances it, in order for the integration of the cost engineer in the project development process, and to allow to reach the identified outcomes. The framework uses BIM and 5D BIM as the main instrument of integration.



A major point to highlight from the research, is that by having a broader scope, and having a more holistic approach such as activity theory for the development of a research that focused on a specific issue, impacts in different areas were proposed. Among the main findings of the research are the ratification that cost engineers are indeed not well integrated in BIM based project development. It was also found that supporting or managerial roles such as project managers and systems engineers have a potential key role in the integration of cost engineers. Another important finding is that BIM models, and BIM software alone is currently inadequate for a complete development of cost estimates, non-graphical elements being the prime example of information that needs to be costed, but cannot be handled by BIM, and as such, requires the use of additional instruments. In this case, the use of conceptual models as a complement to BIM models is suggested.

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1. Introduction.

1.1. Introduction

BIM is far from being a new concept. The first notions of it were introduced by researchers as early as the 1970's (Eastman et al., 1974), and it has reached technical maturity in recent years (Borrmann, König, Koch, & Beetz, 2018). Although not a single universally accepted definition exists, BIM is not a specific software tool or piece of technology, nor a mere graphical representation of a physical built asset. A definition is given by the National Institute of Building Sciences (2015), in which the acronym BIM is expanded as *Building Information Modelling*, and *Building Information Model*, to represent both the process and the product of BIM. They state that "*Building Information Modelling is a business process for generating and leveraging building data to design, construct and operate the building during its lifecycle. BIM allows all stakeholders to have access to the same information at the same time through interoperability between technology platforms. … Building Information Model is the digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onwards.*" (National Institute of Building Sciences, 2015, p. 3). This definition shows how BIM has evolved into both a process and a product, which makes use of an ever-growing array of technological instruments to improve the way in which projects are developed (Ghaffarianhoseini et al., 2017). During the research, the definition as both a process and a product will be used.

One of the most important reasons for the use of BIM in the Architecture Engineering and Construction (AEC) industry is because of its potential benefits. Several studies have been carried out to establish the scope of these benefits, with promising results. Azhar (2011) carried case studies and gave evidence of the benefits of BIM in improving the predictability of project execution, and in turn, improvements in profitability, and cost and time management. These benefits however, are based on a narrow point of view of traditional project management, and nowadays more than ever, additional indicators are necessary to define the success of projects, such as improvements in the information systems, benefits to the organization, and benefits to the stakeholder community (Atkinson, 1999).

On the other hand, we have cost estimation. Cost estimation is a crucial step in the development of projects. Both overestimating and underestimating a project's costs can be catastrophic, potentially affecting all parties involved in the project development (Nicholas & Steyn, 2017). Cost estimations have been traditionally, and still are developed mostly by cost engineers, whose main function, as defined by the International Cost Engineering Council is "*to provide independent, objective, accurate, and reliable capital and operating cost assessments usable for investment funding and project control*" (International Cost Engineering Council, 2002). The work of cost engineers is therefore vital for the proper development of projects, and no project nowadays is developed without first establishing a proper estimate. Cost estimation is the process through which cost estimates are produced. For the remainder of this research, the term *"cost estimation"* will refer to the process and *"cost estimate"* will refer to the product.

The introduction of BIM has had some important effects on cost estimation. Arguably the most important one, is the possibility to automatically extract Quantity Take-Offs (QTO's), the basis of a cost estimate, from a BIM model, instead of manually extracting this information from visual 2D representations, as it is traditionally done. However, the relation between BIM and cost estimation is not limited to that single feature. In order to reap all potential benefits that BIM may have in a construction project, it is possible to look at the different "dimensions" of information included in BIM (Charef, Alaka, & Emmitt, 2018). One of such is the cost dimension, what is nowadays commonly, although not universally, known as 5D BIM. A 5D BIM model can be seen as one in which cost information is associated with model objects (Eastman, Teicholz, Sacks, & Lee, 2018). This allows the model to hold cost information of the elements composing it. Adding the dimension of cost and working with 5D BIM has some identified benefits such as improved visualization for engineer (as in construction details), easier project conceptualization (alternative analysis), more efficient QTO's, earlier risk identification, among others (Stanley & Thurnell, 2014).

At industry level there is currently a high degree of detachment of cost engineers in the BIM-based project development. The research is carried out looking at the heart of BIM-based project development, in the engineering consultancy company Witteveen+Bos. By working in the company, and using it as a case study, a practical and applicable solution will be designed to solve the problem. A process change approach has been hinted as a possible solution (Mayouf, Gerges, & Cox, 2019; Stanley & Thurnell, 2014). Thus, this research focuses on the development of a framework in which cost engineers are thoroughly incorporated in the development of projects based on BIM, analysed from a holistic perspective, and explores the potential impacts this integration may have in cost estimation and project development.

1.2. Problem definition

The construction industry is suffering from poor performance when compared to other industries such as manufacturing (Barbosa, Woetzel, & Mischke, 2017). Additionally, the AEC industry and its projects are becoming increasingly complex (Baccarini, 1996; Barbosa et al., 2017; Luo, He, Jaselskis, & Xie, 2017). The use of traditional project management methodologies in the development of complex projects is found to be lacklustre (Luo et al., 2017). It has been proposed that extensive use of digital technologies, and advanced automation is one of the crucial measures to improve the efficiency of the industry as a whole, and handle the increased complexity (Barbosa et al., 2017). With incrementing urgency, it is necessary to appeal to innovative practices that allow for better project development (Barbosa et al., 2017; Sohi, Hertogh, Bosch-Rekveldt, & Blom, 2016).

One of the most prominent technological innovations of the industry over the past decades is BIM (Azhar, 2011; Barbosa et al., 2017; Eastman et al., 2018). BIM has allowed a more thorough use of digital technologies in all phases of the development of projects in the AEC industry, but especially in front-end development (Borrmann et al., 2018). As projects are essentially composed of different types of information, and cost information is one of such types (Nicholas & Steyn, 2017), BIM has the potential to impact the cost estimation process of a project.

However, traditional processes are still broadly used in the industry, and cost estimation is an example of this. Traditionally, cost estimation processes are highly manual, prone to errors from human interpretation, and very time consuming(Eastman et al., 2018; Monteiro & Martins, 2013). Furthermore the processes follow a linear flow, and only begin after the design has reached a certain maturity, preventing key decision making early in the front end development of projects (Forgues, Iordanova, Valdivesio, & Staub-French, 2012). This late integration makes it that proposed design solutions that are too expensive are only identified in late design stages, and normally requires repetition of design loops, costing additional time and resources (Greves & Joumier, 2003).

BIM has been identified as having the potential to solve some of the problems of traditional cost estimation, and among its important identified benefits are more reliable early cost estimates, and faster and more accurate estimates through automatic QTO's (Eastman et al., 2018; Sunil, Pathirage, & Underwood, 2017). However, use of BIM and 5D BIM in the industry has not resulted in the integration of cost engineers in BIM-based project development. A study carried out in Australia by Aibinu & Venkatesh (2014), showed that 63% of the cost consultants involved in the research had never been involved in any BIM-based project, and when performing QTO's, only 20% of them were using BIM models for the task, with the vast majority, 94%, doing these based on 2D Drawings (Aibinu & Venkatesh, 2014). On a similar line, Mayouf, Gerges, & Cox (2019) state that cost engineers are often uninvolved in the BIM component of project development, highlighting collaboration as a major issue. Among the reasons for the poor adoption of 5D BIM by cost engineers, researchers cite resistance to change, uncertainty, lack of skills, and lack of understanding of the process and its workflow (Mayouf et al., 2019; Sunil et al., 2017).

While BIM has already been identified as bringing benefits for project development during the design phase (see section 2.3.1), its adoption is asymmetrical, and has not successfully integrated all relevant actors. Quite the opposite, literature shows that cost engineers are still following traditional processes and have not been integrated in BIM-based project development. Detachment of cost engineers from BIM-based project development, while perhaps not the single main problem of the industry, does present a major obstacle in the transition to more digital approaches. Since the transition to digital instruments has been identified as one of the key aspects to increase productivity, the problem is of considerable importance. Without full integration of main stakeholders in a common information environment, information is produced in isolated "islands" and it is not be possible to unlock the full potential of digital instruments.

1.3. Research questions

1.3.1. Main question

From the introduction and the problem statement, the following main question was synthetized.

How can integration of cost engineers in a 5D BIM-based process impact the constellation of activities associated with cost estimation of infrastructure projects?

1.3.2. Sub questions

To answer the main question, the following sub questions are derived from it, which form a logical sequence in which each of the answers, contributes to the complete answer.

1. What are the processes related to the production of cost estimates of infrastructure projects?
2. What is the role of BIM and 5D BIM in the context of cost estimation of an infrastructure project?
3. What potential impacts exist in the integration of cost engineers in a BIM process for infrastructure project development?
4. How can cost engineers be integrated in BIM-based processes to realize potential benefits in the development of an infrastructure project?

How these sub-questions are answered will be described in the following sections.

1.4. Research methodology and strategy.

The research approach to be used is based on a mixed research approach, more precisely, on an Exploratory Sequential Design (Creswell, 2009). The research approach is summarized in Figure 1. A mixed approach is selected due to the qualitative nature of the initial exploratory phase of the research, and the aim to gather quantitative feedback at the end of it. This method provides the ground for carrying out a research that builds sequentially upon each previous step to provide answers to every identified sub question, and ultimately, the main question.

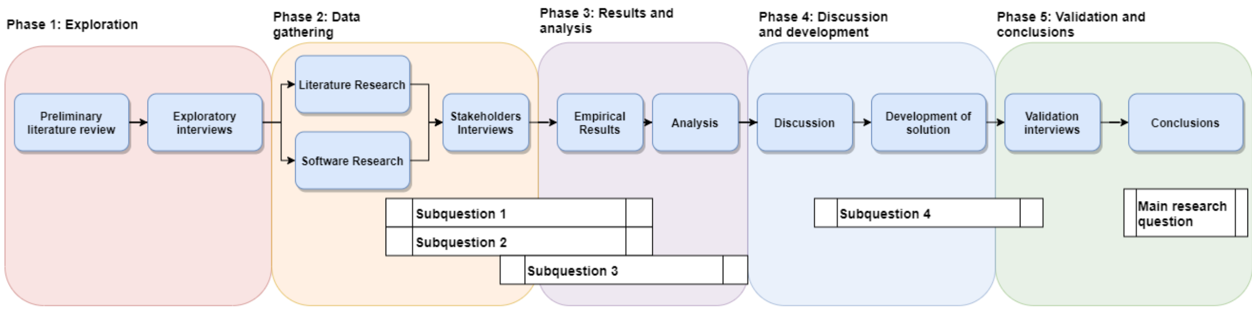

Figure 1: Research Methodology Scheme (based on Creswell (2009))

1.4.1. Scope

The scope of this research is the development of a feature that answers the main research question. For this specific research, it is expected that the feature is a novel framework for cost estimation, which is structurally supported by 5D BIM, fully integrates the cost engineers in the BIM environment, and offers advantages and improvements over traditional costing methods. The framework is to be non-restrictive and to set some basic guidelines for the integration of cost engineers in BIM-based project development. In general terms it is meant to be applicable to companies in the industry, using commercially available software and standards without being restricted to specific ones. The framework will be designed to solve the problems identified both in the literature, and the case study. At the end of the research the potential impacts of implementing the framework and the effects of integrating the cost engineer in BIM-based project development will be presented, discussed and validated.

The following subsections set the methodology through which the scope will be achieved.

1.4.2. Phase 1 exploration

The first phase is meant to explore the general themes surrounding the research, the company where the research is being carried out, and gives an initial context. This stage is split in two. The first one is a preliminary literature review, in which an initial problem is stated, from an academic perspective. The second subphase consists of exploratory interviews, which are carried out at the company. Exploratory interviews are useful in clarifying the frame of the study before actually carrying out the principal interviewing activity (Weiss, 1994). these interviews, were in the form of phone calls and informal meetings, and allowed to identify the processes and actors participating in the production of cost estimates, while also gaining some insights regarding the perceived problem.

1.4.3. Phase 2: Data gathering

The next phase is data gathering, and its mainly focused on learning about cost estimation and associated processes, and gain some insights on the role of BIM, which relates directly and gives a partial answer to sub question 1, and provides some basic ground to answering sub question 2.

This stage is split in two subphases. The first one, consists of two main activities: literature research and software research. Literature research is focused on the cost estimation process and usage of BIM from the academic perspective, but also some supporting definitions and concepts are explored, and a theoretical framework is introduced. The second part of this subphase is software research, which explores and analyses the capabilities of some of the most widely used 5D BIM software such as Bexel Manager, and iTWO CostX. It also covers grey literature produced by the developers of the software, specifically regarding documentation and capabilities of the instruments.

The second subphase consists of a case study carried out at the company. A case study is selected as it facilitates an in depth investigation of the particularities of processes within a real industry context (Fellows & Liu, 2015). From this case, the cost estimation process and its integration with BIM are analysed and documented. The cost estimation process is roughly mapped, identifying related processes that have an impact. The roles of the stakeholders, are documented, and key roles are identified for further development of a solution.

The case study data gathering is collected by means of semi-structured interviews with open-end questions, to stakeholders in roles close to the cost estimation and BIM modelling processes. The semi-structured interviews allow two-way communication between the interviewer and interviewee, allowing additional transfer of nonverbal meaning from the latter, to the former, in order to reduce the chance of introducing interpretation bias to the analysis by the researcher (Fellows & Liu, 2015).

At the end of the data gathering phase, it is expected to have collected sufficient information to move on to the third phase of the research.

1.4.4. Phase 3 Results and analysis

Results and analysis are the third phase. The first part consists of the presentation of empirical results from the data gathered. For the presentation of the results, elements from thematic analysis are used in order to analyse the data gathered in the interviews. Thematic analysis is meant to create themes that aggregate the information previously gathered. The themes and subthemes are *"essentially recurring motifs in the text that are then applied to the data."* (Bryman, 2012, p. 579). This is done by means of codifying data and clustering these codes into themes, a process which in this case, is carried out with the aid of computer software. In the end, the results are presented for each of the identified themes, and assigned to a specific research sub question which they aid in answering. At the end of the results section, complete answers are given to research sub questions 1 2 and 3, and provides basic concepts to answers sub question 4.

In the second part of this section, activity theory is used to carry out the analysis of the results. Activity theory allows the analysis of entire activity systems, basic units of analysis which allow to have a holistic perspective on cost estimation and associated processes. Section 2.6 contains a more detailed introduction to activity theory and how it will be used.

1.4.5. Phase 4: Discussion and development of solution

Activity theory is again used to perform the discussion of the results. In this subphase, a discussion based on the constellation of interconnected activity systems is carried out, connecting the literature and discussing recurring themes, which will be further used for the development of solutions. The use of activity theory for this discussion allows to use a boundary object in the analysis of independent but interconnected and interdependent activity systems that have a partially shared objective (Engeström & Sannino, 2020). In this case, the boundary object that connects all activities, as will be explained further, is BIM.

With a complete overview of the results and the discussion in place, the development of a solution can be started. This important phase of the research provides solutions to the previously identified problem statement. Activity theory is used again, this time as a collaborative process reworking tool. This is one of the main characteristics of the selected framework, and allows to derive solutions based on the previous analysis of activity systems. A major change made during the usage of activity theory during this research, is the development of solutions entirely by the researcher, which were then socialized with members of the case study for feedback and improvement. The solution is aimed at closing gaps and limitations in the integration between cost engineers and BIM project development. At the end of this phase, a complete answer is given to sub question 4.

1.4.6. Phase 5: Validation and conclusions

The final step in the proposed methodology is that of validation and conclusions. The proposed solution and expected outcomes are validated by interviewing expert practitioners. This step aims at determining whether the solutions are feasible and appropriate at answering and realising the main research question, from the practitioners' point of view, and to add required rigorousness to the research.

In the conclusions section, the main conclusions of the research are presented and some of the author's ideas regarding the research are shared, including the impacts that the research can have at both industry and academic level. Furthermore, a complete answer to the main research question is presented. Finally, limitations are identified and possible further developments proposed.

2. Theoretical framework

The objective of this chapter is to explore the concepts that will be used to carry out the analysis of results, the discussion, and further proposal of solutions. The research uses 5D BIM as an integrator concept. Important to note this is not an exhaustive review of the concepts that build up what 5D BIM is. The chapter follows the following structure.

Section 2.1 explores some important general organizational definitions and concepts that are thoroughly used during the research such as business process, and standardization. These support other important, more specific concepts. Section 2.2 follows with a brief overview of concepts related to project quantification and estimation, focusing on the ones that are more extensively used throughout the research, and which are key for the latter parts of the report. Section 2.3 focuses on digital transformation in the framework of the research, and presents an introduction to the concepts of BIM and 5D BIM. Section 2.4 aims to expand the previous section by presenting capabilities review on 5D BIM software. Section 2.5 presents the specific review of the literature related to integration of cost engineers in 5D BIM, the solutions presented so far, and some of the limitations. Finally, section 2.6 introduces the analysis framework to be used throughout the research: activity theory, which is a pillar for the analysis and development of solutions.

In the end, this chapter will provide an answer from a literature perspective to the sub question:

What are the processes related to the production of cost estimates of infrastructure projects?

And it will set the ground to the main concepts of BIM to start building an answer to the sub question:

What is the role of BIM and 5D BIM in the context of cost estimation of an infrastructure project?

2.1. General concepts and definitions.

2.1.1. Business Process

This research makes extensive use of the concept of "process", both to define the problem, and propose a solution, so it is important to define it. The definition by Weske (2019), is selected as one of the most detailed and adequate: *"a business process consists of a set of activities that are performed in coordination in an organizational and technical environment. These activities jointly realize a business goal. Each business process is enacted by a single organization, but it may interact with business processes performed by other organizations (Weske, 2019)"*. The initial part of the definition describes a process as a set of activities performed in coordination, meaning they follow a logic that has been deliberately worked. But additional to this, is performed in an environment, which is defined by the organization and technology. It can therefore be said that the organizational structure and the technological instruments that surround the process directly influence it. In the research's context, this means that the way in which cost engineers are integrated and interact within the organization and the use of BIM have an effect on the process. Following, it is said that processes should lead to achieving a business goal. This is noteworthy, as it allows to analyse how a process leads to achieving business goals, and sets the ground for measuring improvement (Bharosa, 2015). The definition by Weske is appropriate to be used for the remainder of the research, and it is compatible with the activity theory, which is introduced in section 2.6.

For the remainder of the development of this research, both Cost Estimation, and BIM-based project development are analysed as processes, following the definition by Weske. This is especially important in the case of BIM, as it will not be regarded as a standalone technology unless noted.

2.1.2. Standardization

Standards can be found everywhere in today's globalized world. They facilitate communication and trade between different actors by providing a base for mutual understanding (European Committee for Standardization, 2021). Standardization has been identified to improve productivity in industries such as manufacturing (Mor, Bhardwaj, Singh, & Sachdeva, 2019), and as having potential to bring improvements to the construction industry (Aapaoja & Haapasalo, 2014; Roy, Low, & Waller, 2005). Construction projects are traditionally defined as unique endeavours, that take place only once, and as such it is difficult to talk about standard projects (Nicholas & Steyn, 2017). However, standards are key elements of the construction industry, from construction codes to material standards, and allow the successful execution of projects by setting a common language to all parties involved in their development.

In the context of this research, standards will refer not only to technical documents (e.g., ISO or CEN standards), but have a broader sense; a standard can be any commonly accepted and widely used practice or way of doing something, which can be repeated to achieve similar results. Standardization can be found in some key areas of the development of a construction project, and in this specific research, standardization related to BIM and cost estimation will be central themes that will be explored as an enabler of improvement.

As BIM is based on both intra and interorganizational collaboration, a common language must be set in order to ensure that information is transferred seamlessly, as a requirement to achieve the benefits of BIM (Poljanšek, 2017). One way to achieve this is through the use of standards. Poljanšek (2017), states that standardization in BIM can be divided in three parts: Concepts, for all parties to speak the same language, common Data Models, so that parties and systems can exchange information freely and accurately, and finally Process Rules, to define the guidelines to be followed and the process of information exchange (Poljanšek, 2017). This is summarized in Figure 2. These elements of BIM standardization are in line with the elements of activity theory, and will be used to develop the proposed solutions. Finally, there is not a single international standard for BIM, so during the development of the research different standards from recognized bodies such as ISO, and the European CEN will be cited.

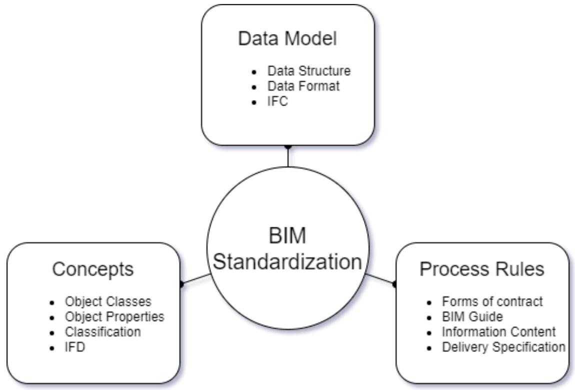

Figure 2: BIM Standardization platform (based on Poljanšek (2017))

2.1.3. Collaboration

Increased complexity of projects has highlighted the need for better project management approaches. Bosch-Rekveldt, Jongkind, Mooi, Bakker, and Verbraeck (2011) identified some sources of complexity of construction projects. Among them, number of stakeholders, dependencies between tasks, and interfaces between disciplines stand out, as they relate to how different parties or systems interact to deliver a common result. In parallel, new project development methods that consider the entire lifecycle of built assets, extensively make use collaboration (Shelbourn, Bouchlaghem, Anumba, & Carrillo, 2007). However, the construction industry has been characterised as a loosely coupled system. Projects are historically perceived to have a specific lifespan and relations between different projects are scarce, discouraging cooperation (Dubois & Gadde, 2002). Traditionally, relations in the industry have been described as highly "adversarial", limiting the possibilities for learning and knowledge sharing, and limiting the industry's performance improvement. (Bishop et al., 2009). More collaborative relations both at an industry and organizational level have been identified as having the potential to solve some of the problems caused by adversarial relations (Bishop et al., 2009; Shelbourn et al., 2007). There is a link between collaboration and project management, with project management success becoming more likely as the degree of collaboration increases (Bond-Barnard, Fletcher, & Steyn, 2018). Furthermore, different dimensions of collaboration (duration, intensity, depth and width) play a role in sustainable project management, and each of the dimensions affect in a positive manner different aspects of project development (Larsson & Larsson, 2020)

Along those lines, BIM itself is fundamentally based on collaboration in order to achieve its potential benefits (Borrmann et al., 2018). It can be said that BIM is a collaborative approach to project development. However, collaboration is not an immediate result of a more extensive use of Information and Communication Technology (ICT) instruments such as BIM, and an effort is required to attain it (Shelbourn et al., 2007). In other words, collaboration is achieved by actively stimulating it, not by only by the use of specific instruments.

2.1.4. Stakeholder Theory in Construction

Stakeholder theory was initially developed for strategic management, but has expanded to different fields, construction project management among them (Atkin & Skitmore, 2008). The main idea behind the stakeholder theory, as described by one of its earliest proponents, is that *"managers must formulate and implement processes which satisfy all and only those groups who have a stake in the business. The central task in this process is to manage and integrate the relationships and interests of [stakeholders]."* (Freeman & McVea, 2001). Furthermore, stakeholders are defined as *"any group or individual who is affected by or can affect the achievement of an organization's objectives"* (Freeman & McVea, 2001).

Construction projects are complex endeavours in which a wide array of parties with different backgrounds participate in order to deliver an asset. These numerous, multidisciplinary relations are in turn a source of complexity of projects (Baccarini, 1996). These parties can be considered as stakeholders, and per definition, stakeholders can be both internal and external. Internal stakeholders are those directly involved within an organization's decision making process, such as owners and employees, while external stakeholders are those who are affected by the organization's activities but are outside of the decision making sphere, such as the community, neighbours, and general public (Atkin & Skitmore, 2008). In cost estimation, a number of internal stakeholders participate in the process, and the research focuses mainly on interactions of internal stakeholders. Although (almost) all stakeholders within a company participate in project development with the common goal of achieving project success, they do not always have their individual objectives aligned to others, and as such, the concept of stakeholder theory can be beneficial to propose comprehensive solutions, that satisfy the needs of the different stakeholders.

2.1.5. Innovation

Although not a single definition exists, innovation is referred to as something positive, and Slaughter (1998) relates it to changes that bring improvement in products and services (Slaughter, 1998). Innovations allow companies to increase productivity, and remain relevant in a world that is in constant change. However, the construction industry has been identified as a slow adopter of innovation, and lags behind other industries such as manufacture (Barbosa et al., 2017; Dubois & Gadde, 2002; Seaden & Manseau, 2001).

In recent years, the concept of industry 4.0 has gained strength in the manufacture industry, as a means of further improving the field through digitization, automation and increased use of ICT (Alaloul, Liew, Zawawi, & Kennedy, 2020). Terms like construction 4.0 have already been used by some researchers, and there have been efforts in finding ways to adapt and implement those same concepts in the construction industry, in aiming to bring innovation to the field (Alaloul et al., 2020; Oesterreich & Teuteberg, 2016).

Innovation and the use of new technology is precisely one of the points that has been identified as key to reinvent the construction industry, which can potentially bring a major increase in productivity and reduce the performance gap that exists with other industries.(Barbosa et al., 2017). This is supported by additional research in which it has been identified that in the past decades, labour productivity in the construction industry has not only stopped growing, but is actually decreasing, while manufacturing industry has almost doubled in productivity indicators (Oesterreich & Teuteberg, 2016). BIM has been identified as one digital innovation that can lead the change towards an increased overall performance of the field.(Barbosa et al., 2017; Oesterreich & Teuteberg, 2016), and as such is selected as a central topic in the research.

2.2. Project quantification and estimation concepts

2.2.1. Project Breakdown Structures

A key concept in the management of projects is that of breakdown structures. Arguably, the most well-known, and widely used of these, is the work breakdown structure or WBS. As defined by the PMI on its PMBOK guide, *"the WBS is a hierarchical decomposition of the total scope of work to be carried out by the project team to accomplish the project objectives and create the required deliverables. Each descending level of the WBS represents an increasingly detailed definition of the project work."* (Project Management Institute, 2017, p. 157), and further states that its key benefit is to provide a framework of what has to be delivered. This benefit is true not only for WBS, but also for other forms of breakdown structures. Drawing from the definition given by the PMI, breakdown structures are hierarchical decompositions of work to be carried out. As such, there are other breakdown structures additional to the WBS, although they are not as well defined. In the Netherlands, where the case study company is located, official documents point at the use of systems breakdown structure, or SBS, which refer to the decompositions of systems in a project (Rijkswaterstaat, 2021). Another relevant breakdown structure is the cost breakdown structure, or CBS, which although not clearly defined in the literature, refers to the decomposition of costs of a project, and which may or may not share the same form with the WBS (Cerezo-Narváez, Pastor, Otero-Mateo, & Ballesteros-Pérez, 2020). For the remainder of the research, different breakdown structures will be referred to, and will be considered as independent structures from one another.

The most basic rule in the development of a WBS, but which also applies to other breakdown structures, is the 100% rule, which states that *"the next level decomposition of a WBS element (child level) must represent 100 percent of the work applicable to the next higher (parent) element"* (Haugan, 2001). In practical terms, this means that in a first level decomposition of a project, all major elements must be accounted for, and care must be taken not to leave any of the scope outside from the breakdown structures. This applies to all breakdown structures, and a comprehensive decomposition allows that all work is accounted for, to provide a proper framework to develop projects.

2.2.2. Cost Estimation of a Project

Cost estimation is a critical step in the development of any construction project. As construction (and with increasing importance operation and maintenance) costs may determine the feasibility of a project, there is a need for accurate cost estimates. Traditional cost estimation has been identified as inaccurate, subjective on estimators' own knowledge, lacking standardized guidelines and procedures, and ultimately not well suited to aid in decision making (Akintoye & Fitzgerald, 2000). This becomes more critical as projects increase in complexity, requiring innovative solutions by cost engineers to cope with increased risks and uncertainty, something traditional costing methods fail to do (Kujala, Brady, & Putila, 2014). Furthermore, traditional cost estimation is subordinate to the design process, and depends to an extent on the timeliness and quality of the design drawings to produce quality estimates (Elbeltagi, 2014). There is a delay between the delivery of designs as input to the estimation process, and the output of the cost estimate. This delay is usually lengthy as the manual estimation process is characterized as slow and inefficient (Forgues et al., 2012). This creates additional issues, and an example is that a project's costs can be influenced the most at earlier stages, and this influence decreases as it advances through the different phases, as shown in Figure 3. Because of this, traditional costing processes generally produce cost information when the ability to influence a project's cost has already been reduced.

Nowadays, increased use of BIM by designers has aided in the cost estimation process, by producing semi-automatic, relatively accurate, Quantity Take-Offs (QTO's), greatly reducing the time needed to quantify the line items and elements that compose a cost estimate. Nevertheless, Microsoft Excel is still being extensively used for cost estimation after QTO's are exported from the BIM model, preserving in part the traditional costing methods, and making limited use of the collaborative capabilities of BIM processes (Eastman et al., 2018). Furthermore, innovation efforts by professional cost engineering bodies have focused on adapting and standardising traditional processes, and have given limited attention to the use of innovative technologies. An example is the development and publication of the New Rules of Measurement (NRM) by the Royal Institution of Chartered Surveyors (RICS), which in its latest version (2012), doesn't fully realize the potential of new technologies, although it does hint at them (Royal Institution of Chartered Surveyors (RICS), 2012).

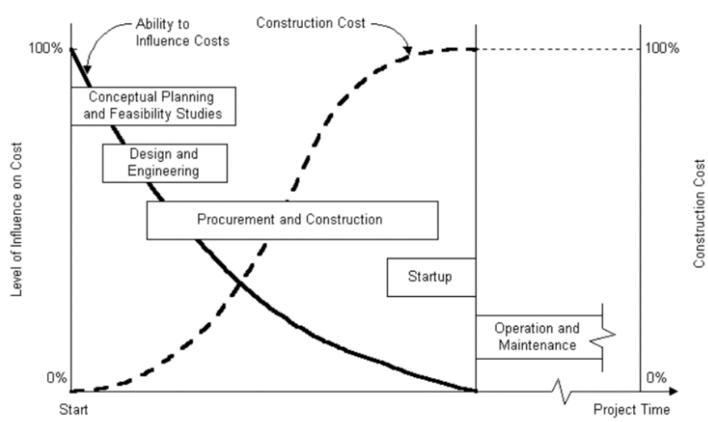

Figure 3: Ability to Influence Construction Cost Over Time (Hendrickson, Hendrickson, & Au, 1989)

2.2.3. Cost Estimate Classifications

Cost estimation happens throughout a project's lifecycle, and each estimate differs depending on the level of project definition (Nicholas & Steyn, 2017). While at conceptual stages cost estimates of a project are mostly "educated guesses", they tend to become more accurate and detailed as the level of definition of the project increases. The Association for the Advancement of Cost Engineering (AACE), has developed a matrix containing the classifications of cost estimates depending on the level of project definition, as seen in Figure 4. This matrix divides cost estimates in five different classes, each represented by a level of project definition, and related to its typical end usage, methodology, expected accuracy and preparation effort. Such a classification system allows cost engineers to select the most appropriate costing methods for each project development phase, allowing them to reach a level of detail of the estimates that is in line with the available information. Each level of cost estimates also sees an evolution of the elements that compose it. At the earliest conceptual stages of a project a parametric model with rough geometric figures may be the only information available to build the cost estimate upon. By the end of the development phase, the cost estimate may consist of hundreds or even thousands of line items, depending on the size and complexity of the project. Defining the cost classifications and their attached level of project definition can help set appropriate estimates for each phase.

	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 variation in low and high ranges	**PREPARATION EFFORT** Typical degree of effort relative to least cost index of 1
Class 5	0% to 2%	Concept Screening	Capacity Factored, Parametric Models, Judgment, or Analogy	L: -20% to -50% H: +30% to +100%	1
Class 4	1% to 15%	Study or Feasibility	Equipment Factored or Parametric Models	L: -15% to -30% H: +20% to +50%	2 to 4
Class 3	10% to 40%	Budget, Authorization, or Control	Semi-Detailed Unit Costs with Assembly Level Line Items	L: -10% to -20% H: +10% to +30%	3 to 10
Class 2	30% to 70%	Control or Bid/ Tender	Detailed Unit Cost with Forced Detailed Take-Off	L: -5% to -15% H: +5% to +20%	4 to 20
Class 1	50% to 100%	Check Estimate or Bid/Tender	Detailed Unit Cost with Detailed Take-Off	L: -3% to -10% H: +3% to +15%	5 to 100

Figure 4: Cost estimate classification matrix for the process industries. (Christensen et al., 2005)

2.2.4. Cost Classification Systems

From a project owner's point of view, the objective of elaborating a cost estimate is to know the project's costs. However, just as a project is built up from smaller elements that form a whole, cost estimates of a project are made up of smaller, simpler cost elements that add up to form the entirety of the costs (Nicholas & Steyn, 2017). This breakdown, however, can be done in numerous ways, depending on the person carrying out the task. Because of this, it is important to set basic rules for the way in which costs are divided and classified. As defined by the Oxford Quick Reference, cost classification is *"the process of grouping [cost] according to common characteristics"* (Oxford Reference). A cost classification system can be set by an individual, a company, or even a country. Several countries have their own Cost Engineering associations which can propose guidelines for Cost Classifications. In the Netherlands, one of such examples is the Standaardsystematiek voor Kostenramingen (SSK), which lays down a common language for classifying and presenting costs. On an international level, in an effort to provide a common global cost classification system, the International Construction Measurement Standards, or ICMS was created in 2015. ICMS *"are principles-based international standards that set out how to classify, define, measure, record, analyse, present and compare construction project life cycle costs in a structured and logical format."* (Royal Institution of Chartered Surveyors (RICS), 2020). It provides a system that allows for comparison of costs of construction projects at a regional, state, national or international level, by setting common rules for classification of costs of a project (See-Lian et al., 2019), and as per their guidelines, accounts for the management of cost information in BIM-based projects. Regardless of the specific system used by a cost engineer, the selection and use of one of such systems is an important step in cost estimation, especially in projects using BIM, as standardization of information is paramount for proper usage of it (Sunil et al., 2017).

2.2.5. Quantity Take-Offs (QTO)

Quantity Take-Offs (QTO) are one of the most important tasks in the cost estimation process of a project. The QTO is in essence, the amount of elements composing a building or a built asset (Monteiro & Martins, 2013), classified within the rulesets of a cost classification system (see 2.2.3). Through QTOs, it is possible to know the resources required to carry out a project. Traditionally, elaboration of QTOs has been a highly manual process involving the assessment of all construction elements on a 2D representation of an asset, and although the process is improved with the use of CAD software, it is still challenging and prone to errors (Mayouf et al., 2019; Monteiro & Martins, 2013). The emergence of BIM has substantially changed the way in which QTOs are done, and popular software such as Revit (Autodesk, 2021) and ArchiCAD (Graphisoft, 2021), have built in capabilities that allow for semi-automatic QTO production, greatly speeding up the process. However, these applications are not fully capable of producing automated QTO without human intervention, and parametrization and standardization is required to obtain accurate results (Monteiro & Martins, 2013). Additionally, for a higher level of customization of the QTO produced, and for an enhanced management and use of cost information, more specialized 5D software is required.

2.3. Digital Transformation

2.3.1. BIM

The definition of BIM to be used in the research was introduced in section 1.1. BIM is more than a change from a 2-dimensional to a 3-dimensional representation of a built asset. It is a complete paradigm shift in the way projects are developed. BIM places more emphasis and focuses efforts on the conceptual design stage of a project, as it is during this stage that the most impactful decisions of a project are made (Eastman et al., 2018). 3D visualization is one of the most acknowledged benefits of BIM, however, it is but one of them. Clash detection, increased team collaboration, improved data sharing, information control, scenario analysis, reduction in errors and reworks, and the possibility to implement changes in the models in real time, as opposed to traditional 2D design are some of the identified benefits (Azhar, 2011; Eastman et al., 2018; Ghaffarianhoseini et al., 2017).

The potential benefits have already been identified not only by academics, but also by countries, and some of these have lead country wide transitions to BIM processes. At European Union level, the importance of BIM has not gone unnoticed, and proof of this is the creation of the EU BIM task group, which in 2017 released the "Handbook for the Introduction of Building Information Modelling by the European Public Sector". The document aims to provide guidelines for the stakeholders in the public sector to incorporate a standardized EU wide BIM policy for the development of public works (EU BIM Task Group, 2017). However, BIM adoption is still not global, and even in the European Union, implementation amongst the different member states is highly asymmetrical, with some countries governments' having already mandated the use of BIM, such as the UK, Finland and The Netherlands, while some have not even planned a public adoption it, such as Belgium, Greece and Hungary (Charef, Emmitt, Alaka, & Fouchal, 2019). On top of it, there's not a single universally accepted measure of level of BIM implementation (Jung & Lee, 2016), and when talking about implementation levels, researchers and professionals will find themselves with high degrees of disparity in the industry.

2.3.2. 5D BIM

BIM has developed further from 3D modelling, and additional "dimensions", or "D's" have been introduced. As early as the 1990's, the "dimension" of time was studied and identified as a possible integration to the 3D models, to be able to visualize the execution of a project through its different phases, and was referred to as 4D BIM (Collier, 1994). Afterwards, came the introduction of 5D to refer to the cost dimension. The term 5D to refer to the costing element in projects was used by Popov, Juocevicius, Migilinskas, Ustinovichius, and Mikalauskas (2010), who provided a conceptual framework for the use of the different "dimensions" of BIM identified so far (3D space, time, and cost) to develop a construction project in a virtual environment. However, this was not the first time the potential inclusion of cost, or even the different n dimensions of BIM were mentioned. As early as in 2005, Aound, Lee, and Wu (2005) mentioned the possibility to expand the information included in the models, and brought up the term of "nD" modelling. It is possible to further expand the potential of BIM by including several additional "dimensions" to it, such as sustainability, accessibility, safety, energy, acoustics, among others (Charef et al., 2018).

Among the benefits of 5D BIM are more reliable early "rough" estimates, faster and more accurate detailed estimates, (Eastman et al., 2018), increased collaboration in the project team, increased project understanding, improved visualization of construction details, reduction of change orders

(Hasan & Rasheed, 2019), and enable key decision-making by means of enhanced interpretation of information (Lee, Tsong, & Khamidi, 2016). Furthermore, 5D BIM, integrated with 4D BIM, are nowadays being regarded as potential cost and schedule management tools during the lifecycle of projects (Lu, Lai, & Tse, 2018; Smith, 2016).

However, there are still limitations. Fully automatic cost estimation is not possible, and quantity take-off, one of the main advantages of 5D BIM at the moment, is just one of the steps in the process. BIM helps cost engineering practitioners in their tasks but does not replace them (Eastman et al., 2018). Furthermore there are also challenges in the implementation of 5D BIM in companies, such as specific technological skill requirements by experienced professionals, resistance to change, the relatively high costs of implementation, and the need for collaboration (Sattineni & Macdonald, 2014)

2.4. 5D BIM Software: review of main features.

The review is based on the features of Bexel Manager for cost estimation, but is not unique to it. From preliminary tests carried out in iTWO CostX, and supported by a 5D software review by Vigneault, Boton, Chong, and Cooper-Cooke (2019), it was found that most 5D capable BIM software shares similar functionalities, especially when focusing on the cost estimation process (Vigneault et al., 2019), and it is expected that most of these findings are applicable to similar software.

2.4.1. 5D BIM: Enhanced Quantity Take-off (QTO)

One of the strongest points of 5D BIM is the possibility to create semiautomatic Quantity Take-Offs. Non-specialized BIM software has basic QTO capabilities, that are further enhanced by 5D BIM software. One of the main differences is the existence of a dedicated QTO editor, which allows to create flexible breakdown structures to better adapt to each project's specific characteristics. These characteristics can be from physical aspects of the project such as type, size or number of systems, but also parameter information such as classification types or standards used in the BIM model. QTO's can be done for the entire project, or for specific parts of it. The divisions are free of choice, and range from specific families, phases, or elements, to visual selections of the virtual model. However, if the original model has a poorly parametrised breakdown of the objects and elements, and is not properly classified, the parametrization of the QTO must be done manually, a process that can become very labour intensive for larger projects.

To make the most of the capabilities of the program, it is possible to create QTO templates, which allow automatic generation of QTO's for any project, following a specified ruleset, based on the model's information in the parameters. It is therefore possible to create a companywide QTO template that allows to create QTOs without having to redo the entire classification of costs, greatly improving efficiency, as long as projects share a common breakdown of objects and families.

The QTOs can be exported to Microsoft Excel, with a varied number of options. Starting from a simple export of the line items in the QTO, it is possible to export the full breakdown, and even a graphic report in which each line item exported is accompanied by an image highlighting the location of the element being quantified in the model. This powerful instrument further enhances visualization, as will be further explained. Although exporting to Microsoft Excel is convenient because of its familiarity for cost engineers, it creates a static snapshot of information that is no longer linked to the model, which needs to be manually updated each time there is a change. An alternative, BIM based solution will be explored in section 2.4.4.

2.4.2. 5D BIM: Enhanced Model Breakdown

Already mentioned in the previous paragraph, specialized 5D Software allows for an enhanced breakdown of the model, when compared to modelling BIM software. The enhanced model breakdown allows to create semi-automatic divisions based on the model's elements, spatial structure, or systems. The creation of custom breakdowns is also possible, by using not only the basic standard parameters included in the BIM modelling software, but also custom parameters created by the user. This instrument benefits greatly from a Systems Engineering approach, as it allows a flexible management of the different breakdown structures of a project such as the previously mentioned WBS or OBS. With the appropriate parameters, it is possible to divide the project into phases, sections, levels, or even permanent or temporary works, providing the cost engineer with valuable additional information.

2.4.3. 5D BIM: Enhanced Visualization

5D BIM software has functionalities that allow visualizing relevant cost information in a model. One of the benefits is the possibility to add colour coding to the model depending on specific element properties. Through the selection of a specific colour scheme, Cost Engineers are given an aid to identify elements belonging to specific categories, from any of the basic or custom breakdowns as mentioned in paragraph 2.4.2. This allows to visually detect for example temporary elements, or elements which are hidden. Another possibility is the visual detection of elements which have not been yet included in a QTO, and diminishes the risk of having unquantified elements.

Although not limited to 5D BIM, visualization aids the cost engineers to properly assess and analyse the specific context, details and requirements of objects and elements. This additional information helps identify the objects which require complementary resources in order to be built (e.g., a double height poured concrete slab which requires additional scaffolding to support the formwork). It is also possible to visualize the different breakdown structures of the project, and analyse the breakdown at any decomposition level.

2.4.4. 5D BIM: Cost Databases

5D BIM software allows the use of cost databases to assign costs to QTO's and generate entire cost estimates. The databases can be internal, meaning that cost information can be added and stored directly in the software, or it can be imported from an Excel file[1]. This functionality allows Cost Engineers to work directly on the 5D BIM software, similarly to Excel, while pricing QTO's. Among the benefits of this is the possibility to omit the QTO export step, which breaks all existing dynamic links between the model and the QTO. By working directly in the software environment, it is possible to make use of BIM's parameter queries, to parametrize the cost calculation of different elements, and save the information for further iterations.

Another possibility is the use of cost information stored directly in the elements' parameters. If the model's elements contain cost information within their own parameters, it is possible to make use of these, and create cost structures entirely with this information. The process follows the extraction of the information by following a set of rules determined by the user, which can be done either manually, using the software's assistant, or parametrized. The result is a cost estimate that can be done in a very short time, and draws from the model's own information. Important to notice, this is only possible after first loading the cost information to all elements in a model, or to a library of objects, a process which can be resource intensive.

Semi-automatic cost estimation can be achieved with aid from cost databases that follow standard classifications such as Masterformat or Uniformat. If a cost engineer has cost information in a BIM supported format, which follows the classification of the model, it becomes easy to import the information to the 5D BIM software and automate cost allocation to each element. Once cost information has been included in the model, it is possible to use it in junction with other BIM capabilities, such as 4D BIM for the creation of schedules with cost information to obtain dynamic cash flows of a project. This powerful tool allows to make use of BIM and cost classification standards for the automation of some labour-intensive tasks of the cost estimation process

2.4.5. 5D BIM: Changes to the Model and Automatic Quantity recalculation.

One of the major benefits of 5D BIM software is the automatic recalculation of QTO's from updated versions of a model. If a model is properly parametrized, and there is a properly established QTO structure in the 5D BIM software, it is possible to semi-automatically recalculate the quantities from an updated version of the model. The procedure is fairly straightforward although not automatic, as it requires manually uploading the newer version of the model from the modelling software into the 5D BIM software. Quantities of already existing and parametrized elements are automatically updated, while new elements can be easily identified through the colour coding tool mentioned in paragraph 2.4.3, and included in the parametric QTO for further updates. If the cost information is already included in the 5D BIM model, it means that it is possible to have a truly integrated dynamic cost estimate of the project that is linked to the model and reflects the latest changes in (virtually) real time, and reduces the resources required for updating cost estimates.

[1] Bexel Manager is limited to importing cost databases from Microsoft Excel, though other 5D BIM solutions have extended support for additional file extensions.

2.4.6. 5D BIM: Limitations

Although 5D BIM software has a number of strong capabilities and potential benefits at the disposal of the user, it has also limitations that must not be overlooked. The first one is that for the benefits to be realized, it is necessary to have a high level of parametrization and standardization of the BIM models. Without this, much of the time saved by the automation of processes is lost by requiring the users to manually configure the parameters in the 5D BIM software. Proper element codification, following a pre-established ruleset that is known and used by the different people involved in the model development is a requirement.

Another limitation is that the program tested, and various others such as iTWO CostX, work with proprietary file formats, and to use models developed in other programs, a conversion to a "neutral" format is required, such as IFC, or the use of specialized file convertors. Although the use of neutral formats allows the transfer of information from different proprietary software (Laakso & Kiviniemi, 2012), the process is not without flaws and it can lead to loss of information, if the model is not carefully parametrized following IFC standards. Bexel manager has an add-in for Revit, which allows the export of Revit models into bx3 files, which is the proprietary file extension of Bexel. Through this add-in, it is possible to easily export models from Revit to Bexel, with no apparent information loss.

An important point to look into is related to the cost databases and the spreadsheet capabilities of the 5D BIM software. While certainly drawing from Microsoft Excel, which is still one of the most used tools of cost engineers, the capabilities of 5D BIM software are still far from being on par. Aside from lacking the full capabilities of Excel, the 5D BIM software is also less intuitive to use, as it uses a different approach to cost calculations, based on queries from the parameters of the models, instead of direct cell formulation.

In general terms, good practices of BIM are fundamental when working with 5D BIM. Without a proper set up, the use of 5D BIM software can quickly lose appeal, and it is possible that the benefits become outweighed by the drawbacks of using a less intuitive, more complex software, to a point in which a great amount of manual parametrization is necessary to produce even the simplest of results.

2.5. Integration of Cost Engineers in 5D BIM

In a 2012 study, Forgues et al. (2012), researched the limitations of traditional cost estimation methods, and made some initial propositions to overcome these by using 5D BIM in the process (Forgues et al., 2012). However, almost a decade later, contemporary studies are still identifying similar problems in cost estimation, and keep pointing at the potential benefits of using 5D BIM to improve it (Elghaish, Abrishami, Hosseini, & Abu-Samra, 2020; Matejka & Vitasek, 2018; Santos, Costa, & Ferreira, 2020).

Matejka and Vitasek (2018), describe ten different methods of estimating costs through a BIM-based process, with each method depending on the integration between cost databases and information models, pointing at a lack of a generally accepted method of cost estimation through BIM (Matejka & Vitasek, 2018). A research by Aibinu & Venkatesh (2014), showed 94% of the quantity take-offs done by cost practitioners were based on 2D Drawings and that participation of the actors in BIM-based projects was low, with 63% of the interviewees having never been integrated in the process (Aibinu & Venkatesh, 2014). These are surprising results, taking into account that costing in BIM is a concept that has been around for almost two decades, and hints at a low adoption rate of BIM and 5D BIM for cost estimation.

Change in the construction industry is usually met with heavy resistance and has been cited as one of the major challenges for the widespread adoption of BIM by several authors (Alaloul et al., 2020; Azhar, 2011; Ghaffarianhoseini et al., 2017; Hasan & Rasheed, 2019). Lack of collaboration is another major challenge in the implementation of 5D BIM on a company level, and highlights the importance of integrating stakeholders such as cost engineers (Santos et al., 2020; Stanley & Thurnell, 2014). Finally, in words of Matejka and Vitasek (2018), the topic of cost estimation using BIM, although contemporary, it is not new, and both companies and public institutions are still struggling with its full implementation.

A point of attention is that several of the forementioned studies focus mainly on the interaction of cost engineers with 5D BIM as a technology, and tend to isolate the definition of the problem to this interaction alone. Only some of the authors tackle the problem in an integrative manner, analysing not only the relation between the technology and the main subject, but including also the processes and environment. Even there so, there is a lack of a comprehensive analysis of the activity of cost estimation based on BIM processes, and thus the current research intends to close this existing knowledge gap, by utilising a holistic analysis method to examine the integration of cost engineers with BIM and 5D BIM based project development.

2.6. Analysis framework: Activity Theory

For the analysis of the results of the research, an analysis framework is required. For this end, activity theory is used as such a framework. The activity theory to be used, is based on the work by Engeström, who is the principal founder of what nowadays is known as the Finnish school of activity theory (Engestrom, 2000; Engeström & Sannino, 2020). This is a holistic theory that captures the dynamics of object-oriented "activity systems", focusing more on processes than outcomes (Robinson, Chan, & Lau, 2016). It rejects the *"isolated human as an adequate unit of analysis"*, and instead through the introduction of activity systems it *"encourages discussions by groups of stakeholders"*, making it *"useful in situations where it is necessary to explore diverse communities"*, as is the case with the current research (Lu, Chen, Lee, & Zhao, 2018, p. 319). Furthermore, activity theory has been used both as an analytical tool and as basis for proposing interventions or solutions (Floricel, Bonneau, Aubry, & Sergi, 2014), and this double use is precisely one of the main reasons for choosing it.

Activity systems, fundamental in activity theory, are composed of interrelated elements as depicted in Figure 5. (taken directly from Robinson et al. (2016)):

- **The subjects**: the individuals and groups directly engaged in the activities.
- **The instruments:** the artifacts that mediate social action in the activity system.
- **The object:** the purpose of the activity system.
- **The outcome**: the desired outcome of the activity; the materialization of the object.

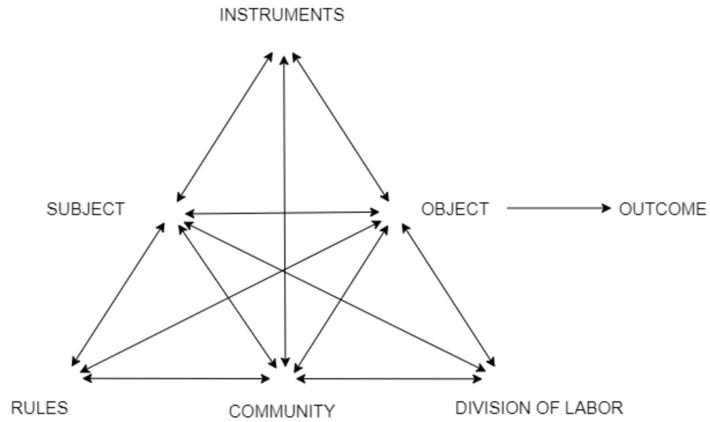

Figure 5: Basic Activity System model.

- **The division of labour**: the relational and hierarchical structure governing the subjects within the system.
- **The community**: all the individuals and groups involved in or affected by the activity system, including those not directly involved in executing the activity.
- **The rules**: the processes, procedures, and contractual, legal, or regulatory rules governing the activity system.

The theory has evolved throughout the years, and Engeström and Sannino (2020) mention four different generations of the theory. For this research focus will be put on the concepts of the second and third generations of it. These two have some differences, but have in common the use of activity system as an essential "building block" of the analysis. In the activity system, different elements are in constant tension, as depicted by Figure 5, which shows the basic model of the activity system. These tensions can lead to contradictions. Engeström (2015), proposes four different types of contradictions, although for the analysis, focus will be on the primary and secondary contradictions. Primary contradictions occur within each element of the activity system, while secondary contradictions appear between elements of the activity system. In the end, it is through the analysis of such contradictions that solutions are proposed in the Activity Theory.

In the second generation of activity theory, a single activity system is seen as a standalone unit of analysis, and the solutions are proposed through analysis of the internal contradictions between the different elements. The third generation of activity theory, goes a step further and combines multiple (two or more) activity systems which share a common outcome and/or environment as the basic unit of analysis, and besides analysing the internal contradictions within individual activity system, it also analyses lateral interactions across activity systems (Engeström & Sannino, 2020).

An important deviation from the activity theory is present in the research. For the development of solutions, Engeström proposes a cycle of expansive learning, a circular process that in his studies, relies heavily on the active participation of research subjects. The process includes not only the modeling of the solutions, but also implementation, reflection, and consolidation and generalization of new practices. Due to strict time constraints, for the research, the solutions will be developed only through analysis of the collected data and through a feedback session with an expert, and will later be validated with experts in the field. The implementation of the proposed solutions can be a topic for further research.

As a closing comment to the introduction to activity theory, it is also understood it is not perfect. For example, when compared to actor network theory, activity theory is not a strong conceptual framework for the analysis of interest and power of actors (Floricel et al., 2014). However, it is still deemed that due to its holistic approach, activity theory is suitable and interesting for the current research. Mentioned by Vakkayil (2010), the framework is useful to analyse project based case studies. Furthermore, the reduced number of articles using activity theory as a framework for data analysis in the realm of project management and BIM, makes it an exciting opportunity to both draw new and interesting conclusions, and support already existing ones.

2.7. Chapter summary

The chapter introduced a number of concepts that will be used throughout the report. Each concept is explored within the context of the research and sets the ground for the reader to become familiar with them. The concepts of business process, standardization, collaboration, stakeholders and innovation all come throughout the research, and are central to de analysis of results and the development of solutions. It is recommended for readers to read each definition carefully and become acquainted by it.

In regards to cost estimation, a basic definition of the activity was introduced, and of relevance is to note that it is currently undergoing a transition from traditional, to more technology-based, partly thanks to BIM. Some drawbacks from the traditional process are identified, such as being slow and highly manual, and not being suited for effective decision making. A and a number of supporting concepts was also introduced. These concepts are all used in the analysis of the results, but also in the proposal of solutions of the final chapters of the report. Project breakdown structures and QTO's are extensively used in the further sections of the research, while elements of cost estimate classifications and cost classification are also used, especially in the development of a solution.

BIM was described not only as a specific software tool, but as a process, an important distinction. 5D BIM was analysed and a brief recount of its history helps understand how it has developed and what are its capabilities. Some of its main capabilities were introduced, namely enhanced QTO's, enhanced model breakdown, enhanced visualisation, cost databases and changes to the model, all of which will be used in the development of recommendations and the proposed framework for integration. Additionally, some limitations were introduced such as not yet being able to produce fully automated cost estimates. In regards to the integration of cost engineers with 5D BIM processes, the literature shows lack of general adoption, and a call to develop additional research in said area.

Cost estimation, and project development through BIM are both considered processes in the frame of this research. As such, theoretical concepts of business process aid in defining them, an important point to be able to propose valid solutions. Furthermore, activity theory is introduced as the selected framework to be used for the analysis of results and development of solutions, and it can be seen that this framework is in line with the selected definition of business process, and can be said that cost estimation is an activity following the definition given by the activity theory.

3. Empirical Results

3.1. Introduction

This chapter presents the empirical results of the case study as gathered by the researcher. This research was carried out in the form of semi-structured interviews. The chapter is intended to offer a complementary industry perspective to the literature review presented in the previous chapter. The results from the interviews were classified in 11 main themes, which were all thought to answer in some way the research sub questions. The selected themes, in alphabetic order, are: Attitude Towards Change, BIM Usage, Connectedness, Digital Capabilities, Expectations, Perceived Problem, Process Relevance, Risks, Software Usage, Standardization, State of Affairs, and Views on BIM. Furthermore, the structure the chapter follows is set by the research questions.

A point of attention, is that one of the first findings from the respondents' answers, the specific process of project development, and specifically of cost estimation, varies depending on the project characteristics. The main quality used to describe the different types of projects is the size, namely, small, medium and large. Complexity was also stated by a respondent as one of the characteristics that define which processes are followed during a project's development. As a project's size is a source of complexity (Bosch-Rekveldt et al., 2011), it can be suggested that respondents refer to complexity, when talking about a project's size. Respondents were asked to focus their answers on the larger projects which follow the most comprehensive workflow, and embrace BIM more thoroughly.

3.2. Interview process

Five professional profiles were identified as relevant to get a complete overview of the associated processes leading to obtaining a cost estimate, and to get an insight on the use of BIM, and 5D BIM software instruments. These are: Cost Engineers, BIM Modellers, BIM Managers, Project Managers and Systems Engineers. Following the methodology stated in section 1.4 semi-structured interviews were carried out with a total of 17 participants from identified roles. To reduce the risk of bias, and to be able to contrast answers from the interviews, a minimum of two professionals from each of the identified profiles were interviewed. A code was assigned to each of the roles, and to each interviewee. Annex 1 presents the list of the interviewees with their roles the code representing them, the group and PMC (an acronym used for the specific market within the company) they belong to, their position, and finally the years they have been working at the company.

To choose the most appropriate interviewees for the research, it was decided to make a selection based on the projects they had participated in. These projects needed to comply with specific characteristics that fit within the boundaries of the research, and which were deemed to gather meaningful quantitative and qualitative information straight from the actual development of them.

Interviews were carried out through Microsoft Teams, due to the effect of the Covid-19 pandemic that took place during the development of this research, and made it impossible to carry out personal interviewing. All interviews were recorded with previous approval of each interviewee.

The data gathered from the interviews was processed in two ways. First, the interviews were transcribed with the aid of the software Otter.ai, which greatly sped up the transcription process. Second, the transcribed interviews were managed through the software Atlas.ti. In this software, all information was grouped, codified and later analysed in order to write this section. The codification process, although time consuming, proved to be an excellent tool to filter the main information, classify it, and allow to easily revisit it as required. It also made it possible to identify key quotes that aid to highlight important points.

3.3. Current situation for producing cost estimates.

The first part of the results related to what are the processes carried out within the organization associated to delivering a cost estimate, and how the people within interact in order to achieve this. Data collected from the interviews under the codes of State of Affairs, and Connectedness will be used. At the end of this section, the reader will have an answer to the question

What are the processes related to the production of cost estimates of infrastructure projects?

3.3.1. State of Affairs

The state of affairs shows a snapshot of how processes are being carried out currently at the company. This is not limited to cost estimation, but covers additional processes that precede, or impact it either directly or indirectly. The identified processes or tasks that influence cost estimation are: Systems Engineering, Project Development, Model Development, Quantity Take-off, Quantities Outside the Model, Pricing, and Cost Estimates Update, and will be explained in this section.

A main result shows that nowadays at the company, most designs for larger projects are done through BIM processes and software. For the remainder of the research, projects will be assumed as being developed this way.

The findings presented in numerals a) through g) are the most important highlights from each of the findings. Annex 3 presents the complete results of the category State of Affairs.

a) State of Affairs: Systems Engineering

Systems engineering principles are used in most project, but are used more in detail in larger projects.
For projects an object tree is created using the software relatics, and OBS, WBS, and SBS are commonly also created.
WBS and SBS can be used for development of BIM models, and have an impact in the form of QTO's
For all projects a unique coding system is created, based on Dutch standards.
There is not a standardized way to break down projects, and which breakdown structures to use.
Systems engineer is responsible for creating breakdown structures that are suitable for stakeholders such as BIM designer, cost engineer, and client.

There are efforts in integrating different areas through systems engineering but this has not been achieved yet.

b) State of Affairs: Project management

Projects are developed in (usually 3) design loops, which relate, but are not the same, as design stages.
During loops, disciplines work mostly individually, and at the end, are brought together in a single model.
In the middle of the design loops process is Relatics, i.e., the systems engineering approach to breaking down the work.
Cost engineers frequently come in at the last moment, after the individual specific designs are complete.
The company has designers, and not draftsmen. This allows to have a broader overview and look not only at individual models, but also how they interact with each other.
Projects are developed as entirely unique endeavors

"…unfortunately, often we come in too late, the design is ready, and some project manager asks, 'hey, what will this cost?' So that's not a cost optimized design" (CE01)

"With BIM in general as well, we encounter each project as special every time. We think, 'this project is totally different scope, we never did before'. And it's true. But there are also components we did before. It is also … about the breakdown what we use, and it's not standardized there as well. So, people do not recognize the objects that are the same." (PM02)

c) State of Affairs: Model development

As projects move in phases, cost engineers require more specific information from models for cost estimations.
In earlier stages, basic information such as an object's name can be enough for estimation, and as a project progresses, codification and subdivision of elements is required to quantify the project.
Level of detail of information delivered to the cost engineer at the end of a design loop can be inadequate.
Codification of objects is based on the breakdown structures, usually the SBS, with different levels of detail. However, there is no standardization in this step.
Object codification is automated through the use of Dynamo scripts
The company has project templates in which parameter fields are created for all objects to be used.
In model development BIM modeler works collaboratively with specialist engineers, but not with cost engineers.
Design decisions are not based on cost information.

"…there are so many different classifications already around. Yeah, which one do you choose? There's not really one that stands out." (MO03)

"…if everything goes correct, and everything goes fine the way that it should, I am able to make a design without the interference of the cost engineer entirely." (MO04)

d) State of Affairs: Quantity Take-Off

When a model reaches an appropriate development at the end of a loop, a QTO is generated by BIM modelers.
QTO's are extracted directly from the models, after interface validation and clash detection, to Excel.
QTO generation requires proper model parametrization.
BIM modelers often do not know what exactly is required to be delivered to the cost engineers, and it is necessary that the latter explicitly states it, creating tensions between the two actors.
The form and content of the QTO is not standardized.
Information given to the cost engineers is usually an Excel file, but can vastly vary in form, (2D drawings, models, or links to locations on Google Maps Street View).
Supporting documentation of the QTO can lack depth.
Quantities in QTO's generated by BIM instruments can be "not perfect", and not always complete.
Quantities in the QTO exclude non-graphical elements which are not modelled in BIM.

"We cannot make the quantity take-off ourselves, or we cannot show or export any information from the model, and that's something to work on." (CE02)

e) State of Affairs: Non-graphical elements.

Not all elements or requirements from a project are graphically modeled in BIM
These elements usually fall in two categories: temporary works, and complementary elements
Non-graphical elements have a considerable impact in cost estimates.
Not a standard, way of accounting for these elements, but commonly the responsibility of the cost engineers and project manager
Accounting for non-graphical elements is described by a project manager as "reactive and not very proactive"

"…it's up to us from experience or up to the project leader from his experience to insert other things that are not on the drawing. The temporary issues, items to help to put the project together, the things beneath the surface, or things in the surroundings of the project that have to be prepared." (CE02)

f) State of Affairs: Estimating costs.

Estimating costs is done by pricing the elements of a project, this is QTO, non-graphical elements, general cots, risk, profit, etc., and is the responsibility of the cost engineer.
The process is dependent on the stage of the design
Rough dimensions of elements are enough in earlier stages for rough cost estimates, but detailed QTO's become necessary for accurate estimates.
Cost engineer modifies Excel QTO's, to fit in an SSK template, and then adds cost to each line element.
Cost information can be added directly to each element based on own expertise, or specialized costing software Cleopatra is used to make detailed unit rates.
Especially at earlier stages, only cost driver elements are costed in detail.
Similar objects, or elements, for example a square meter of asphalt road, can have different costs, depending on the context and requirements of the element and the project.
There's no standard for transmitting additional project information to allow accurate costing, but usually cost engineers use 2D drawings and seldom 3D models.

Other roles hold high regards for cost engineers, citing their knowledge and autonomy as some of their strong points.
The costing process is not transparent for the rest of the stakeholders involved in a project.
Cost engineers almost always join at the end of project development to carry their cost estimation.

"…the level of detail of a calculation, its cost calculation, strongly depends on the stage of the design" (PM05)

"I've not had any BIM information for my projects. So basically, I've been getting my information the same way for the past 14 years" (CE03)

"…it's my perception of the cost estimators that [they] are very self-sufficient, capable team, so sort of give them a job, and then once they're done, they have done the job correctly, and you get the results that you want." (PM04)

"…it's more of an organizational thing, where the cost estimators are always only added at the last moment, and then have to do it on the spot instead of being involved in time." (PM03)

g) State of Affairs: Updates to the cost estimate.

Updates can occur either because of changes in the design, or progress through the phases.
At a minimum, there are updates at the end of each design loop
Updates usually are done by extracting a new QTO by the BIM modeler. However, updates usually modify not only quantities, but the form of the QTO itself
Some respondents mentioned that it is preferrable for the cost engineers to prepare an entirely new cost estimate with the updated information
If the model has been properly set up, extraction of an updated QTO is a (semi) automatic process.

"I prefer to start over … The reason I would like to start from scratch again, is because if there's a lot of changes, then I might miss one." (CE03)

3.3.2. Connectedness

The results from this cluster provide a general overview on how people and groups in the company are connected to one another. Important to note then, the results of this section rely more on tendencies, and do not mean to constitute a thorough snapshot of the relations between all stakeholders in the company.

The first finding that is worth mentioning, connectedness depends mostly on the project that is being carried out, but also, on the project leader, and how they wish to carry out the project. For the current research, and to have a link with the literature review, collaboration, or lack of, was an important theme to be identified from the relationships between stakeholders. As such the major sub themes within the major theme of connectedness were identified: collaboration, one way communication, and lack of communication.

The results are summarized below, and Annex 4 presents the complete results from the interviews.

Connectedness through collaboration
Generally seen during the design activity, especially between the 3D modelers, and the specialist engineers
Design decisions are made, ensuring that the output meets the technical requirements and expectations.
Project managers are involved in the design process in order to make decisions.
Collaboration at the end design loops to bring everything together.
Collaboration is cited as important for BIM, and BIM allows to work together between disciplines.
Review of cost estimates can be done collaboratively between cost engineers and project managers or BIM modelers.
"…the relation between the structural engineers and the designers [modelers], I think, it's kind of like a symbiotic relationship. That's what I would describe it, I think, we cannot have one without the other." MO04 *"… that is what I think, currently is BIM: working together in a digital environment."* CE01

Connectedness through one sided communication
Interaction between cost engineers, and 3D modelers or project managers, is predominately one sided, especially previous to preparing the estimates.
Cost engineers receive a package of information for the preparation of estimates, and once ready, deliver back their results.
The same applies generally for the update of cost estimates.
"A cost engineer, however, cannot have a cost estimate without our input. So, it's a more one-sided relationship in that case." (MO04)

Connectedness: lack of communication.
Cost engineers are seldomly are they integrated early in project development
Problems with transferring QTO information between BIM modellers and cost engineers.
"…the cost engineers are not really integrated in the team. So, they work in their own their own silo." (SE02) *"I think they [the 3D modelers] struggle in getting the information across. So, I think the cost estimator, always expects something else than what they're getting from, from the modelers. "*(PM04)

3.4. The role of BIM for cost estimation.

This section of the results focuses on the role that BIM has in the creation of cost estimates, focused mainly on the software and technology instruments aspect of it. The section starts with the results from the interviews from the category Software Usage, to have a broader overview of the use of technology in the processes related to cost estimation, and identify where BIM has not yet been implemented. The next category presented is Digital Competences, which focused on the proficiency level of the different roles when using various types of software, especially BIM. Following, the category of BIM Usage presents the current extent of the usage of BIM at the company, and the people using it. Finally, the category Views on BIM is presented, from the viewpoint of the already tried use of the technology. This will show what the users think of the use of BIM for their activities. By the end of the section, the reader will have an answer to the research question:

What is the role of BIM and 5D BIM in the context of cost estimation of an infrastructure project?

3.4.1. Software Usage

To present the information related to the usage of software, it was decided to create a table showing the list of all different software mentioned during the interview process as being used by one or more of the interviewees. The table contains, additionally to the software name, the uses given to it as explained during the interviews, and the level of use given by each of the identified roles. This data was extracted from interviews, and was validated by a person working at the company, who is close to the BIM management process. The results are presented in Table 1. Gray cells mean the software is not used by the role.

Table 1: Software usage at the case study company.

	Software	**Uses**	**Usage per role**				
			Project Manager	**Systems Engineer**	**BIM Modeler**	**BIM Manager**	**Cost Engineer**
BIM	Revit	Modelling Parametrization, Model Coordination, 2D Drawing extraction	Low		High	Medium	
	BIM 360	Model Coordination, Visualization, Clash Detection, Common data environment	Medium	Low	High	High	Low
	Forge (ANT)	Model Coordination, Visualization, Customization of Information	High	Low	Medium	High	
	Navisworks	Model Coordination, Model Review, Visualization, Quantity Take-off, Clash Detection, 4D BIM coordination	Low	Low	Medium	High	Low
	Relatics	Systems engineering, Project Breakdown, Parametrization	High	High	Medium	Medium	Low
	Dynamo	Revit automation, Scripting, Modelling, Parametrization			Medium	Medium	

	Software	Uses	Usage per role				
			Project Manager	Systems Engineer	BIM Modeler	BIM Manager	Cost Engineer
	Civil 3D	Modelling, Model Coordination			High	Medium	
	Synchro	4D BIM coordination				Low	
	Allplan	Modelling				Low	
	iTWO Cost X, Bexel Manager	N.A. (Not used)					
Non-BIM	AutoCAD Viewer	Visualization, Dimensioning					High
Non-BIM	Word	Report writing, Additional visual design information	Medium		Low		Medium
Non-BIM	Geographic Information Systems	Environmental assessments, Project context					Medium
Non-BIM	Excel	Quantity Take-off, Estimation of Costs, Parametrization, Report, writing, Fact sheet,	High	Medium	Low	Medium	High
Non-BIM	PDF	Quantity Take-off, Project context	Medium		Medium		Medium
Non-BIM	Power BI	Quantity Take-off				Low	
Non-BIM	Microsoft Teams	Coordination, Communication	High	Medium	Medium	Medium	Medium
Non-BIM	Google Maps Street view	Project context					High
Non-BIM	Microsoft access	Cost database					Medium
Non-BIM	MS Project	Scheduling					Low
Non-BIM Specialized for costing	Cleopatra	Detailed cost estimation					High
Non-BIM Specialized for costing	SSK	Estimation of costs, Detailed cost estimation,					High
Non-BIM Specialized for costing	Primavera	Scheduling, Risk analysis, Probabilistic simulations					Medium
Non-BIM Specialized for costing	KPD	Estimation of costs, Detailed cost estimation,					Low
Non-BIM Specialized for costing	GWW	Estimation of costs, Detailed cost estimation,					Low

Worth to highlight from these results, is the usage of software by cost engineers. The table shows that the usage of BIM software by cost engineers ranks lower than the other roles. The reason behind this is that, when asked about BIM software, the interviewed Cost Engineers barely mentioned the use of these instruments, or they used “weak” adjectives to refer to their usage. When asked about the software used for carrying out their daily activities, CE01 answered:

“…from time perspective from a week work, it's 90% Excel, 10% Cleopatra, a few percent for the other.” (CE01).

Additionally, as mentioned in the previous sections, cost engineers expressed their preference to use 2D CAD software to review design information to add context to the quantities received. From all interviewees, cost engineers were the only ones who mentioned to still use CAD tools. However, it is interesting to point out that aside from the usage of BIM instruments, cost engineers make use of a considerable number of specialized tools, although to a lesser extent than the main ones: Excel and Cleopatra.

3.4.2. Digital Competences

In general terms, there is not a single level of proficiency among the different stakeholders and between roles in the process. For example, while the competence in the use of BIM by modelers is high in general terms, for project managers, this is usually not the case. In general, there is limited knowledge regarding the full capabilities of BIM. This is recognized by some stakeholders as an issue, and regarding this matter, PM05 stated:

“…if you don't use Navisworks a lot, then it's quite hard to use it. Because all of the tooling that is in this tool. I should use it more.” (PM05)

Some roles, such as BIM managers and BIM modelers are leaders in the use of BIM and in the developing innovative uses, while others, lag behind on its adoption. A general observation, is that cost engineers have a lower level of BIM competences. Some quotes exemplify this.

“I imagine that maybe they [the cost engineers] may be a bit reluctant [to adopt BIM], perhaps because the technology's not so familiar to them.” (MO01)

“Since we have Navisworks, we can look into the models. Before that we actually had to ask the designers to get some snapshots from the models, to show what is in it. So, since we have Navisworks, [and] not all of us can work with Navisworks, that's an important thing, we can see more what is the design is… I think two months ago I had also an introduction course of Navisworks to use it ”(CE02)

3.4.3. BIM Usage

The results from this cluster, refer to how the BIM instruments are used, within the context of producing cost estimates. The results are presented in two main ways. First, Table 2 presents a list of the functions given to the BIM instruments, regardless of the users, and links are presented to the preparation of cost estimates. Second, the uses of BIM software by cost engineers are shown.

Table 2: BIM usage by function, regardless of user.

Function	Uses	Link to cost estimation
Modelling	Modelling in general, merging of individual models, and assigning information to objects.	Modelled objects contain information such as physical dimensions, which are quantified, and are the base for cost estimates.
Model coordination and/or validation:	Review of changes and adjustments, check of interfaces, model development, missing objects and elements, merging of individual designs, measurement of dimensions, clash detection.	For the costing of projects, it is important to check for interfaces, solve clash detections to avoid duplicates, that may interfere with the correct quantities.
Visualization	Visual checks of model, review of soundness and constructability, set project's context (general level, and per object), and presenting model to clients.	Analyse the specific characteristics of a project and the context in which the activities are to be developed to price them.
Model information management	Codification of objects and elements, inclusion of object physical properties and environmental information, requirements check, document design decisions.	Manage the project specifications for good costing. Codification and parametrization for QTO's. Add parameters to the elements to extract physical dimensions information.
Quantity Take-Off	(Semi) automatic extraction of quantities from a model based on the parameters of the objects (requires initial parametrization). Export of 3D element information.	Generate a list of quantities of the various objects and elements composing a project.
BIM automation	Object quantification (by scripted calculation of the dimensions), object parametrization and codification, revisions for errors in quantification and parametrization, others not relevant for cost estimation.	Additional method for quantifying. Automatic parametrization and codification to add information to object parameters for QTO set up.

- BIM usage by cost engineers.

Overall, the use is very limited for daily work. Two of the cost engineers mentioned that they have used BIM for visualization, to gather additional data to produce cost estimates. In words of CE02:

"For me, BIM is just a quantity take-off from BIM. And I can look into the model. That's the only thing as far we use BIM right now." (CE02)

CE01 expressed their enthusiasm for a project where BIM was used to automate design alternatives, and their will to explore other different uses of BIM in the field of cost estimation.

3.4.4. Views on BIM: tested

In addition to the current uses of BIM, it was desired to know the perceptions of the users regarding the technology, specifically for those cases in which it has been tested. The results were divided in three categories: positive, neutral, and negative views. Table 3 presents the results.

Table 3: Views on BIM: tested.

Positive and tested	Neutral and tested	Negative and tested
More structured costing process and less prone to mistakes	BIM QTO's requires manual work due to difficulties with correct inputs in model.	Responsibilities per role are shifted out of balance, too much reliance on BIM modelers.
Possibility to generate faster design alternatives.	Cost engineers are still not integrated in BIM.	Lack of common standard and language for element coding and naming.
Possibility of using BIM as a common data environment.	Lack of clarity of added value of 5D BIM, and sometimes, even for 4D BIM.	QTO's extracted from BIM models are not always exact.
3D and 4D visualization.	Use of BIM is still limited.	Not all elements can be modelled.
Data extraction from models, such as QTO's.		

"…when you see it for 20 years ago, or you see it now, yeah, I think [BIM] is the holy grail for cost estimation." (MA03)

3.5. Perceptions on integrating cost engineers in BIM-based processes.

A key element of the research, identifying the perceptions of the effects of integrating cost engineers in BIM-based processes, and was one of the main focuses of the interviewing process. The aim of this section is to present the results that answer the research question:

What potential impacts exist in the integration of cost engineers in a BIM process for infrastructure project development?

The structure adopted for the section is the following. First, the current perceived problems in relation to cost estimation and associated processes are presented. Following, the results from the perceived risks is shown. Next section presents the perceptions of the relevance of the cost estimation process for the different roles, and also identifies how the output, and throughput of the process affects other roles and processes. After this, the Views on BIM will be revisited, to present the perceptions on the potential uses of BIM. Finally, the section closes with the results from the "Expectations" category, which clusters the responses of what they perceive is expected from cost estimation and associated processes. This last chapter is focused but not limited to the expectations from integrating cost engineers in BIM-based processes, and the increased use of BIM.

3.5.1. Perceived Problem

When asked, interviewees had a wide variety of answers of what they considered were the problems encountered in the current process of cost estimation and associated processes. The results were grouped by themes, and are presented roughly by perceived relevance.

a) Lack of involvement of the cost engineer in the project development process.

Main identified problem by almost all respondents.
Limited input from the cost estimators during project development makes it that pproject and design decision making is carried without cost information.

Cost estimators are integrated at the end of each of the design phases, making it difficult to make changes based on cost.
Cost estimates are produced with limited time and knowledge of the project, potentially affecting their quality.

"… cost engineers are not really integrated in the team. So, they work in their own silo … when I make a design decision, it's only roughly cost based. It doesn't really involve any input from the cost engineer … cost figures come too late, and you can't really change the design anymore." (SE02)

"… for us as the estimators, and I don't know how to say, it's going too fast. You're not getting involved with a project, you have no feeling with the project, you miss [important information]. And I think sometimes it is also affecting the quality of the estimate." (CE02)

b) Inappropriate information.

Information taking an incorrect form (e.g., Conversion from Navisworks to Excel)
Information transfer and loss of information (e.g., Sending information by email, losing traceability)
Static information (e.g., Excel QTO's not updating with model updates)
Mismatching detail levels of information (e.g., detailed models in early design)
QTO's having limited information (e.g., QTO's not including non-graphical elements information)
Inability to determine the value of information (e.g., focusing too much on less-important information)

"But the downside is that we generate so much data or information, that establishing the actual value of that information, and the correctness and the usefulness for the cost estimate is actually maybe taking more time than it would actually save time in making it easier" (PM04)

c) Lack of standardization

Identified in almost every process associated to cost estimation.
Heterogeneous outputs of processes that are the input for subsequent processes makes it necessary to invest resources in modifying the outputs, and leads to information problems.
Non-standardized project breakdowns determine how projects are developed, and have an impact in the form of the QTO used by cost engineers reducing their usability.

"I think one of the biggest problems within the company is the lack of a standardized structure. We have over 1300 employees, and maybe hundreds of them think about their own structure and reinventing the wheel… we've seen hundreds of different ways of working, and ways of engineering projects." (CE01)

" Sometimes you notice…that the people for planning are using slightly different [breakdown structures] then you get a problem on all kinds of levels because everybody's talking about something slightly different. And that's something you don't want." (MO03)

d) Asymmetrical adoption of technological instruments.

Use and lack of use, of BIM by the different actors, especially by cost engineers to produce cost estimates, creating gaps between roles.
Discontinuity in the search for efficiency through the use of new technologies

"… I'm just a little bit sometimes too far ahead for the rest of the company. So, I can discuss it with those guys [the cost engineers], but then I get the classical issues about that those guys are not really

developing that fast or get innovative … It's a classical process [production of cost estimates], based on classic technology. That's, I think, the biggest problem." (MA02)

"If some parties don't want to [use] design 3d, then you have a missing link. And then you must guess it on the old way, old school way, what you did 20 or 30 years ago by hand" (MA03)

e) Inadequate communication.

One sided and reactive communication with cost engineers results in reprocesses and loss of efficiency.

"And sometimes I get a list and I'm like, this is not really thought about, or it doesn't make sense, the way you've put this, so then, I talk to the designer and tell what I would have expected … I kept running into the problem that these Junior designers were sending me stuff that wasn't really useful." (CE03)

3.5.2. Risks

Similar to the perceived problem, there is not a single unique answer to what perceived risks are in the process of producing a proper cost estimate. Answers fall under two major categories: risk of working with incomplete or incorrect information, and risk of miscommunication. Additional to these, two extra risks were mentioned just by a few or a single respondent, but were deemed impactful enough to include in the results, these are unclear responsibilities, and failure to identify added value.

a) Risk of working with incomplete or incorrect information.

The latent risk is that any party, but more specifically the cost engineer, will deliver results of inferior quality if he is working with incomplete or incorrect information.

"[The biggest risks are] Old information, wrong information, wrong versioning, not the latest, not incorporating the latest stages, and also, a loss of information. So, let's say for example, sometimes there's a structural designer calculating amount of concrete. And then later on, because we have new insights that will change, … we forgot to communicate that to cost designers. So yes, let's say 50 kilograms in his reinforcement, and we calculated it should be 150. That makes a huge difference" (MA02)

b) Risk of miscommunication.

The risk is that information is not correctly transferred between two or more parties can harm the quality of the cost estimate.

"Because it's information in many different forms, but information flowing from one to the other and back and needs to be checked" (PM03)

c) Risk of unclear responsibilities.

The risk is that while working with BIM division of responsibility becomes less clear, and loss of quality of a cost estimate can be affected, without clear traces of where errors happened.

"…when you have a quantity of thousands, you have a certain unit rate. And when the designer changes that design and becomes a quantity of ten, the unit rate [may], maybe triple. The software doesn't know,

the designer doesn't know, maybe the cost engineer, maybe he knows [that the unit rate may triple]. So, who's responsible for what? … So that's a question, I also think. How are we responsible for the costs in a BIM model?" (CE01)

d) Risk of failing to identify the added value of a task or process.

4D, and 5D BIM, have the risk of requiring additional investment of resources in a process without getting a proportionate return for the investment, netting in a loss.

"Making a 4D movie planning is lovely, it always looks beautiful. And you can really get a lot of out of it. But has it been asked to do? Or do we say 'no, we always do it because we see so many bonuses to it, because when using the 4D phasing movie, we see a lot of things getting out of it?' ... And that's mainly also a lesson that we learned from clients. 'Oh, yeah. yeah. Nice that you did it. But I didn't ask for that'. So, they don't pay for it. It's always a balance." (MO03)

3.5.3. Cost Estimation Relevance

An interesting question in the research, interviewees were asked to answer what they perceived was the most relevant of cost estimation. The question was deliberately open, to inquire whether the perceived importance lies in the process itself or in the final outcome.

a) Decision making by the client.

Possibility to aid in decision making, by the client. The importance lies in the final figure, and also in the intermediate cost estimates to make decisions during the development.

"…[Cost estimation] is very important when making choices. And most of choices are cost driven." (PM01)

b) Increased cost-benefit of the end product.

Increase the quality of the product to be delivered, by allowing to make optimal design decisions based on cost information.

"…the client has the benefit of a well-chosen design, and the well-chosen design is not only good quality of the design itself, but also a balanced design based on a good cost." (PM05)

c) Risk quantification.

Cost estimation allows to quantify risks of a project and translate them in monetary terms.

3.5.4. Views on BIM: Potential of the integration of cost engineer.

Paragraph 3.4.4 presented the results from the tested views on BIM. In this paragraph, focus will be on the potential uses of BIM. Again, these are divided in positive, neutral, and negative.

a) Positive and potential:

There was an overwhelming majority of answers regarding the potential positive uses of BIM and 5D BIM in the frame of the research, related to cost estimation. Table 4 presents the results.

Table 4: Perceived potential benefits of BIM.

Benefits for cost estimation	Benefits for project design	Benefits for project development
Faster, automatized or even real-time cost estimate updates through 5D BIM.	Increased and enhanced cost-based design decisions.	Increased standardization in project structure.
(Virtually) instant quantity take-offs	Possibility to achieve a real generative design with the integration of 5D BIM.	Increased integration of actors.
Generation of cash flows through 5D BIM	Automation through full digitization.	Reduction of human errors.
Live links between model quantity information and costing software.		
Increased project understanding for cost engineers (through visualization, specific requirements analysis, etc.).		
Earlier, almost zero-hour rough estimates through 5D BIM		
Increased influence on project's cost outcome by earlier estimates.		

"…the 5D I think if you put also the cost items, or some cost information within, it will be easier for the design, for the for the designers, to see the impact of their changes. It would be much better, the process will be much faster, or a higher quality to see them." (CE02)

b) Neutral and potential:

Two responses lie in this category:

- Increased difficulties in implementation of 5D BIM
- Uncertainty in the added value of the use of BIM and 5D BIM

c) negative and potential:

A single response fits in this category.

- A potential negative impact of 5D BIM is the increased workload, and heavy reliance on existing modelers for the implementation.

"For the designers, and the people who work with the models. Perhaps, sometimes it might be a little bit too much workload, I suppose, because the project relies so much on this type of information, and the work gets outsourced to the modelers." (MO04)

3.5.5. Expectations

The results under this subsection are interesting the way they include not only expectations from a number of categories, but also provides inspiration for potential benefits to be achieved through integration of cost engineers in BIM-based project development. Four sub-categories were created, namely cost estimation, model development, project management, and systems engineering. Each category relates to one of the processes that is associated to the production of cost estimates of a project. The results are presented in the form of tables, with the first column, "Expectations" stating the synthetized responses of the interviewees, and the second column, "Why", gives some context as to why it is considered important, extrapolated from the respondents' answers.

a) Expectations: Cost estimation

Expectations	Why
Earlier production of cost information (e.g., cost estimates, identifying cost drivers, etc.)	Allow to make meaningful project decisions earlier in the project.
Unit rates and costs including all factors that influence them (e.g., constructability, project's context, context of the activity in the project, etc.)	Increase cost accuracy by having an increased understanding of the activities being costed.
Traceable and accurate quantities and unit rates	Allow the process of tracking back the steps to understand the reason behind a cost.
Effortless intermediate cost estimates updating or dynamic cost estimates.	Possibility to have cost estimates information at shorter intervals.
Clearer and more standardized cost structures (e.g., such as those based on International Construction Measurement Standards (ICMS))	Allow to use BIM more efficiently by creating standard cost structures, and allows for benchmarking between projects and allow other actors in the process to better understand cost estimates.

b) Expectations: Model Development

Expectations	Why
Increased input and collaboration with cost engineers from the beginning of the modelling phase	Obtain cost information input early on to make design decisions at the early stages of a project, and create cost-optimised designs.
Improved review for specific object and element requirements, including project context.	Improve the output for cost estimators to establish costs based on realistic project scenarios and requirements
Common structured guideline for modelling process. (Codification, parameter input, modelling of objects etc)	Allow the standardization of codification steps of the modelling process and aid in the creation of standardized, automatic QTO's.
Integrated and open model information access throughout the company for a shared project view.	Allow the different actors to have simultaneous access to a single source of information.
Increasingly appropriate QTOs	Reduction of time waste due to incorrect or incomplete QTO's, or with inappropriate levels of detail.

c) Expectations: Project Management

Expectations	Why
Earlier and increased involvement of cost engineers in the development of projects	Allow impactful cost-based design decision making through the early input of cost engineers in the project.
Increased collaboration and communication between actors, especially with cost engineers.	Allow actors, especially cost engineers, to get additional contextual information of a project by receiving direct input from the people carrying specific tasks and vice versa.
Increased value generation for internal and external stakeholders	Increase the quality of the final product delivered by the company.
Adequate distribution of responsibilities.	Distribute responsibilities in such a way that no party is unduly held accountant for something they should not. Especially important in the context of BIM.

d) Expectations: Systems Engineering.

Expectations	Why
Systems engineering as a framework for organized project development and integration of all disciplines.	Allow to have a framework that provides a common ground and facilitates the development of projects.
Earliest moment involvement of the systems engineer in the project	Allows establishing the most adequate project breakdowns for projects from the beginning of these.
Production of comprehensive standard breakdown structures upon which projects are developed from the earliest stages	Allows to develop models that follow pre-established breakdowns, ultimately enhancing the production of automatic QTO's from the model.
Government intervention in the creation of national standards for object classifications	Creation of a county wide standard to allow information sharing and facilitate communications within and between companies (with clients, contractors, etc.).

3.6. Integration of cost engineers in BIM processes.

The last section of the results, this part wants to initiate the discussion that will later lead to answering the research question:

How can cost engineers be integrated in BIM-based processes to realize potential benefits in the development of an infrastructure project?

This question cannot be directly answered by the results from the interviews, and requires further discussion. The full answer of this question is given in section 5.3.2. However, two of the categories from the empirical results fit to provide an introduction prior to the actual discussion. These are standardization at the company and attitude towards change. Results under the first category, present a snapshot of the level of standardization present in the different sub processes related to cost estimation. The second one, presents the perceived attitude of interviewees in regards to adopting change.

3.6.1. Standardization at the company.

The first and most evident conclusion with regards to standardization, is that there is not a single clearly defined use of standards. Some respondents stated that standards are used in their specific activities, while some mention they do not at all and it depends on the project, and the person carrying out the tasks. There is in general terms, awareness of the existence of national and international standards, however, the general feeling is that on a national (Dutch) level, the standards are lacking. Standards, are still sporadically used and there's not a clear guideline to use them. Several respondents stated that they develop their own standardized way of working based on best practices from previous projects. Lastly, two respondents mentioned the importance of making more extensive use of standards. In more specific terms, the use of standards varies per discipline.

"With BIM in general as well, we encounter each project as special every time. We think, 'this project is totally different scope, we never did before'. And it's true. But there are also components we did before. It is also … about the breakdown what we use, and it's not standardized there as well. So, people do not recognize the objects that are the same." (PM02)

a) In systems engineering

It was mentioned that for asset management, another task developed by systems engineers at the company, there are good standards in use, and the NEN 4767, is a Dutch one which sets the rules for breaking down assets for asset owners. However, when asked about standards to develop breakdown structures of projects, respondents stated that the process is non-standardized, and the results are always different, depending on the person doing the breakdown.

b) In model development:

The development of BIM models uses standards such as the NLRS, OTL Rijkswaterstaat, and ILS. These standards are used to properly create and parametrize objects and elements, following a predetermined set of rules but the use of each depends on each modeler. It was also mentioned that there is a standardized workflow in use in BIM, and it is stated that this allows automation of certain steps. However, there are none standards for QTO generation, and usually the form taken by this is determined by either the modeler or the cost engineer.

> *"…on each project is it's like we discuss a standard. So, it's like we set up for each project, we set a unique coding system. And that's because we're working for a lot of different parties."* (MA02)

c) In cost engineering.

In cost engineering, the way of presenting costs is fairly standardized. It follows the SSK, and the RAW (Rationalisatie en Automatisering in de Grond-, Water- en Wegenbouw, roughly translated as Rationalization and Automation in Earth, Water and Road Construction) standards. Presenting the cost estimate follows then a standard form, but the way in which the breakdown of the project is done, is not. Additionally, these standards are not optimised to be integrated with BIM.

d) Role of clients.

Clients play a major role in defining the form that a breakdown, project modelling and cost estimate will take. Major governmental clients, such as the Dutch Rijkswaterstaat have their own standards, and state them in their own contracts. However, although these are very large clients, the standards are not always nationwide, and not all clients follow them.

3.6.2. Attitude Towards Change.

The results in this section were extrapolated from the respondents' answers, to assess their willingness to adopt new methods, instruments or processes. Attitude towards change can be positive, neutral and negative. Answers focus on cost engineers and a more extensive use of BIM.

In general terms, the company has a positive attitude towards change, with the majority of answers in this code category being positive statements about implementing changes.

> *"Now, I'm more than happy to start working in another tool. … So, we're not there yet, very close. But let's start BIMing."* (CE01)

However, when asked about the possible more extensive use of BIM, CE02 answered with a neutral stance, stating that they themselves are using BIM, but apparently not seeing enough benefits to it, and suggesting that a change is not necessary:

"In my situation, I work most of the time in the [PROJECT'S NAME], it's done in models. I hope the rest of the team is still working with drawings, because it's easier to understand the project in a drawing." (CE02)

Finally, there was a statement by CE03 which leans more to a negative side of attitude towards change, not showing much interest in making the change:

"it's not that I'm opposed to change. But what I'm doing now works. So that makes it harder to start with something else." (CE03)

As an important closing note, the attitude towards change of the different respondents is presumed to be influenced by the level of knowledge of the potential benefits of the proposed change. In this case, CE01 has shown the most knowledge about BIM from the three respondents, followed by CE02, who has worked already with the instruments, and ending with CE03, who mentioned never having used the tool before.

3.7. Summary

Although the aggregate results are deemed highly interesting, there are two main takeaways the researcher wishes to draw attention to. First, the conclusion that cost engineers are not well integrated into BIM-based working process, corroborating what was identified in the literature review, and are also not fully integrated with the processes associated with cost estimation. The second highlight, is that almost unanimously, respondents see a wealth of potential benefits in the enhancement of this integration.

The processes or steps identified which are related to producing cost estimates are systems engineering, project management, model development (a subsequent quantity take-off), and cost estimation, which includes the activities of quantifying non-graphical elements, estimating costs, and updates to the cost estimate. All of these share the characteristic that they influence in some way the production of cost estimates. This is an important statement, and means that not only do these processes impact the work of cost engineers, also the opposite may also hold, that the work of cost engineers may influence the other processes.

Furthermore, it was shown that between the processes, different levels of connectedness exist, with the identified levels being collaboration, usually seen in the design process, one sided communication, seen in the stage of information transfer between modelers and cost engineers, and lack of communication, predominant in the relation between cost engineers and other actors in other stages of the project.

The usage of BIM instruments and processes is well underway and it is clear that the company has identified some benefits, and has resorted to its use for project development. However, in the context of cost estimation, usage of BIM and 5D BIM is having an effect on the process mainly in an indirect manner as cost engineers have not transitioned to an extensive use of this technology. Not only is cost information not added to the BIM models yet, cost engineers are majorly not even consulting design information from the models.

The perceived problems of the current processes are, lack of involvement of the cost engineer in the project, inappropriate information, lack of standardization, asymmetrical adoption of technological tools, and inadequate communication. Along similar lines, the perceived risks were working with incomplete or incorrect information, risk of miscommunication, unclear responsibilities and failing to identify the added value of tasks and processes.

Relevance of cost estimation is perceived as decision making by the client, increased cost benefit of the end product and risk quantification. In the section of views on BIM, interviewees clearly stated that they perceive more benefits than drawbacks for wider implementation of BIM, and among the results, benefits were stated for cost estimation, project design, and project development.

Interviewees perceive that in each of the identified different sub processes that relate to the generation of cost estimates, namely cost estimation, model development, project management, and systems engineering, there are expectations that if achieved, may positively impact, not only the process and outcome of cost estimation, but also project development in general.

Results showed that there is no common ground in the use of standards in the company.

It was presented that there's not unity in the attitude of cost estimators towards changing to a more extensive use of BIM for carrying out their work. CE01 summarizes very nicely in a single quote the potential benefits of using 5D BIM for projects and including cost information in the models:

"So, it's not that my job has gone because the computer is making the cost estimates. No. We're going to learn from automating and digitalizing our processes, you have more time to be smart, and you need to spend less time for repetition work entering data" (CE01)

Lastly, one final observation must be made. Although it is the objective to present the results from a general, broad perspective, there are limitations to the results. First of all, the number of interviews, especially per role is still limited, with respondents per role ranging from 2 to 5. This means that claims cannot be assumed as universal, given the small sample size.

4. Analysis

4.1. Introduction

This section focuses on the analysis of the information gathered in sections 2 and 3, by using activity theory as an analysis framework. Activity theory is selected for three reasons. First, activity theory allows the analysis and redesign of work, precisely the objective of the research, analysis of results and design of a solution. Second, activity theory provides a holistic approach, first by analysing the various components that compose activities without losing the scope by focusing excessively on specific elements. Furthermore, it allows to analyse the interaction between different activities to analyse entire systems. Third, compared to similar frameworks such as Business Process Management (BPM), activity theory provides a more flexible approach with the concept of activity, as compared with the business processes of BPM, which is more rigid when representing them in Business Process Model and Notation (BPMN), and requires a higher level of detail for each specific case.

The first step in analysing the data through the activity theory, is choosing the activity systems. Activity systems are object-oriented, and these objects are, "an invitation to interpretation, personal sense making, and societal transformation" (Engeström & Sannino, 2020). Also, important to keep in mind that objects should aim at durable, long term objectives, instead of an individual, short-term goal. To choose the activities, use was made of the results from chapter 3, and more specifically, from the processes and subprocesses associated with cost estimation as identified in section 3.3.1. For the sake of clarity, three activity systems were created from the results, which group the categories identified per common themes. As a clarification note, the activity system of project management and development involves the processes of systems engineering and project management.

- Activity system 1: Cost estimation.
- Activity system 2: Project design and modelling
- Activity system 3: Project management and development

Since the research will make use of the third generation of activity theory, in which a constellation of activity systems is the basic unit of analysis, a boundary object that clusters the individual activity systems is identified. Star and Griesemer (1989), defined boundary objects as: "*…useful theoretical constructs to think about how conceptual knowledge work happens at the intersections of distinct communities of practice. Boundary objects are flexible epistemic artefacts that 'inhabit several intersecting social worlds and satisfy the information requirements of each of them', adaptable to different viewpoints while being robust enough to maintain identity across them*", and furthermore, Neff, Fiore-Silfvast, and Dossick (2010) concluded that BIM could be one of such objects. As the concept of BIM is central for the research, the activities will be clustered together by it.

The analysis of activity systems will be based on elements of 5D BIM, namely on using cost information in BIM-based project development. However, this cannot be considered as fully implemented 5D BIM.

4.2. Activity system 1: Cost estimation with 5D BIM.

The first activity system is based on the actual process of cost estimation. Each of the elements from this, and the subsequent activity systems come directly from the results in chapter 3, mostly from section 3.3 which presents the results of state of affairs and connectedness. First, the (1) Subject was selected as the main executor of the activity per the results in section 3.3.1. The (2) Instruments were identified from section 3.4.1, which presents the software usage, and was complemented by results from section 3.3.1. The (3) Object element relates to a *desired object*, which in this case refers to the usage of elements of 5D BIM to realize the object, in this case, cost estimation. This in line with what was stated in the previous section, and will allow to analyse the potential impacts of using cost information in BIM-based project development. The (4) Outcome of the activity system, is to be determined further in section 5.3.2, and remains empty in this section. (5) Division of labour is drawn from the results in sections 3.3.1 and 3.3.2, and presents the current way of developing the activity. The (6) Community that is involved or affected by the activity but is not directly executing it is extrapolated from results in sections 3.3.1 and 3.3.2. Lastly the (7) Rules governing the activity are drawn from results in sections 3.3.1 and 3.6.1. The elements of the first activity system, as well as its internal contradictions, are depicted in Figure 6.

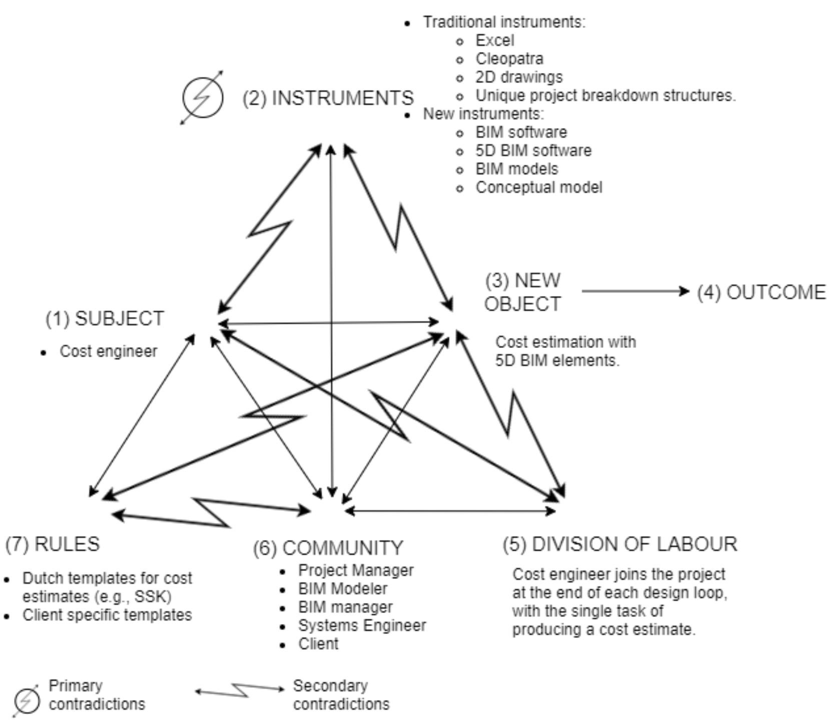

Figure 6: Activity System for Cost estimation with 5D BIM elements.

With the activity system defined, the analysis framework focuses on the contradictions, both primary and secondary for the analysis of the results and for the further proposal of solutions, as explained in section 2.6. Table 5 presents a summary of the analysis of contradictions, while the full analysis can be found in Annex 6.

Table 5: Activity system 1 contradictions analysis.

Code	Type	Elements	Description of contradicting elements	Contradictions
2-2	Primary	(2) Instruments	Current non-BIM instruments - new, BIM based instruments	Old and new software may overlap, causing redundancies and waste.
2-2	Primary	(2) Instruments	BIM Model as an instrument - BIM Software	More attention is put to the usage of BIM software than information contained within BIM models.
1-5	Secondary	(1) Subject - (5) Div. of labour	Perceived importance of cost engineers - "siloed" work	Cost engineers perceived as having an important role but carry their work in a non-integrated manner.
2-1	Secondary	(2) Instruments - (1) Subject	Cost engineer's low BIM competences - costing with 5D BIM	Lack of knowledge and training in use of BIM tools by cost engineers doesn't allow development of cost estimates assisted by 5D BIM.
2-3	Secondary	(2) Instruments - (3) Object	Non-BIM software - costing based on 5D BIM	Non-BIM software usage is not suitable for making cost estimations based on 5D BIM.
2-3	Secondary	(2) Instruments - (3) Object	Traditional tools and BIM software - complete cost estimates.	Current costing and BIM software are not appropriate for quantifying and costing non-graphical elements
5-3	Secondary	(5) Div. of labour - (3) Object	Limited and late involvement of cost engineer - 5D BIM based costing.	Proper BIM implementation requires collaboration by all interested stakeholders. In the case of 5D BIM, of the cost engineer.
7-3	Secondary	(7) Rules - (3) Object	"Weak" guidelines - costing based on BIM	Diffuse and subjective selection of rules for cost estimation don't allow effective use of BIM and specifically, 5D BIM.
7-6	Secondary	(7) Rules - (6) Community	Subject specific rules - broad community.	Specialised rules such as SSK do not account for the existence of a broader community in the activity.

"…so, my point of view, the cost engineers, with W+B, they have their own methods, they're very good at what they do. So, like [COST ENGINEER'S NAME], he's very good. … in civil engineering sectors he's quite well known about his knowledge about costs, so he's very good…"
(SE02)

4.3. Activity system 2: Project design and modelling with 5D BIM elements

This is identified as the second activity system to developed for two reasons. It was identified to potentially be able to influence and be influenced by cost information. The process of project design and modelling will shape the cost estimation process, e.g., by means of generating quantity take-offs. But also, inclusion of cost information in the development of the design and the model, has a potential impact on the end product e.g., by means of making cost-based design decisions.

As an important note, the term "conceptual model" is introduced in this activity system, and will be used extensively for the remainder of the research. The conceptual model, is represented by the object tree, the different breakdown structures (OBS, SBS, WBS, etc.), and the information of decomposition and classification of an asset being developed. While the BIM model can be seen as the realization of a virtual design in line with the project requirements, the conceptual model includes the project requirements on a more abstract level, will be used as the system engineering analogue of the BIM model.

Figure 7 shows the activity system with its elements and contradictions, and the selection of elements follows the same process explicated in for the previous activity system. Table 6 presents the summary of the contradictions while Annex 7 contains the complete analysis.

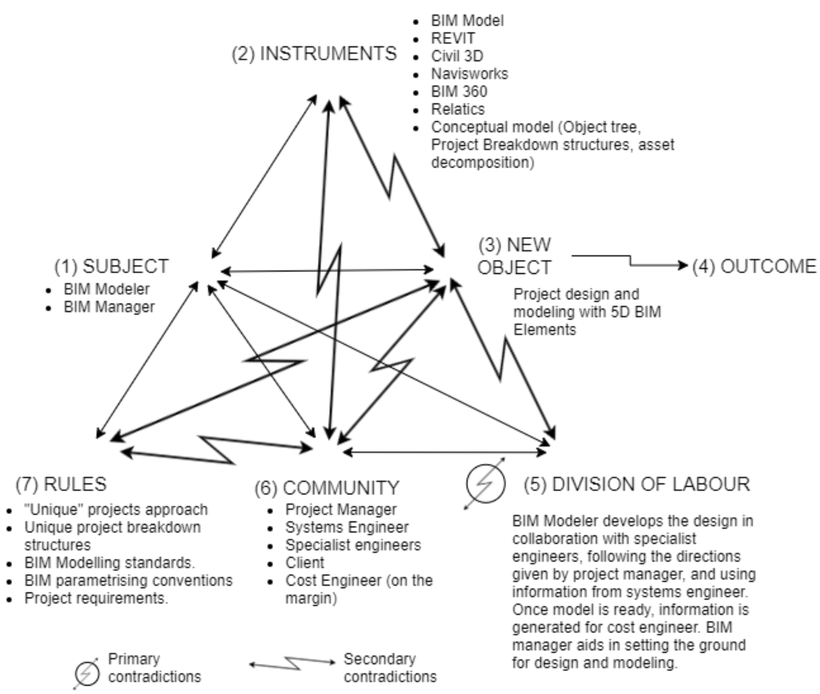

Figure 7: Activity system for project design and modelling with 5D BIM elements.

Table 6: Activity system 2 contradictions analysis.

ID	Type	Elements	Description of contradicting elements	Contradictions
5-5	Primary	(5) Div. of labour	Unbalanced division of labour - more labour-intensive BIM with cost information.	Current division of labour is already unbalanced towards the BIM modeler, which may worsen with inclusion cost information in design and modelling of projects in BIM.
2-3	Secondary	(2) Instruments - (3) Object	Lack of use of 5D BIM capable instruments - design and modelling with 5D BIM elements	Current instruments do not support 5D BIM modelling and design.
2-3	Secondary	(2) Instruments - (3) Object	Conceptual model in Relatics - design and modelling with 5D BIM elements	The non-optimised conceptual model does not account for cost information and is not an appropriate basis for design and modelling with 5D BIM elements.

2-6	Secondary	(2) Instruments - (6) Community	BIM as a collaboration-based instrument - loose community.	The objective of BIM being fundamentally based on collaboration cannot be realized with a loose community, specifically with the cost estimator on the margin.
5-3	Secondary	(5) Division of labour - (3) Object	Lack of cost information as input - design and model with 5D BIM.	Division of labour doesn't account for using cost information as input for design and modelling, contradicting with the objective of 5D BIM.
6-3	Secondary	(6) Community - (3) Object	Cost Engineer on the margin of community - design and model with cost information.	Current marginal position of cost engineer in community does not promote design and modelling including cost information.
7-3	Secondary	(7) Rules - (3) Object	"Weak" modelling rules - design and modelling with 5D BIM elements.	Existing rules do not account for management of cost information, which is inappropriate for 5D BIM modelling.
7-3	Secondary	(7) Rules - (3) Object	Unique projects approach - design and modelling with 5D BIM elements	5D BIM based design requires increased management and parametrisation of information, which can become unviable if treating all projects as entirely unique.
7-6	Secondary	(7) Rules - (6) Community	Weak, subject based guidelines - Community with cost engineer on margin.	Current rules and guidelines for design and modelling do not account for dealing with cost information while the community further puts the cost engineer on the margin.

4.4. Activity system 3: Project management and development

The third activity system identified is based on the process of project management. The activity of project management and development is chosen to be analysed because it can influence and give direction to both cost estimation, and project design and modelling. By establishing specific management and development practices, this activity can shape the outcomes of the other two. Figure 8 shows the activity system with the elements and contradictions, following the same process explicated for activity system 1. Table 7 presents the summary of the contradictions while Annex 8 contains the complete analysis.

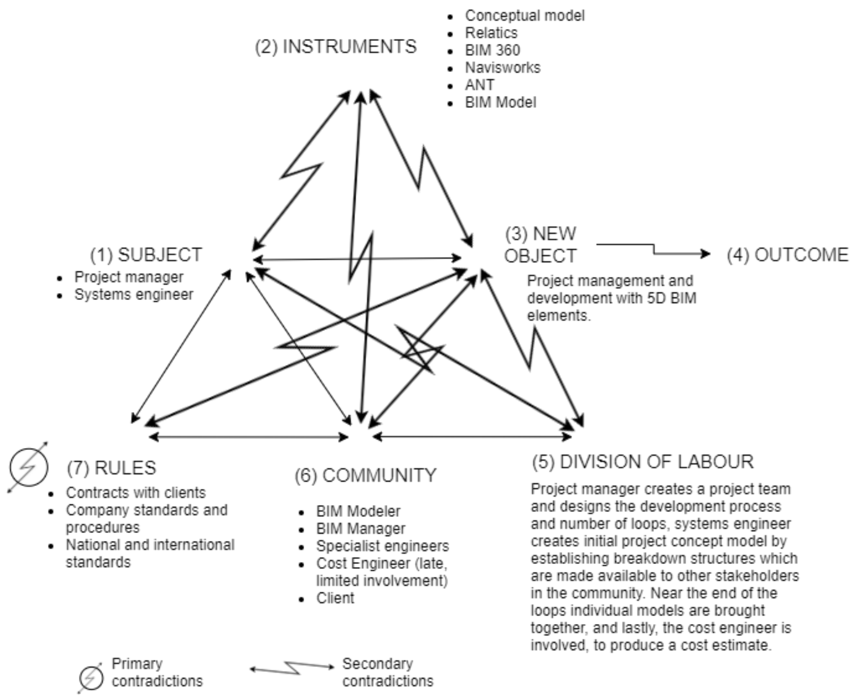

Figure 8: Activity system for project management and development.

Table 7: Activity system 3 contradictions analysis.

ID	Type	Elements	Description of contradicting elements	Contradictions
7-7	Primary	(7) Rules	Contracts with clients - company standards and procedures - national and international standards.	Three identified major rulesets potentially overlap and contradict each other, with the client's contract ultimately having the most weight.
1-2	Secondary	(1) Subject - (5) Instrument	PM and SE limited BIM proficiency - Use of more specific BIM tools	The limited proficiency of PM and SE in the use of BIM is an obstacle to the use of more specialized, 5D BIM capable tools.
1-5	Secondary	(1) Subject - (5) Div. of labour	Systems engineers as enablers and integrators of project development - Untimely involvement of systems engineer.	Systems engineers potential to act as integrators and enablers in the project development is limited by untimely, late involvement.
2-3	Secondary	(2) Instruments - (3) Object	Non specialized BIM instruments - Project dev. and mgmt. with 5D BIM elements.	Non specialized BIM tools may not be able to present and handle 5D BIM information on a managerial level.
2-3	Secondary	(2) Instruments - (3) Object	Conceptual model not optimised for cost info. - Project dev. and mgmt. with 5D BIM elements.	Conceptual model does not account for management of cost information required for 5D BIM project development.
2-6	Secondary	(2) Instruments - (6) Community	Conceptual model not optimised for cost info. - Integration of cost engineer in community	Conceptual model has the potential, but does not account for integration of cost engineer, and further positions them on the margin of the community.
5-3	Secondary	(5) Div. of labour - (3) Object	Untimely and limited participation of cost Eng. with a highly linear process - project dev. with cost info.	Untimely participation of cost Eng. and a linear process prevents early decision making in project dev., and limited participation contradicts with collaborative nature of BIM.

6-3	Secondary	(6) Community - (3) Object	Late, limited involvement of cost engineer - project dev. with cost information.	Position of the cost engineer in the community hinders object of developing a project with cost info.
7-3	Secondary	(7) Rules - (3) Object	Traditional contracting - Project development with 5D BIM elements.	Traditional contracts such as RAW, by design, are not optimised for project development through 5D BIM practices.
7-3	Secondary	(7) Rules - (3) Object	Open and lax company and national standards - Project development with 5D BIM elements.	Dev. of projects through BIM, and 5D BIM, require use of well-defined standards, opposed to the current open and lax standards.

"And I would say, it would be preferable to start off with the systems engineers first, to make these breakdowns to make the structures ***and then make the other people work in these structures****. And what you see, because all these people start at the same time.* ***Sometimes there is, there is already different structures****. So, like, for example, with [COST ENGINEER NAME], he could have his cost structure ready, Before I have my system breakdown structure ready, or my work breakdown…"* (SE02)

4.5. Summary

At the beginning of the chapter, a brief explanation over the decision of using activity theory is presented. Three main reasons were cited, the theory allows both analysis and redesign of work, it provides a holistic approach, and it is more flexible than similar frameworks such as BPM. Furthermore, the current chapter presented the process of analysis of the activity systems as proposed in activity theory. First, three activity systems were created from the results of chapter 3, these are namely cost estimation, project design and modelling, and project management and development. It was further presented how the elements of each activity system were selected, again based on the results chapter. Finally, the identification and analysis of the contradictions in the individual activity systems was presented. In the following chapter, the constellation of activity systems will be discussed, and progress will be made towards developing the solution.

5. Discussion

5.1. Introduction

With the analysis of the results in place, the next step calls for the discussion of the results. In this section, the activity systems are not to be considered individually, but grouped in what is called a constellation of activity systems. This constellation is a way of representing a part of an organization (Engeström & Sannino, 2020), in this case, cost estimation and associated processes, and allows to analyse the interactions between individual but interconnected activity systems. In section 4 it was stated that one of the reasons why activity theory was selected was its holistic nature, and this is precisely the reason for it. By discussing the contradictions within activity systems but also between them, an additional dimension of depth is added to the analysis, allowing the proposal of solutions that take into account the context in which activities are developed. The present chapter opens with the discussion of the constellation of activity systems.

5.2. Discussing the constellation of activity systems.

Already mentioned in the introduction of chapter 4, 5D BIM was selected as a boundary object that integrates the different activity systems into a single constellation of activity systems, as represented by Figure 9. Having a boundary object grouping the individual systems entails two things. First, it means that proposed adjustments or changes to the boundary object, in this case, 5D BIM software, will span across all activities bound by it. Secondly, it means that for proper development of solutions, the impact on them on the different individual activity systems must be assessed and tested.

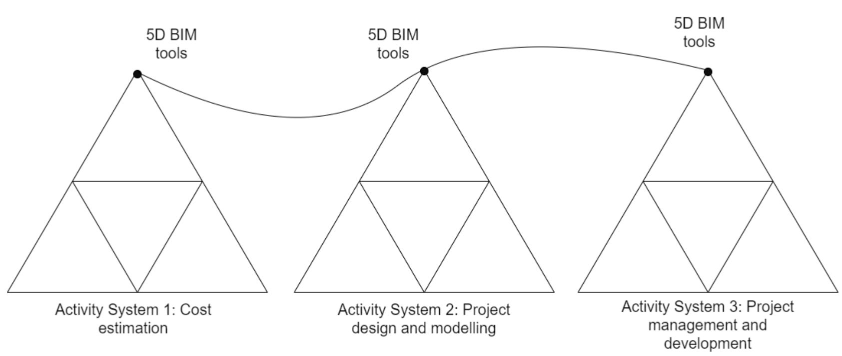

Figure 9: Visualization of the constellation of activity systems with 5D BIM acting as a boundary object connecting the individual activity systems (adapted from (Vakkayil, 2010).

To begin the discussion, it is interesting to highlight that most contradictions in all three activity systems appear in regards to the "object" element. It is reasonable to state this is due to the fact that all objects are "desired objects", and the intention was to identify the clashes and contradictions that exist in the current situation in order to achieve the development of activities with 5D BIM elements. Contradictions with the object originate from every element connected to it, excepting the subject. A possible reason behind this is that from the results of section 3.6.2, it was found that none of the subjects strongly oppose nor are misaligned with the more extensive use of cost information, or in BIM terms, the addition of a "cost dimension", that leads to moving a step closer to achieving 5D BIM project development.

It is seen that either when implicit or explicit, rules play a major role in the development of the activities, and it can be seen that rules actually follow a flow, from project management, to design and modelling, and finally to cost estimation. This is in line with the linear process followed at the company with each loop. Although it is understood that rules are activity specific, because of the different nature of each, there is no apparent harmony in the rules for the different activity systems, and actually they may clash between different activities. Vakkayil (2010) makes a highly interesting point and states that "*technologies contribute to the establishment of standards that can function as effective boundary objects*.". In this case, 5D BIM could help set standards that bind together the activities, not only by the instruments, but also by rules, further increasing their integration. Furthermore, as mentioned earlier, in the specific case of BIM, appropriate rules are fundamental for the correct use of the instrument. However, it is interesting to notice that while some rules are chosen by the actors within activity systems, others come from external factors, specifically from clients, and from national and international standards, meaning that rules cannot be fully influenced from within the company, which has implication for the proposal of solutions.

The main instrument that binds the activities together is BIM. However, there are clashes among the instruments, and it can be argued that the current set-up is not optimal, and only partly achieves its objective as a boundary object. These clashes have mainly two sources as reported in the results, lack of use (e.g., use of 2D drawings by cost engineers instead of using the model itself), and inadequate use (e.g., conceptual model not optimised for including cost information) of the instruments. It is also possible to state that instruments are a key element for integration of different activities. An important observation, it is seen that instruments take the form of actual tools, but also of information. In the case of tools as instruments, use of BIM and 5D BIM software is crucial, and in words of Vakkayil (2010), provides a common vocabulary and is the basis for inter-group efforts. However, no less important is information as an instrument. In this case, two main information instruments were identified, the conceptual model and the BIM model. In specific regards to BIM as an instrument in a broad sense, it must be highlighted that a major limitation is how inadequate it is for handling of non-graphical elements, given the inherent reliance of the instrument on graphical information, requiring the use of complementary instruments.

Division of labour is interesting in the sense that several contradictions are generated by the inappropriate involvement of actors in an activity. Perhaps not surprising, given that the research is focused on the integration of the cost engineer in BIM-based project development, the majority of the contradictions in the division of labour relate to this actor. However, it is noteworthy to see that to reach this objective, there are contradictions in the division of labour of other actors as well, namely of BIM modelers and systems engineers. Untimely involvement of actors is a source of contradictions in various cases. Specifically, it was identified that untimely involvement of cost engineers and systems engineers poses an obstacle to realizing their full potential on their activities. There is an issue relevant to highlight which is the blurred division of responsibilities in projects developed with BIM, which may worsen with the integration of additional actors. This finding is supported by studies, which highlighted the importance of properly defining roles and responsibilities in the development of projects through BIM (Barison & Santos, 2010), and how this requirement further increases as BIM becomes more specialized and adds additional information dimensions (Zanni, Soetanto, & Ruikar, 2017).

From the community, almost all of the identified contradictions have the same source, an inappropriate integration of the cost engineer. The analysis of the community in the context of the activity systems further delves into the impacts of lack of involvement of the cost engineer as presented in sections 3.3 and 3.5.1, and will be used for the development of solutions.

Regarding subjects, there are only two contradictions in all three activities. This, as explained earlier, comes from the results which show that virtually all subjects share an open vision for improvement of their activities, and see the potential that using elements of 5D BIM has for reaching that goal. An interesting result from the analysis of the tensions of the subjects is that two subjects, cost engineers and systems engineers, are seen as having unused potential that should be further developed.

In the end, contradictions to reaching 5D BIM based activities can be summarized in 4 main categories, which are in line with the corner elements of the activity systems, plus the main subject: lack of integration of the cost engineer, lack of standards, lack of defined guidelines, and lack of use of technological instruments. Important to note, these are in line, though not the same, with what was identified in the perceived problem from section 3.5.1.

5.3. Development of recommendations and solution.

5.3.1. Recommendations

Activity Theory establishes that analysis of contradictions allows to focus efforts on the root causes of problems in order to propose solutions (Engestrom, 2000). These solutions should be developed in a collaborative manner with members from the community identified in the analysis. To comply with this, the recommendations here presented were initially drafted by the researcher, then discussed over with members of the company, where they were refined, in one feedback session. In total, three main recommendations are proposed, which permeate through the constellation of activity systems, aiming at solving the contradictions identified. Furthermore, through these recommendations a final solution is developed, presented in section 5.3.3. The recommendations are written from a general point of view, and are intended to be applicable in the civil engineering consultancy sector, to facilitate more extensive adoption of 5D BIM, by exploring different benefits of an increased integration of cost engineers in the project development process. The detailed analysis of the recommendations can be found in Annex 9.

R1. Acquisition, implementation, and specialized training of 5D BIM software.

As presented in section 2.3.2, there are a number of available software in the market to choose from. In order to avoid the problem of inappropriate information identified in section 3.5.1, care must be put in selecting software that is compatible with the technological tools of the company. The minimum functions that should be performed through the 5D BIM software are:

Custom quantity take-offs.	Allow to focus on costing per different levels of detail, or based on different breakdowns.
Visualization of the model.	Gather contextual information, and aid in the process of cost estimation, through tools such as colour coding that enhance visualization.
Inclusion of rough cost information in 5D BIM software.	To be added semi-automatically through scripts allowing semi-automatic cost estimation of design alternatives.
Model updating and change tracking.	Allow comparison of versions of a model, easily identify changes, and allow the cost engineer to easily deal with said changes.
Cost information reports.	Costs per object, element, system, etc., cost of different alternatives, cost drivers, and cash flows, allows stakeholders make cost-based decisions, having a potential positive impact in the quality if the final product.

Additional to the acquisition and implementation of the software, specialized training by the users of the software is required as asymmetrical adoption of technological tools was identified as one of the current problems. Specific training is crucial as uses of the instrument will differ greatly between stakeholders. For the case of cost engineers, training should be mainly focused to perform the functions presented above.

R2. Well timed and more extensive integration of cost engineer and systems engineer in the project development process.

The integration of the cost engineer should be aimed at providing earlier input, mostly cost information, to other actors in the project development process. A study by Citroen (2011), concludes that with more relevant information available, rational decision making is facilitated. Furthermore, the timeliness of cost information is important from the possibility to impact a project's outcome through time (Hendrickson et al., 1989). Thus, it is expected that by having timely access to appropriate cost information, better decisions can be made during the project development process. In general, the integration of the cost engineer should allow to:

Provide cost information to allow cost-based decision making both for project development and for the design process aiming at improving end product quality.
Provide cost information to allow the discussion and analysis of different alternatives.
Provide input to select information that should be included in the models.

In the case of systems engineer, they can become a key piece in the integration of other actors, including the cost engineer as based on results (3.3.1) and analysis (4.4). It is recommended that systems engineers join the project development at the earliest possible moment. This will allow them to incorporate requirements and feedback from other relevant stakeholders, including the cost engineer. In the end, two main benefits are expected in regards to cost estimation. First, through the earlier involvement of the systems engineer, input from the cost engineer is taken into account earlier on, effectively integrating him into the process, and second, the conceptual and BIM models can be developed in a more organized manner, allowing the addition of cost information.

R3. Adoption of companywide standards and guidelines for conceptual model development and use, BIM modelling and use of models, and management of cost information.

Standardization has been identified as having the potential to bring improvements in the construction industry (Aapaoja & Haapasalo, 2014; Roy et al., 2005), and as a requirement for achieving the full benefits of BIM (Poljanšek, 2017). Adoption of companywide standards and guidelines is recommended in a broad sense, but specifically for three major objects: (a) conceptual model development and use, (b) BIM modelling and use of models, and (c) management of cost information.

a) Conceptual model development and use.

One of the most interesting findings from the research was identifying the potential function of a conceptual model as an integration instrument. Development of these conceptual models by systems engineers should precede the development of detailed designs and the BIM model, and contain information that is not modelled through BIM, such as non-graphical elements. It is suggested therefore that a single companywide standard process for the development of this conceptual model is created. The standard should account for at least:

Development of model in consensus with stakeholders	Guarantee that conceptual models are appropriate to integrate the work of other disciplines in BIM project development.
Development of model in loops	On each loop of the conceptual model, elements are broken down in a level of detail matching the target LOD of the BIM model.
Use of standardised conceptual objects as “building blocks”	More standardised library of conceptual objects, that is easier to parametrise and use in the modelling phase.
Clear timing of the development of the conceptual model.	Prevent issues related to rework due to use of different breakdown structures per role.
Management of non-graphical project requirements	Allow project managers and cost engineers take into account non-graphical elements to produce complete cost estimates.

b) BIM modelling and use of models

BIM models become the source of information for the cost estimations. As such, the use of standards in regards to this point should account for at least:

International BIM information standard (e.g., ISO 19650).	Through the standard develop a companywide framework for the management of information for Building Information Modelling, and in the context of this research, management of cost information
Clear responsibilities guideline.	Allow development of projects based on BIM and further 5D BIM modelling avoiding responsibility and role conflicts that may affect product quality.
Shift responsibility of QTO generation to the cost engineer.	Increased control of cost engineer over the information, and to extract only what is relevant to them. by working on the model, itself, involvement with the project is increased.
BIM models as unique source of project information.	Allow model to be used by all relevant parties as the main source of information, reducing the chance for information errors in the process.

c) Management of cost information.

Use of standard for cost information management such as ICMS to allow development of cost breakdown structures that can be used with BIM processes which in turn is an enabler to move towards 5D BIM project development. Such a standard will also increase the level of organization of information and reduce the number of issues arising from inappropriate information.

5.3.2. Expected outcome

With the recommendations in place, it is possible to propose new activity systems, and identify the potential outcomes. These updated activity systems are intended to solve the existing contradictions, and be able to carry out the "desired object". Some outcomes are therefore proposed, which are immediately related to the potential impacts of using 5D BIM elements in carrying out the activities. Figure 10 to Figure 12 present the updated activity systems with the identified outcomes. The subsections include a summarized description of the outcomes, and expanded Annex 10 presents the complete analysis.

5.3.2.1. Activity system 1: Cost estimation with 5D BIM expected outcomes:

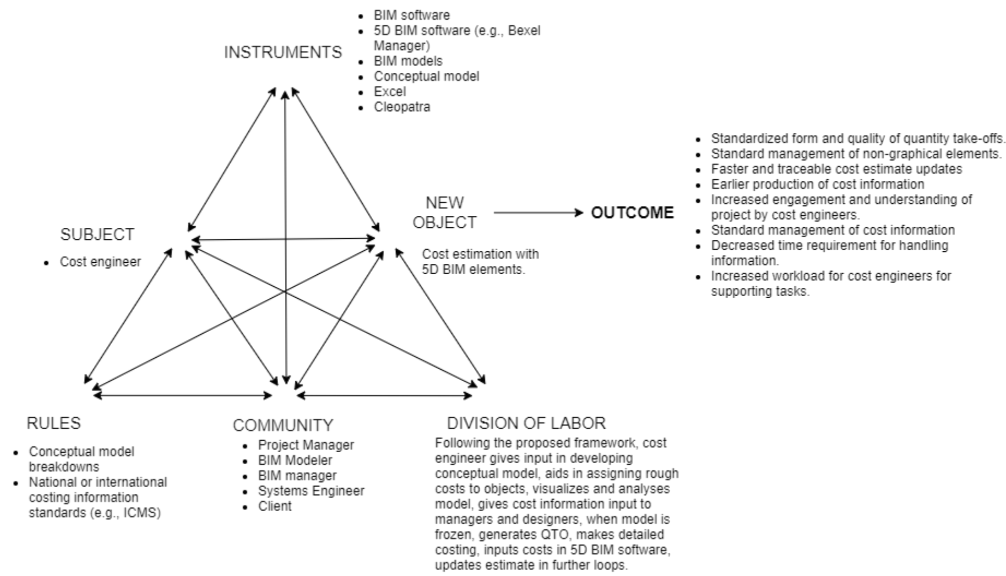

Figure 10: Updated Activity System for Cost estimation with 5D BIM elements.

Outcome	Description
Standardized form and quality of quantity take-offs	By the cost engineering producing QTO's directly in 5D BIM and by following a more standard approach from conceptual model development to account cost information.
Standard management of non-graphical elements	By including these elements in the conceptual model, with their requirements and specifications, cost engineers will have a standard method to properly account and cost them.
Faster and traceable cost estimate updates	By having a structured approach to developing conceptual and BIM models, QTO's extraction can be largely automatized to quickly update quantities
Earlier production of cost information	By reduction of time needed to produce QTO's and updating estimates. Also allows the production of intermediate cost estimates during the project development process
Decreased time requirement for handling information	By requiring less time to handle information, as a result of a more structured process. In turn, this increases available time for the cost engineer to carry other more impactful tasks.
Increased engagement and understanding of projects by cost engineers	By working hands-on with the BIM model, cost managers can get information directly from the original source and connect better to the development of the project.
Standard management of cost information	By using cost information standards, and accounting for cost information for the development of BIM models, information is better structured.
Increased workload for cost engineers for complementary tasks.	By more extensively involving cost engineer in supporting tasks aimed at improving project development, they will take additional tasks not previously carried out.

5.3.2.2. Activity system 2: Project design and modelling with 5D BIM elements

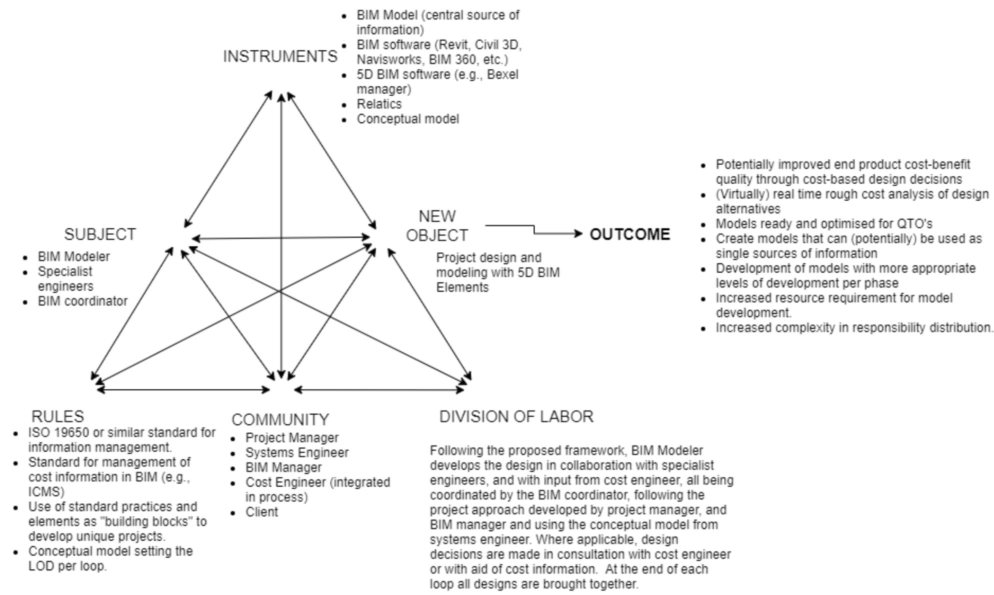

Figure 11: Updated Activity system for project design and modelling with 5D BIM elements.

Outcome	Description
Improved end product cost-benefit quality through cost-based design decisions	By involving the cost engineer earlier on, and having access to earlier cost information, it is possible to assess design decisions from a cost perspective.
(Virtually) real time rough cost analysis of design alternatives	By adding rough cost information to the parameters of objects in a model, (virtually) instant cost estimates of different design alternatives becomes possible.
Creation of models ready and optimised for QTO's	Through the development of models based on information management standards (ISO 19650), accounting for cost information (ICMS), and based on an appropriate BIM plan
Creation of models that can be used as single sources of information:	by producing comprehensive BIM models that account for complete project information, cost information included.
Development of models with more appropriate levels of development per phase	By following an evolving conceptual model, models can develop with a more coherent flow, providing the levels of detail appropriate to each design stage.
Increased resource requirement for model development.	By the addition of additional parameters including cost information, additional resources are required for proper 5D BIM model development.
Increased complexity in responsibility distribution.	By including cost information in the model, the responsibilities and roles for said information become less clear, as the party who includes the information is not necessarily responsible for it.

5.3.2.3. Activity system 3: Project management and development

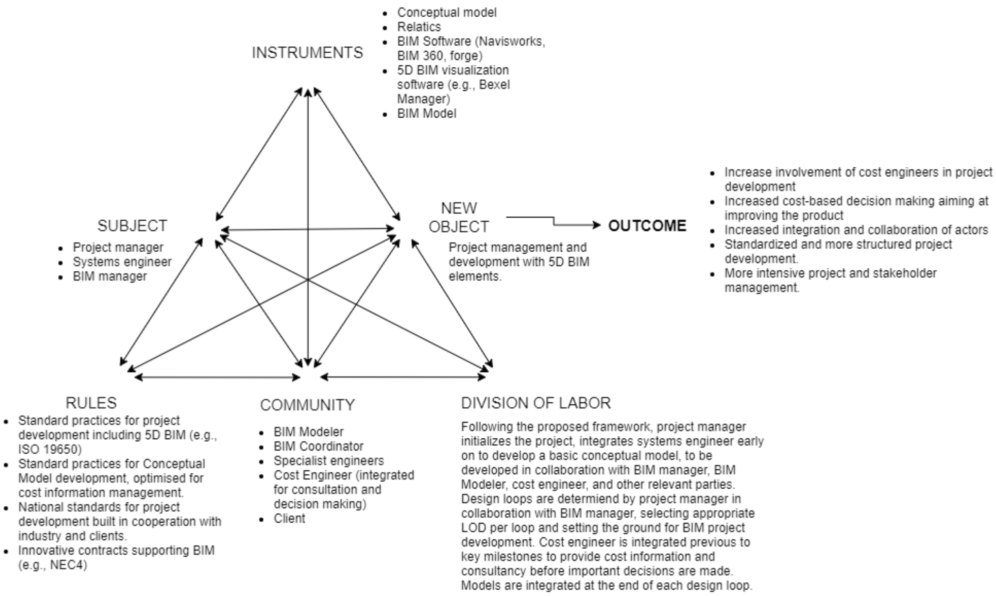

Figure 12: Updated Activity system for project management and development.

Outcome	Description
Increase involvement of cost engineers in project development	Through a more structured usage of cost information in the project development, cost engineers can have earlier and periodical interaction in the process, and creates a space to provide their input and knowledge.
Increased cost-based decision making aiming at improving the product	By having decision makers base their choices on input from the cost engineers, there is potential to improve the quality of the outcome, in this case, the final product to be delivered.
Increased integration and collaboration of actors	Through hands-on, BIM -based development of projects, and a conceptual model that accounts for other stakeholders, increasing collaboration, to reach a more comprehensive process.
Standardized and more structured project development	Through the use of companywide standards and guidelines for project development (conceptual model, BIM model development).
More intensive project and stakeholder management.	By a more extensive involvement of cost engineer in the process, additional stakeholders need to be managed, and project has additional input which also needs to be managed.

5.3.3. Proposed framework

With the recommendations in place, the proposed activity systems in place, and the potential outcomes identified, a framework based on BIM project development is proposed, which integrates the cost engineer. While it cannot be deemed as full-scale implementation, it lays the ground for working with 5D BIM elements. The framework, in addition to the recommendations previously stated, solves the research question 4:

How can cost engineers be integrated in BIM-based processes to realize potential benefits in the development of an infrastructure project?

The framework proposes a way of integrating cost engineers in the process of project development through BIM, in order to reap some of the benefits identified in answering sub question 3. Figure 13 shows the framework, including the first design loop, and the intervention of the different actors at different moments in the project development process. The framework, can be expanded to any number of design loops as required or established by the project manager.

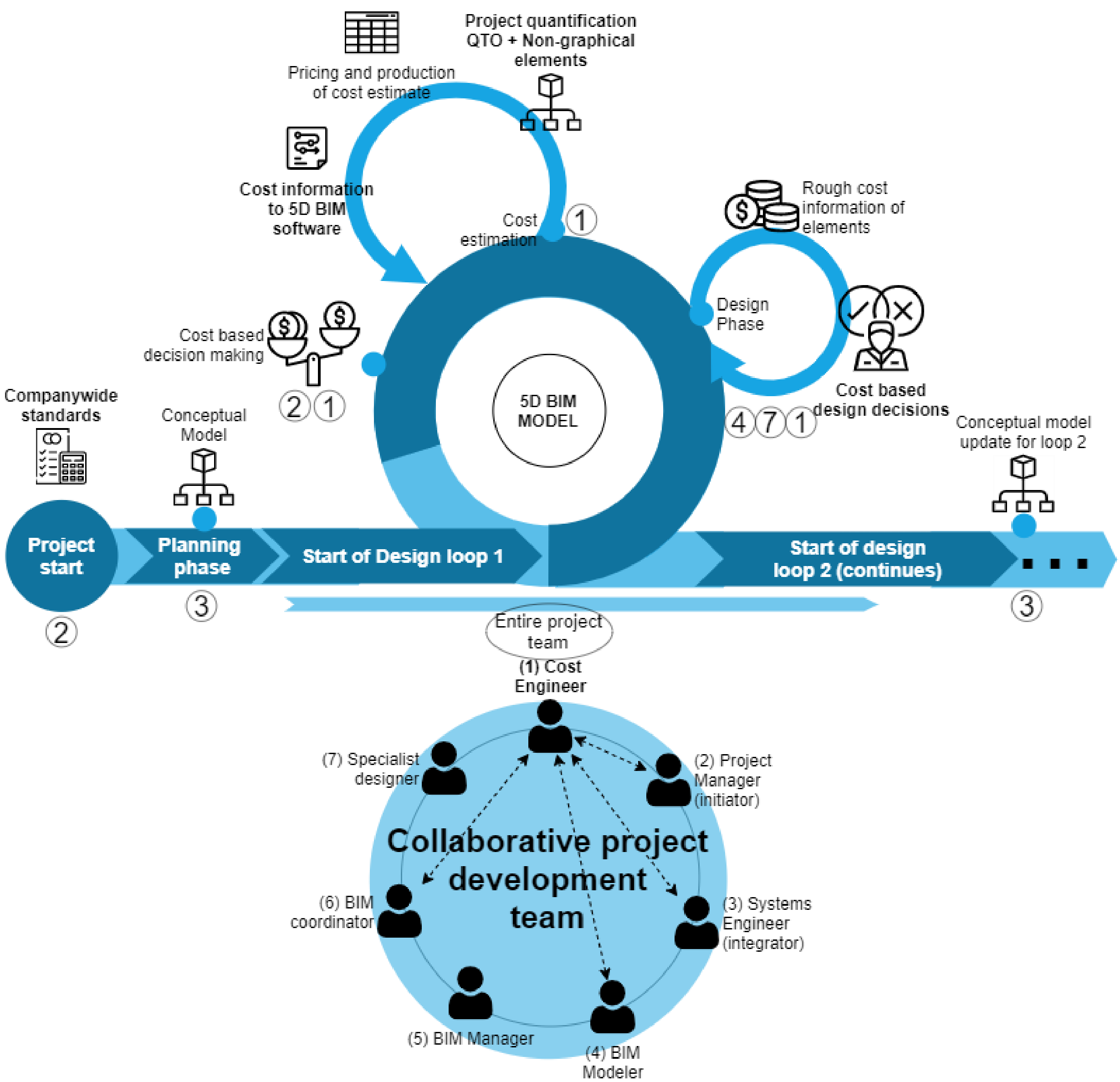

Figure 13: Proposed framework for integration of cost engineers in the development of a project using BIM and cost information.

In general terms, the framework is expected to contribute in solving the identified contradictions of the activity systems, but some elements should be highlighted. The first highlight is that through the framework, the basis for a more integrated and collaborative process for cost estimation is proposed. Through the framework, some specific concepts of costing such as QTO, and bill of quantities (BOQ) lose some of their relevance, and instead, the focus is laid on how information is to be added to the model, and how it will be handled and transformed to provide the output of a cost estimate, and furthermore, how this in turn can be used in other moments of project development.

Another point of attention is the management of non-graphical elements, which is realized through the use of the conceptual model, which act as a precursor, but also as a complement to the BIM model, in terms of handling information which the latter cannot handle.

The framework is centred on the concept of a single source of information, which in this case is a 5D BIM model. The exact form of the source may change with iterations of the framework or specific applications. However, the concept remains the same, and is intended to reduce errors in information types, and to foster collaboration.

Collaboration in turn is expected to increase engagement of stakeholders following the findings of (Larsson & Larsson, 2020), setting the ground for developing more comprehensive projects, as laid down in stakeholder theory (Freeman & McVea, 2001). In general, it is expected an increase in collaboration leads to improved project development.

Use of standards and standardized guidelines is another highlight of the framework. It is not aimed at the use of specific standards but at the establishment of more homogenous practices that allow the different stakeholders to share a common language, producing information in a way that is suitable for each task. In turn, standards may improve collaboration by setting rules for the management of specific information during project development, in way that suits different actors.

An important point to note is the framework also introduces additional requirements. These requirements are generally in terms of resources, mostly human. The more extensive involvement of cost engineers means these will need more of their time carrying or supporting tasks. Inclusion of cost information in a BIM model, that is, 5D BIM models, requires additional resource investment to be properly developed, following the findings of Sattineni and Macdonald (2014) In turn, this also means project managers require additional resources as there are additional elements to be managed in the project.

In regards to the responsibilities, it is expected that the inclusion of cost information in BIM models, will make the division of responsibilities more complex, as it becomes less clear who is responsible for information on different points in the development in the project.

A last important note is that it is not only through the application of the specific framework that changes can be achieved. Integration of the cost engineer, as the prime example, in general terms, is deemed of great importance. This integration can be done sequentially, starting by making the cost estimation process a more collaborative one, communicating to the BIM modellers what information is required, and keeping decision makers up to date with the latest cost information. These changes are not necessarily based on BIM, and are expected to solve some of the identified problems, specifically those which can be solved by having a more collaborative approach.

5.4. Validation

It is important to review the quality, and validity of the proposed recommendations, solutions and outcomes of the research, in order to maintain the rigorousness of the research. The validation was carried out via interviews with two independent experts in the field of BIM, who work at the case study company and are members of the BIM accelerator group, but were not interviewed during the data gathering process. The first validator is a BIM coordinator, while the second one is the leader of several BIM modelers and BIM coordinators.

The methodology followed was that of a one-hour feedback session held through Microsoft Teams, which was divided in three parts. The first part consisted on a presentation by the researcher, emphasising on the results from the recommendations, outcomes, and lastly, on the proposed framework. The second part consisted on a two-way feedback session from the presentation, aimed at detecting problems, errors, inconsistencies, or failures that would undermine the statements presented. The third and final part consisted on explicitly asking the validators whether they thought the presented research was valid or not.

In general terms, both experts validated the recommendations proposed, highlighting their adequacy for solving the existing problems and contradictions. The framework was also validated, underscoring the potential it has as a guideline in the implementation of 5D BIM, and the integration of the different actors in it. Finally, regarding the identified outcomes, the validators agreed on the feasibility of achieving them through the proposed framework and recommendations. As a final remark, both validators made emphasis on the importance and relevance of the research, and the potential of exploring the possibilities existing in the area of BIM.

The importance of appropriate information transfer was emphasized by validator 1, and they stressed on the importance of having a common data environment, supporting the recommendation of using the BIM model as a single source of information.

Another highlight made by validator 1, was the importance of having intermediate cost estimates. It was made more explicit therefore that through addition of rough cost information to elements on a preliminary phase, and the addition information in a 5D BIM model at the end of the first loop, intermediate rough cost estimates can be delivered. By stating the inclusion of such recommendation, validators accounted the issue as addressed by the framework.

In specific terms, some recommendations were made. Validator 2 highlighted the current problems and importance of non-graphical elements for costing. This had already been identified as an important aspect of cost estimation, and had been accounted in general terms. However, it was deemed as appropriate to explicitly include it in the final framework and in the recommendations, as is presented.

An important adjustment made to the framework, by request of Validator 1, was the addition of the figure of BIM coordinator as lead of the design process. This figure had previously been mentioned by interviewees, but the exact scope of work was unclear, as their functions would sometimes overlap and jump between BIM managers and BIM modelers. The feedback was included, and as such, the figure of BIM coordinator was added in the framework and the updated activity systems to reflect the need for coordination in design and modelling.

Another important adjustment, it was suggested to make modifications in the form of the recommendations, so that they can convey their purpose in a more direct manner. Initially, a great number of specific recommendations was included. In the final version, as presented, recommendations were synthetized into six to make them well-defined and clearer.

The feedback from the validators proved useful in maintaining the rigorousness of the research, but also in improving the proposed solution and its presentation. The step then allows to draw conclusions based on the developed solutions and to continue the research.

5.5. Findings

A main finding is that while other roles have been integrated in BIM-based project development, for example specialist engineers and modelers, cost engineers have not been actively involved and are currently at the margin of the process. This goes in line with the findings of other researches who had come to similar conclusions (Aibinu & Venkatesh, 2014). This is still an ongoing situation as the research could confirm. The effects of this vary, but a finding linked to this is that design decisions are mostly not cost based. Whether this affects the quality of the designs and to which extent is out of the scope of this research, although some authors have concluded decision making is improved by having complete information (Citroen, 2011).

Along the same lines, a finding from the research is that cost engineers are still deemed to play an important role in the development of projects, and that their knowledge is valuable. None of the respondents expressed that the role of the cost engineer was obsolete or would become so in the foreseeable future.

Another finding to highlight is that non-graphical elements are an important part of costing which is often overlooked when working with BIM. The basis of BIM is to make graphical representations of elements and then assign additional information to them. If an element cannot be modelled for any reason, it will not be present anywhere in a BIM model, and there are currently no alternatives for accounting for these elements in BIM, and the use of additional instruments becomes necessary. This is a major limitation of BIM which should be accounted for.

In line with the non-graphical elements, an interesting finding in the role systems engineering may have in this. The previously defined conceptual model was found to have the potential to manage non-graphical elements, complementing the use of BIM. Furthermore, systems engineers were found to have potential in integrating different disciplines through the early development of conceptual models, setting the ground for proper project development.

It was found that usage of software at is still highly divided by role specialization. In the case study, a total of 26 software instruments were mentioned by one or more of the interviewees, and it was shown that there is a high level of disparity in their adoption. Even in BIM software, the use of different instruments is required as it serves different functions. Having different software means working with information in different formats, many of which are incompatible between programs, and can deteriorate into inadequate information, one of the identified problems.

Along the same lines of information, and software, a finding in the research clearly states the impacts of this problem and the difficulties it poses. Problems with information are not only between software but also between roles. There is lack of knowledge on the specific necessities of the work of other roles, leading to tensions between actors in producing and receiving appropriate information that is in line with their requirements. This is showcased by the information transfer problem between BIM modeler and cost engineer, where it was mentioned by several respondents that the QTO's delivered did not match the expectations. It can also be theorized that this is aggravated by the lack of integration between the two actors, which was also present in the results.

One last finding worth mentioning is that the division of responsibilities is still an ill-defined topic in BIM, and from the gathered data it is still uncertain how the division should be made. The topic however is important and is in line with the findings of (Barison & Santos, 2010). Some specific suggestions are made in this regard, but a deeper discussion should take place although that is outside of the scope of the research.

5.6. Summary

This chapter presented the analysis of the results through the activity theory analysis framework, which serves as a holistic approach for data analysis. The usage of activity theory in the field of BIM is relatively low[2], and using it for the current research presented an interesting opportunity. Among the most interesting points is the possibility to analyse the usage of 5D BIM, not only focused on the cost estimation activity, but also include other activities that are associated to it, namely project design and modelling, and project management and development. The analysis showed that within the constellation of activity systems that compose the process for producing

[2] A search in Scopus with the query *"TITLE-ABS-KEY ("activity theory" AND "BIM")"*, i.e., a search for research with the keywords "activity theory" and "BIM" yielded a total of 20 results, while another query, *"TITLE-ABS-KEY ("framework" AND "BIM")"*, i.e., research with the keywords "framework" and "BIM" yielded 2,149 results.

cost estimates, not only are there currently contradictions, primary and secondary, inside of each of the activity systems, but that also some of the contradictions have a similar root cause, and are shared between activity systems. After the contradictions were identified, the transformative process of activity theory was put in use, in order to propose a series of recommendations that would help solve the contradictions identified.

Through the recommendations, it is expected that the instrument of BIM becomes a more sturdy boundary object, and that in turn, the technology impulses de adoption of standards that also, can function as boundary objects themselves, as proposed by Vakkayil (2010), integrating individual activities together, to form a truly comprehensive and integrative framework for project development, and specifically, cost estimation.

The framework was elaborated by the researcher with feedback from personnel from the case study company who were close to the research, to improve its validity. The feedback was included and the recommendations and framework adjusted as necessary.

Lastly, as a closing step in the activity theory analysis, the expected outcome of the activity systems was analysed, and updated activity systems were created. The outcomes are direct benefits from the integration of the cost engineer in a 5D BIM based project development process, as based from the case study company, marking thus the end of the main research task. In the next chapter, conclusions from the research will be presented, alongside limitations, and further research suggestions.

6. Conclusions

6.1. Conclusions

The objective of the research was to provide a foundation for integration of cost engineers in a BIM based project development and explore the potential impacts of said integration. This was done through the analysis of literature and a case study at a company, Witteveen+Bos, to have both a theoretical an empirical basis upon which the analysis would be carried out. The analysis focused on identifying the main issues that currently exist in regards to producing cost estimates based on BIM and 5D BIM elements. From the empirical results, it was clear that focus needed to be put not only on the cost estimation process from the perspective of the cost engineer, but also on preceding complementary processes, as decisions made "upstream" have an impact on the subsequent activities. Activity theory was used as an analysis framework that puts aside the individual as a unit of analysis, and instead focuses on the activity system as a whole in order to encourage discussion by stakeholders, to propose solutions that are fitting for entire communities (Q. Lu et al., 2018). By identifying the contradictions between elements of the activities, and between activities in the cluster, the main issues in reaching BIM based cost estimation were identified, namely lack of integration of the cost engineer, lack of standards, lack of defined guidelines, and lack of use of technological instruments. Adjustments to three key activities are proposed: cost estimation, project design and modelling, and project management and development A framework was proposed to integrate cost engineers in BIM-based project development, and furthermore, to allow cost estimation based on BIM and 5D BIM. The framework aims to link the activities together through a series of recommendations, and allows them to be performed in a logical collaborative manner that have the potential of bringing benefits to cost estimation, but also to other components of the development of a project, such as cost-based decision making which can improve the quality of the end product.

From a theoretical perspective one of the most relevant specific issues identified is the lack of integration of cost engineers in the process of developing a project though BIM, which had already been described by Aibinu and Venkatesh (2014). The results from interviews also showed that cost engineers have seen their participation in projects decrease over the years, partly due to the introduction of BIM, which among others, transferred the responsibilitiy of generating QTO's from the cost engineer (manual QTO) to the BIM modelers (semi-automatic QTO from BIM model). This hints at a BIM and 5D BIM adoption approach that doesn't account for the cost engineers, placing them at the margin of the project development process, further validating previous research.

Furthermore, cost engineers seem to still rely on traditional software and processes, that are not fully integrated with BIM-based project development, with an interviewee making an explicit statement in this regard. This is a point of attention given that the first concepts of BIM were introduced as far back as in the 1970's, and 5D BIM has been studied since the early 2010's, yet still, widespread adoption of the instrument has not been achieved. This research aims at providing an alternate view at this matter, by choosing a broader scope, and a holistic analysis tool that has not been commonly used in this field. The researcher is optimistic that the framework proposed has the potential to allow an increased integration of the cost engineer in BIM based project development, allowing in turn, the implementation of full scale 5D BIM. It should be noted, however, that the use of specialized cost estimation software such as Cleopatra, and Excel add-ons is still necessary in the cost estimation process, as they exceed current 5D BIM software features. Further research can be carried out in the integration of these specialized software with BIM.

Another identified issue which is deemed interesting in the research field of cost estimation and BIM-based project development is that of the management of non-graphical elements. This issue was not encountered in the literature review, but through the analysis of the empirical results it was identified that while easily overlooked, needs to be addressed. There are currently no provisions for the management of such elements, which still form part of a project and need to be accounted for. A solution is presented in the research, but further analysis is encouraged.

From a practical perspective, aside from the theoretical issues which are also relevant, the use of standards was the most widely recognized issue. Literature review presents that there are a number of available resources to be used in this regard, but in practice, their use is still not commonplace. The industry and individual companies should take a look in this aspect, to find convergence in a topic that has been researched, but is still not fully implemented.

There are some potential benefits of BIM that have been identified in the empirical results, but that are not realized through the solution and framework here stated. For these, it is required that another approach is taken, possibly analysing different activity systems to the ones selected for this research. This constitutes a potentially interesting case for further research.

During the research, it was observed that the potential of using BIM as a collaborative instrument goes beyond the realm of design and modelling, and higher dimensions of BIM have the possibility to make BIM models a unique source of information for actors involved in a project, and to create direct and indirect benefits. In this case, it was presented how integration of the cost engineer in a BIM based project development may have benefits not limited to the cost estimation process, but also for the development of projects in general terms. Thus, the importance of a broader analysis, such as the one that was possible through activity theory, to be carried out.

BIM, like other technologies (e.g., car, personal computer), has had an impact far beyond its initial concept. Nowadays, BIM does not only make it easier to design projects, based on three-dimensional geometry and information, BIM has created a paradigm shift that allowed the development of projects in an entirely new way, when compared to the traditional design with pen and paper (or computer aided) drawings. BIM has reached a point in which instead of focusing on adapting the instrument to fit within an organization's traditional processes, organizations should aim at adapting their subjects, instruments, rules, processes, and communities to it, in order to maximise the potential offered by such a technology, which has still not been exploited to its maximum potential. BIM is an instrument that thrives with collaboration, and has the potential to integrate the work of diverse actors in ways that were not possible before its introduction. It is of the belief of the author that the topic of BIM should be addressed from a broader perspective, instead of focusing on individual uses of the instrument, as isolated solutions may clash and overlap between themselves.

At the end of the research, it is possible to answer the main research question:

How can integration of cost engineers in a 5D BIM-based process impact the constellation of activities associated with cost estimation of infrastructure projects?

Integration of cost engineers in a 5D BIM process has benefits and implications that exceed the specific activity of cost estimation. To realize the integration, a framework was proposed, which revised the roles and scope of work of the main subjects that participate in the activities connected to cost estimation. Benefits were identified in three major activities, namely cost estimation, project design and modelling and project management and development. From the proposed framework, it is expected to obtain benefits as summarized in Table 8. These benefits can be classified in five major areas: improved information management, increased collaboration and communication, process improvement, increased product quality, and increased standardization.

Table 8: Benefits of integration of cost engineer in a 5D BIM based project development process.

Cost estimation	Design and modelling	Management and development
Standardized form and quality of quantity take-offs	Improved end product cost-benefit quality through cost-based design decisions	Increase involvement of cost engineers in project development
Standard management of non-graphical elements	(Virtually) real time rough cost analysis of design alternatives	Increased cost-based decision making aiming at improving the product
Faster and traceable cost estimate updates	Creation of models ready and optimised for QTO's	Increased integration and collaboration of actors
Earlier production of cost information	Creation of models that can be used as single sources of information:	Standardized and more structured project development
Decreased time requirement for handling information	Development of models with more appropriate levels of development per phase	More intensive project and stakeholder management.
Increased engagement and understanding of projects by cost engineers	Increased resource requirement for model development.	
Standard management of cost information	Increased complexity in responsibility distribution.	
Increased workload for cost engineers for complementary tasks.		

The proposed framework heavily relies on two major components, aside from the technological aspect: standardization, and collaboration. Research has already stated the importance of standardization (Poljanšek, 2017; Sunil et al., 2017), and of collaboration (Borrmann et al., 2018; Santos et al., 2020; Stanley & Thurnell, 2014) in implementation of BIM and 5D BIM. This research backs up these findings and the solution here proposed is based on both. It can be noted though that there is a two-way relationship between standardization and collaboration, and when implementing the framework, one should not go without the other. Collaboration without standardization will result in communication issues and with outcomes of individual tasks to lack consistency, while standardization without collaboration will result in individual tasks being carried in an isolated manner, without fully realizing complete integration perpetuating the identified problems related to communication and information. It is thus important to look at the proposed framework as more than the sum of its parts, which is precisely one of the foundations of activity theory.

An interesting point to highlight when answering the main research question, is that in order to achieve integration of cost engineers in 5D BIM project development, and further realize the benefits, some of the key recommendations come from outside of the immediate process of cost estimation and the role of the cost engineer. Namely, a standardised development of the previously defined conceptual model (with input from cost estimation standards), and the use of standards in BIM model development, are of vital importance, as they set the rules for the activities that precede cost estimation. At the same time, the key role of the systems engineer was identified, as they have the potential to act as integrators of activities and, are fundamental in reaching collaboration.

To finalize, the role of the cost engineer is far from becoming irrelevant, and should not be deemed as threatened due to the introduction of 5D BIM. Practitioners recognize the value of the cost engineer, and although it is acknowledged by some, it is important to highlight it: 5D BIM software and computers alone, will not replace cost engineers. If anything, the use of this software will make the work of cost engineers more efficient, so that they can better use their resources to have an impact in improved project development, and producing better end products.

6.2. Limitations.

One of the major limitations of the research is that only one case study company was used to gather the empirical data. Results, therefore cannot be generalised outside from a specific niche in the industry, which is that of companies in the engineering consultancy sector, focused on infrastructure projects. Nevertheless, the framework and recommendations were based not only on empirical results, but backed up by research previously carried by independent authors, and an effort was made to propose solutions that were not unique to the case study company, but to any company in the same industry. In general, the findings of the benefits of integration of the cost engineers can still be applicable, to companies in the engineering consultancy industry, to different extents.

It was not possible to follow a case study project, and the results are on a general level. This doesn’t allow to identify specific problems that may be overlooked by interviewees, but that can make up for unidentified issues. The research also does not appoint at specific solutions, and proposes recommendations and possible outcomes in a broad sense.

Due to time constraints, the results could not be implemented and tested in an actual project. As such, a quantitative analysis of the impact and extent of the identified benefits was not measured. Nevertheless, in order to validate the results of the research, validation interviews were carried out with experts in the field of BIM, to maintain rigorousness in the research method, and receive feedback to further optimise the results.

An important limitation is the location of the company, and the use of local guidelines, that is, being located in the Netherlands, and the use of Dutch guidelines, rules and standards. Although it was in the best of the interests of the researcher to keep the contents of the research as general as possible, some of the standards, roles, and names given to specific instruments and tools are specific to the Dutch engineering industry.

There are also limitations to the analysis framework used, activity theory. The theory includes a cycle of expansive learning, which was only partially achieved in the research, as the solutions were not fully realized in collaboration with the practitioners, but instead feedback was received to improve the solutions. Additionally, the theory accounts for implementation and testing, which, as already mentioned, did not fully take place in the research. Finally, up to the third generation, activity theory has been more widely used and tested as a framework for analysing and redesigning work, which can make it hard to reach general solutions, as individual activity systems are analysed, in this case, from a single company. Nevertheless, as the case study selected was a company instead of a single project, attention was put at leaving specifics on a side, and taking a broader perspective, that while it doesn't provide enough data to support full generalizations, allows to provide recommendations and solutions that are applicable in the same niche of the case study company.

The research focused also on the organizational and managerial aspects related to the integration of cost engineers in the development of projects developed through BIM, and while generalities were included in regards to the use of the instrument, there is necessarily a technical component to this integration which was out of the scope. This is a limitation, and a suggestion for further research, as the usability and interoperability of the instrument is key for successful integration of cost engineers, as inadequacies in the tool, can undermine the proposed framework's potential.

6.3. Further research

For future research, the first recommendation is to carry out an analysis based on activity theory, just as the current research, with either a larger case study sample, or at different companies in other geographical locations, in order to benchmark the results, and assess their applicability in other contexts, and be able to make claims on a general level.

The second one is the implementation of the proposed framework on a case study project, either directly in the Netherlands, or adapted to another country, and carry out a quantitative research of the benefits the framework can bring. Furthermore, additional benefits which have not yet been identified could become apparent in the implementation phase of the framework.

An additional suggested research is to carry out an activity theory analysis of the creation of a framework that further integrates planners, to reach 4D and 5D BIM, or even higher dimensions of BIM, keeping a holistic perspective that allows to account for the overall process and the activities that are integrated in it.

Further research can be carried out in the integration of specialized costing software with BIM or 5D BIM. Currently, the need for traditional non-BIM tools for costing is apparent, and developments need to be made to reach greater integration.

There are some potential uses of BIM that have been identified in the empirical results, but that are not realized through the solution and framework here stated. For these, it is required that another approach is taken, possibly analysing activity systems different to the ones selected for this research. This constitutes a potentially interesting case for further research.

7. Abbreviations

List of abbreviations used in the report, sorted alphabetically.

AEC	Architecture, Engineering and Construction
BIM	Building Information Modelling
CAD	Computer-Aided Design
CBS	Cost Breakdown Structure
CEN	European Committee for Standardization
ICMS	International Construction Measurement Standards
ICT	Information and Communications Technology
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
LOD	Level of Development
LOD	Level of Development
OBS	Object Breakdown Structure
PMBOK	Project Management Body of Knowledge
PMI	Project Management Institute
QTO	Quantity take-off
RICS	Royal Institution of Chartered Surveyors
SBS	System Breakdown Structure
SSK	Standard System for Cost Estimates
W+B	Witteveen + Bos
WBS	Work Breakdown Structure

8. Bibliography

Aapaoja, A., & Haapasalo, H. (2014). *The challenges of standardization of products and processes in construction.* Paper presented at the Proceedings of the 22nd Annual Conference of the International Group for Lean.

Aibinu, A., & Venkatesh, S. (2014). Status of BIM Adoption and the BIM Experience of Cost Consultants in Australia. *Journal of Professional Issues in Engineering Education and Practice, 140*, 04013021. doi:10.1061/(ASCE)EI.1943-5541.0000193

Akintoye, A., & Fitzgerald, E. (2000). A survey of current cost estimating practices in the UK. *Construction Management and Economics, 18*(2), 161-172. doi:10.1080/014461900370799

Alaloul, W. S., Liew, M., Zawawi, N. A. W. A., & Kennedy, I. B. (2020). Industrial Revolution 4.0 in the construction industry: Challenges and opportunities for stakeholders. *Ain shams engineering journal, 11*(1), 225-230.

Aound, G., Lee, A., & Wu, S. (2005). From 3D to nD modelling. *ITcon, Vol. 10*(Special issue From 3D to nD modelling), pg. 15-16. Retrieved from https://www.itcon.org/2005/2

Atkin, B., & Skitmore, M. (2008). Editorial: stakeholder management in construction. *Construction Management and Economics, 26*(6), 549-552. doi:10.1080/01446190802142405

Atkinson, R. (1999). Project management: cost, time and quality, two best guesses and a phenomenon, its time to accept other success criteria. *International journal of project management, 17*(6), 337-342.

Autodesk. (2021). Revit Overview. Retrieved from https://www.autodesk.eu/products/revit/overview?term=1-YEAR&support=null

Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and management in engineering, 11*(3), 241-252.

Baccarini, D. (1996). The concept of project complexity—a review. *International journal of project management, 14*(4), 201-204.

Barbosa, F., Woetzel, J., & Mischke, J. (2017). *Reinventing Construction: A Route of Higher Productivity*. Retrieved from

Barison, M. B., & Santos, E. T. (2010). *An overview of BIM specialists.* Paper presented at the Proceedings of the International Conference on Computing in Civil and Building Engineering.

Bharosa, N. (2015). *CHALLENGING THE CHAIN: Governing the automated exchange and processing of business information*: Ios Press.

Bishop, D., Felstead, A., Fuller, A., Jewson, N., Unwin, L., & Kakavelakis, K. (2009). Constructing learning: adversarial and collaborative working in the British construction industry. *Journal of Education and Work, 22*(4), 243-260.

Bond-Barnard, T. J., Fletcher, L., & Steyn, H. (2018). Linking trust and collaboration in project teams to project management success. *International Journal of Managing Projects in Business*.

Borrmann, A., König, M., Koch, C., & Beetz, J. (2018). *Building information modeling : technology foundations and industry practice* (1st edition. ed.). New York, NY: Springer Berlin Heidelberg.

Bosch-Rekveldt, M., Jongkind, Y., Mooi, H., Bakker, H., & Verbraeck, A. (2011). Grasping project complexity in large engineering projects: The TOE (Technical, Organizational and Environmental) framework. *International journal of project management, 29*(6), 728-739.

Bryman, A. (2012). *Social research methods* (4th ed.). Oxford ; New York: Oxford University Press.

Cerezo-Narváez, A., Pastor, A., Otero-Mateo, M., & Ballesteros-Pérez, P. (2020). Integration of Cost and Work Breakdown Structures in the Management of Construction Projects. *Applied Sciences, 10*, 1386. doi:10.3390/app10041386

Charef, R., Alaka, H., & Emmitt, S. (2018). Beyond the third dimension of BIM: A systematic review of literature and assessment of professional views. *Journal of Building Engineering, 19*, 242-257.

Charef, R., Emmitt, S., Alaka, H., & Fouchal, F. (2019). Building Information Modelling adoption in the European Union: An overview. *Journal of Building Engineering, 25*. doi:ARTN 100777

10.1016/j.jobe.2019.100777

Christensen, P., Dysert, L. R., Bates, J., Burton, D., Creese, R., & Hollmann, J. (2005). Cost Estimate Classification system-as applied in engineering, procurement, and construction for the process industries. *AACE, Inc, 2011*.

Citroen, C. L. (2011). The role of information in strategic decision-making. *International Journal of Information Management, 31*(6), 493-501. doi:https://doi.org/10.1016/j.ijinfomgt.2011.02.005

Collier, E. B. (1994). *Four-dimensional modeling in design and construction.* Stanford University,

Creswell, J. W. (2009). *Research design : qualitative, quantitative, and mixed methods approaches* (3rd ed. ed.). Los Angeles: Sage.

Dubois, A., & Gadde, L.-E. (2002). The construction industry as a loosely coupled system: implications for productivity and innovation. *Construction management & economics, 20*(7), 621-631.

Eastman, C., Fisher, D., Lafue, G., Lividini, J., Stoker, D., & Yessios, C. (1974). An outline of the building description system. *Research Rep, 50*, 1974.

Eastman, C. M., Teicholz, P. M., Sacks, R., & Lee, G. (2018). *BIM handbook : a guide to building information modeling for owners, managers, designers, engineers and contractors* (Third edition. ed.). Hoboken, New Jersey: Wiley.

Elbeltagi, E. (2014). *Construction Site Layout Planning*.

Elghaish, F., Abrishami, S., Hosseini, M. R., & Abu-Samra, S. (2020). Revolutionising cost structure for integrated project delivery: a BIM-based solution. *Engineering Construction and Architectural Management*. doi:10.1108/Ecam-04-2019-0222

Engestrom, Y. (2000). Activity theory as a framework for analyzing and redesigning work. *Ergonomics, 43*(7), 960-974. doi:10.1080/001401300409143

Engeström, Y. (2015). *Learning by Expanding*: Cambridge University Press.

Engeström, Y., & Sannino, A. (2020). From mediated actions to heterogenous coalitions: four generations of activity-theoretical studies of work and learning. *Mind, Culture, and Activity*, 1-20.

EU BIM Task Group. (2017). Handbook for the Introduction of Building Information Modelling by the European Public Sector.

European Committee for Standardization. (2021). What is a Standard? Retrieved from https://www.cen.eu/work/endev/whatisen/pages/default.aspx

Fellows, R. F., & Liu, A. M. (2015). *Research methods for construction*: John Wiley & Sons.

Floricel, S., Bonneau, C., Aubry, M., & Sergi, V. (2014). Extending project management research: Insights from social theories. *International journal of project management, 32*(7), 1091-1107. doi:https://doi.org/10.1016/j.ijproman.2014.02.008

Forgues, D., Iordanova, I., Valdivesio, F., & Staub-French, S. (2012). *Rethinking the cost estimating process through 5D BIM: A case study.* Paper presented at the Construction Research Congress 2012: Construction Challenges in a Flat World.

Freeman, R., & McVea, J. (2001). A Stakeholder Approach to Strategic Management. *SSRN Electronic Journal*. doi:10.2139/ssrn.263511

Ghaffarianhoseini, A., Tookey, J., Ghaffarianhoseini, A., Naismith, N., Azhar, S., Efimova, O., & Raahemifar, K. (2017). Building Information Modelling (BIM) uptake: Clear benefits, understanding its implementation, risks and challenges. *Renewable & Sustainable Energy Reviews, 75*, 1046-1053. doi:10.1016/j.rser.2016.11.083

Graphisoft. (2021). Graphisoft ArchiCAD. Retrieved from https://graphisoft.com/solutions/products/archicad

Greves, D., & Joumier, H. (2003). Cost Engineering for Cost-effective space programmes. *ESA bulletin, 115*, 71-75.

Hasan, A. N., & Rasheed, S. M. (2019). The Benefits of and Challenges to Implement 5D BIM in Construction Industry. *Civil Engineering Journal-Tehran, 5*(2), 412-421. doi:10.28991/cej-2019-03091255

Haugan, G. T. (2001). *Effective work breakdown structures*: Berrett-Koehler Publishers.

Hendrickson, C., Hendrickson, C. T., & Au, T. (1989). *Project management for construction: Fundamental concepts for owners, engineers, architects, and builders*: Chris Hendrickson.

International Cost Engineering Council. (2002). *What are Cost Engineering, Quantity Surveying and Project Management? [White Paper]*. Retrieved from http://www.icoste.org/about/whatare/

Ismail, N. A. A., Adnan, H., & Bakhary, N. A. (2019). *Building Information Modelling (BIM) adoption by quantity surveyors: a preliminary survey from Malaysia.* Paper presented at the IOP Conference Series: Earth and Environmental Science.

ISO. (2018). ISO 19650-1:2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling. In (Vol. ISO 19650-1:2018).

Jung, W., & Lee, G. (2016). Slim BIM Charts for Rapidly Visualizing and Quantifying Levels of BIM Adoption and Implementation. *Journal of Computing in Civil Engineering, 30*(4). doi:Artn 04015072

10.1061/(Asce)Cp.1943-5487.0000554
Kubba, S. (2012). Chapter 14 - Types of Building Contract Agreements. In S. Kubba (Ed.), *Handbook of Green Building Design and Construction* (pp. 633-676). Boston: Butterworth-Heinemann.
Kujala, J., Brady, T., & Putila, J. (2014). Challenges of cost management in complex projects. *International Journal of Business and Management, 9*(11), 48.
Laakso, M., & Kiviniemi, A. (2012). The IFC standard: A review of history, development, and standardization, information technology. *ITcon, 17*(9), 134-161.
Larsson, J., & Larsson, L. (2020). Integration, application and importance of collaboration in sustainable project management. *Sustainability, 12*(2), 585.
Lee, X. S., Tsong, C. W., & Khamidi, M. F. (2016). *5D Building information modelling–a practicability review.* Paper presented at the MATEC Web of Conferences.
Lu, Q., Chen, L., Lee, S., & Zhao, X. (2018). Activity theory-based analysis of BIM implementation in building O&M and first response. *Automation in construction, 85*, 317-332.
Lu, W., Lai, C. C., & Tse, T. (2018). *BIM and Big Data for Construction Cost Management*: Routledge.
Luo, L., He, Q., Jaselskis, E. J., & Xie, J. (2017). Construction project complexity: research trends and implications. *Journal of Construction Engineering and Management, 143*(7), 04017019.
Matejka, P., & Vitasek, S. (2018). Comparison of different cost estimation methods with use of building information modelling (BIM). *Engineering for Rural Development, 17*, 843-849.
Mayouf, M., Gerges, M., & Cox, S. (2019). 5D BIM: an investigation into the integration of quantity surveyors within the BIM process. *Journal of Engineering, Design and Technology*.
Monteiro, A., & Martins, J. P. (2013). A survey on modeling guidelines for quantity takeoff-oriented BIM-based design. *Automation in construction, 35*, 238-253.
Mor, R. S., Bhardwaj, A., Singh, S., & Sachdeva, A. (2019). Productivity gains through standardization-of-work in a manufacturing company. *Journal of Manufacturing Technology Management*.
National Institute of Building Sciences. (2015). National BIM Standard - United States® Version 3. In *3 Terms and Definitions*.
Neff, G., Fiore-Silfvast, B., & Dossick, C. S. (2010). A CASE STUDY OF THE FAILURE OF DIGITAL COMMUNICATION TO CROSS KNOWLEDGE BOUNDARIES IN VIRTUAL CONSTRUCTION. *Information, Communication & Society, 13*(4), 556-573. doi:10.1080/13691181003645970
Nicholas, J. M., & Steyn, H. (2017). *Project management for engineering, business and technology* (Fifth Edition. ed.). London ; New York: Routledge, Taylor & Francis Group.
Oesterreich, T. D., & Teuteberg, F. (2016). Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Computers in industry, 83*, 121-139.
Oxford Reference. (Ed.).
Poljanšek, M. (2017). Building information modelling (BIM) standardization. *European Commission*.
Popov, V., Juocevicius, V., Migilinskas, D., Ustinovichius, L., & Mikalauskas, S. (2010). The use of a virtual building design and construction model for developing an effective project concept in 5D environment. *Automation in construction, 19*(3), 357-367. doi:10.1016/j.autcon.2009.12.005
Project Management Institute. (2017). *A guide to the project management body of knowledge / Project Management Institute* (Sixth edition. ed.). Newtown Square, PA: Project Management Institute.
Rijkswaterstaat. (2021). *Werkwijzebeschrijving Systeem Ontwikkeling & Specificeren Opstellen van een objectenboom*.
Robinson, W., Chan, P., & Lau, T. (2016). Finding New Ways of Creating Value: A Case Study of Servitization in Construction. *Research-Technology Management, 59*(3), 37-49. doi:10.1080/08956308.2016.1161405
Roy, R., Low, M., & Waller, J. (2005). Documentation, standardization and improvement of the construction process in house building. *Construction Management and Economics, 23*(1), 57-67.
Royal Institution of Chartered Surveyors (RICS). (2012). *RICS NEW RULES OF MEASUREMENT NRM 2: Detailed measurement for building works*. Coventry: Royal Institution of Chartered Surveyors (RICS).
Royal Institution of Chartered Surveyors (RICS). (2020). *ICMS explained A user guide for the second edition of the International Construction Measurement Standards*. Retrieved from London:
Santos, M. C. F., Costa, D. B., & Ferreira, E. d. A. M. (2020). *Conceptual Framework for Integrating Cost Estimating and Scheduling with BIM.* Paper presented at the International Conference on Computing in Civil and Building Engineering.

Sattineni, A., & Macdonald, J. A. (2014). *5D-BIM: A case study of an implementation strategy in the construction industy.* Paper presented at the ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction.

Seaden, G., & Manseau, A. (2001). Public policy and construction innovation. *Building Research & Information, 29*(3), 182-196.

See-Lian, O., Muse, A., O'Sullivan, G., Aronsohn, A., Baharuddin, D., Chatzisymeon, T., . . . Ki-Cheung, T. (2019). *International Construction Measurement Standards: Global Consistency in Presenting Construction and Other Life Cycle Costs*.

Shelbourn, M., Bouchlaghem, N., Anumba, C., & Carrillo, P. (2007). Planning and implementation of effective collaboration in construction projects. *Construction Innovation*.

Slaughter, E. S. (1998). Models of construction innovation. *Journal of Construction Engineering and Management, 124*(3), 226-231.

Smith, P. (2016). Project cost management with 5D BIM. *Procedia-social and behavioral sciences, 226*, 193-200.

Sohi, A. J., Hertogh, M., Bosch-Rekveldt, M., & Blom, R. (2016). Does lean & agile project management help coping with project complexity? *Procedia-social and behavioral sciences, 226*, 252-259.

Stanley, R., & Thurnell, D. (2014). The benefits of, and barriers to, implementation of 5D BIM for quantity surveying in New Zealand.

Star, S. L., & Griesemer, J. R. (1989). Institutional ecology,translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social studies of science, 19*(3), 387-420.

Sunil, K., Pathirage, C., & Underwood, J. (2017). *Factors impacting Building Information Modelling (BIM) implementation in cost monitoring and control.* Paper presented at the 13th International Postgraduate Research Conference (IPGRC): conference proceedings.

Vakkayil, J. D. (2010). Activity Theory: A Useful Framework for Analysing Project-Based Organizations. *Vikalpa, 35*(3), 1-18. doi:10.1177/0256090920100301

Vigneault, M.-A., Boton, C., Chong, H.-Y., & Cooper-Cooke, B. (2019). An Innovative Framework of 5D BIM Solutions for Construction Cost Management: A Systematic Review. *Archives of Computational Methods in Engineering, 27*, 1-18. doi:10.1007/s11831-019-09341-z

Weiss, R. S. (1994). *Learning from strangers : the art and method of qualitative interview studies*. New York

Toronto: Free Press ;

Maxwell Macmillan Canada ;

Maxwell Macmillan International.

Weske, M. (2019). *Business Process Management: Concepts, Languages, Architectures*.

Zanni, M. A., Soetanto, R., & Ruikar, K. (2017). Towards a BIM-enabled sustainable building design process: roles, responsibilities, and requirements. *Architectural Engineering and Design Management, 13*(2), 101-129. doi:10.1080/17452007.2016.1213153

9. Annexes

9.1. Annex 1

Annex 1: List of interviewees

Role	PMC	Group	Position	Years at company
Project Managers				
PM01	Infrastructure construction	BIM Model development and coordination	Project manager	13
PM02	Construction Management	BIM - Project information management	Group leader	12
PM03	Construction Management	Management	PMC Leader	11
PM04	Ports, waterways and dredging	Sustainable ports development	Project manager	13
PM05	Infrastructure construction	Design management	Project manager	29
BIM Modellers				
MO01	Lifecycle management	Circular design and redesign for infrastructure	Modeller	3
MO02	Replacement and renovation of construction works	3D design	Modeller	6
MO03	Infrastructure construction	Dynamic modelling	Senior modeller, Revit administrator	11
MO04	Infrastructure construction	Dynamic modelling	Modeller	5
BIM Managers				
MA01	Ground infrastructure	Construction technique	BIM manager	2
MA02	Infrastructure construction	BIM Model development and coordination	BIM manager	15
MA03	Infrastructure construction	BIM Model development and coordination	BIM manager	40
Cost Engineers				
CE01	Construction Management	Cost Management	Team manager of cost engineers	22
CE02	Construction Management	Cost Management	Cost engineer / advisor	28
CE03	Construction Management	Cost Management	Cost engineer	14
Systems Engineers				
SE01	Smart infra systems	Systems integration	Systems engineer	3
SE02	Lifecycle management	Asset information management	Group leader	6

9.2. Annex 2

Annex 2: Requirements for selecting interviewees.

The first characteristic, is that projects must have used BIM for the development of their designs. The size of the project is of less importance, as long as it was developed in a BIM environment. Projects following good practices of BIM were highly desirable, although exploration of projects in which BIM is not fully parametrized was also acceptable. The second hard requirement was that the cost estimation of these projects was done in-house at the company, so that the process was followed internally, and a full overview of it could be attained.

In terms of the design levels, it was desired to gain explorative data of projects in different design phases, namely Preliminary Design, Definitive Design, and Construction Design, to explore the transitions of the models and cost estimates between these phases.

People interviewed were asked not only about their experience in the projects they were currently developing, but also to answer from their past experiences, in order to obtain more general overview. In terms of types of projects, the research leans more towards the infrastructure sector, as that is where BIM is better implemented in the company, but answers from other types of projects were also accepted.

9.3. Annex 3

Annex 3: State of affairs full results

a) State of Affairs: Systems Engineering

To a greater or lesser extent every project contains elements of Systems Engineering. However, the involvement of Systems Engineers becomes more necessary the larger the project is. The process starts with the construction of an object tree (OBS), in the level of detail required specifically by the project, in the environment of the software Relatics. However, OBS is not the only breakdown structure used, and WBS and SBS are also commonly used.

The WBS and SBS are commonly used further for the development of the BIM models, and frequently become the base for the QTO's. On each project, a unique coding system is developed for the model, due to the company working with a number of different clients, each having their own requirements on the presentation of information. Nevertheless, the coding systems of projects are based on a number of standards such as ILS (Informatie Leverings Specificatie), OTL (Object Type Library) Rijkswaterstaat (Directorate-General for Public Works and Water Management of the Netherlands), NLRS (Nederlandse Revit Standaard), among others, and at the company, it is mostly BIM coordinators who decide which structure to follow. This goes in contrast with asset management, where an interviewee explained how they use standards such as the NEN 2767, which sets a method for breaking down assets, making it likely that independent systems engineers in different companies come down to a similar decomposition if working with the same standard.

It was mentioned by a respondent that in construction projects, there is always debate on what is the best way to decompose projects, i.e., which breakdown structure form to use. It was also remarked that the systems engineer is responsible for creating systems breakdowns that are suitable for the BIM designer, cost engineer, client, and any other important stakeholder. It is added that breakdown structures are inherently interrelated between themselves. A quote by SE02 summarizes the relation between breakdowns:

> *"If, I do a project and I'm a cost engineer, my project is an Excel sheet. But if I do a project, and I am a designer, my project is this AutoCAD, or something. And when I'm the systems engineer, my project is Relatics. But these are the same products with very different views"* (SE02)

Lastly, adding to the interrelatedness of the different breakdowns, it was expressed by one of the systems engineers, that efforts and progression is being made into achieving integration of the different areas participating in a project through systems engineering, but the company has not fully succeeded there yet.

b) State of Affairs: Project management

In the company, projects are often developed in design loops. These loops are usually related though not perfectly aligned with the different design stages, e.g., preliminary, detailed, final, etc. There is not a set number of loops, but respondents mentioned it is normally three, and it is the project manager's decision to select this number. During the loops, all different disciplines and actors working on the project, do so mainly in an individual manner, and at the end of the loops, all the work is brought together, and a single, coordinated model is created. In the middle of the design loops process, is Relatics, i.e., the systems engineering approach to breaking down the work. One advantage mentioned by a project manager respondent of this work methodology, is the possibility to have all different disciplines aligned at specific moments in time. However, this is not an advantage for all stakeholders, and in this methodology, cost engineers frequently come in at the last moment, after the individual specific designs are complete. CE01 summarized the situation as:

"…unfortunately, often we come in too late, the design is ready, and some project manager asks, 'hey, what will this cost?' So that's not a cost optimized design" (CE01)

Another interesting observation, is the position of BIM modelers in the project development. They generally seem well connected with other stakeholders, and one respondent mentioned that one of the reasons, is that the company has designers, and not draftsmen. This allows the modelers (designers) to have a broader overview and look not only at individual models, but also how they interact with each other. However, an important remark was made by PM02, who stated:

"With BIM in general as well, we encounter each project as special every time. We think, 'this project is totally different scope, we never did before'. And it's true. But there are also components we did before. It is also … about the breakdown what we use, and it's not standardized there as well. So, people do not recognize the objects that are the same." (PM02)

This shows that projects are developed as entirely unique endeavors.

c) State of Affairs: Model development

As was mentioned in the preceding paragraph, the projects normally follow a series of loops during their development. As projects move forward in phases, there are additional needs from the cost engineers to have specific information in the model, in order to prepare an appropriate cost estimate at the end of each loop. This is key in the development of the models, as these requirements usually drive the modelers to add information. In earlier stages, something as simple as an object's name can already be enough to make a rough cost estimate. As phases progress, object codification and subdivision become necessary to include information parameters required by the cost engineer to properly quantify the project, and deliver a correct cost estimate for each phase. However, a recurring remark is that oftentimes, the level of detail of information delivered to the cost engineer at the end of a design loop mismatches the phase of the design, and regularly, too much detail is given at early stages, when it is deemed unnecessary.

For the codification of objects in the modelling software, the breakdown structures of systems engineering are regularly used. Mostly, the systems breakdown structure is employed, and the SBS code corresponds to a "major" string composed of substrings, where each substring represents a level of the object tree of the project. At the lowest level of the code, the element is identified, and it is possible to include within its parameters additional physical metadata useful for cost engineers, such as width, length, etc. In most larger projects, this breakdown is managed through Relatics. In these cases, codes are transferred from Relatics to the BIM models in two steps. First, the information from Relatics is exported to Excel. Second, the information is extracted from Excel and added to each element in the model with the use of Dynamo scripts, an instrument that allows the automation of tasks in Revit through simplified programming. To aid in adding information to objects in the model, templates have been created at the company, in which parameter fields are already created and ready to be filled in, so that designers can directly input information within them. When a new project is started, these parameter fields are automatically included in all elements created.

Nevertheless, there are often still problems with codification in regards to standardization. Although the codification is said to follow the divisions made by the systems engineer in the breakdown structures, this does not always happen, and some projects are still being developed with the modeler codifying the model as they see most fit. There is also not a single BIM guideline in use in the Netherlands, and MO03 states the current situation:

"…there are so many different classifications already around. Yeah, which one do you choose? There's not really one that stands out." (MO03)

An additional aspect that attracts attention from the development of the model is the differences in the relationships between the BIM modelers and other stakeholders. It was mentioned in several interviews that for a successful development of the designs, it is expected that the BIM modeler works closely with the specialist engineers (structural, geotechnical, hydraulics, etc.). However, this is diametrically opposed to what was expressed about the relation between the BIM modelers and cost engineers, as commonly, the former is expected to simply deliver their output to the latter, and seldom is there backwards communication, except for the cases in which there are inquiries by the cost engineer. A quote by MO04 bluntly shows the extent of this lack of collaboration:

"…if everything goes correct, and everything goes fine the way that it should, I am able to make a design without the interference of the cost engineer entirely." (MO04)

In the end, this translates to design decisions usually not being made based on cost information.

d) State of Affairs: Quantity Take-Off

Once a model has reached a sufficient development level, towards the end of a design loop, a quantity take-off is done, mostly by extraction of the quantities from the model. Before the extraction of quantities however, the models usually undergo a validation process, in which the interfaces are checked, and clash detections are carried out.

It is mentioned that in order to be able to properly do the take-off, proper parametrization of the model must have been defined in the BIM protocol in earlier stages. This step is done by the BIM modelers. The actual process of quantity extraction from Navisworks to Excel is deemed as highly automatized, given that all parameters have been properly set. However, the form and content of the quantity take-off is not standardized. BIM modelers often do not know what exactly is required to be delivered to the cost engineers, and it is necessary that the latter explicitly states it, creating tensions between the two actors. This is mainly due to specific requirements from clients. It is mentioned that information given to the cost engineers can vastly vary in form, and some examples are spreadsheets, 2D drawings, models, or even links to locations on Google Maps Street View. However, the main deliverable is usually an Excel file with the quantities of the model, and some supporting documentation to give context to the project, although this can sometimes lack in depth. When inquired as to why are the quantity take-off not done directly by cost engineers, CE02 said:

"We cannot make the quantity take-off ourselves, or we cannot show or export any information from the model, and that's something to work on." (CE02)

Additional to the state of affairs of the quantity take off, this also sheds some light on the usage of BIM instruments by the cost engineers.

As for the quantity take-off from the BIM model itself, there are a number of comments regarding it. Firstly, the use of BIM instruments for the (semi-automatic) quantity take-off is seen as generally an improvement when compared to more traditional CAD or 2D processes, which had to be done "by hand". However, a number of respondents mentioned that the quantities in these take-offs generated by the BIM instruments are oftentimes reported as "not perfect", and not always complete. Furthermore, the form of these is not standardized. Finally, it is mentioned that there is not a live link between the model and the cost estimation software, and the QTO is deemed as "quite static".

e) State of Affairs: Non-graphical elements.

An interesting finding from the interviews, is that commonly, not all elements or requirements from a project are graphically modeled in BIM. These elements usually fall in two categories: temporary works, and complementary elements. Some of the elements that fall in the first category are formwork, and temporary sheet piles. In the second one, bird housings, or fauna protection elements were mentioned. These elements do impact the cost estimate. As such, it is mentioned that there is not a standard, single way of accounting for these elements, but that it commonly falls under the responsibility of the cost engineers and project manager to estimate them. CE02 describes the situation as:

"…it's up to us from experience or up to the project leader from his experience to insert other things that are not on the drawing. The temporary issues, items to help to put the project together, the things beneath the surface, or things in the surroundings of the project that have to be prepared." (CE02)

It is then seen that this is an issue commonly dealt with based on the experience of either cost engineer, or project manager. Lastly, this step is described by a project manager respondent as "sort of reactive and not very proactive".

f) State of Affairs: Estimating costs.

Estimating costs is the name given to the activity of actually including cost information to a project. A first result here, is that the task does not only comprise estimation of costs in the QTO, but also those activities outside of the model, and furthermore, the quantification of bottom-line items such as general costs, profit, risks, etc. The process is dependent on the stage of the design, with the detail level of the design, and the cost estimate being directly related, with PM05 emphasizing:

"…the level of detail of a calculation, its cost calculation, strongly depends on the stage of the design" (PM05)

This was further exemplified by various respondents, and it was mentioned that generally, in earlier stages, rough dimensions of entire objects (viaducts, tunnels, roads, etc.) are enough to create rough cost estimates, and it is only at later stages, that detailed QTO's become necessary to provide more accurate cost estimates. In any case, the process of estimating costs usually is done in the same manner. The cost engineer receives information from the BIM modeler, frequently in the form of a QTO in an excel spreadsheet, with some additional information to allow the cost engineer understand better what is being costed. With the QTO in excel, the cost engineer commonly modifies or extracts the data to be fit in an SSK template. The SSK has a plugin that creates templates in Excel to present costs in a standardized manner. Once the project information is in the SSK template, the cost engineer proceeds to add costs to each line element. This is done in mainly two ways. First, the cost engineer can add cost information directly to each element, based on his own knowledge and expertise, or second, he can make use of the software Cleopatra, a specialized costing software, to make detailed unit rates. During this process of adding cost information to the elements, two cost engineering respondents mentioned the importance of identifying cost driver elements in the design, as these are sometimes the only ones costed in a detailed manner, while the rest can be roughly estimated.

Along the lines of the actual cost information cost engineers emphasized that two similar objects, or elements, for example a square meter of asphalt road, can have different costs, depending on the context and requirements of the element and the project. Some of the mentioned factors that impact the cost are geographical location of the element or object in relation with its surroundings (for example location surrounded by buildings), but also in relation to the project itself (paving with asphalt next to a plant, vs deep in a tunnel), the amount of the element to be installed (thousands of square meters for a road, vs. ten square meters for a reparation), and temporary structures required for carrying the works. Because of this, additional information regarding the project's context is commonly asked to be delivered with the QTO's. However, this point is seen as problematic, and cost engineers are commonly finding the information received insufficient. When asked about this matter, and if they received enough information to assess the context and characteristics of the elements and the project, CE01 answered:

"No, no, people do not even know the words. There's no proper word for it in Dutch" (CE01)

As previously mentioned, the additional information that is sent to the cost engineers in addition to the QTO's, varies vastly in form, and it is the former who decide which information to deliver to the latter. Of special importance for the research was determining the way in which cost engineers receive design information, specifically whether this was delivered as 2D drawings or 3D (or higher D) models. When asked specifically about this, the cost engineers interviewed actually had different opinions. CE01 and CE02 both expressed they had worked previously with 3D models, having received design information in a BIM format. However, CE02 expressed their preference for working with 2D drawings, by stating:

"In my situation, I work most of the time in the [PROJECT'S NAME], it's done in models. I hope the rest of the team is still working with drawings, because it's easier to understand the project in a drawing." (CE02)

Furthermore, CE03 stated that they had never worked with BIM models, and still uses design information from traditional design methods, expressed as:

"I've not had any BIM information for my projects. So basically, I've been getting my information the same way for the past 14 years" (CE03)

Also interesting from the interviews, is the high regards that most of the other roles hold for the cost engineers, with many citing their knowledge and autonomy as some of their strong points. When referring to the work of cost engineers, PM04 answered:

"…it's my perception of the cost estimators that [they] are very self-sufficient, capable team, so sort of give them a job, and then once they're done, they have done the job correctly, and you get the results that you want." (PM04)

However, this autonomy was also highlighted as a negative point. Several respondents answered that the costing process carried out by the cost engineers is not transparent for the rest of the stakeholders involved in the process. No mention is made of the cost engineers receiving input from other areas during this step, aside from clarification of quantities. Regarding this, MA02 mentioned:

"… what they [the cost engineers] are really doing is for the designers, and let's say structural engineers, really like a black box. (MA02)

This is accentuated by the usually late involvement of the cost engineers in the process. Respondents from all five roles mentioned that the cost engineer almost always join at the end of the process. On the reason behind this, PM03 replied:

"…it's more of an organizational thing, where the cost estimators are always only added at the last moment, and then have to do it on the spot instead of being involved in time." (PM03)

g) State of Affairs: Updates to the cost estimate.

These updates can occur either because of changes in the design, or progress through the phases. The updates happen at irregular intervals, depending on the characteristics of the project. At a minimum, there are updates at the end of each design loop. The updates usually take form in the extraction of a new QTO by the BIM modeler. However, updates usually modify not only quantities, but the form of the QTO itself, to the point that some respondents mentioned that it is preferrable for the cost engineers to prepare an entirely new cost estimate with the updated information. CE03 said regarding to this:

"I prefer to start over … The reason I would like to start from scratch again, is because if there's a lot of changes, then I might miss one." (CE03)

Lastly, it was mentioned that if the model has been properly set up, the extraction of an updated QTO is a simple (semi) automatic process by the BIM modeler.

9.4. Annex 4

Annex 4: Connectedness full results.

a) Connectedness through collaboration

In the development of projects, a collaborative relationship is generally seen during the design activity, especially between the 3D modelers, and the specialist engineers. This is usually a close collaboration, and MO04 describes it as:

"…the relation between the structural engineers and the designers [modelers], I think, it's kind of like a symbiotic relationship. That's what I would describe it, I think, we cannot have one without the other." MO04

In this collaboration, design decisions are made, making sure that the output meets the requirements and expectations. However, this extends further than just a relationship between the two, and the project managers also expressed the importance of being involved in the design process together with the other stakeholders, in order to make decisions. Collaboration is also seen in the project development process of executing design loops. As mentioned by a project manager, the idea of the loops is to bring everything together at the end of each loop. Furthermore, it is an important characteristic of the company to reduce the distance between senior and junior colleagues, so that there can be better communication.

BIM is also mentioned in the themes of collaboration, and the importance of managing the different interfaces of the model in order to get proper information in time. Additionally, it is mentioned that BIM increases collaboration. CE01, said about this:

"… that is what I think, currently is BIM: working together in a digital environment." CE01

Lastly, it is mentioned that for the preparation of cost estimates, there can be collaboration between the cost engineers and other parties such as the project managers, or the BIM modelers. This collaboration however, is usually for review purposes, only carried out after an initial cost estimate is made, and only after the cost engineer has formulated questions regarding the quantities or designs, in order to clarify information.

b) Connectedness through one sided communication

Although it was mentioned that there is collaboration for the review of cost estimates, the interaction between cost engineers, and 3D modelers or project managers, is predominately one sided, especially in the process immediately previous to preparing the estimates. It was mentioned by a majority of respondents, that the cost engineers merely receive a package of information prior to the preparation of their estimates, and once ready, deliver back their results, or gather for a review session. The same is said to apply generally for the update of cost estimates, in which modelers or project managers simply provide new information to the cost engineer, usually in the form of an email. When asked to compare their relationship to the cost engineer, to that of the specialist engineers, MO04 said:

"A cost engineer, however, cannot have a cost estimate without our input. So, it's a more one-sided relationship in that case." (MO04)

c) Connectedness: lack of communication.

It is mentioned that there is commonly a lack of communication between the cost engineers and the rest of the team developing the project, and seldom are they integrated early in the project. SE02 expressed about this integration and its impact for decision making:

"…the cost engineers are not really integrated in the team. So, they work in their own their own silo … when I make a design decision, it's only roughly cost based. It doesn't really involve any input from the cost engineer." (SE02)

Additionally, lack of communication has been mentioned as well in the transfer of quantity information from the modeler to the cost engineer. PM04 concisely explained the situation as this:

"I think they [the 3D modelers] struggle in getting the information across. So, I think the cost estimator, always expects something else than what they're getting from, from the modelers … So, I think it's not a very good relationship because of different expectations most of the time. "(PM04)

Interesting to mention, several of the respondents expressed surprise and self-reflected when asked about the topic of relations, especially where lack of communication was present. This surprise was expressed in the form of non-verbal communication such as long pauses, and stuttering before answering, but SE02 openly mentioned after being asked such a question:

"…now that you mentioned it, I would say that we should have closer relationship [with the BIM modelers]." (SE02)

9.5. Annex 5

Annex 5: Problem perception full results.

a) Lack of involvement of the cost engineer in the project development process.

With an almost unanimous consensus, lack of involvement of the cost engineer in the project development is seen as a problem of the current process. The answers here vary also as for why this is a problem, but two sub themes were identified:

- Lack of involvement of the cost engineer in the project development process: Limited input from the cost estimators to the project.

Respondents from all five roles agree that currently, cost estimators are generally not involved early in the development of a project to provide input that may have an impact on it, and decisions are made without cost information being able to influence the outcome. A comment by SE02 summarizes the generalized feeling of respondents:

"… cost engineers are not really integrated in the team. So, they work in their own silo … but I think, on an engineer level, or system engineer level, where you just know, when I make a design decision, it's only roughly cost based. It doesn't really involve any input from the cost engineer … cost figures come too late, and you can't really change the design anymore." (SE02)

- Lack of involvement of the cost engineer in the project development process: Insufficient project information to produce quality cost estimates.

This problem, expressed by cost engineers themselves, but also backed by interviewees from other roles, states that generally cost estimators are added at the end of each of the design phases, and need to produce a cost estimate with limited time and knowledge of the project itself, possibly affecting the quality of cost estimates. CE02 explains this from his point of view:

"… for us as the estimators, and I don't know how to say, it's going too fast. You're not getting involved with a project, you have no feeling with the project, you miss [important information]. And I think sometimes it is also affecting the quality of the estimate." (CE02)

b) Inappropriate information.

A number of identified issues with information were mentioned by respondents that relate back to the same root. The identified issues with inappropriate information are: information taking an incorrect form (e.g., having to convert information from a Navisworks raw export into a useable excel spreadsheet), information transfer and loss of information (e.g., sending a QTO exported from Navisworks by email, losing traceability), static information (e.g., exports from Navisworks being static and not updating dynamically with model updates), mismatching detail levels of information (e.g., having very detailed models in early design where only rough geometric dimensions are needed), QTO's having limited information (e.g., QTO having only physical quantity information without giving contextual information of the elements, or project. Also, QTO's not including non-graphical elements information) and lastly, but not least important, not being able to determine the value of information (e.g., focusing too much on less-important information such as elements that are not cost drivers of the project, while relegating important ones). The answers were varied, however, PM04 makes an interesting statement with regards to the issue of information generated by BIM for cost engineers to make the cost estimates:

"But the downside is that we generate so much data or information, that establishing the actual value of that information, and the correctness and the usefulness for the cost estimate is actually maybe taking more time than it would actually save time in making it easier" (PM04)

c) Lack of standardization

Lack of standardization permeates the entire project development process, and was identified in almost every step that leads up to the production of a cost estimate. The general issue, is that the lack of standardization leads to having heterogeneous outputs of intermediate processes which in turn are the input for subsequent processes. Important to note in this point, reference was made both to standardization as in the use of national, or international standards (e.g., ISO standards), but also to standardization as a common way of carrying out processes. Two quotes, from SE02 and CE01 exemplify the issue of lack of standardization, and sheds some light on how it extends through different stages in the project.

"… we're not really able to really define the architecture [breakdown structures], I'm currently doing this in a new project, but to define the architecture of everything working together, and we, I think, in our company, we don't have enough people that really have the skills to really work the entire structure out with all the specialists and all the different needs." (SE02)

"I think one of the biggest problems within the company is the lack of a standardized structure. We have over 1300 employees, and maybe hundreds of them think about their own structure and reinventing the wheel… we've seen hundreds of different ways of working, and ways of engineering projects." (CE01)

- Special note: Standardization of project breakdown.

An issue related to standardization, but relevant enough in the context of the research to be mentioned individually. The absence of a single standardized method for project breakdown starts at the creation of an object tree, but has far reaching consequences that also affect the cost estimation process. The conceptual breakdown of a project at the systems engineering phase will determine how the project is designed and modelled, and further, has an impact in the form of the QTO used by cost engineers to produce a cost estimate. Regarding this, MO03 stated:

" Sometimes you notice…that the people for planning are using slightly different [breakdown structures] then you get a problem on all kinds of levels because everybody's talking about something slightly different. And that's something you don't want." (MO03)

d) Asymmetrical adoption of technological instruments.

Relates to the use (or lack of) of different software or processes, namely BIM within the context of this research, by the different actors that participate in the development of projects, but more specifically (although not limited) by cost engineers to produce cost estimates. Noteworthy, this is a problem identified and expressed by roles other than cost engineers themselves, meaning the latter do not consider this to be a major issue. The consequences of this asymmetry are loss of continuity in the search for being more efficient through the use of new technologies. Two quotes, by MA02 and MA 03 exemplify the consequences and general feeling of this.

"… I'm just a little bit sometimes too far ahead for the rest of the company. So, I can discuss it with those guys [the cost engineers], but then I get the classical issues about that those guys are not really developing that fast or get innovative … It's a classical process [production of cost estimates], based on classic technology. That's, I think, the biggest problem." (MA02)

"If some parties don't want to [use] design 3d, then you have a missing link. And then you must guess it on the old way, old school way, what you did 20 or 30 years ago by hand" (MA03)

e) Inadequate communication.

Within the boundaries of this research, inadequate communication focuses, although is not exclusive, on communication to and from the cost engineer. Several issues arise from this, but most relate to reprocesses and loss of efficiency. The specific problem stated is that communication with the cost engineers is often one sided, reactive, and overall, inadequate. CE03 shares their experience on this as:

"And sometimes I get a list and I'm like, this is not really thought about, or it doesn't make sense, the way you've put this, so then, I talk to the designer and tell what I would have expected … I kept running into the problem that these Junior designers were sending me stuff that wasn't really useful." (CE03)

9.6. Annex 6

Annex 6: Activity System 1 complete contradiction analysis.

Primary contradictions:

- Within instruments: New and traditional instruments, while not fully incompatible, overlap each other. The adoption of BIM based instruments is expected to make the use of traditional instruments such as 2D drawings unnecessary, and coexistence of both at the same time, can be deemed as wasteful and redundant. Another important contradiction exists in regards to BIM instruments usage. Currently, more focus is put on the use of the software per se (e.g., learning to use the software, capabilities, troubleshooting, etc.), than the information contained in the model.

Secondary contradictions.

- Instruments – Object: The current instruments being used in the costing process by cost engineers, namely Excel, Cleopatra, and 2D drawings, are inadequate for carrying out a cost estimation process based on 5D BIM elements, because they are fundamentally structured in traditional non-BIM methods, creating a contradiction. This result is in line with what was reported by Eastman et al. (2018), where they highlighted cost engineers still make extensive used of traditional, non-BIM instruments for cost estimation.
- Instruments – Object: As presented in the results in section 3.3.1, non-graphical elements are an important component of projects which need to be quantified and costed in order to obtain complete cost estimates. However, the current instruments do not allow the quantification of non-graphical elements of the project, as these are not accounted for in the models and as such, creates a contradiction.
- Rules – Object: The current SSK templates and client specific templates are a weak set of "guidelines", which are not optimized for BIM-based cost estimation, and still limits the delivery of estimates on predetermined Excel formats. This lack of specific standards and subjectivity for cost estimation is in line with Akintoye and Fitzgerald (2000). Furthermore Sunil et al. (2017) stated the need for a suitable costing standard or set of "rules" in order to effectively use BIM. Without a proper, BIM optimized set of rules for cost estimation, the desirable object will remain in contradiction.
- Division of Labour – Object: The current division of labour in the research case company has the cost engineer working on "silos" that is, working independently from the network, and only included at the last step of the process. This is not unique to the case study, as Forgues et al. (2012) had already identified the late involvement of cost engineers in the development of a project as a common practice. Borrmann et al. (2018) and Mayouf et al. (2019) stated the importance that collaboration has in the full implementation of BIM, and henceforth, the current non-collaborative division of labour is in contradiction with the desired 5D BIM based costing.
- Instruments – Subject: As revealed by the results, and discussed in section 3.4.1, cost engineers have a low level of proficiency in the use of BIM instruments and software. This is in line with what was reported by Ghaffarianhoseini et al. (2017) and Ismail, Adnan, and Bakhary (2019), who both concluded that adoption rate of BIM for cost engineers and related professions is low in general terms. The lack of proficiency in the use of BIM instruments is in direct contradiction to the proposed, more extensive use

of them. Without a proper level of proficiency, it is not possible to use BIM to all its potential, and most probably, cost engineers will return to using the traditional instruments.

- Subject – Division of labour: As previously mentioned there is a "siloed" division of labour, with late involvement of the cost engineer in the project. As mentioned already, this is backed with the findings from Forgues et al. (2012). The results however, show that the cost engineers are considered to be important and hold relevant knowledge for the project, as stated by SE02:

  "…so, my point of view, the cost engineers, with W+B, they have their own methods, they're very good at what they do. So, like [COST ENGINEER'S NAME], he's very good. … in civil engineering sectors he's quite well known about his knowledge about costs, so he's very good…" (SE02)

  There is a contradiction between the perceived importance and knowledge of the cost engineer and the division of labour in which he develops his work. Unless changes are made to the division of labour, there will be unused potential from the cost engineer.

- Rules – Community: The results show how QTO's, the basis for cost estimates, are shaped by the actions of a community of actors to deliver a final product. At the same time results showed that current costing rules and standards, are rigid. The SSK, for example is developed only through the perspective and purpose of presenting cost estimates in a common template, without taking into account the process through which such estimates are made, or other stakeholders that participate. The rigid and highly focused rules are in contradiction to a broader community participating in the activity system, and will remain to be in contradiction unless a more adaptative set of rules is developed.

9.7. Annex 7

Annex 7: Activity System 2 complete contradiction analysis.

Primary contradictions:

- Within division of labour: Current division of labour has already been identified as inappropriate in the results. MO 04 stated about this:

  "I think the responsibilities are maybe a little bit too, you know, shifted, it's out of balance perhaps, a little bit too reliant on the modelers" (MO04)

  The division of labour therefore already shows signs of contradictions in itself. Although not fully dysfunctional, a weak division of labour can make the design and modelling of projects a task that suffers from issues. Addition of cost information to design and modelling means that the BIM model becomes increasingly comprehensive. Adding responsibilities to a single party contradicts with the already out of balance division of labour, and the BIM modeler cannot possibly be held accountable for the entirety of the information contained in the model.

Secondary contradictions:

- Instruments – Object: There are two parts of this contradiction. First, although a relatively good use of BIM instruments is already present at the company for the design and modelling activity, it is not optimised to include cost information. Results in section 3.4.1 clearly showed that there is no current use of specialised 5D BIM software. In section 2.3.2, the main capabilities of 5D BIM instruments were presented, and although some of them, such as visualization, and quantity take-offs are also present in some instruments currently in use by the company (see section 3.4.3), the more advanced features are limited to specialised programs. The second one, is related to the conceptual model. The current use of the conceptual model is not optimised for the management of cost information, exemplified in the results by the inadequate form taken by QTO's, which are directly influenced by the breakdown structures. The lack of specific 5D BIM software and non-optimised conceptual models are in direct contradiction to realising the object of project design and modelling with 5D BIM elements.

- Rules – Object: The rules and object contradict in two main ways. First, the results in section 3.6.1 show that currently, there are not specific rules for management of cost information, and that most of the current rules relate to modelling workflow and object creation and parametrisation, and even so, the same rules are not always followed. This is in line with Poljanšek (2017), who shows how standardised rules are required for the proper development of projects with BIM. This "weak" set of rules is in contradiction to realising the object. The second point comes from an interesting highlight in the results. Currently, the traditional approach is that of treating each project as entirely unique, as stated by PM02 and MA02. This contradicts with the object of project design and modelling with 5D BIM elements, as it can be expected that the increased complexity of models (by inclusion of additional cost information), makes the traditional approach of unique project with unique elements even more resource intensive to use, and may hinder the completion of the object.
- Community – Object: In the current composition, the results show that the cost engineer is located on the margin of the community. On the other hand, the new object specifically states the desire of designing and modelling a project with, cost information. This is supported by studies which have found that cost engineers have historically not been clearly integrated in the development of project based on BIM (Mayouf et al., 2019). There is then a contradiction between a community that doesn't fully integrate the cost engineer, and achieving the object of designing and modelling projects using cost information.
- Division of Labour –Object: As shown in the results, the current division of labour generally does not account for the input of cost information during design and modelling stage. This lack of, or untimely input of information for design and modelling is backed by literature, and Akintoye and Fitzgerald (2000) conclude in their study that cost estimation is more widely used for planning, and less so for decision making. A division of labour that doesn't provide for, nor establishes responsibilities for the input of the cost information, is in direct contradiction, and will not allow to achieve, the new object of designing and modelling a project with 5D BIM elements.
- Instruments – Community: The literature shows that usage of BIM both as a software and as a design instrument is fundamentally based on the concept of collaboration (Borrmann et al., 2018). The results in section 3.3 show that indeed, the project design and modelling process has collaborative attributes. However, the current activity composition has the cost engineer on the margin of the community. Marginalization of the cost engineer contradicts with the collaborative nature of BIM instruments, and does not allow the creation of a true common data environment that is both enriched, and accessible by the community.
- Rules – Community: As has been mentioned in the previous paragraphs, the current activity system has the cost engineer on the margin of the community. The rules, at the same time, are shown in the results to be lacking in defining guidelines for managing cost information, and consequentially, the integration of the cost engineer. These rules are lacking both on company, and national standards level, and there is no consensus for their use, as shown in sections 3.3.1 and 3.6.1. These results are backed by findings of Matejka and Vitasek (2018), where they pointed at a lack of generally accepted rules for cost estimation through BIM. A set of rules that poorly defines the role of actors, specifically the cost engineer, is in direct contradiction to having a community that further integrates the cost engineer into it.

9.8. Annex 8

Annex 8: Activity System 2 complete contradiction analysis.

Primary contradictions:

- Within Rules: Three major sets of rules can be identified; contracts with clients, company standards and procedures, and national and international standards. These three are in constant tension, and sometimes can contradict one another. The results in section 3.6.1 show that while there are internal project management standards in place (ISO), there is not a single set of standards or guidelines followed in all projects, as this can be influenced and changed depending on the client and type of project itself. As clients are diverse, and they don't follow a single national or international standard for project development, it is possible that a client's contract is in direct contradiction to a set of rules adopted by the company. The number of possible contradictions here is vast, and not to be underestimated. The rules in the context of project management and development are in constant internal tension, although it can be said that in the end, the contract with a client had more weight in determining ultimately the set of rules to be used.

Secondary contradictions:

- Instruments – Object: The results from section 3.4.1 show that there is no use of specialized 5D BIM software. The object of project management with 5D BIM elements does not require usage of 5D BIM software on a modelling level, but does require software that displays a managerial perspective of a model, including cost information. This would then lead to a contradiction in achieving the object. However, the main contradiction comes from the conceptual model. The results show that conceptual model is not optimised for proper use between different specializations, including cost engineering, and a quote by SE02 exemplifies this:

  "… we're not really able to really define the architecture [breakdown structures], I'm currently doing this in a new project, but to define the architecture of, of everything working together, and we, we, I think, in our company, we don't have enough people that really have the skills to really work the entire structure out with all the specialists and all the different needs." (SE02)

  The lack of an instrument that can be used by, and integrates all interested parties goes in contradiction to achieving project management and development using 5D BIM elements, because ultimately, the instruments will not be suitable to manage cost information.
- Rules – Object: Moving past the internal tensions, there are two important points to analyse. First, the results from section 3.6.1, show that current rules with the client, that is, contracts, generally follow a traditional approach. In the Netherlands, this takes the form in RAW contracts, which are mostly based on design-bid-build practices. These contracts are not optimised for BIM usage, and can go in contradiction with the object of project development with 5D BIM elements, as most of the time, the contracts are front-cost-based, leaving little room to implement innovations such a BIM (Kubba, 2012). The second point, the results show that there are no strict rules for using a single guideline for project development. Instead, the use of these is open for selection. Poljanšek (2017) determined that proper development of projects based on BIM, requires the use of standards. An open and lax rule selection is therefore in contradiction to achieving the object.
- Community – Object: This contradiction is similar (although not equal in terms of outcome), to the Community – Object interaction in the Activity System 2. The results from section 3.3 show that in generally during the development of a project, the cost engineer has a limited involvement, and joins at

the last moment. Again, this is backed by the literature, as Mayouf et al. (2019) states that cost engineers are not clearly integrated in the development of project using BIM. This poor integration in the community is in contradiction to reaching the object, as without timely and appropriate integration of the cost engineer in the process, they will not be able to contribute with their input for project development including cost information.

- Division of labour – Object: Once more, this contradiction is similar (and again, not equal in terms of output), to the Division of labour – Object interaction in Activity System 2. Results from section 3.3 show the limited and untimely participation the cost engineer has in the division of labour for managerial and development decisions in the project, and the "siloed" work. Additionally, the results also show that a project's development, within each loop is mainly a linear process. A project management and development approach that takes elements from 5D BIM requires that the project receives cost information input early on, which is when decision-makers have the largest potential to influence a project's outcome, as backed by Hendrickson et al. (1989), and must be based on collaboration (Borrmann et al., 2018). As such, the current division of labour, with limited participation of the cost engineer, working in silos, and linear, is in contradiction with the desired object, and specifically, with allowing to make cost-based managerial and development decisions.
- Instruments – Community: In the context of project management and development, the results showed that the conceptual model, or specifically the OBS, is key to enable the management and development of the project. SE01 exemplifies this by stating:

  "…object breakdown structure is used very often. It's mainly at the basis for a lot of the projects I do at least. So, we already start very early on with it to get the scope of the project, to also assign requirements, risks, design decisions…" (SE01)

  However, it was also shown that in the conceptual model, cost information is generally not optimised or taken into account, and the same SE01, stated after:

  "…cost breakdown structure is not something I have worked with personally and also not something I have seen explicitly in my project." (SE01)

  It is then concluded that the conceptual model as an instrument can be used as the basis for the development of projects. However, the conceptual model is not fully integrating the requirements of the entire community, specifically the cost engineer. At the same time, the community has the cost engineer on the margin of it, and has not achieved proper integration. Therefore, there is a double contradiction between an instrument that has the potential, but does not successfully integrate the community involved in the development of a project, and a community that does not integrate all its relevant actors.
- Subject – Division of labour: The results from section 3.3 show that systems engineers can provide a common ground upon which other parties develop their work in the project. However, the current division of labour does not always have the systems engineer join the project at the earliest moment. Untimely integration of the systems engineer is in direct contradiction with his role as enabler and integrator of project development. SE02 exemplifies in a single answer both the importance of the role, and the existing contradictions:

  "And I would say, it would be preferable to start off with the systems engineers first, to make these breakdowns to make the structures ***and then make the other people work in these structures****. And what you see, because all these people start at the same time.* ***Sometimes there is, there is already different structures****. So, like, for example, with [COST ENGINEER NAME], he could have his cost structure ready, Before I have my system breakdown structure ready, or my work breakdown…"* (SE02)

- Subject – Instrument: The results from section 3.4 show that project managers have limited proficiency in the use of BIM software., that nevertheless allows them to carry out their current tasks. However, a more extensive usage of more advanced and/or specialised instruments is expected from an activity that involves 5D BIM elements. This then creates a contradiction between a limited knowledge and use of the instruments by the subject, and an expected increase in the instruments use and specialization.

9.9. Annex 9

Annex 9: Recommendations complete analysis.

R1. Acquisition, implementation, and specialized training of 5D BIM software.

A crucial step in the proposal of solutions is the acquisition, implementation and training in the use of an appropriate 5D BIM capable software. As presented in section 2.3.2, there are a number of available software in the market to choose from. The choice, however needs to be analysed from the perspective of each company. It is interesting here to point at one of the problems identified in section 3.5.1, inappropriate information. One of the identified roots of this problem was conversion of information between different software. As such, it is key that when choosing a software to acquire, interfaces and integration with already existing software not only by a company, but also by its significant external stakeholders is analysed.

The main features that should be included in the 5D BIM software, as seen from the perspective of use by cost engineers are:

- Custom quantity take-offs. As mentioned in section 2.4.1, 5D BIM instruments possess powerful custom QTO's capabilities which can reduce the number of problems and errors currently found in the generation of these reports by the BIM modellers. Custom QTO's also allow to focus on costing per different levels of detail, or based on different breakdowns, thus allowing cost engineers to focus on specific parts of a project, in order to better analyse it.
- Visualization of the model. One of the main general benefits of BIM is visualization of a digital representation of a project. 5D BIM instruments also possess this benefit, and as mentioned in section 2.4.3, it can come with additional functionalities useful for the cost engineer. It is recommended that visualization is used for two main reasons. First, to replace the use of 2D drawings, and consult design information directly from the model, as this allows cost engineers to get more involved in a project, and to gather contextual information that has been mentioned as important for cost estimation. The secund one, is the use of colour coding to aid in the process of cost estimation. Through colour coding, it is possible to identify elements or objects which require special attention, e.g., because they are cost drivers, or because they have not been able to be properly costed.
- Inclusion of rough cost information in 5D BIM software. From the results, it was apparent that detailed cost calculations require specific software (Cleopatra, in the case study) with specialized features which are not found in 5D BIM software *yet*. However, 5D BIM software does allow for input of cost information in a similar manner to Microsoft excel spreadsheets. It is then recommended that cost engineers include rough cost information of (main) objects and elements of the project. Furthermore, rough cost information can be added semi automatically in the modelling software with the help of dynamo

scripting, similar to the process of adding coding strings to the object's parameters. These two sub-recommendations combined can allow the semi-automatic cost analysis of different alternatives, analyse the cost of changes in the design, generate intermediate cost estimates, and generate specialized cost information reports.

- Model updating and change tracking. In section 2.4.5, it was mentioned how 5D BIM can automatically run recalculations of QTO's and even full cost estimates from updated models. Something important mentioned in the results in section 3.3.1, is that there is not a clear way in dealing with changes to the QTO's and with updates to the model. 5D BIM software has tools that allow comparison of versions of a model, to easily identify changes, and allow the cost engineer to decide how to deal with said changes, depending on the level of the differences.
- Cost information reports. Reports such as costs per object, element, system, etc., cost of different alternatives, cost drivers, if scheduling is available cash flows, all will help not only cost engineers but also project managers in making cost-based decisions. If combined with the automatization capabilities of 5D BIM, there is potential of quickly generating reports that can improve decision making, possibly having a positive impact in the product to be delivered to the client.

Additional to the acquisition and implementation of the software, specialized training by the users of the software is required. Lack of proficiency in the use of BIM and 5D BIM instruments by actors outside from the design and modelling process, was clear from the results of software usage, and asymmetrical adoption of technological tools was identified as one of the current problems. It was found also that there is motivation by these actors to use the instruments more extensively, but do not have the training to do so. CE02 expressed:

"… but then we have never worked [on Navisworks] freedom, and it's not easy for, Navisworks freedom is something else than Navisworks manage. We cannot make the quantity take-off ourselves, or we cannot show or export any information from the model, and that's something to work on." (SE02)

Specific training is crucial, because even though instruments may be the same between actors, their uses will differ greatly between them. For the case of cost engineers, training should be mainly for the generation and extraction of QTO's, model visualization and consultation of parameters, and inclusion of cost information to a model, although the precise scope of the training should be tailored to the needs of the user. In the case of project managers, training can be given to efficiently consult information from a management level.

R2. Well timed and more extensive integration of cost engineer and systems engineer in the project development process.

It is strongly suggested that the cost engineer is integrated earlier on and more extensively in the project development, and to relinquish the involvement at the last moment. The integration of the cost engineer should be aimed at providing earlier input to other actors in the project development process. The input by the cost engineer should mainly be cost information, but also information relevant to other actors, especially decision makers. A study by Citroen (2011), strongly concludes that with more relevant information available, rational decision making is facilitated, and that correct strategic decisions can only be taken on correct and complete information. The timeliness of the reception of cost information is important as seen from the perspective of the ability to impact a project's outcome through time (Hendrickson et al., 1989), (see section 2.2.1). Thus, it is expected that by having timely access to appropriate cost information, better decisions can be made during the project development process, and additionally to the cost engineer being able to analyse and cost a project more appropriately, a better product can be delivered in the end. In general, this recommendation should:

- Provide cost information to allow cost-based decision making both for project development and for the design process, potentially improving the quality of the end product of the client by providing quality information on time.
- Provide cost information to allow the discussion and analysis of different alternatives.
- Provide input and communicate what relevant information should be included in the models and how it should be presented. Namely, this applies to how the conceptual models should be developed, and the information that should be present in quantity take-offs, and supporting it.

In the case of systems engineer, they can become a key piece in the integration of other actors, including the cost engineer. It was seen that the development of the conceptual model, has a direct impact on the BIM modelling process, and eventually, on the QTO's, by means of the different project breakdown structures developed. The results (3.3.1) and analysis (4) sections explored the potential role of integrator of the systems engineers. Similar to the recommendation of involving cost engineers in a timely manner, it is also recommended that systems engineers join the project development on time. It is recommended that they are integrated to the project development process at the earliest possible moment. This will allow them to develop a conceptual model from the beginning, incorporating requirements and feedback from other relevant stakeholders, including the cost engineer. In the end, two main benefits are expected in regards to cost estimation. First, through the earlier involvement of the systems engineer, input from the cost engineer is taken into account earlier on, effectively integrating him into the process, and second, the conceptual and BIM models can be developed in a more organized manner, taking into account the specific requirements from cost engineers, allowing the production of QTO's that are suitable to be used without the need for intensive data manipulation.

R3. Adoption of companywide standards and guidelines for conceptual model development and use, BIM modelling and use of models, and management of cost information.

Standardization has been identified as having the potential to bring improvements in the construction industry (Aapaoja & Haapasalo, 2014; Roy et al., 2005), and as a requirement for achieving the full benefits of BIM (Poljanšek, 2017). The results from section 3.6.1 show that there is not a strong use of standards at a company level, and the analysis of these from chapter 4 shows that there currently are several contradictions with regards to these, causing problems such as the production of inappropriate information as output from processes. As such, the adoption of companywide standards and guidelines is recommended in a broad sense, but specifically for three major objects: (a) conceptual model development and use, (b) BIM modelling and use of models, and (c) management of cost information.

d) Conceptual model development and use.

One of the most interesting findings from the research was identifying the potential function of a conceptual model as an integration instrument. Development of these conceptual models by systems engineers should precede the development of detailed designs and the BIM model, and contain information that is not modelled through BIM, such as non-graphical elements. It is suggested therefore that a single companywide standard process for the development of this conceptual model is created. The standard should account for at least:

- Development of conceptual models in consensus with and following the needs and requirements of the relevant stakeholders (BIM managers, BIM modelers, cost engineers, client), to guarantee that the models are appropriate to integrate the work of other disciplines in the project development process. As an example, it should be accounted for the way to breakdown objects so that QTO's are usable by cost engineers without extensive manipulation and transformation of information.

- Development of conceptual model in loops, following the logic behind the design loops. Through this, it is expected that on each loop of the conceptual model, elements are broken down in a level of detail comparable to the target LOD of the model at the end of the design loop. At the end of each loop, conceptual model should be reviewed, and further developed, following a logical order.
- Extensive use (as applicable) of standardised conceptual objects and elements as elemental "building blocks" for the development of unique projects. This can be done with aid from BIM modelers and specialised designers. The outcome is a more standardised, and easier to use library of conceptual objects and elements, that is easier to correctly parametrise and use in the modelling phase. In the end, this will increase the chances that information from specific elements, such as physical properties for QTO's, is correctly derived from the model.
- Clear timing of the development of the conceptual model. This will prevent further issues related to rework. In general terms, the conceptual model should be one of the first steps in developing a project.
- Management of non-graphical project requirements, such as specific temporary works, complementary works, or anything which is not graphically included the models. This will help project managers and cost engineers take into account specific project requirements which are outside the scope of the model, as mentioned in section 3.3.1. By accounting for these requirements in the conceptual model, cost engineers can refer to it in order to assess necessary information to produce a complete cost estimate.

In the end, it is expected that a proper conceptual model will give direction to the work to be carried out (standardize), will integrate actors (improve connectedness), and help create in general terms a more robust BIM model that suits the needs of different actors (single source of information). In terms of 5D BIM, a conceptual model can account for the way in which cost information should be managed in a model, and the information to be included. As an example, the conceptual model can define the unit of measurement of each specific element, to allow cost engineers to assign correct unit rates or prices to it.

e) BIM modelling and use of models

The company-wide use of an international BIM information standard such as the ISO 19650, is highly recommended. The standard should not be seen as a strict way of carrying out the designs and modelling in the company but instead as a *"document [that] provides recommendations for a framework to manage information including exchanging, recording, versioning and organizing for all actors."* (ISO, 2018), and that is precisely the use that should be given to such a standard. From the recommendations in the standard, it is suggested to develop a specific and predictable companywide framework for the management of information for Building Information Modelling, and in the context of this research, management of cost information is to be included. By this, it is expected to partly solve the problem of inadequate information presented in the perceived problem.

Another topic that the guidelines should help to set is that of responsibilities, and specifically, responsibilities in BIM and further 5D BIM modelling. Studies have been carried out, highlighting the importance of properly defining roles and responsibilities in the development of projects through BIM (Barison & Santos, 2010). Furthermore, when BIM becomes more specialized and adds additional information dimensions, the need for specialized roles and responsibilities is further increased (Zanni et al., 2017). In order to avoid responsibility and role conflicts, it is suggested that a clear roles and responsibilities guideline for the development of BIM projects is created. In the context of this research, the guideline needs to take into account the responsibilities for the cost information in the model.

Defining the precise responsibilities guideline is outside from the scope of this project. However, it can be mentioned that the it needs to account not only for the party responsible for adding cost information to the model, but also define the scope of said responsibility. For example, cost engineer can be responsible for adding cost information of an element in the model. However, if the model is drastically changed, and said element is now to be carried out under different circumstances that make for a price change, (e.g., poured concrete walls on ground level, versus on a high floor) then the cost engineer cannot be held responsible for errors in said cases, unless he is informed of the changes and asked to review the costings.

In regards to QTO's, the results show that these are currently done entirely by BIM modellers, in contrast to how it was done in the past, before the widespread adoption of BIM. This was stated to have an impact in the process, and CE02 mentioned in this regard:

> *"At the time we did it ourselves [the quantity take-offs], we got more involved with the project, you saw the drawings, you measured things, you studied the drawing, you knew more about the project itself… Nowadays is just a short list, maybe a drawing with it, and make an estimate, and after two days the project is finished… You're not getting involved with a project, you have no feeling with the project, you miss [important information]. And I think sometimes it is also affecting the quality of the estimate."* (CE02)

It is therefore suggested that the responsibility for generating QTO's from a BIM model is shifted to the cost engineer. By this, it is expected that the cost engineer has more control on the form taken by the information, and to extract only the information that is relevant to them, helping to solve the problem of inappropriate information. It would also be expected that by working on the model itself, involvement with the project is increased, and that quality of cost estimates is improved.

Lastly it is recommended that the guideline sets the ground to make the BIM models the unique source of project information. Information is at the centre of BIM and allows the addition and integration of different types of information of a built asset through a digital representation of elements. It is proposed that the model starts being used by all relevant parties as the main source of information, using specialized software, reducing the chance for errors in the process. In the case of cost engineers, they should be able to visualize the model, understand the context of each element, understand the element decomposition, acquire additional information from the element's parameters, and get quantity information to generate the QTO.

f) Management of cost information.

The exact standards to use can be replaced by another equivalent, but the adoption of a standard for managing and using cost information such as ICMS is highly recommended, especially in the aim of 5D BIM implementation. In words from the RICS, ICMS *"are principles-based international standards that set out how to classify, define, measure, record, analyse, present and compare construction project life cycle costs in a structured and logical format."* (Royal Institution of Chartered Surveyors (RICS), 2020). In other words, ICMS sets a common language for the management of cost information. The results show that currently, there is not a single standard way of presenting cost information, although the Dutch SSK standard is generally used, especially when working with governmental clients. However, it was also mentioned in section 3.6.1, that it is not optimised to be used with BIM. On the other hand, ICMS does actually account for the use of BIM, and is structured in such a way that it can be used as the cost breakdown structure in BIM based projects.

The use of a standard such as ICMS for cost information management, sets a common ground for all parties working with the standard. In an optimal case, the standard is not used only at a company, but at a national, or even international level. However, the usage at company level can already bring benefits for the company. In the context of the research, the use of the standard allows developing cost breakdown structures that can be used with BIM processes which in turn is an enabler to move towards 5D BIM project development. Such a standard will also increase the level of organization of information and reduce the number of issues arising from inappropriate information.

9.10. Annex 10

Annex 10: Outcomes complete overview.

Activity system 1: Cost estimation with 5D BIM expected outcomes:

- Improved form and quality of quantity take-offs: This outcome is reached in two ways. First, by directly taking the responsibility of making the QTO's directly in 5D BIM software themselves, cost engineers have more direct control over the form of the QTO and the information contained in it. The second way, is that by following a more standard approach for conceptual model development from the beginning of a project, cost information can be accounted for, and systems, work, and cost breakdown structures can be developed in a way that facilitates the QTO generation by setting the ground for model element decomposition, and having appropriate parameters for elements in the models.
- Improved management of non-graphical elements: An important topic mentioned by respondents and further highlighted by validators (see section 5.4 for further discussion), accounting for non-graphical elements is required for good cost estimation. By establishing that these elements will be included in the conceptual model, including their requirements and specifications, cost engineers will have a standard method to properly account for them, and use this information to generate improved cost estimates.
- Faster and traceable cost estimate updates: By having a structured approach to developing the conceptual model and the BIM model, based on costing standards, QTO's extraction can be parametrized in such a way that further QTO's follow the form of previous ones, allowing to quickly update quantities while reducing the requirements for data manipulation, and making comparison of estimates and changes tracking easier. This last part is further facilitated by 5D BIM software enhanced visualization capabilities, which allows visual comparison of different versions of a model.
- Earlier production of cost information: Building up from the previous two outcomes, it is expected that cost information of a specific project is produced and is available at earlier moments, due to the reduction of time needed to produce QTO's and updating estimates. Furthermore, earlier production of cost estimation also allows the production of intermediate cost estimates during the project development process. This, in turn, has repercussions on the outcomes of activity systems 2 and 3.
- Decreased time requirement for handling information: Again, building from the previous three expected outcomes, it is expected that the cost engineer will require less of his time to handle (convert, extract, modify, add, etc.) information, as a result of speedier processes. This decreased time requirement can be translated directly into more available time for the cost engineer to carry other more meaningful tasks, which has repercussion in the outcomes of activity systems 2 and 3.
- Increased engagement and understanding of projects by cost engineers: By adopting the proposed framework, it is expected that the cost engineer works hands-on in the BIM model, which in turn will increase his engagement in the project, by working directly on it, instead of simply waiting to receive information. In turn, using the model as their source of information, cost engineers can make use of the visualization capabilities of BIM, and the objects' information to gain increased understanding of the project, including specific requirements and the full context of it.

- Better management of cost information: By using cost information standards during the development of a project, and accounting for cost information early in the project, it is possible to improve the management of it. A structured information management approach allows for easier benchmarking (e.g., comparing cost information between projects), transfer (e.g., sharing cost information with internal and external stakeholders), and analysis (e.g., standard reporting of cost information), providing a common language that is maintained throughout different projects, reducing the need for transforming information to a usable form per stakeholder.

Activity system 2: Project design and modelling with 5D BIM elements

- Improved end product cost-benefit quality through cost-based design decisions: By involving the cost engineer earlier on, and having access to earlier cost information, it is possible to assess design decisions from a cost perspective, in order to identify alternatives that are more cost-efficient in a specific project, adding benefit to the end product. Outside from the scope of this research, but along the same lines, it is theorized that this outcome can be further enhanced to include life-cycle cost design decisions, allowing to analyse the most economically advantageous alternatives in a project (e.g., lower front cost and higher maintenance and operation costs versus higher front cost and lower maintenance and operation costs).
- (Virtually) real time rough cost analysis of design alternatives: By adding rough cost information to the parameters of objects in a model, it is possible to generate (virtually) instant cost estimates of different design alternatives. This can be achieved by producing quantity take-offs that simultaneously extract cost information from the parameters, providing a rough cost estimate of a given design alternative.
- Creation of models ready and optimised for QTO's: Through the development of models based on information management standards (ISO 19650), accounting for cost information (ICMS), and based on an appropriate BIM plan, it is expected that objects contain information within their parameters that allow specialized 5D BIM software to be configured to generate QTO's in a custom manner, that can be replicated through various projects.
- Creation of models that can (potentially) be used as single sources of information: Similar to the previous outcome, by using information management standards, accounting for cost information, and based on an appropriate BIM plan, progress is made towards producing comprehensive BIM models that account for complete project information. In turn, increasingly comprehensive models can be used as a source of information for a greater number of stakeholders. In the boundaries of this research, including cost information in models would allow the community to use the model as a common data environment that contains all required information to carry out the activities.
- Development of models with more appropriate levels of development per phase: By following information management standards, a BIM plan, and an evolving conceptual model, it is expected that models will develop in a more coherent flow, providing the levels of detail appropriate to each design stage. The appropriate levels of detail, in turn, mean that other stakeholders using the model will have access to appropriate information, which is suitable to carrying their own activities, such as the case of the cost estimation.

Activity system 3: Project management and development

- Increase involvement of cost engineers in project development: Through the direct earlier involvement of cost engineers in the project development process as drawn in the proposed framework, and a decreased time requirement for carrying out their tasks, a potential outcome is that cost engineers have an increased involvement in project development. This involvement allows them to have earlier and periodical interaction in the project development process, and creates the possibility to have a meaningful impact on it by providing their input and knowledge.

- Increased cost-based decision making aiming at improving the product: Building up from the previous outcome, and as proposed in the framework, it is possible to have decision makers base their choices on input from the cost engineers. As was previously stated in section 5.3.1, decision making based on additional relevant information has the potential to improve the quality of the outcome, in this case, the final product to be delivered.
- Increased integration and collaboration of actors: Through hands-on, BIM -based development of projects, a conceptual model that accounts for other stakeholders, and the proposed framework which seeks to involve actors at earlier stages, it is expected that an outcome is the increased integration of actors in project development, but also increased collaboration, in order to reach a more comprehensive project development that includes the knowledge and expertise of several actors in the community.
- Standardized and more structured project development: Through the use of companywide standards for project development (conceptual model, BIM development, contracting, BIM plan), and the pursue of a consensus in the use of such standards on national and international level, companies, but also the industry, may achieve more standardized and structured project development, which allows to share a common language. On a long-term vision, such an outcome can allow for easier integration and collaboration between companies in the industry.