UNIVERSITEIT TWENTE.

ARCADIS Design & Consultancy for natural and built assets

COMPARISON OF EARLY-STAGE QUANTITY ESTIMATION METHODS

Master of Science Thesis

Paul van Wee

6 September 2018

Master thesis

Comparison of early-stage quantity estimation methods

Author:
P.J.A. (Paul) van Wee BSc
S1485601
Student Construction Management and Engineering
University of Twente

Commissioned by:
Ing. R. J. (Robert Jan) Roos MSc
Arcadis Nederland B.V.

Supervised by:
Dr. Ir. L. L. (Léon) olde Scholtenhuis
Civil Engineering & Management
Faculty of Engineering Technology
University of Twente

Dr. J. T. (Hans) Voordijk
Civil Engineering & Management
Faculty of Engineering Technology
University of Twente

Arcadis Nederland B.V.
P.O. Box 220
3800 AE Amersfoort
The Netherlands

PREFACE

In front of you lays the final version of the report "*Comparison of early-stage quantity estimation methods*". This report serves as the last assignment to complete the master Construction Management & Engineering at the University of Twente.

This report compares three quantity estimation methods that can be used to estimate quantities of early-stage designs of infrastructure projects. Two of the methods use Building Information Modelling (BIM). BIM is a term most construction companies have used at least once, though not every construction company implements BIM in their work practice. Most scientific literature describe Building Information Modelling as a utopia. However, implementing BIM in the work practice of a company is complex and is not always beneficial for a company.

This master thesis was conducted at Arcadis Amersfoort, a worldwide design and consultancy firm that focuses on infrastructure, water, environment and buildings. I conducted my study at the cost department of the infrastructure division with the focus on Building Information Modelling and early-stage quantity estimation. I would like to thank everyone at the cost department of Arcadis for creating a good working atmosphere, delivering information for my study and participating in the workshop used for this study. In specific I would like to thank ing. Robert Jan Roos MSc for supervising and assisting this study. Robert Jan Roos is the head of the cost department.

I would also like to thank my thesis supervisors Dr. Hans Voordijk and Dr. ir. Léon olde Scholtenhuis for the support throughout the whole thesis project. Both supervisors work in the Civil Engineering & Management department of the faculty of Engineering Technology at the University of Twente.

I hope this report helps you understand the possibilities of using Building Information Modelling for estimating product quantities of infrastructure projects. I wish you a pleasant reading.

Paul van Wee

Amersfoort, 2018

SUMMARY

Decisions made during the early-stage design phase account for 70-80% of the total costs. Therefore, early-stage cost estimation is decisive for the future success of a project. Efficiently and accurately estimating the quantities of the materials of a project is of great importance for the efficiency and accuracy of the cost estimation. Multiple quantity estimation methods can be distinguished; however, no Building Information Modelling (BIM) literature exists regarding the comparison of early-stage quantity estimation methods, because literature often focuses on near-fully developed designs. Therefore, this report focused on comparing early-stage quantity estimation methods. This study compared the overall performance of three early-stage quantity estimation methods: fully-automatic BIM-based QTO, semi-automatic BIM-viewer and manual quantity estimation using 2D drawings. BIM-based QTO concerns automatically extracting object quantity information of three-dimensional models and the BIM-viewer is a tool that displays a three-dimensional model including the dimensions of the objects in the project. The objective of this study was to compare the performance of automatic BIM-based QTO to using a BIM-viewer and manual quantity estimation for early-stage quantity estimation of cost determining objects, and to give a recommendation regarding implementing BIM to estimate product quantities in the work practice of Arcadis. The next paragraph describes the methodology this study used, the third paragraph describes the results of this study, followed by the conclusion.

This study used interviews with cost engineers and literature regarding quantity- and cost estimation to determine the comparison criteria. This study used three criteria to compare the three quantity estimation methods, namely: efficiency, accuracy and traceability. The efficiency is defined as the ability to accomplish a job with a minimum expenditure of time. The accuracy is the degree to which the estimated quantity conforms to the actual quantity and the traceability is the ability to discover to what objects the quantities belong. The weights of the criteria have been determined by six cost engineers that assessed the importance rating of the criteria on a scale of zero to hundred. The six cost engineers assessed the importance ratings of the criteria for early-stage quantity estimation. Other criteria are important for early-stage quantity estimation compared to detailed quantity estimation. For example, the accuracy will be of more importance for detailed quantity estimation than for early-stage quantity estimation, because the bandwidth of early-stage cost estimations is larger. The researcher normalized the importance ratings to weight factors. This study used interviews with cost engineers, a historic cost estimation of a bridge project and literature regarding decomposition of bridges to identify the cost determining objects of a bridge project that has been used as case study. This study used cost determining objects, because early-stage designs do not contain enough information to estimate the costs of all construction objects. A workshop was performed using this case study of a bridge project located in Zwolle. During this workshop, six cost engineers estimated the quantities of the cost determining objects of the case study using the three quantity estimation methods. The researcher recorded the time the cost engineers needed to estimate the quantities and determined the deviation of the estimated quantities to compare the quantity estimation methods. The traceability of the quantity estimation methods was assessed by the cost engineers that participated in the workshop. This study required a multi-criteria decision analysis (MCDA) method, because the performances of the three criteria used different units, namely: minutes, percentage and assessment score. To operationalize the performance per criterium, a MCDA method was required. This study used the Simple Multi-Attribute Rating Technique (SMART) with utility functions that range from the lowest score to the highest score for every criterium. SMART used utility functions to operationalize the performances of the criteria to similar units named utility scores. The utility scores multiplied by the weights resulted in the overall performance of the quantity estimation methods. To validate the overall performance, all six cost engineers that participated in the workshop were asked for their preferred quantity estimation method. For verification purposes, this study performed a sensitivity analysis of the weights and this study used a different MCDA method. The Multi-Attribute Utility Theory (MAUT) was used instead of SMART to verify if the result, i.e. quantity estimation with the highest overall performance, changed.

Literature regarding decomposition structures of bridge projects resulted in the conclusion that there is not one single best decomposition structure. Literature uses different decomposition structures. Therefore, this study used the decomposition structure of Arcadis. During the workshop, the six cost engineers estimated the quantities of nine cost determining objects. The six cost engineers that participated in the workshop determined the weights of the criteria. The weights of the criteria efficiency, accuracy and traceability are respectively: 0.29, 0.38, and 0.33. Therefore, the cost engineers considered accuracy the most importance criterium, followed by traceability. The result of

the workshop was that BIM-based QTO and the BIM-viewer are equally accurate. This was expected, because BIM-based QTO and the BIM-viewer use the same 3D model. Manual quantity estimation was significantly less accurate than the quantity estimation methods that used BIM. Regarding efficiency, BIM-based QTO performed best, followed by the BIM-viewer. This was expected, because BIM-based QTO automatically estimates the quantities. On the other hand, for the BIM-viewer the cost engineer must select the objects of which the quantities are required. All cost engineers considered the quantities estimated using the BIM-viewer most traceable, because the objects to which the quantities belong are directly visualized and highlighted. The quantities estimated using BIM-based QTO are least traceable, because the six cost engineers consider it difficult to understand to what object the quantity belongs. The BIM-viewer had the highest overall performance, mainly because the cost engineers assessed the BIM-viewer more traceable than BIM-based QTO. The result was validated by the cost engineers. All six cost engineers that participated in the workshop preferred early-stage quantity estimation using the BIM-viewer over the alternative quantity estimation methods. The result of the verification was that the quantity estimation method with the highest overall performance did not change. Therefore, the result has been validated and verified.

This study shows that for early-stage quantity estimation, using a BIM-viewer has a higher overall performance compared to fully automatic quantity estimation using BIM-based QTO and manual quantity estimation. Literature currently often proposed BIM-based QTO using detailed designs. However, this study shows that for early-stage quantity estimation, the BIM-viewer has a higher overall performance. Therefore, using the BIM-viewer for early-stage quantity estimation results in improved cost estimations. Improved early-stage cost estimations result in enhanced decision-making during the early-stage design phase and contributes to decreasing the high rate of failure of contractors. Previous scientific literature that focused on estimating quantities using BIM did not use traceability as criteria for determining the overall performance. This study shows that cost engineers consider traceability of high importance for quantity- and cost estimation. Using traceability as comparison criteria for quantity estimation methods results in enhanced comparisons.

This study concludes by mentioning that for early-stage quantity estimation of infrastructure projects the expertise of cost engineers is always required. Expertise is required, because the additional costs of phasing of a project and surroundings are not possible to automatically estimate, however, do determine a large part of the total costs of a project.

SAMENVATTING

Keuzes die gemaakt worden tijdens een vroegtijdig stadium bepalen 70-80% van de totale kosten van een project. Kostenramingen tijdens een vroegtijdig stadium zijn daarom van groot belang voor het slagen van een project. Efficiënt en accuraat de hoeveelheden bepalen is cruciaal voor het accuraat en efficiënt bepalen van de kosten. Wetenschappelijke literatuur beschrijft meerdere methoden om hoeveelheden te bepalen, echter is er geen Building Information Modelling (BIM) literatuur beschikbaar waar methoden om hoeveelheden te bepalen tijdens een vroegtijdig stadium worden vergeleken. Literatuur richt zich vaak op gedetailleerde ontwerpen in plaats van ontwerpen in een vroegtijdig stadium. Daarom is de focus van dit rapport op het vergelijken van methoden om hoeveelheden te bepalen in een vroegtijdig stadium. In dit rapport zijn drie methoden om hoeveelheden te bepalen onderscheiden en vergeleken op basis van prestaties: automatisch d.m.v. BIM-based QTO, semiautomatisch d.m.v. een BIM-viewer en handmatig d.m.v. 2D tekeningen. BIM-based QTO betreft het automatisch uitrekken van object hoeveelheidsinformatie uit een driedimensionaal model. De BIM-viewer is een tool dat object informatie weergeeft in een driedimensionaal model. Het doel van dit rapport was het vergelijken van de prestatie van BIM-based QTO met het gebruik van een BIM-viewer en handmatig hoeveelheden bepalen in een vroegtijdig stadium en het geven van een aanbeveling betreffende het implementeren van BIM om hoeveelheden in een vroegtijdig stadium te bepalen. De volgende alinea beschrijft de gebruikte methodologie voor deze studie en de derde alinea beschrijft het resultaat en er wordt afgesloten met de conclusie.

Interviews met kostendeskundigen en literatuur betreffende methoden om hoeveelheden en kosten te bepalen resulteerde in criteria om de methoden om hoeveelheden te bepalen te vergelijken. Deze studie gebruikte drie criteria, namelijk: efficiency, accuraatheid en traceerbaarheid. Efficiency is gedefinieerd als het vermogen om een taak te volbrengen met een minimale tijdsbesteding. De accuraatheid is de mate waarin de bepaalde hoeveelheid overeenkomt met de werkelijke hoeveelheid. De traceerbaarheid is het vermogen om te achterhalen tot welk object een bepaalde hoeveelheid behoord. De gewichten van de criteria zijn bepaald door zes kostendeskundigen het belang van de criteria te laten beoordelen op een schaal van nul tot honderd. De kostendeskundigen beoordeelden het belang van de criteria gebaseerd op hoeveelheden bepalen in een vroegtijdig stadium. Andere criteria zijn van belang voor hoeveelheden bepalen in een vroeg stadium vergeleken met een vergevorderd stadium. Bijvoorbeeld accuraatheid is van groter belang in een vergevorderd stadium, aangezien de bandbreedte van de kostenraming kleiner is in een vergevorderd stadium vergeleken met een vroegtijdig stadium. De onderzoeker normaliseerde het belang van de criteria tot gewichten. Deze studie gebruikte interviews met kostendeskundigen, literatuur over decompositiestructuren van bruggen en een reeds uitgevoerde kostenraming van een brugproject om de kostenbepalende objecten van de casestudie te identificeren. Voor de workshop werd de casestudie van een brugproject in Zwolle gebruikt. Tijdens de workshop bepaalde zes kostendeskundigen de hoeveelheden van de kostenbepalende objecten van de brug in Zwolle door gebruik te maken van de drie methoden om hoeveelheden te bepalen. Deze studie gebruikte kostenbepalende objecten, omdat ontwerpen in een vroegtijdig stadium niet voldoende informatie bevatten om de kosten van alle constructie objecten te bepalen. De onderzoeker registreerde de tijd die benodigd was om de hoeveelheden te bepalen en vergeleek de hoeveelheden met de daadwerkelijke hoeveelheden om de prestatie van de methoden te bepalen. De traceerbaarheid van de drie methoden om hoeveelheden te bepalen is beoordeeld door de zes kostendeskundigen. Deze studie vereiste een multicriteria-analyse (MCA) methode, aangezien de prestatiescore van de drie criteria verschillende eenheden gebruikten, namelijk: minuten, percentage en een beoordelingsscore. Deze studie gebruikte een MCA-methode om de prestatie per criterium te operationaliseren. Voor deze studie is de Simple Multi-Attribute Rating Technique (SMART) gebruikt met utiliteitsfuncties van de laagste tot de hoogste prestatiescore voor elk criterium. Deze utiliteitsfuncties zijn gebruikt om de prestatiescore van de criteria te operationaliseren naar gelijke eenheden, namelijk utiliteitsscores. De utiliteitsscore vermenigvuldigd met de gewichten resulteerde in de algemene prestatiescore van de methoden om hoeveelheden te bepalen. Het resultaat is gevalideerd door kostendeskundigen. Aan het eind van de workshop hebben de kostendeskundigen hun voorkeur uitgesproken over de drie methoden om hoeveelheden te bepalen. Ter verificatie heeft deze studie een gevoeligheidsanalyse over de gewichten uitgevoerd en een andere MCA-methode gebruikt. De Multi-Attribute Utility Theory (MAUT) was gebruikt i.p.v. SMART om te verifiëren of dezelfde methode om hoeveelheden te bepalen de hoogste algemene prestatiescore heeft bij het gebruik van een andere MCA methode.

Literatuur betreffende decompositiestructuren resulteerde in de conclusie dat er niet één correcte decompositiestructuur bestaat. De literatuur beschrijft vele verschillende decompositiestructuren. Deze studie gebruikte de decompositiestructuur van Arcadis. De decompositiestructuur is gebruikt om de kostenbepalende objecten te identificeren. Tijdens de workshop hebben zes kostendeskundigen de hoeveelheden bepaald van negen kostenbepalende objecten. De zes kostendeskundigen bepaalde aan het begin van de workshop de gewichten van de criteria. De gewichten van de criteria efficiency, accuraatheid en traceerbaarheid zijn respectievelijk: 0.29, 0.38 en 0.33. Oftewel, de kostendeskundigen achten accuraatheid het belangrijkste criterium gevolgd door traceerbaarheid. Het resultaat van de workshop is dat BIM-based QTO en de BIM-viewer gelijkwaardig zijn wat betreft accuraatheid, handmatig hoeveelheden bepalen was minder accuraat. Dit was verwacht, aangezien BIM-based QTO en de BIM-viewer hetzelfde 3D model gebruikten. Hoeveelheden bepalen d.m.v. BIM-based QTO vereiste het minste tijd, gevolgd door gebruik maken van de BIM-viewer. Dit was verwacht, aangezien de hoeveelheden automatisch bepaald worden d.m.v. BIM-based QTO. Voor het gebruik van de BIM-viewer moet de kostendeskundige selecteren van welke objecten de hoeveelheden benodigd zijn, dit vereist tijd. Er is unaniem bepaald dat de hoeveelheden bepaald met de BIM-viewer het meest traceerbaar zijn, gevolgd door de handmatig bepaalde hoeveelheden. Hoeveelheden bepaald d.m.v. BIM-based QTO zijn het minst traceerbaar volgens de kostendeskundigen, aangezien lastig te traceren is tot welk object de hoeveelheden behoren en lastig is te volgen uit welke onderdelen de hoeveelheden bestaan. De BIM-viewer visualiseert direct het object waar de hoeveelheid tot behoort. De algemene prestatiescore van de BIM-viewer is beter dan van BIM-based QTO en handmatig hoeveelheden bepalen. Dit komt voornamelijk doordat de hoeveelheden bepaald met de BIM-viewer beter traceerbaar zijn. De validatie had een uniform resultaat aangezien alle kostendeskundigen het gebruik van de BIM-viewer prefereren over gebruik maken van BIM-based QTO en handmatig hoeveelheden bepalen. Het resultaat van de verificatie was dat de BIM-viewer de hoogste algemene prestatiescore behield. Derhalve is het resultaat geverifieerd en gevalideerd.

Deze studie laat zien dat semiautomatisch hoeveelheden bepalen in een vroeg stadium door gebruik te maken van de BIM-viewer een hogere algemene prestatiescore heeft dan de andere methoden. Momenteel oppert de huidige literatuur vaak BIM-based QTO om de hoeveelheden op basis van gedetailleerde ontwerpen te bepalen. Uit dit rapport blijkt echter dat hoeveelheden bepalen tijdens een vroeg stadium door gebruik te maken van een BIM-viewer een hogere algemene prestatiescore heeft dan BIM-based QTO. Daarom zal het gebruik van een BIM-viewer om hoeveelheden te bepalen in een vroeg stadium een beter kostenramingsproces opleveren. Verbeterde kostenramingen in een vroeg stadium heeft als gevolg dat het besluitvormingsproces in een vroegtijdig stadium zal verbeteren. Dit draagt bij aan een lager faalpercentage voor aannemers. Huidige literatuur dat focust op het bepalen van hoeveelheden d.m.v. BIM gebruikten traceerbaarheid niet als criterium om de prestatie van de methoden te bepalen. Deze studie laat zien dat kostendeskundigen traceerbaarheid van belang achten voor het bepalen van de hoeveelheden en kosten. Het vergelijkingsproces kan verbeterd worden door gebruik te maken van het criterium traceerbaarheid.

Deze studie sluit af met het vermelden dat voor het in een vroeg stadium bepalen van de kosten van infrastructuurprojecten de expertise van kostendeskundigen altijd benodigd is. Expertise is benodigd, aangezien aanvullende kosten vanwege fasering en de omgeving van een project momenteel niet mogelijk zijn om automatisch te bepalen. De aanvullende kosten kunnen een groot deel van de totale kosten van een project omvatten.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Table 1: Definitions of important terms

Term	Definition
BIM	Building Information Modelling: "*The processes and collaborative behaviours associated with the creation and sharing of object orientated databases of an asset in its environment, relevant to all stages of the asset's life cycle including design, construction and operation*" (Arcadis, n.d.).
BIM-based QTO	Automatic quantity take-off using Building Information Modelling. Object quantity information of the three-dimensional models can be extracted by using BIM-based QTO, e.g. volume of a brick.
BIM-viewer	Tool that can be used to display a three-dimensional model including the dimensions of the objects in the project, e.g. the width, height and depth of a brick is displayed. The quantities stored in the BIM-viewer can be connected to the cost estimation.
Building information model	Digital model of a construction project existing of objects that contain information of the construction project
Conceptual cost estimating	"*Conceptual cost estimating is the determination of the project's total costs based only on general early concepts of the project*" (Phaobunjong, 2002).
Cost determining objects	Objects that are the main costs of a project and are therefore of importance for estimating the early-stage costs. For bridges, cost determining objects are the main components of a bridge, e.g. abutments and slabs.
IFC	*"Industry Foundation Class (IFC) was developed by buildingSMART and is a common data 'schema' intended for holding interdisciplinary information for building lifecycle in a building information model and exchanging it among software applications used in the Architecture Engineering and construction sector"* (BuildingSMART UK, 2010).
Manual quantity estimation method	Non-automatic method to estimate the product quantities of a design, e.g. measuring the dimensions using a 2D drawing.
MCDA	Multi-criteria decision analysis is a method to prioritize or make a rational and transparent decision based on multiple criteria.
Performance	Performance refers in this research to how well quantity estimation methods perform. This study determined the criteria to compare the performance.
Preliminary design	The preliminary design does not contain detailed information of the design, it contains the approximate geometry of the objects of a construction project. The preliminary design is an early-stage design.
Quantity	*"The extent, size, or sum of countable or measurable discrete events, objects, or phenomenon expressed as a numerical value."* (Businessdictionary, 2018)
Utility	*"The total satisfaction received from consuming a good or service."* (Investopedia, 2018)

1 INTRODUCTION

This study has been performed for Arcadis, a worldwide design and consultancy firm that focuses on infrastructure, water, environment and buildings. This study focused on estimating the product quantities within preliminary designs. The product quantities of construction components within a preliminary design are necessary to estimate the costs using a preliminary design. For example, the volume of an abutment in the preliminary design of a bridge should be used to determine the costs of the bridge.

This section describes the most important concepts of the study and starts by describing the importance of cost estimation, followed by the design phases of a project, because cost estimation methods differ per design phase. Several quantity estimation methods can be used to estimate the costs, three quantity estimation methods have been described. Furthermore, Building Information Modelling (BIM) has been described. BIM can be used to automatically extract the product quantities, called BIM-based quantity take-off (QTO). This section finishes with the practical relevance of this study and the reading guide.

The cost estimation department is of high importance for a company. It is important to have a realistic estimation of the costs before the project starts. At the start of the project, the cost estimation is based on a rough design, making it difficult to gain sufficient information for the cost estimation. Information about objects that are not captured in the design are often estimated by the cost engineer based on the work conditions. Therefore, the preliminary cost estimation is not completely objective, but partly subjective (Lee et al., 2014).

1.1 Design phases

There are multiple phases of designing where cost estimations are executed during an infrastructure project. The first design phase is determining the ambition and creating a reference image. The next phase is the schematic design. During the schematic design phase, the first design is made. This design contains the first sketches without details. The preliminary design contains practical information, e.g. existing project conditions, such as cables under the ground. The preliminary design contains roughly 75% of the final design and contains the first spatial and aesthetical design of the project. All the feedback during preliminary design phase will be used for the detailed design. The detailed design contains the definitive materials and product quantities (ipv Delft, n.d.).

1.2 Early-stage cost estimation

Whether an infrastructure project is successful, can be determined by two factors: adherence to budget and time. The cost estimation that determines the budget, is often made in the preliminary stage of design, making it a challenge to accurately determine the budget (Fragkakis et al., 2015). Making the decision process regarding choosing a design alternative easier, is of great importance for the costs (Bhimani and Mulder, 2001; Barrie and Paulson 1992; The Construction Industry Institute, 1995). Since it is found out that decisions made during the conceptual phase, i.e. early-stage, account for 70-80% of the total eventual cost (Daschbach et al., 1988), the cost estimation in the preliminary stage is decisive for the future success of a project. Figure 1 shows the influence curve of decisions on project cost performance. Therefore, efficiently and accurately estimating the product quantities of the materials of a project is of great importance. During the schematic and preliminary design, most of the decisions are made and to evaluate the alternatives, quick, accurate quantity estimates are required. The cost estimation in the preliminary stage is based on designs that are not finished. Therefore, the cost estimation is an attempt to predict the costs. The cost estimation determines the feasibility of the project and therefore determines if the organization, e.g. municipality, will continue with the project (Popham, 1996). The information that is available for the consultant is often of a low detail level, e.g. the approximate dimensions of a bridge. Historical records of cost estimations are often used to determine the unit costs, e.g. approximate price per meter of a road (Phaobunjong, 2002).

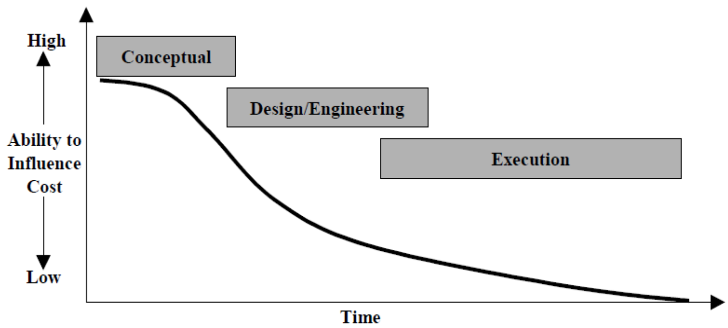

Figure 1: Influence curve of decisions on project cost performance (Phaobunjong, 2002)

1.3 Quantity estimation methods

Product quantities are required to estimate the construction costs. Several methods for estimating product quantities could be distinguished. This study used only three quantity estimation methods, because they are applicable with Revit and are the most common used quantity estimation methods. Furthermore, Arcadis already uses one of the quantity estimation methods, namely manual quantity estimation.

A manual, semi-automatic and automatic quantity estimation method are described. The methods to estimate the quantities can be seen in Table 2. For the first quantity estimation method (A), the designer makes 2D drawings of the project and the cost engineer uses these drawings to estimate the quantities. For the second quantity estimation method (B), the designer makes a 3D model, which should be uploaded to a BIM-viewer. The BIM-viewer is a tool that displays the 3D model of the project including its dimensions. This BIM-viewer should be used by the cost engineer to estimate the quantities. The third method (C), the designer makes a 3D model and the cost engineer uses BIM-based QTO to automatically extract the quantities, which is described in the next paragraph.

Table 2: Quantity estimation methods

Method	Task of designer	Task of cost engineer
A	Makes 2D drawing.	Manual quantity estimation by measuring based on 2D drawing.
B	Makes 3D model and uploads it to a BIM-viewer.	Semi-automatic quantity estimation by using the BIM-viewer. Dimensions are displayed in the BIM-viewer, but not automatically transferred to the cost estimation. The cost engineer determines what dimensions to use and places those in the cost estimation.
C	Makes 3D model and sends it to the cost engineer.	Automatic quantity-extraction (BIM-based QTO).

1.4 Building Information Modelling

Building Information Modelling (BIM) can be used to make quick, accurate quantity estimations. BIM is a process and technology that altered the construction industry. Since the mid-2000s, BIM has transformed from a concept to the focal point of the construction industry (Eastman et al., 2011). The definition of BIM in this study is: *"The processes and collaborative behaviours associated with the creation and sharing of object orientated databases of an asset in its environment, relevant to all stages of the asset's life cycle including design, construction and operation*" (Arcadis, n.d.). Building information models can be used for quantity take-offs (QTO). QTO is an operation that involves taking the quantities of an information model to create a list of individual construction units as taken from project documentations (Vitásek and Matějka, 2017). BIM-based QTO is the automatic extraction of the product quantities of a construction project using a 3D model.

1.5 Practical relevance

Arcadis is often involved in the early-stage design phase and therefore has no access to detailed data. Arcadis consults other organizations by estimating construction costs, to do so Arcadis uses manual quantity estimation method A to estimate the product quantities using preliminary infrastructure designs. Arcadis wanted to improve their work and considered implementing BIM in their work practice to estimate the product quantities of the components of their infrastructure projects using a preliminary design.

Using BIM to estimate product quantities might be faster and more accurate compared to manual quantity estimation. Faster quantity estimation results in faster cost estimation. Fast cost estimation is useful during the early-stage design phase, because most decisions of a construction project are made during the early-stage design phase. Early-stage decisions have great influence on the total costs of a construction project. Accurately estimating the quantities results in an accurate cost estimation. Therefore, a more accurate early-stage quantity estimation method would be beneficial (van der Knoop, 2018; Volleberg, 2018).

For Arcadis it is of importance to explore the overall performance of the three early-stage quantity estimation methods. Therefore, a comparison of the early-stage quantity estimation methods for infrastructure projects would be beneficial for Arcadis. Infrastructure projects differ with building projects, because building projects are often located on a greenfield site, i.e. an undeveloped site (Carvalho, 2014; Shelton et al., 2015).

Therefore, the surroundings do not play a part in estimating costs of building, though the surroundings do play a part in estimating the costs of an infrastructure project (van der Knoop, 2018; Volleberg, 2018). For Arcadis it is of importance to explore the performance of early-stage quantity estimation methods for infrastructure projects.

1.6 Reading guide

This paragraph describes the structure of the report. The next section describes the conceptual background of this research. The conceptual background section describes the problem statement, research objective and research questions. Furthermore, the next section describes the scope and research model of this research.

The third section elaborates on the methodology that this study used. The methodology section describes the criteria, alternatives and MCDA method that this study used to determine the performance of the quantity estimation methods. Furthermore, the methodology section describes how the researcher identified the cost determining objects and how this study determined the overall performance.

The fourth section describes the results of this study. The results are the cost determining objects and the performance of the quantity estimation methods. The results section is followed by the discussion, conclusions, limitations and recommendations. Figure 2 displays the structure of this study.

Figure 2: Structure of this study

2 CONCEPTUAL BACKGROUND

The conceptual background starts by describing the current literature regarding comparing early-stage quantity estimation methods. The literature resulted in the problem statement, that formed the basis for the research objective. Research questions were formed based on the research objective, forming the structure of the study. The research questions paragraph is followed by the scope to delimit the research and the research model.

2.1 Problem statement

During the tender phase, contractors use detailed cost estimations based on a detailed design, because the cost estimation must be accurate, otherwise the risk of the contractor is too high (Phaobunjong, 2002). Therefore, the quantities and unit prices of all construction objects are known. The quantities can be extracted from a model or estimated from a drawing (Phaobunjong, 2002). BIM has significant benefits for detailed designs. According to Whang and Park (2016) BIM-based quantity take-off has a higher accuracy compared to manual quantity estimation. However, Whang and Park only focused on extracting quantities for a building frame in a detailed design and not for a preliminary design. Furthermore, Whang and Park (2016) did not focus on other criteria to determine the performance of BIM-based QTO, e.g. efficiency. Other studies that focused on the benefits of BIM for the complete construction process mention that benefits of BIM are time reduction and accuracy (Bryde et al., 2013; Chou and Chen, 2017). However, those studies do not focus on only estimating the quantities using a preliminary design, the studies focus on the complete construction process and do not compare quantity estimation methods.

The scientific database Scopus was used to determine the amount of existing literature regarding this study. The searching procedure considered article title, abstract and keywords. The researcher used different search clusters regarding BIM, quantity estimation, quantity take-off, comparison and preliminary design to determine the amount of existing literature. There is a gap in literature regarding the performance of BIM-based QTO in the preliminary design. Most studies regarding the benefits of BIM focus on either the detailed design, or the complete construction process. If the study focuses on quantity- and cost estimation using BIM during the preliminary design, the method is not compared with alternative methods (Soto and Adey, 2016; Nesticò et al., 2017; Cheung et al., 2012; Choi et al., 2015; Barg et al., 2018; Marzouk and Hisham, 2012; Vitásek and Matějka, 2017). These studies only apply the quantity- or cost estimation method and therefore there is not known whether the estimation method using BIM is performing better than alternative estimation methods. The existing literature is described in more detail in Appendix A.

The study that is most closely related to this study is the research of Hafez et al. (2015) that focused on comparing detailed cost estimation methods, of which one is BIM-based cost estimation. The researchers used four criteria: generality, flexibility, efficiency, and accuracy to determine the performance of the methods. To determine the weights of the criteria, the eigenvector prioritization method was used. For the eigenvector prioritization method, importance factors are required, which were based on authors' industry experience and related studies. The study of Hafez et al. (2015) used the total costs of the project to determine the accuracy. However, when the costs of one object are estimated too low and of another object too high, it would seem that the method is accurate, although the method might be inaccurate. The conclusion of the research was that a BIM-based cost estimation method performed better than manual cost estimating methods. It is unclear whether BIM-based quantity estimation performs better than alternative quantity estimation for a preliminary design, because the study of Hafez et al. (2015) used a detailed design and the total costs, instead of a preliminary design and the quantity per cost determining object. Preliminary design has a different focus than detailed design, e.g. efficiency is more important during preliminary design. Quick cost estimation is more beneficial during preliminary design than during detailed design, because most decisions regarding the design and construction are made during preliminary design. When the costs of decisions can be estimated quicker, the design can be adapted to the costs of the decisions (Bhimani and Mulder, 2001; Barrie and Paulson, 1992; The Construction Industry Institute, 1995).

It is of importance to understand the performance of the early-stage quantity estimation methods, because a better performing quantity estimation method has a high impact on the project performance (Phaobunjong, 2002). Therefore, understanding the performance of the quantity estimation method could result in a better project performance. Poor cost estimations contribute to the high rate of failure of contractors (McIntyre, 2007). Improved quantity estimation methods can contribute to decreasing the high rate of failure of contractors. Literature on effectiveness of BIM-based QTO mostly assumed that the design is near-fully developed. However, for early-stage cost estimation this is not the case. Since there is limited literature regarding the performance of quantity estimation methods using preliminary designs, it is unknown whether implementing automatic BIM-based QTO (C) using a preliminary design is beneficial compared to alternative quantity estimation methods (A and B). Literature currently states that automatic BIM-based QTO (C) is effective and accurate. This, in principle, assumes that the design models used for quantity extraction are near-fully developed and thus complete. Therefore, the problem statement is:

Early-stage designs do not contain a high level of development. The performance of automatic BIM-based QTO (C) compared to alternative quantity estimation methods (A/B) for early-stage quantity estimation is not explored extensively to date, though BIM could improve cost estimations significantly.

2.2 Research objective

To solve the problem stated in the previous paragraph, a research objective was formulated. The main research objective is defined as:

To compare the performance of automatic BIM-based QTO (C) to alternative quantity estimation methods (A/B) for early-stage quantity estimation of cost determining objects, and to give a recommendation regarding implementing BIM to estimate product quantities in the work practice of Arcadis.

To understand the additional performance of BIM-based QTO, it is required to understand the overall performance of alternative quantity estimation methods, otherwise the performance cannot be compared. Based on the overall performances of the quantity estimation methods, a ranking was created, and a preferred quantity estimation method was determined. This resulted in a recommendation regarding implementing BIM to estimate product quantities in the work practice of Arcadis.

2.3 Research questions

The main research question is based on the research objective and determines the structure of the research. The main research question is as follows:

What is the overall performance of the manual quantity estimation method, the BIM-viewer and BIM-based QTO for early-stage quantity estimation?

The main research question could be answered by answering the sub questions. The first sub question identifies the criteria used to determine the performance of the quantity estimation methods. The second question investigates what method should be used to determine the overall performance of the quantity estimation methods. The third question is related to cost determining objects. It is required to understand what objects determine the costs of a project and what information about these objects should be acquired from a preliminary design. The cost determining objects were used in combination with the criteria and method to answer the last research question. The overall performances of the quantity estimation methods were used to create a ranking of the quantity estimation methods. The quantity estimation method with the best performance is the preferred alternative. The research questions are:

1. Based on what criteria can the performance of the quantity estimation methods be compared?

2. Based on what method can the overall performance of the quantity estimation methods be compared?

3. What are cost determining objects and what information of the cost determining objects is required to accurately estimate the early-stage costs using a preliminary design?

4. Based on the overall performance of the three quantity estimation methods, what quantity estimation method is recommended to use for early-stage quantity estimation?

2.4 Scope

In this study, the scope of BIM was on the features that support estimating the quantities. There has not been focused on what other features of BIM could be used. Therefore, the focus was on what information should be extracted of the design model to gain sufficient information needed to estimate the costs using a preliminary design. The focus was on quantity estimation, because estimating the quantities takes most of the time of estimating the costs of a construction project.

This study used only three quantity estimation methods, namely the quantity estimation methods that are described in the introduction. This study used these three quantity estimation methods, because they are either implemented in the work practice of Arcadis (quantity estimation method A) or Arcadis wants to implement the method (B and C).

The focus of the study was on bridges. It is impossible to find out the cost determining objects of all infrastructure projects within the time period of this study, therefore to limit the study, this study focused only on bridges. Furthermore, a bridge project is a common project for Arcadis.

This study only focused on designs made with the design software Autodesk Revit and therefore the tool to automatically extract quantities of the design had to be compatible with Autodesk Revit. This study chose this focus to create one uniform method to estimate the quantities of a bridge project. Furthermore, the standard design software for bridges at Arcadis is Autodesk Revit.

2.5 Research model

To accomplish the research objective and answer the research questions, automatic BIM-based QTO was compared with alternative quantity estimation methods. The quantity estimation methods were compared by using the case of a bridge project in Zwolle that Arcadis was working on. This project was chosen, because Arcadis possesses 2D drawings and a 3D model of this bridge. The 2D drawings and 3D model are both required to determine the performance of the quantity estimation methods A, B and C. Furthermore, a bridge is a common project within the infrastructure department of Arcadis. The case project was used for a workshop. During this workshop, cost engineers estimated product quantities of the cost determining objects of the case project.

The research model that was used for this research can be seen in Figure 3, the vertical arrows mean by comparing and the horizontal arrow means results in. The phrasing of the research model is as follows: (a) Interviews with cost engineers, a historic cost estimation of a bridge project and literature regarding decomposition of bridges, MCDA methods, cost estimation and quantity estimation, resulted in (b) comparison criteria, a multi-criteria decision analysis (MCDA) method to compare the performance of the three quantity estimation methods and the cost determining objects of a bridge project. (c) The criteria, MCDA method and workshops where cost engineers estimated product quantities of the cost determining objects of the case project were used to compare the overall performance of the quantity estimation methods. Comparing the performance of the three quantity estimation methods resulted in (d) a recommendation regarding implementing BIM in the work practice of Arcadis to estimate product quantities using a preliminary design.

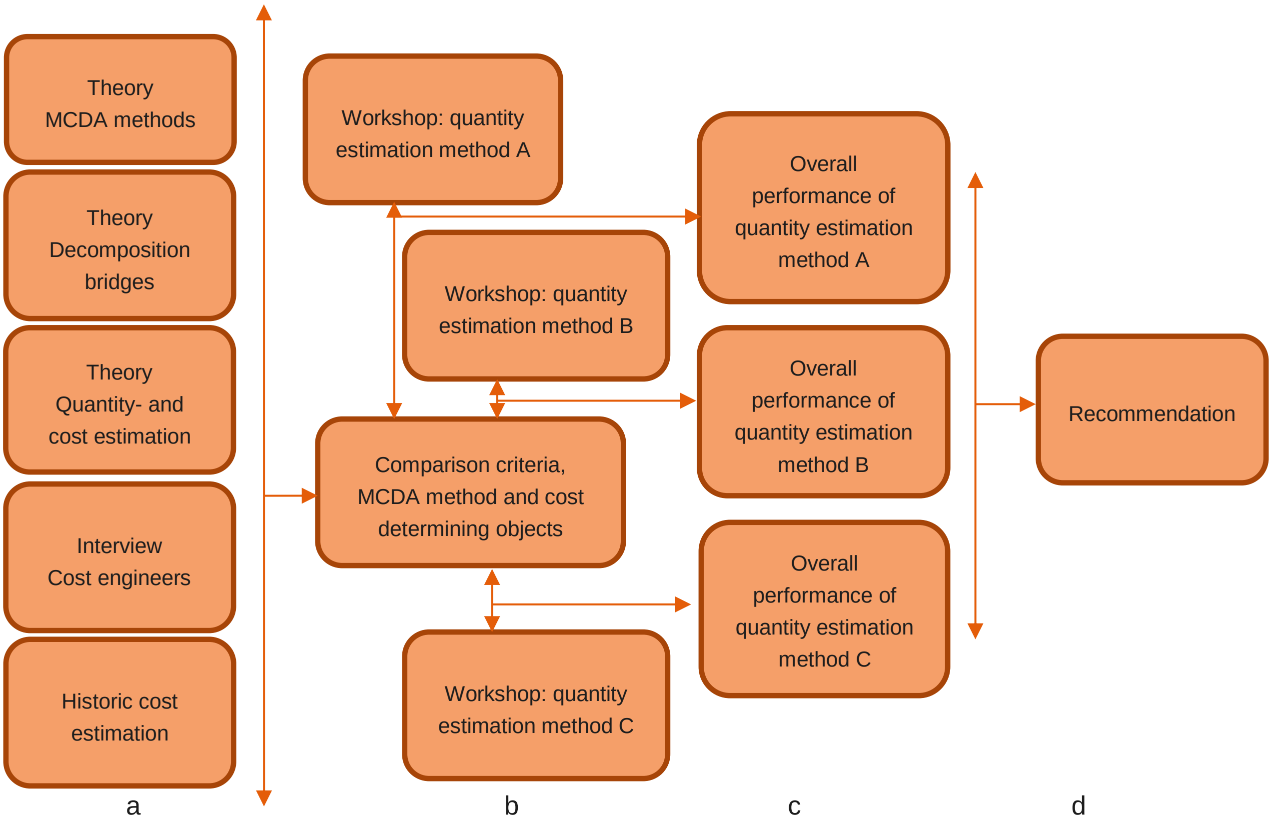

Figure 3: Research model

3 METHODOLOGY

This section elaborates on the methodology used to adequately answer the research questions. This section describes how the data required for the study was collected and what research methods were used per phase. The section was divided in four successive phases based on the research questions.

To determine the overall performance of the quantity estimation methods, criteria and a MCDA method were determined. How the criteria and MCDA method were determined and what criteria and MCDA method were used is described in this section. Furthermore, this section describes how the cost determining objects were identified and how the overall performance was determined. The results section, section four, describes the cost determining objects and overall performance of the quantity estimation methods.

Figure 4: Comparison process (Baker et al., 2002)

The comparison process by Baker et al. (2002) was used to compare the alternatives and to determine the alternative with the highest overall performance. The comparison process contains of 8 steps, as illustrated in Figure 4. The first step, which has already been performed in the previous section, is describing the problem. The problem is that it is unknown whether BIM-based quantity estimation methods perform better compared to alternative quantity estimation methods, therefore quantity estimation methods should be compared to determine the quantity estimation method with the highest overall performance using early-stage designs.

The next section describes the case project that this study used. Step two to five of the comparison process are performed in paragraph 3.2, namely determining the requirements, establishing the goals, identifying the alternatives and developing the criteria. In paragraph 3.3, step six was performed, a multi-criteria decision analysis method was selected (Baker et al., 2002). The MCDA method was applied, and the result of the application is displayed in section four. The result is checked in the paragraphs validation and verification.

3.1 Case project

This study used a case of a bridge project in Zwolle that Arcadis worked on. This project was chosen, because Arcadis possesses 2D drawings and a 3D model of this bridge. The 2D drawings and 3D model are both required to determine the performance of all three quantity estimation methods. A bridge is a common project within the infrastructure department of Arcadis. The case project was used for the workshop. During this workshop, cost engineers estimated product quantities of the cost determining objects of the case project. The bridge type is a fixed flat car bridge of which the road is made of asphalt, the pavement of concrete and the wingwalls of the bridge are made of white concrete. A visualization of the 3D model of the bridge that will be constructed in Zwolle is displayed in Figure 5.

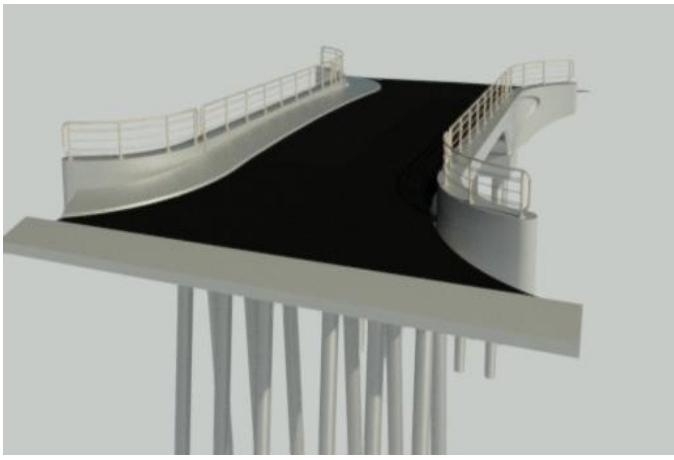

Figure 5: 3D model made in Autodesk Revit

3.2 Alternatives and criteria

This paragraph describes the criteria and alternatives that were used to determine the overall performance of the quantity estimation methods by describing the comparison context and process of this study.

This study used a desk study and interviews to determine the requirements and goals of the quantity estimation methods. The requirements and goals were used to determine the alternatives, i.e. quantity estimation methods. The researcher transformed the goals into criteria based on the quantity estimations methods.

3.2.1 Requirements

The requirements determined the conditions the alternative, i.e. quantity estimation method, had to meet. Alternatives that do not meet the requirements were automatically discarded. An otherwise good alternative that does not meet a requirement, should be automatically discarded.

The quantity estimation method must be applicable with the software Autodesk Revit, because this software is in use at Arcadis. The designers do not want to change their design software, because that will change their design process. Therefore, the alternatives must be applicable with designs made with Autodesk Revit.

The quantity estimation method must be applicable for infrastructure projects, because the quantity estimation method will be used by the infrastructure department at Arcadis. Not all quantity estimation methods are applicable to determine product quantities of infrastructure projects.

The quantity estimation method must be applicable for early-stage designs, because this is the scope of this study. Early-stage quantity estimation differs from detailed quantity estimation as was mentioned in the introduction section. The quantities of larger objects are required for early-stage quantity estimation methods.

The quantities estimated using the quantity estimation method must be traceable, meaning that another cost engineer or the client should be able to trace the origin of the quantity. This is required, otherwise it is impossible to verify the quantities. Quantities are of great importance for estimating the costs and are vulnerable for mistakes. Verification of quantities is important and for verification purposes, the quantities must be traceable (RISE Research Institutes of Sweden, 2018).

3.2.2 Goals

Goals for this study were set up based on interviews and literature to describe the preferences of a quantity estimation method according to cost engineers and literature. The quantity estimation method should fulfil as many goals as possible. Goals differ from requirements, an alternative must fulfil all requirements, otherwise the alternative will be discarded. An alternative can fulfil many goals but often not all goals will be fulfilled. The alternative scores better when more goals are fulfilled. In the criteria paragraph, the goals are translated to criteria and possible measurement methods are described. This paragraph only describes the goals and not the measurement methods. The goals are based on interviews with cost engineers and scientific literature.

Accuracy

The quantity estimation method should be accurate, because the quantities will be used to estimate the costs of the project. Therefore, accurate quantities contribute to an accurate cost estimation. The early-stage costs that are estimated using an early-stage design often determine the budget of a project and if a project will be constructed. This study focuses on preliminary quantity estimation, therefore the accuracy is less important than for detailed quantity estimations, because a larger bandwidth is used for cost estimating using early-stage designs. The goal is to maximize the accuracy (Hafez et al., 2015; van der Knoop, 2018; Volleberg, 2018).

Efficiency

The efficiency of the quantity estimation method is of importance, because the time required to estimate the quantities determines a big part of the time required to estimate the costs. Therefore, minimizing the time required to estimate the quantities results in less man hours required to estimate the costs of a project. Therefore, a more efficient quantity estimation method results in cheaper and quicker cost estimating. The goal is to maximize the efficiency (Hafez et al., 2015; van der Knoop, 2018; Volleberg, 2018).

Generality

It should be possible to estimate the quantities of all cost determining objects using the quantity estimation method. All cost determining objects are of importance to estimate the costs. However, if one quantity of a cost determining object is not possible to estimate using an alternative, another quantity can be used. Therefore, it is not required that all quantities can be estimated, because another quantity might be used, e.g. volume instead of length. However, it is desired that all quantities can be estimated, because it makes estimating the costs less complicated. Therefore, the goal is to maximize the generality (Hafez et al., 2015).

Flexibility

Design features can be difficult to describe in text; therefore, visualization can provide flexibility to make it possible to differentiate design features, e.g. special ceiling features. It is beneficial when more special design features are visualized, because visualizing the features makes estimating the costs easier. The goal is to maximize the flexibility (Hafez et al., 2015).

Time predictability

Arcadis estimates the costs of the construction of a project. However, the costs of making a cost estimation should also be estimated. If a municipality wants to know how much constructing a bridge will cost, the first step is that the municipality makes notice that companies can submit a tender to estimate the costs. Furthermore, the municipality states what their desires are. The next step is that several companies submit a tender. This tender shows the price for which a company wants to estimate the costs of a project. The price is of huge influence for winning the tender. The lower the price the higher the chance of success. The time required to estimate the costs is required for the tender, therefore, the goal is to maximize the time predictability (KPI Working Group, 2000).

Traceability

The quantities used in the cost estimation should be traceable, otherwise the client and other cost engineers do not understand to what object the quantities belong and if the quantities are correct. It is important to understand the origin of the quantities to estimate the costs, because multiple aspects are important to estimate the costs of the object, not only the quantity. For example, the location of an object is important for estimating the costs, because other equipment or material might be required for different locations, e.g. a tower crane cannot reach the location. Traceability reduces the probability of recording errors and increases the transparency. Furthermore, the traceability might increase the efficiency in the long term, because in the subsequent project phase the substantiation of quantities is already performed, and the quantities are traceable. The cost estimation must be structured and interpretable for everyone (CROW, 2010). Therefore, the goal is to maximize traceability of the quantities (van der Knoop, 2018; Volleberg, 2018; RISE Research Institutes of Sweden, 2018).

Staff expertise

Using a new quantity estimation method requires new skills of employees. Not all employees are experienced with 3D modelling software. Less required expertise to use the quantity estimation method would be advantageous for Arcadis and it is of importance that data of the project is presented on the level of training or experience of the persons that use the data. Therefore, the goal is to minimize the required staff expertise (Volleberg, 2018).

An overview of the seven goals that were described in this paragraph is given in Appendix C. Furthermore, the definition of the goals has been displayed in Appendix C.

3.2.3 Alternatives

As mentioned in the introduction section, three quantity estimation methods were compared. The quantity estimation methods were determined based on the requirements and goals mentioned before. The three quantity estimation methods are a manual, semi-automatic and automatic quantity estimation method. The quantity estimation methods all meet the requirements stated in section 3.2.1.

Manual quantity estimation

The traditional method that is in use at Arcadis is manual quantity estimation. The designer creates 2D drawings of the project and the cost engineer uses these drawings to estimate the product quantities. The product quantities are stored in an Excel file. The hypothesis is that manual quantity estimation takes more time and therefore is less efficient than using BIM to estimate quantities. Furthermore, it is possible that a cost engineer forgets to estimate the quantity of a certain object and therefore the cost of this object is not taken into account in the complete cost estimation.

BIM-viewer

Quantity estimation using a BIM-viewer is a semi-automatic approach. The quantities are estimated automatically; however, the quantities are not stored automatically. The cost engineer has to determine the quantities that should be stored. IBIS, a software developer, developed BIM-meetstaten, software to estimate product quantities using a building information model. The building information model created in Autodesk Revit or other design software can be exported as Industry Foundation Class (IFC) file, a general file format used for building information models. The IFC file can be uploaded in BIM-meetstaten. The 3D information model is shown in the software and quantity information of all objects is available. Figure 7 shows a 3D designed building uploaded as IFC file in BIM-meetstaten.

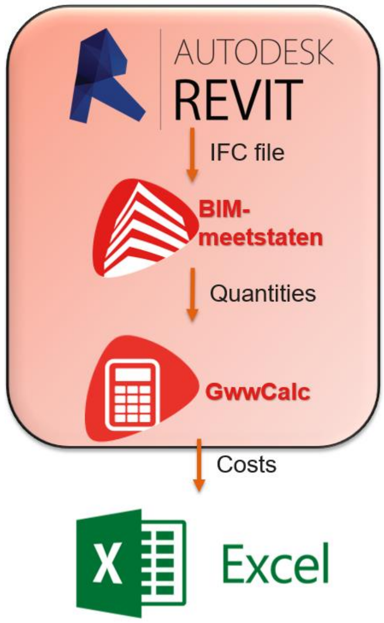

Figure 6: Workflow software semi-automatic quantity estimation method

All quantities and dimensions can be extracted from the objects. In Figure 7, all abutments are selected. The volume of the abutments is shown, and the sum of the volumes was calculated. The quantities can be exported to GwwCalc or Excel. Because Arcadis stores all unit prices in GwwCalc, the logical way is to export the quantities to GwwCalc. In GwwCalc, the quantities can be multiplied by the unit prices stored in GwwCalc. An advantage of BIM-Meetstaten is that the quantities are traceable, because the quantities are connected with the 3D model. If you click on the quantities stored in GwwCalc, the 3D model opens and displays the object to which the quantities belong. Therefore, there is automatically visualized of what object the quantities are. Traceability is of high importance for early-stage quantity estimation, therefore the BIM-viewer is useful for early-stage quantity estimation. The quantities can be multiplied by the unit prices to create a cost estimation of the object. The cost estimation of all objects can be exported to Excel. The workflow of the software used can be seen in Figure 6. The red box in Figure 6 illustrates the focus of this study. Since this study focused on estimating the quantities, only Autodesk Revit and BIM-meetstaten were used for this study and the unit prices have not be taken into account.

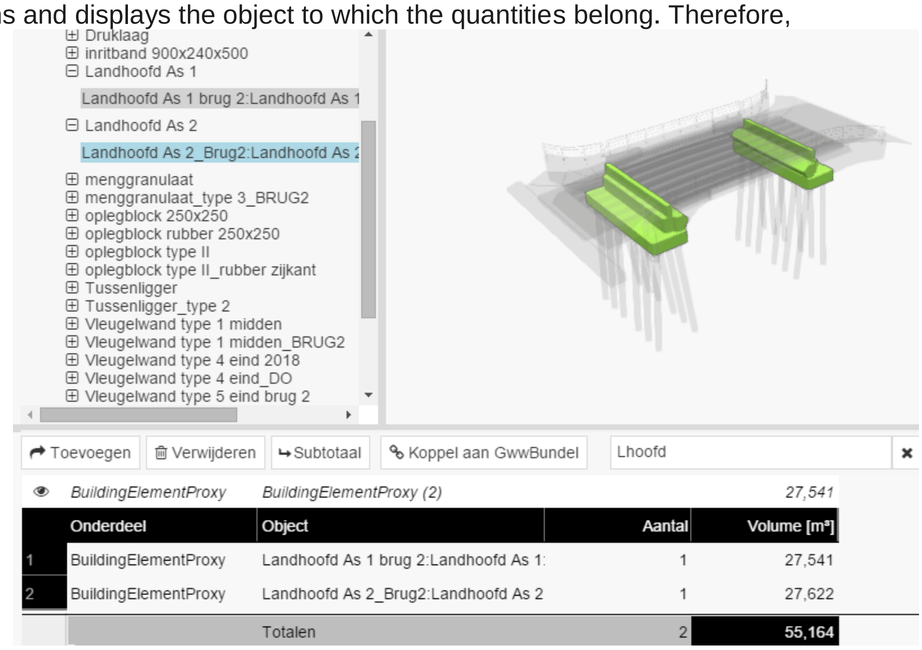

Figure 7: Example BIM-meetstaten

BIM-based QTO

BIM-based QTO is an automatic quantity estimation method using Building Information Modelling. Object quantity information of the three-dimensional models can be extracted by using BIM-based QTO. The designer makes a 3D model of the project using Autodesk Revit. This file was used by the cost engineer to extract the product quantities required to estimate the costs.

The requirement was that the quantity estimation method should be applicable with designs made in Autodesk Revit. To automatically extract the quantities multiple methods can be used. It was advised by Ted Peek (2018) to use the Autodesk Revit material take-off function to automatically extract the quantities of the construction objects, because it is a quick and reliable method that uses Autodesk Revit designs to automatically extract product quantities. Quick quantity estimation is especially beneficial for early-stage quantity estimation, because multiple design alternatives are considered during the early-stage design phase.

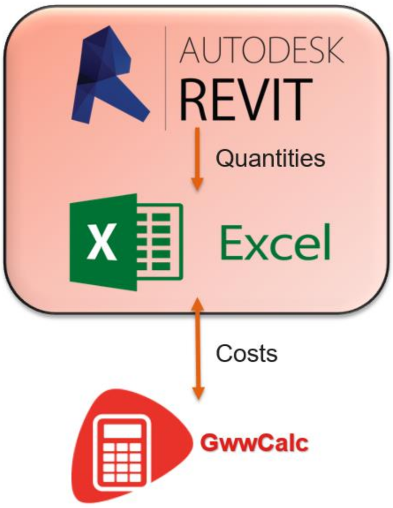

Figure 8: Workflow software BIM-based QTO

A material quantity take-off can be seen in Figure 9. A schedule of all product quantities and dimensions can be extracted in Autodesk Revit. This schedule can be exported to Excel. It is of importance that the cost engineer determines beforehand what quantities and dimensions are required to estimate the costs. For some objects, the area is required to estimate the costs, for other the volume. The extracted quantities can be automatically stored in an Excel file. The unit prices of Arcadis are stored in GwwCalc. To estimate the costs, the unit prices in GwwCalc should be multiplied by the quantities stored in the Excel file for all objects. Therefore, a codification system is required to connect the quantities and unit prices. The same codes should be added to the object in the building information model as was used in GwwCalc.

The workflow of the software used can be seen in Figure 8. The red box in Figure 8 illustrates the focus of this study. Since this study focused on estimating the quantities, only Autodesk Revit and Excel were used for this study and the unit prices have not been taken into account.

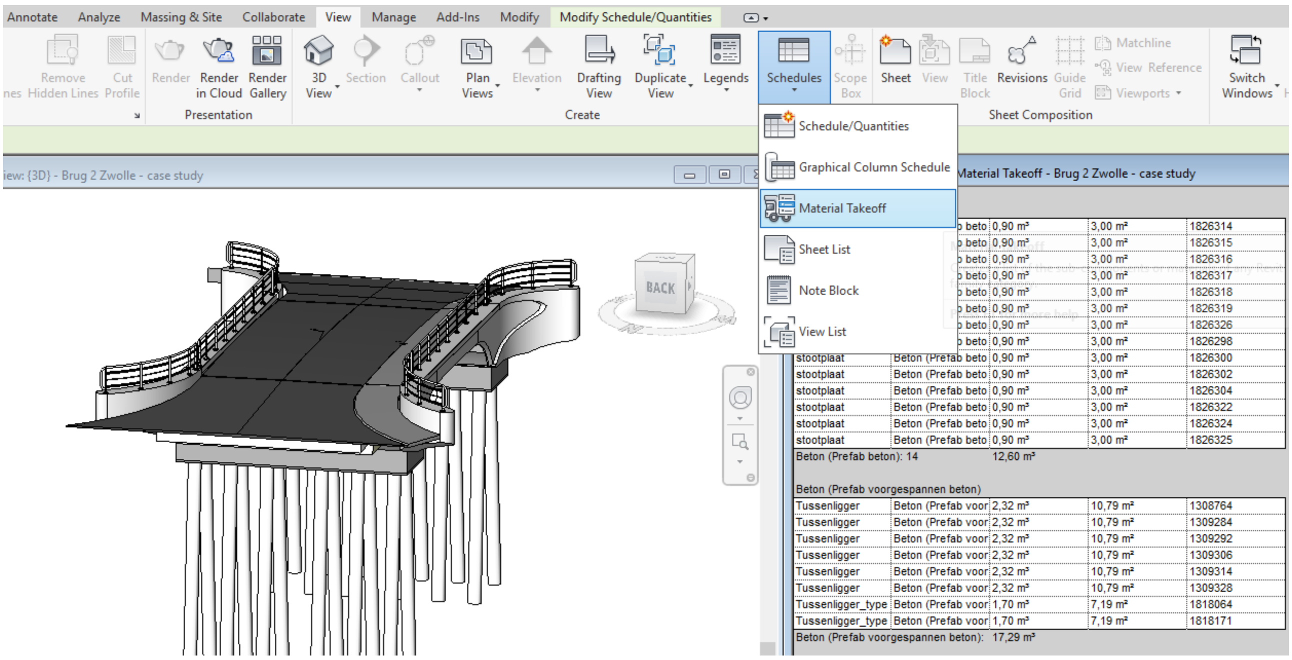

Figure 9: Example material take-off Autodesk Revit

3.2.4 Criteria

To determine the alternative with the highest overall performance, the alternatives were compared based on several criteria. Those criteria were based on the goals of the organization and the alternatives. The goals mentioned before were translated into criteria. Often, there is not one alternative that performs the best regarding all goals. Therefore, criteria are required to determine the alternative with the best overall performance. Not all goals can be used as criteria, according to Baker et al. (2002) criteria should be:

- *"Able to discriminate among the alternatives*
- *Complete – include all goals*
- *Operational – meaningful to the decision maker's understanding of the implications of the alternatives*
- *Non-redundant – avoid double counting*
- *Few in number – to keep the problem dimensions manageable"*

The criteria are shown in Table 3, where possible measurement methods are also mentioned. Measurement methods were used to indicate the performance of the quantity estimation methods for all criteria. The availability of data to determine the performance of the quantity estimation methods per criterium is also mentioned. Furthermore, Table 3 displays if the criteria discriminate among the alternatives, i.e. if the performance of the alternatives differ per criterium. If the performance does not differ, the criteria do not have influence on the total performance of the quantity estimation methods. Operationality has not been added to the table, because all goals are operational, the goals are meaningful for understanding the implication of the alternatives.

Table 3: Criteria and possible measurement method

Criteria	Possible measurement method	Is information available?	Does the criterium discriminate among the alternatives?
Accuracy	Deviation of the estimated quantities per method compared to the actual quantities	Yes	Yes
	Deviation of the estimated costs per method compared by the actual costs.	Yes	Yes
Efficiency	Amount of time required to estimate the quantities	Yes	Yes
Generality	Number of trade estimates that can be generated by the method	Yes	No
Flexibility	The number of special design features the evaluated estimating method can differentiate.	Yes	No
Time predictability	Difference between the actual quantity estimation time and the estimated quantity estimation time	No	Yes
Traceability	Time required to verify if all quantities are traceable and correct	Yes	Yes
	The percentage of quantities that are traceable	Yes	Yes
	Cost engineers assess the traceability of the quantities on a scale of zero to ten	Yes	Yes
Required staff expertise	Determining if the staff is able to estimate the quantities	No	Yes

Because the criteria should be few in number according to Baker et al. (2002), it was recommended to remove some criteria. Of the seven possible criteria, generality, flexibility, required staff expertise and time predictability were removed. Generality and flexibility were removed, because the criteria do not discriminate among the alternatives. Therefore, the criteria would not have influence on the total performance of the quantity estimation methods. The criteria do not discriminate, because all alternatives are able to determine the same product quantities and the same special design features.

The criterium required staff expertise was removed, because the criterium was not deemed of high importance by the cost engineers. The cost engineers are well willing to learn the quantity estimation methods (Volleberg, 2018). Furthermore, it is difficult to measure the required staff expertise and it is difficult to measure the current expertise of the cost engineers regarding BIM.

It is possible to measure the time predictability of the quantity estimation methods by determining the expected time that is required to estimate the quantities before the workshop. The expected time could be compared with the actual time that was needed to estimate the quantities. However, the result would not be representable, because the cost engineers have not used BIM before and therefore the cost engineers do not have an accurate expectation regarding the time required to estimate the quantities using BIM.

Ambiguity of the criteria should be prevented. The criteria should not have influence on each other, otherwise some criteria would be weighted double. The remaining criteria were checked for ambiguity. The criteria do not have influence on each other; however, only one measurement method per criterium should be used.

Accuracy

The accuracy of the quantity estimation method is of importance for the cost estimation. Therefore, if the quantities are inaccurate, it is likely that the cost estimation is inaccurate. A preliminary cost estimation often determines the budget of the project and therefore determines whether the project will be constructed. Two measurement methods are displayed in Table 3, the accuracy based on the costs or the quantities. This study focused on the quantities, therefore the measurement method that was used was using the deviation of the estimated quantities based on an early-stage design compared to the estimated quantities of a detailed design. Quantities of the detailed design were used, because the actual quantities after construction are not known, since the project is not yet constructed. Quantities per object were used instead of the total quantities, because otherwise two mistakes, one quantity estimated too high and one too low, might indicate that the quantities are estimated accurately.

Efficiency

The efficiency of the quantity estimation methods is of importance, because the time it takes cost engineers to estimate quantities cause most of the time required to estimate the costs. Therefore, a higher efficiency results in quicker and cheaper cost estimating. Quick quantity estimation is especially beneficial for early-stage quantity estimations, because most design decisions, e.g. material type, are made in the early-stage of construction projects. Therefore, the early-stage decision making process will be improved by quick early-stage quantity estimation. The efficiency of the quantity estimation methods was measured by the amount of time invested to estimate the quantities. A workshop was used to determine the efficiency.

Traceability

The quantities must be traceable, because the client needs to understand the origin of the quantities. Otherwise, the quantities cannot be verified, since the client does not understand to what object the quantities belong or what part of the object is used to determine the quantity. Furthermore, it is important to trace the origin of the quantities for the cost engineer, because in the subsequent project phase the quantities of the previous project phase must be verified, because the design might have been changed. Furthermore, another cost engineer might be involved in the subsequent project phase and should be able to understand the origin of the quantities. Therefore, for internal and external purposes, traceability is of importance. The cost engineers have assessed the traceability of the quantities on a scale of one to ten after taking part of the workshop. During the workshop, the cost engineers gained work experience of using the three quantity estimation methods.

Criteria were formed based on the determined goals and quantity estimation methods. The criteria and measurement methods that this study used to determine the performance per criterium are displayed in Table 4. The measurement methods are used in the results section to determine the performance of the quantity estimation methods.

Table 4: Final criteria and measurement method

Criteria	Measurement method
Accuracy	Deviation of the estimated quantities per method compared to the actual quantities
Efficiency	Amount of time required to estimate the quantities
Traceability	Cost engineers assess the traceability of the quantities on a scale of zero to ten

3.3 Multi-criteria decision analysis

In the previous paragraph the comparison criteria were mentioned. To finish the comparison process, a multi-criteria decision analysis (MCDA) method was used. A MCDA method was required to determine the overall performance of the quantity estimation methods. The performance scores of the three criteria used different units. The unit of the performance score of accuracy was percentage, of efficiency the unit was minutes and for the performance score of traceability was a number between zero and ten. To operationalize the criteria, a MCDA method was required. Similar units are required to estimate the overall performance of the quantity estimation methods. Therefore, this study used a multi-criteria decision analysis method to transform all criteria to the same unit.

The Simple Multi-Attribute Rating Technique (SMART) was used as comparison method for this study. SMART is a simple form of Multi-Attribute Utility Theory. The method uses weights and simple utility relations to determine the ranking of the alternatives. To apply SMART, this study used linear utility functions ranging from lowest performance to the highest performance per criterium. The performance scores per criterium were transformed to utility scores to transform all criteria to the same unit. The utility score based on the performance of the alternatives was multiplied by the weight of the criterium. The sum of the products formed the total value (Fülöp, 2005).

Multiple MCDA methods could be utilized for this study; therefore, several methods were distinguished. The SMART method was chosen based on several requirements and criteria. One of the requirements was that the MCDA method had to be able to use the evaluation criteria and the performance scores of the evaluation criteria.

Scientific literature regarding determining a multi-criteria decision analysis method was used to determine the most suitable MCDA method for this study. The literature provided multiple aspects to consider when determining a MCDA method, those aspects can be seen in Table 5. The table provides the aspects that were considered, the source of the aspects and the situation of this study. The situation of this study describes what MCDA method is required for this study.

The preference elucidation mode describes what type of problem this study focused on. The problem of this study is that prioritization of the quantity estimation methods should be made. To make this prioritization, a straightforward direct rating or trade-off method could be used. The result of the method should be a preference situation, because a total pre-order is requested. Cardinal information was used for the MCDA method, because the result should not only be that an alternative, i.e. quantity estimation method, is better, but also how much better. Compensation between the criteria is allowed, therefore for example a high accuracy can compensate a low efficiency if the importance of both criteria is equal. Since the decision only needs to be made once by the researcher, there are no restrictions regarding time, money and software.

Table 5: Aspects of MCDA method considered by the researcher for determining the most suitable MCDA method

Aspects to consider	Situation	Source
Preference elucidation mode	Straightforward or trade-off	Guitouni and Martel, 1998

Decision moment	A priori	Guitouni and Martel, 1998
Preference structure	Preference situation	Guitouni and Martel, 1998
Order	Total pre-order	Guitouni and Martel, 1998
Kind of information	Cardinal	Guitouni and Martel, 1998; De Montis et al., 2000
Discrimination power of the criteria	Absolute	Guitouni and Martel, 1998
Compensation	Allowed	Guitouni and Martel, 1998
Information inter-criteria	Total and explicit	Guitouni and Martel, 1998
Interdependent criteria	No	Guitouni and Martel, 1998; De Montis et al., 2000
Software package	No constraint	Guitouni and Martel, 1998
Required time	No constraint	Guitouni and Martel, 1998; De Montis et al., 2000; Parnell, 2009
Required money	No constraint	De Montis et al., 2000
Number of criteria	3	Triantaphyllou, 2000; De Montis et al., 2000; Parnell, 2009
Number of decision makers	6	Guitouni and Martel, 1998; De Montis et al., 2000; Parnell, 2009
Number of alternatives	3	Triantaphyllou, 2000; De Montis et al., 2000; Parnell, 2009
Transparency	Desired	De Montis et al., 2000

The most important aspects that were considered for choosing a MCDA method were the preference elucidation method, allowance of compensation, use of cardinal information and the number of criteria and decisionmakers. Since the preference elucidation method is either straightforward or trade-off and compensation of the criteria should be allowed, most MCDA methods were discarded. A total pre-order is desired, and it should be possible to use cardinal information taking these consideration aspects into account; therefore, three MCDA methods were most suitable for this study: weighted sum, Multi-Attribute Utility Theory (MAUT) and SMART.

The researcher decided to use the Simple Multi-Attribute Rating Technique, because the weighted sum method has problems when transforming multi-dimensional criteria to a uniform dimension (Triantaphyllou, 2000). This is required for this study, because the units of the criteria differ. SMART is chosen over MAUT, because SMART can use different scale ranges to determine the utility value. This is required to determine the accuracy, because an accuracy of 90% compared to an accuracy of 95% is a big difference and therefore the utility value should make a significant impact on the overall performance of the quantity estimation method (Guitouni and Martel, 1998; Baker et al., 2002; Fülöp, 2005). Therefore, the SMART method was used for this study ranging from the lowest to the highest performance score per criterium.

3.3.1 Weighting method

The utility values based on the performance of the quantity estimation methods per criterium were multiplied by the weights per criterium to determine the total value of the quantity estimation methods. This paragraph is dedicated to the method to determine the weights of the evaluation criteria.

Different methods were available to determine the weights of the evaluation criteria. The method chosen for this study was the direct rating weighting method. Direct rating is a common weighting method and uses input of stakeholders, in this case cost engineers, to determine the importance, i.e. weight, of the evaluation criteria. This method was chosen, because it is a clear, transparent method that uses input of stakeholders regarding the importance of the evaluation criteria. Furthermore, the cost engineers that assisted the decision making by sharing their opinion are unexperienced decision makers. Therefore, a relatively easy method to determine the weights was favourable (Bai, Labi and Li, 2008).

The direct rating method can use different rating scales, the rating scale in this study was between zero and 100. The cost engineers could give a rating of importance between zero and 100 for every criterium. 100 implies that the criterium has a very high importance and zero a very low importance. The formulas to determine the weights of the evaluation criteria can be seen below:

$$w_i = \frac{\bar{r}_i}{\sum_{j=1}^{n} \bar{r}_j} \quad \text{and} \quad \sum_{i=1}^{n} w_i = 1$$

The mean rating of importance of the cost engineers was used for this study, denoted as $\bar{r}_i$. The weight per criterium is denoted as w_i. The weight per criterium is determined by dividing the mean rating of importance per criterium by the total mean rating of importance of all criteria. Therefore, the sum of all weights equals one. This is done to normalize the weight factors (Bai, Labi and Li, 2008).

To make sure that the cost engineers understood the criteria the same way, the cost engineers were presented the definitions of the criteria. The definitions of the criteria are displayed in Table 6.

Table 6: Definitions of criteria

Criteria	Definition
Accuracy	The degree to which the result of a measurement, calculation, or specification conforms to the correct value or a standard (Oxford Dictionaries, 2018).
Efficiency	Accomplishment of or ability to accomplish a job with a minimum expenditure of time and effort (Dictionary, 2018).
Traceability	Ability to be followed on its course or to its origin (Oxford Dictionaries, 2018). In this study the ability to discover information of the origin of the quantities, i.e. to what objects the quantities belong.

3.4 Cost determining objects

The previous paragraphs mentioned the criteria and multi-criteria decision analysis method that this study used. This paragraph describes the methodology that was used to identify the cost determining objects of the case project. As previously mentioned, for early-stage cost estimation, not all information of the project is available. Cost determining objects can be used to adequately estimate the costs, because to estimate the costs using cost determining objects, not all quantity information is required. Furthermore, an advantage of using cost determining objects is time reduction. Section 4.1 describes what the cost determining objects of the case study are and what information of the cost determining objects is required to estimate the early-stage costs using a preliminary design. To understand the cost determining objects of the bridge project, first a desk study was performed regarding decomposition structures of bridge projects. Decomposition is the process of splitting a project up in modules. Decomposition can be used to explore the cost determining objects, because to estimate the costs of a construction project using an early-stage design, not all detailed objects are known. Therefore, using a higher level of decomposition can be used to estimate the costs. Therefore, quantities of a higher decomposition level are required to estimate the costs. This paragraph focuses mainly on bridges, because a bridge project was used as case study for this research.

Secondly, the decomposition structure that the infrastructure department of Arcadis uses is described. Arcadis made its own decomposition structure existing of eight decomposition levels. Unit prices of objects from every decomposition level were stored in the cost database of Arcadis. Therefore, the cost estimation can be created by only using cost determining objects of a high decomposition level. The unit prices of cost determining objects of a higher decomposition level are substantiated by unit prices and quantities of lower decomposition levels, e.g. the unit price of placing a steel pile is based on multiple tasks, such as delivering, welding and driving the piles.

Thirdly, this study used a historic cost estimation of a bridge project to explore the cost determining objects and the required quantities to estimate the costs of a bridge project. A cost engineer verified the obtained information from the historic cost estimation, because the information could be outdated. Therefore, this study identified the cost determining objects by using a desk study regarding decomposition structures, a historic cost estimation of a resembling bridge project and expert input.

3.5 Performance of quantity estimation methods

This study used a workshop to compare the performance of the three quantity estimation methods based on the comparison criteria. The workshop used the case study mentioned in paragraph 3.1. to compare the performance of the quantity estimation methods. During this workshop six cost engineers of Arcadis estimated the quantities of cost determining objects of the bridge project. The cost engineers used the three quantity estimation methods: manual quantity estimation, BIM-viewer and BIM-based QTO to estimate the quantities of cost determining objects. The researcher created a guide that explains to cost engineers how to use the quantity estimation methods that use BIM, i.e. the BIM-viewer and BIM-based QTO. This guide exists of the steps that are needed to retrieve quantities of cost determining objects. This guide can be seen in Appendix E. The cost engineers followed this guide to estimate the quantities. For the manual quantity estimation method there was no guide needed, because the cost engineers are used to this method. To not make it a competition to be the fastest quantity estimator, the cost engineers took part of the workshop one by one. The cost engineers estimated the quantities based on the three quantity estimation methods. To avoid learning effect due to repetition, the cost engineers used a different sequence of cost estimation methods, e.g. one cost engineer starts estimating based on 2D drawings, the other starts by using BIM-based QTO. The cost engineers used all three quantity estimation methods, because only six cost engineers of the infrastructure department at Arcadis were available to take part in the workshop. Therefore, if the cost engineers only used one quantity estimation method, the data would be limited, namely only two results per quantity estimation method. The complete process of the workshop can be found in Appendix E.

3.5.1 Performance

The result of the workshop was the performance of the quantity estimation methods based on the comparison criteria. All data retrieved from the workshop was stored in an Excel file and the average of the performance scores per criteria was used to determine the overall of performance of the quantity estimation methods. To compare the overall performance of the quantity estimation methods, the results of the workshop and the comparison method were used.

Accuracy

This study used the estimated deviation to determine the accuracy. The following formula was used to determine the deviation per quantity estimation method:

$$Deviation = \frac{|Estimated\ quantity - Actual\ quantity|}{Actual\ quantity} * 100\%$$

The actual quantity is the quantity based on the detailed design of the bridge. The quantity used during construction is not known, because the bridge has not been constructed at present.

The estimated deviation was calculated for all cost determining objects. To estimate the mean deviation of the quantity estimation methods, the sum of the deviations per cost determining object was divided by the number of cost determining objects of which the quantities were estimated. The result is the mean deviation. The following formula was used to determine the mean deviation:

$$Mean\ deviation\ = \frac{\sum_{i=1}^{n} \overline{Deviation_i}}{n}$$

The number of cost determining objects of which the quantities were estimated is denoted as ‘n’ and the cost determining object is denoted as ‘i’.

Efficiency

This study used the time required to estimate the quantities using the three quantity estimation methods during the workshop to determine the efficiency. The cost engineers estimated the quantities of the cost determining objects and the researcher recorded the time the cost engineers used to estimate the quantities.

Traceability

The cost engineers determined the traceability of the quantity estimation methods by assessing the traceability after the workshop. The cost engineers assessed the traceability on a scale of zero to ten, ten being extremely traceable and zero being extremely untraceable.

Overall performance

The overall performance of the quantity estimation methods was determined by multiplying the weight by the utility score. The formula used to determine the overall performance is as follows:

$$Overall\ performance_{quantity\ estimation\ method} = Utility\ score_{accuracy} * Weight_{accuracy} + Utility\ score_{efficiency} * Weight_{efficiency} + Utility\ score_{traceability} * Weight_{traceability}$$

3.5.2 Verification

The quality of the data retrieved from the workshop was ensured by verification. A sensitivity analysis was performed to determine if the overall performance is sensitive for changes of importance ratings determined by the cost engineers during the workshop. The sensitivity analysis was performed by distributing the importance ratings on a normal distribution using a standard deviation of ten. This study performed 10.000 iterations.

To verify if the quantity estimation method with the highest overall performance is correctly determined, another MCDA method was used. The Multi-Attribute Utility Theory (MAUT) was used to verify the alternative with the highest overall performance. This method, in contrast with the SMART method used utility functions ranging from the lowest to the highest possible performance score. The SMART method used utility functions ranging from the lowest to the highest performance that was estimated. The researcher created different utility functions and used similar performance scores and weights.

3.5.3 Validation

To validate the results of the workshop, the cost engineers were asked for their preferences regarding the quantity estimation methods after conducting the workshop. The questions asked after the workshop can be seen in Appendix E. The cost engineers were asked what quantity estimation method they prefer and if they believe BIM has additional value for estimating material quantities. These questions were asked to validate if the result of this study regarding the alternative with the highest overall performance matched with the preferences the cost engineers experienced during the workshop.

4 RESULTS

Section three described the criteria and the multi-criteria decision analysis method that were used to determine the performance of the three quantity estimation methods. To determine the performance, workshops were conducted. Six senior cost engineers of Arcadis have used the three quantity estimation methods: manual, BIM-viewer and BIM-based QTO. The cost engineers used the three quantity estimation methods and the researcher notated the time required by the cost engineer to estimate the quantities. Only quantities of the cost determining objects were estimated, because this study was focused on estimating quantities using an early-stage design. Therefore, the following paragraph describes the cost determining objects that have been used for the workshop.

This section also describes the results of the workshop. The results of the quantity estimation methods regarding accuracy, efficiency and traceability are given, being the performance scores. Utility functions are used to transform the performance of the quantity estimation methods to similar units. The overall performance of the quantity estimation methods was determined, and the result was validated and verified. An elaborated description of the workshop can be found in Appendix E.

4.1 Cost determining objects

Scientific literature was used to explore decomposition structures of bridges. Several scientific studies mention different decomposition structures. The decomposition structures of Marzouk and Hisham (2014), Kim et al. (2009), Rijkswaterstaat (2017), Tah et al. (1999) and Bartholomew et al. (2015) have been described in this paragraph. This section describes the main similarities and differences.

Marzouk and Hisham (2014) decomposed bridges in substructure and superstructure. The substructure is the part of the bridge that supports the superstructure. The superstructure is the part above the ground level. Marzouk and Hisham decomposed the sub- and superstructure. The substructure exists of: piles, foundations or pile caps and piers or abutments. The superstructure was decomposed in: deck, parapet, miscellaneous details and lighting poles. These elements are not further decomposed; however, these elements do have several attributes, e.g. the attributes length, volume and weight. These attributes can be used to estimate the construction costs of the elements. Often, the required measuring unit is an attribute that is used to estimate the costs, e.g. volume of concrete or weight of steel. The decomposition structure by Marzouk and Hisham (2014) is illustrated in Figure 10.

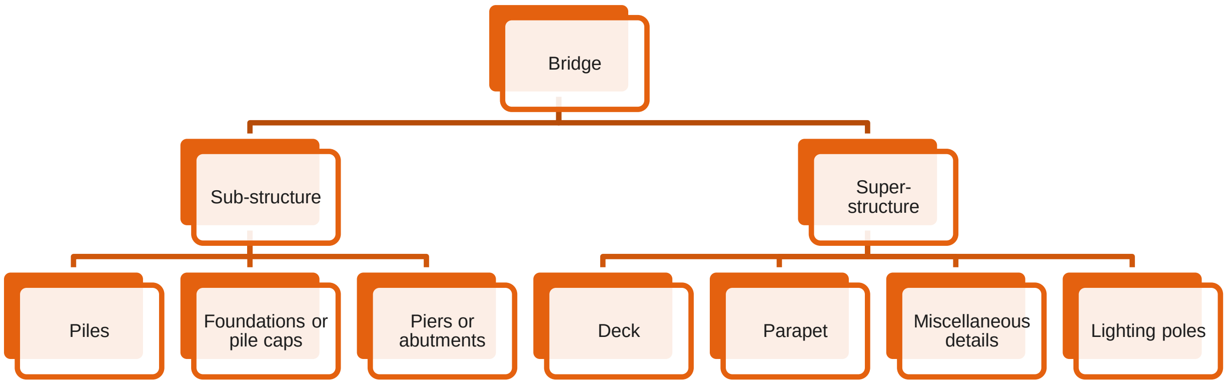

Figure 10: Decomposition structure by Marzouk and Hisham (2014)

Kim et al. (2009) also decomposed a bridge in superstructure and substructure similar to Marzouk and Hisham (2014) and added site preparation and services and ancillaries to the decomposition structure. The decomposition structure is illustrated in Figure 11. Kim et al. (2009) label the superstructure, substructure, site preparation and services and ancillaries the element level of the decomposition structure. The elements can be further decomposed, which can be seen in Appendix D.

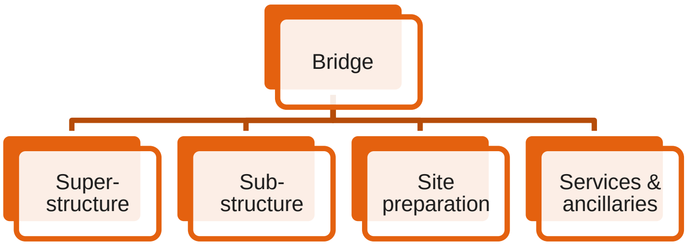

Figure 11: Decomposition structure by Kim et al. (2009)

Rijkswaterstaat, the executive agency of the Ministry of Infrastructure and Water Management in the Netherlands, also created a decomposition structure. The highest decomposition level is the type of bridge, that can be decomposed in the elements: main load bearing structure, support point and foundation. This decomposition structure differs from the decomposition structure mentioned before, because the previous decomposition structure used super- and substructure. Rijkswaterstaat decomposed the main load bearing structure, support point and foundation in several construction components. The decomposition levels used at Rijkswaterstaat are: management object, e.g. bridge; element, e.g. main load bearing structure and construction components, e.g. abutment. Figure 12 illustrates the decomposition structure of Rijkswaterstaat. Only the decomposition levels management object and element are illustrated. The construction components can be seen in Appendix D (Rijkswaterstaat, 2017).

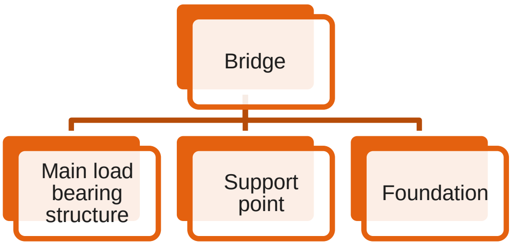

Figure 12: Decomposition structure by Rijkswaterstaat (2017)

Tah et al. (1999) decomposed a bridge in four main components: deck, end support, foundation and intermediate support. The end supports often have wingwalls, therefore Tah et al. (1999) added wingwalls to the decomposition structure. The decomposition structure by Tah et al. (1999) is illustrated in Figure 13.

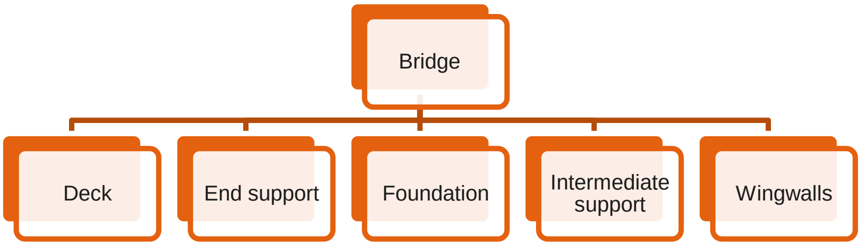

Figure 13: Decomposition structure by Tah et al. (1999)

The Federal Highway Administration of the U.S. department of transportation also used a decomposition structure to decompose bridges. A more direct decomposition structure was used, because the bridge is not decomposed in sub- and super-structure or main load bearing structure, support point and foundation. Therefore, a decomposition level less than the previous mentioned decomposition structures was used by the Federal Highway Administration. The bridge is immediately decomposed in: abutment, piers, bearing, concrete girders, steel girders and framing, decks, bridge railings and miscellaneous. The decomposition structure can be seen in Figure 14 (Bartholomew et al., 2015).

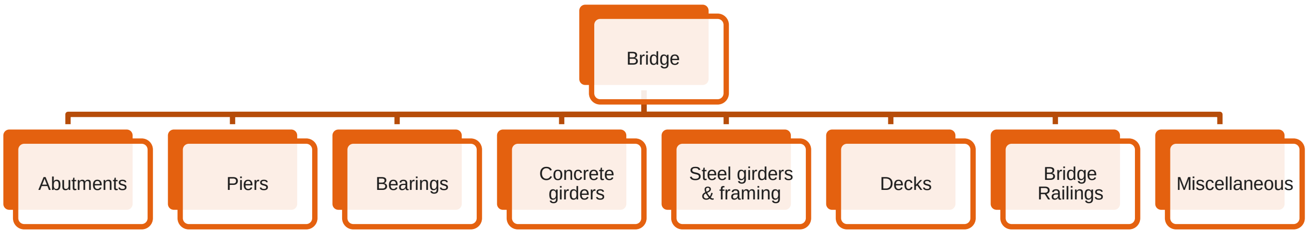

Figure 14: Decomposition structure by the Federal Highway Administration (Bartholomew et al., 2015)

The desk study distinguished several bridge decomposition structures. The scientific studies regarding decomposition structures all used different decomposition structures. There can be concluded that there is not one single best decomposition structure for bridges. Some decomposition structures exist of multiple levels, some of only two levels. Furthermore, some decomposition structures exist of over 30 construction components. This is not advantageous for early-stage quantity estimation, because over 30 quantities are required if you want to estimate the costs based on all construction components. For early-stage quantity estimation it is favourable to require less quantities. Only quantities of cost determining objects are required for early-stage quantity estimation. Furthermore, the different scientific studies used different terms in the decomposition structures. Some studies call the deck an element other call the superstructure an element. Therefore, it is of importance to use one general term in the decomposition structure.

Detailed decomposition

The construction components mentioned in the previous paragraph can be decomposed in smaller components. An abutment is taken as example in this paragraph. The most common type of abutment was used, a full height abutment, illustrated in Figure 15. A full height abutment commonly includes: steel H-pile, U-shaped footing, stem wall, backwall, wingwall, cheekwall and bearing pedestal (Bartholomew et al., 2015). For early-stage cost estimation of an abutment, the quantities of subcomponents of the abutment are not known. However, the total quantity of the abutment is known. Therefore, the total quantity can be used to estimate the costs. It is important to understand what elements of an abutment cause the main costs and to understand if these elements are present in the construction project.

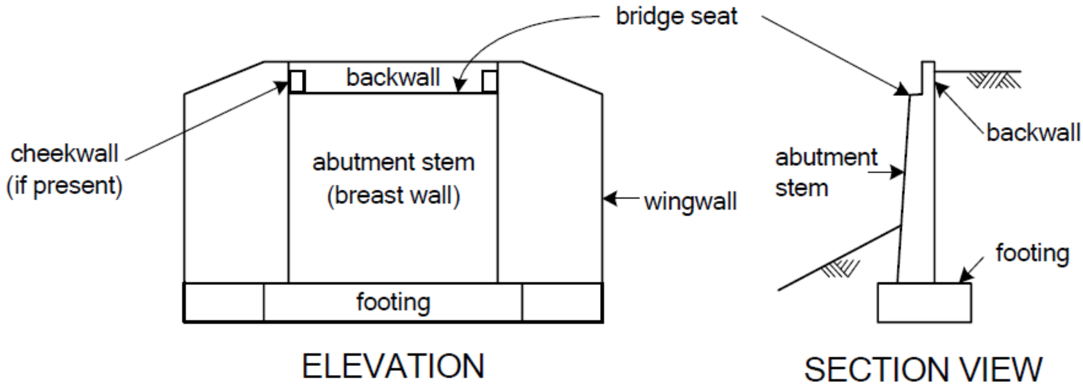

Figure 15: Subcomponents of an abutment (Rossow, 2015)

4.1.1 Decomposition at Arcadis

Arcadis uses its own decomposition structure. The building department at Arcadis uses a different decomposition structure compared to the infrastructure department. The building department at Arcadis is more experienced with using BIM to estimate the costs of a project. This is mainly because the building department has a complete cost database of all construction objects of a building. This cost database is not complete for the infrastructure department at Arcadis, because not all unit prices of infrastructure objects are known. Furthermore, the location of the infrastructure project and phasing of an infrastructure project are one of the main costs of the project, this cannot always be extracted from a building information model (Volleberg, 2018). Furthermore, earthwork is not advanced in 3D models, though it can be a big cost determining object for infrastructure projects, however not for building projects.

The building department at Arcadis uses the classification method NL/SfB. This classification method was customized for Arcadis. Furthermore, the cost database Bouw(kosten)data (BDB) was used by Arcadis. This database is continually updated by the unit prices of completed projects. However, this database lacks information to estimate the costs of infrastructure projects (Peek, 2018). Therefore, the infrastructure department of Arcadis uses its own decomposition methodology, existing of eight levels. Level eight is the highest decomposition level and can be split up in level 7 and so on. Decomposition level one is the lowest decomposition level, containing the primary resources that are used for the unit prices. Therefore, decomposition level one is the substantiation of decomposition level two. Decomposition level two describes the specification of the project, often used for the specification of the project is the RAW-codification. The RAW-codification forms the basis for determining the specification of an infrastructure project.

Table 7 displays the decomposition levels including the name of the decomposition levels and examples. Arcadis is storing historical cost estimation prices in a database that can be used for new projects. Unit prices including its substantiation of already completed projects can be used for new projects. The historical cost information will be stored using the cost estimation software GwwCalc. The prices are stored per decomposition level; therefore, a codification system is required. Arcadis uses its own codification system based on the decomposition levels, the first number of the codification is the decomposition level, e.g. 6.001.002 is an object from decomposition level six, e.g. a bridge (Hensbroek, 2018).

At Arcadis this method to decompose construction projects is referred to as the cost pyramid. The decomposition helps Arcadis making quick cost estimations of construction projects. For example, if the costs of a bridge are requested, Arcadis can start at decomposition level 6. This decomposition level shows the first price of the bridge which exists of object components, i.e. decomposition level 5. Therefore, there is started at a high decomposition level which is substantiated by the lower decomposition levels. Therefore, if you change input information in low decomposition levels, the cost estimation of the high decomposition level, e.g. a bridge will change. Therefore, changing the quantities, e.g. type of material or volume, results in a quick reliable cost estimation (Hensbroek, 2018).

Table 7: Decomposition structure of infrastructure department of Arcadis (Hensbroek, 2018)

Decomposition level	Name	Examples
8	Project	Redesign of city centre Project Betuweroute
7	Module	Area containing multiple objects, e.g. a road and a bridge
6	Object	Bridge Road
5	Object component	Open or closed part of an underpass Super- and sub-structure
4	Element	Abutment Road surface
3	Construction component	Foundation gap Beam
2	Unit price	Price per m^2 formwork Price per m^3 concrete
1	Primary resources	Man hours Costs per litre of fuel

4.1.2 Identifying cost determining objects

To estimate the early-stage costs of a project, it is required to understand what the cost determining objects are of the project. Cost determining objects are the parts of a project that encompass the main costs of a project and are therefore of importance for estimating the early-stage costs. Every project has different cost determining objects. This study is focused on bridges, therefore the cost determining objects of bridges are determined. All types of bridges have different cost determining objects. Therefore, it is difficult to define the cost determining objects of all bridges. The bridge types differ regarding their function or construction type e.g. railroad or car bridges, and construction material, e.g. concrete or wooden bridges.

Because the focus of this study is on one bridge project that will be used for the case study, the researcher identified the cost determining objects of that specific type of bridge. The bridge belongs to decomposition level six and can be decomposed in for example super- and substructure, i.e. decomposition level five. Decomposition level five can be decomposed in e.g. abutments and girders.

For detailed cost estimations, all construction objects must be substantiated. Table 8 is an example of the substantiation of one cost determining object, steel piles. To estimate the costs of placing a steel pile, seven quantities of decomposition level two are required. The unit prices of decomposition level two are substantiated by the primary resources, i.e. decomposition level one. The primary resources are not displayed in the cost estimation because Arcadis wants to keep them private. Table 8 shows the substantiation of the cost determining object steel piles including the percentage of the total costs of placing the steel piles for every unit price. There can be concluded that the material costs of the steel piles determine only half of the total price of placing steel piles. The other half of the costs are determined by the salary of the workers and machine costs. This substantiation is required for a detailed cost estimation. For an early-stage cost estimation, a higher decomposition level can be used.

Table 8: Detailed cost estimation of steel piles (Morren, 2001)

Material and tasks (decomposition level 2)	Quantity and unit	Percentage of costs
Delivering steel piles	Weight (ton)	50,5%
Welding foot plates	Weight (ton)	7,4%
Welding piles	Length (m)	9,4%
Driving piles	Time (days)	11,9%
Transport of pile driver	Amount (pcs)	19,7%
Dragline mats	Time (weeks)	0,7%
Set location piles	Amount (pcs)	0,4%
Steel piles	Length (m)	100%

Placing steel piles is one of the cost determining objects of the historic cost estimation of a bridge project and the total costs of placing the steel piles can be estimated by determining the total length of the steel piles and using a unit price for placing a steel pile. This unit price should consist of the complete substantiation as displayed in Table 8. The same applies for placing concrete girders. The total costs of placing girders requires multiple quantities, namely: volume, weight and amount. The transport costs are often estimated using the weight, volume is often used to estimate the costs of the material. For placing the girders, the number of girders is often used. Therefore, the cost engineer must estimate multiple quantities to estimate the costs. Using the unit prices retrieved from the cost database from a higher decomposition level decreases the required number of quantities. For example, the total costs of buying, delivering and placing could be combined in one unit price, namely the total costs of the construction of girders. This unit price is substantiated by the other quantities. This study estimated less quantities, because this study used unit prices of a higher decomposition level.

The bridge of the case study is a fixed flat car bridge made of concrete. A historic cost estimation of a resembling bridge project was used to identify the cost determining objects of the case project. This study used a bridge project located in Tilburg of which Arcadis estimated the costs. The early-stage cost estimation of this bridge was used. To estimate the costs of this bridge, this study used only cost determining objects.

Table 9 displays the cost determining objects used for the early-stage cost estimation of the bridge project in Tilburg. Since only the cost determining objects of the construction project are used, the objects with a lower influence on the costs are not mentioned. Therefore, the sum of the costs of the cost determining objects is equal to the total costs of the construction project. Multiple objects are not used for the cost estimation; therefore, an additional percentage should be added on top of the costs of the cost determining objects, namely the further detailing expense. The cost determining objects mentioned in Table 9 account for approximately 90% of the total construction costs of the project. Adding 10% to the costs of the cost determining objects, the approximate construction costs can be estimated. Therefore, using an early-stage design, only the quantities of the cost determining objects are required to approximately estimate the costs. The construction costs are not the total investment costs for the client. The construction costs should be multiplied by multiple additional expense percentages, e.g. engineering costs, profit and risk.

Table 9: Cost determining objects of a historic early-stage cost estimation of a concrete car bridge in Tilburg (Karlas, 2014)

Object component	Cost determining object	Required quantities and units	Percentage
Sub-structure	Piles	Length (m)	11,3%
	Sheet pile wall	Length (m)	1,6%
	Well point drainage	EUR	0,4%
	Wale	Volume (m^3)	0,5%
	Columns	Volume (m^3)	0,5%
	Beams	Volume (m^3)	6,8%
	Abutments	Volume (m^3)	5,3%
Super-structure	Prefab girders incl. concrete topping	Area (m^2)	30,0%
	Approach slab	Amount (pcs)	1,8%
Finishing	Stainless steel plating for corners	Length (m)	18,4%
	Lighting	Length (m)	20,8%
	Traffic barrier	Length (m)	1,4%
Temporary measures	Applying traffic management measures	EUR	1,1%

This study did not use exactly the same cost determining objects, because the case study is not exactly similar to the project of the historic cost estimation. The length of the bridge and the location differ. Furthermore, the costs of the lighting of the bridge in Tilburg are very high, because the lighting is placed in one line attached to the stainless-steel plating. This is a special design feature causing higher costs. At the bridge project in Zwolle, no lighting is placed. Furthermore, for the bridge project in Zwolle, the wingwalls are made of white concrete, causing higher costs. The road surface should also be taken into account for the bridge project in Zwolle in contrary to the bridge in Tilburg. The traffic management measures are not required for the bridge project in Zwolle. This project specific information was obtained from a senior cost engineer at Arcadis who has been involved in the bridge project located in Zwolle. The cost engineer also verified the cost determining objects and required quantities. Therefore, this study identified the cost determining objects by using a desk study regarding decomposition structures, a historic cost estimation of a resembling bridge project and expert input.

There can be concluded that to estimate the total costs of cost determining objects only one quantity, the material type and the object type, e.g. abutment is required to understand. Therefore, the combination: quantity, material type and object type determine the price of a cost determining object using an early-stage design. The result of the historic cost estimation and the verification of the cost engineer is Table 10. All cost determining objects determine at least one percent of the costs of the project.

The early-stage costs based on cost determining objects is not sufficient, because costs of all objects with lower individual costs account for approximately 10% of the costs, depending on the uncertainty. Therefore, 10% further detailing expense should be added to the costs of the cost determining objects to form an accurate cost estimation.

Table 10: Cost determining objects of bridge project in Zwolle used for the workshop

Object component	Cost determining object	Required quantities and units
Sub-structure	Piles	Length (m)
	Abutments	Volume (m^3)
	Wing walls	Volume (m^3)
Super-structure	Prefab girders	Area (m^2)
	Concrete topping	Volume (m^3)
	Approach slab	Amount (pcs)
Finishing	Asphalt road surface	Area (m^2)
	Sidewalk	Area (m^2)
	Traffic barrier	Length (m)

4.2 Performance comparison of three quantity estimation methods

This paragraph describes the comparison of the performances of the three quantity estimation methods that were determined using a workshop. The performance scores regarding the accuracy, efficiency and traceability of the quantity estimation methods are described in this paragraph. The performance scores are transformed to utility scores to create one similar unit for all criteria. The utility scores are multiplied by the weights to create the overall performance of the quantity estimation methods.

4.2.1 Weighting method applied

At the start of the workshop, the six cost engineers determined the rating of importance of the three criteria. The ratings of importance determined by the cost engineers are displayed in Table 11. The substantiation of the importance ratings can be found in Appendix F.

Table 11: Importance ratings of the criteria

	Efficiency	Accuracy	Traceability
Cost engineer 1	100	60	80
Cost engineer 2	70	100	80
Cost engineer 3	60	80	100
Cost engineer 4	25	100	25
Cost engineer 5	70	100	90
Cost engineer 6	80	100	100
Average	67,5	90,0	79,2

The researcher normalized the importance rating to weight factors by using the formulas mentioned in the methodology section. The average rating of importance per criterium was divided by the sum of the average importance ratings. Table 12 displays the normalized weight factors. The weights of the criteria efficiency, accuracy and traceability were respectively: 0.29, 0.38, and 0.33.

Table 12: Normalizing weight factors

Criteria	Average rating of importance	Normalized weight factor
Efficiency	67,5	0,29
Accuracy	90,0	0,38
Traceability	79,2	0,33
Total	236,7	1

4.2.2 Performance regarding accuracy

The mean deviation of the quantities estimated by the cost engineers are displayed in Table 13. The average deviation per quantity estimation method is also displayed in Table 13.

Table 13: Average deviation

Participant	Deviation manual quantity estimation	Deviation BIM-viewer	Deviation BIM-based QTO
Cost engineer 1	8,5%	0,9%	1,2%
Cost engineer 2	5,9%	0,9%	0,9%
Cost engineer 3	5,4%	0,9%	0,9%
Cost engineer 4	37,9%	0,9%	0,9%
Cost engineer 5	3,5%	0,9%	0,9%
Cost engineer 6	4,2%	0,9%	0,9%
Average	10,9%	0,9%	1,0%

The deviations of the estimated quantities using the BIM-viewer and BIM-based QTO are for almost every cost engineer similar. The only inconsistency is the deviation of the estimated quantities by cost engineer 1 using BIM-based QTO. This deviation was 1,2% instead of 0,9%, the reason for this difference is that the cost engineer did not use the correct decimal places when creating the material take-off, namely zero instead of two decimal places. For the BIM-viewer all estimated quantities were exactly the same, because the quantities of the construction objects were estimated by Autodesk Revit and exported to the BIM-viewer. Therefore, in the BIM-viewer the quantities attached to the construction objects are similar for every cost engineer. The estimated quantities using the BIM-viewer and BIM-based QTO deviate respectively 0,9% and 1,0% due to small mistakes in the 3D model and rounding. A small mistake in the model was that the estimated area of the girders was the gross area and not the net area.

The deviation of the manual quantity estimations differs for every cost engineer, because for various cost determining objects the quantities were difficult to estimate, particularly wing walls. The wingwalls are curved and estimating quantities of a curved object is more difficult than estimating quantities of straight objects. Furthermore, the concrete topping has a difficult shape to estimate the volume. Therefore, most quantities of the cost determining objects differed from the actual quantities. Certain cost engineers estimated quantities too high and certain cost engineers too low and some cost engineers estimated quantities too high and too low. Therefore, a trend line could not be distinguished. The quantities estimated by the cost engineers using the manual quantity estimation method are described in Appendix F. Figure 16 displays the measured deviation of all cost engineers per quantity estimation method.

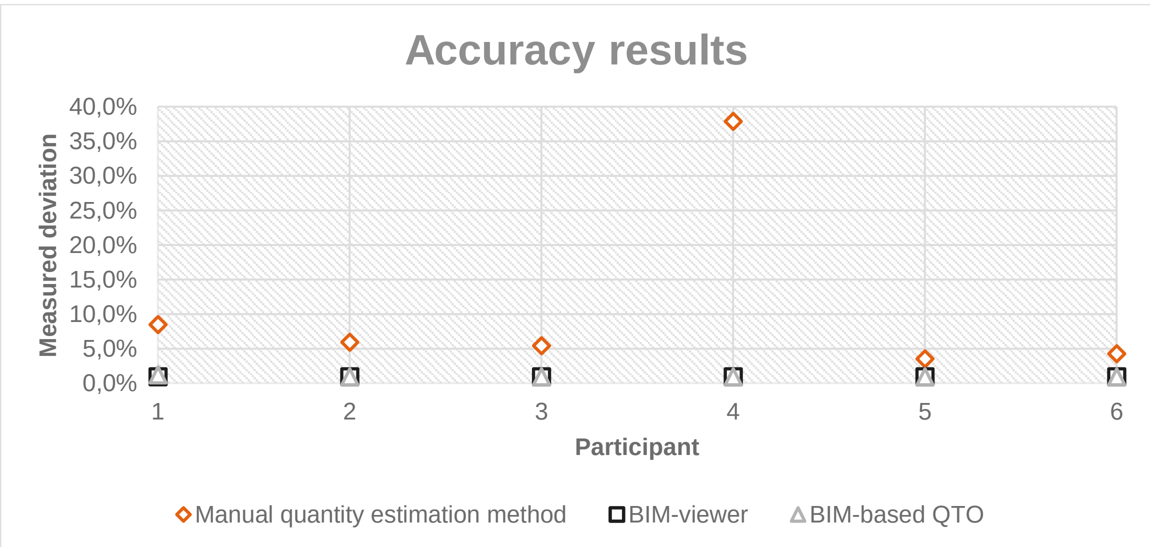

Figure 16: Deviation measured during workshop

4.2.3 Performance regarding efficiency

Time required to estimate the quantities using the three quantity estimation methods was determined during the workshop. The cost engineers estimated the quantities of the cost determining objects. The time used by the cost engineer was measured by the researcher and can be seen in Table 14.

Table 14: Time measured during workshop

Participant	Efficiency manual quantity estimation	Efficiency BIM-viewer	Efficiency BIM-based QTO
Cost engineer 1	33,75 minutes	21,66 minutes	9,50 minutes
Cost engineer 2	59,65 minutes	21,20 minutes	11,58 minutes
Cost engineer 3	41,40 minutes	17,50 minutes	12,75 minutes
Cost engineer 4	19,10 minutes	19,30 minutes	10,50 minutes
Cost engineer 5	51,20 minutes	24,20 minutes	14,30 minutes
Cost engineer 6	46,00 minutes	23,40 minutes	11,20 minutes
Average	41,85 minutes	21,21 minutes	11,64 minutes

BIM-based QTO is the most efficient early-stage quantity estimation method, because the time required to estimate the quantities of cost determining objects is the lowest for BIM-based QTO, followed by the BIM-viewer. One cost engineer estimated the quantities faster using manual quantity estimation compared to using the BIM-viewer. However, the estimated quantities of this cost engineer deviated the most, because he focused more on efficiency than on accuracy. Figure 17 visualizes Table 14 and displays the measured time for all cost engineers. There can be concluded that the BIM-viewer and BIM-based QTO are faster than manual quantity estimation and that BIM-based QTO is faster than the BIM-viewer.

Figure 17: Efficiency results

4.2.4 Performance regarding traceability

The cost engineers assessed the traceability of the quantity estimation methods after the workshop. The cost engineers assessed the traceability on a scale of zero to ten, ten being extremely traceable and zero being extremely untraceable. The results are displayed in Table 15 and Figure 18.

Table 15: Traceability assessment

Participant	Manual quantity estimation	BIM-viewer	BIM-based QTO
Cost engineer 1	6,00	10,00	8,00
Cost engineer 2	9,00	10,00	9,00
Cost engineer 3	7,00	10,00	7,00
Cost engineer 4	5,50	10,00	0,00
Cost engineer 5	8,00	10,00	6,00
Cost engineer 6	7,00	10,00	7,00
Average	7,08	10,00	6,17

All cost engineers were uniform in deciding the most traceable quantity estimation method. The cost engineers unanimously decided that the BIM-viewer is the most traceable method, because all cost engineer assessed the traceability of the BIM-viewer with a score of ten, the highest possible score. There was not unanimously decided whether manual quantity estimation or BIM-based QTO was more traceable. Most cost engineers mentioned that the element ID's of the quantity estimation made with Autodesk Revit helped tracing the construction object to which the quantity belongs. However, everyone should be able to work with Autodesk Revit and if the client cannot work with Autodesk Revit, the client cannot trace the quantities. Cost engineer four mentioned that BIM-based QTO is totally untraceable, because he had no idea where the quantities belong to and how the quantities are estimated. There can be concluded that the BIM-viewer is the most traceable method according to the cost engineers. Manual quantity estimation and BIM-based QTO do not differ much regarding traceability. The manual quantity estimation method is on average more traceable than BIM-based QTO, though this is mainly because cost engineer four assessed the traceability with a score of zero.

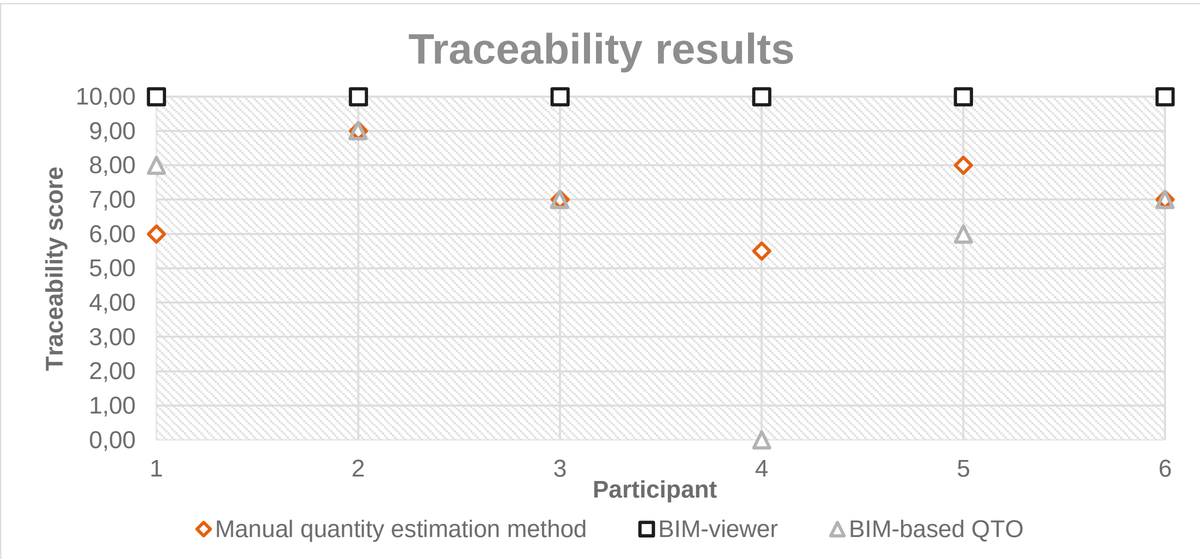

Figure 18: Traceability results workshop

4.2.5 Outcomes MCDA

As mentioned in section 3, the SMART method was used to transform the performance scores of the quantity estimation methods to similar units, namely utility scores. Utility functions were created to determine the utility score for every criterium. The utility functions are linear functions that range between the lowest and the highest performance score. The utility functions are displayed in Figure 19.

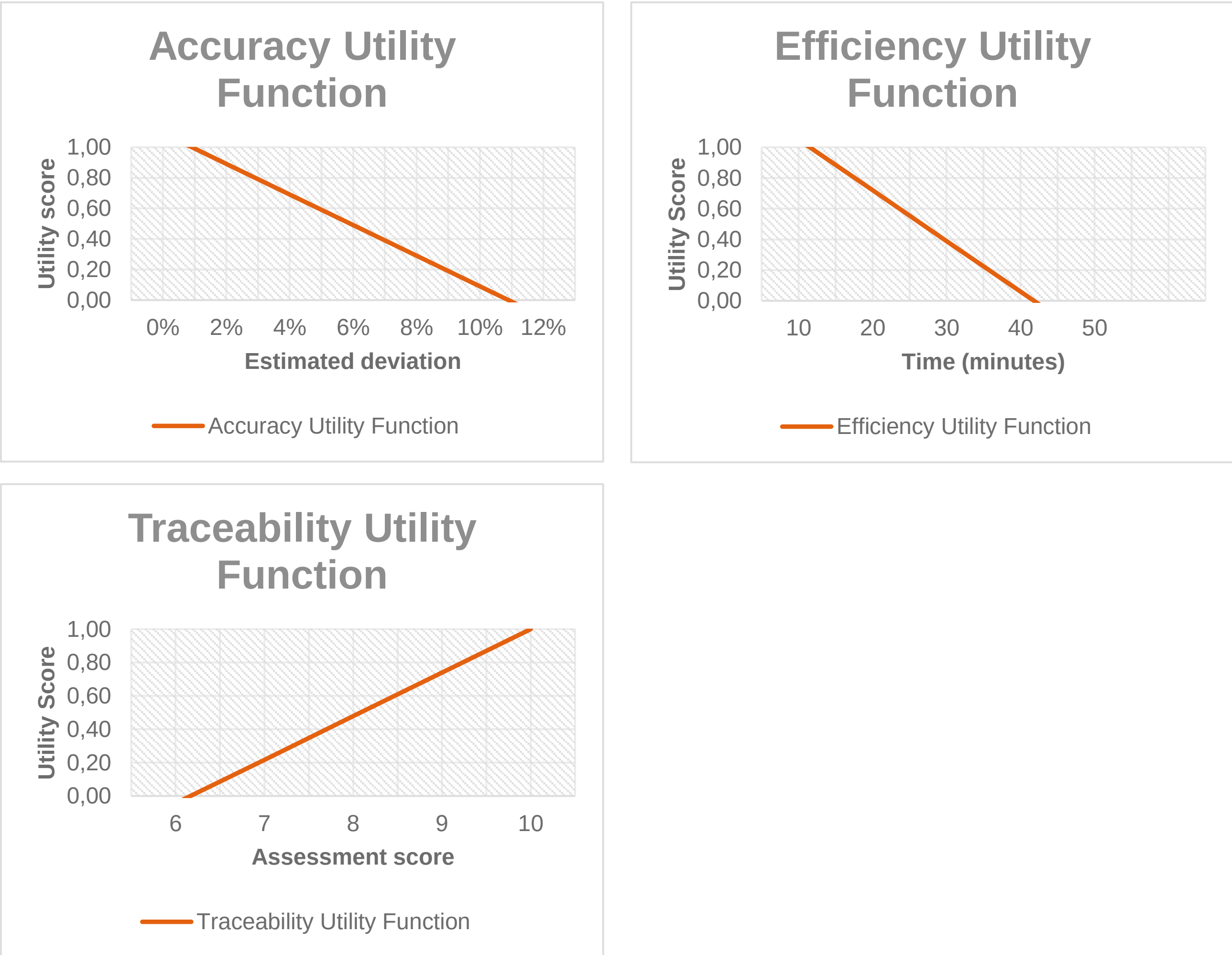

Figure 19: Utility functions

The performance scores described in the previous paragraphs were used to determine the utility score. The performance scores are the estimated deviation, required minutes to estimate the quantities and the traceability assessment score. Using the performance scores and the utility functions, the utility score can be determined. The utility scores are displayed in Table 16.

Table 16: Utility scores

Criteria	Manual quantity estimation	BIM-viewer	BIM-based QTO
Accuracy	0,0	1,0	1,0
Efficiency	0,0	0,68	1,0
Traceability	0,24	1,0	0,0

4.2.6 Overall performance

The overall performance of the quantity estimation methods was determined by multiplying the weight per criterium by the utility score. The formula to calculate the overall performance can be seen in paragraph 3.5.1. The overall performance scores are displayed in Table 17. The BIM-viewer has the highest overall performance and therefore is the preferred alternative, followed by BIM-based QTO and manual quantity estimation. According to the results of the workshop, the BIM-viewer is the quantity estimation method with the highest overall performance and therefore it is recommended to use the BIM-viewer to estimate quantities.

Table 17: Overall performance

Manual quantity estimation	BIM-viewer	BIM-based QTO
0,08	0,91	0,66

4.3 Verification

The result of this study, i.e. the alternative with the highest overall performance, was verified by performing a sensitivity analysis of the importance ratings and by using a different MCDA method.

4.3.1 Sensitivity analysis of importance ratings

The importance ratings determined by the cost engineers during the workshop have an uncertainty, because not all cost engineers regarded the same criterium as most important. To determine if the BIM-viewer is the alternative with the highest overall performance when other importance ratings are used, this study conducted a simulation. A normal distribution with a standard deviation of ten was applied to the importance ratings determined by the cost engineers. The importance ratings were simulated 10.000 times to create 10.000 different importance ratings for accuracy, efficiency and traceability. The importance ratings were used to determine the overall performance of the three quantity estimation methods using the same performance scores per criterium determined during the workshop. Therefore, 10.000 different overall performance scores were determined by the simulation, using only differing weights. Every iteration created a random importance rating based on the given normal distribution. The more iterations, the more likely the frequency of the importance weights resulted in a normal distribution. The result, the spreading of the overall performance scores, can be seen in Figure 20. All overall performance scores between the first and third quartile, i.e. 50% of the scores, are inside the box. The whiskers display the local minimum and maximum of the performance scores.

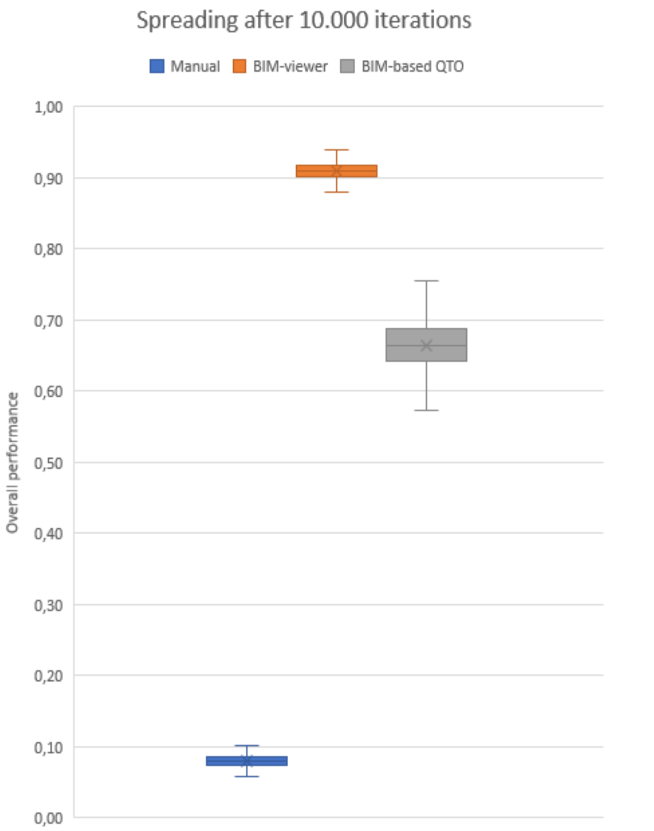

Figure 20: Spreading of overall performance scores using a standard deviation of the importance rating of ten

The result of the simulation is that using a standard deviation of ten over the importance ratings, the BIM-viewer will always be considered the alternative with the highest overall performance instead of the BIM-based QTO and manual quantity estimation. Therefore, there can be concluded that the overall performance is not sensitive for changes of the importance ratings.

4.3.2 Verification using a different MCDA method

The final result, i.e. the alternative with the highest overall performance, was verified by using another multi-criteria method to determine the overall performance. The Multi-Attribute Utility Theory (MAUT) has been used. MAUT used utility functions ranging from the lowest to the highest possible performance score. The utility functions can be seen in Figure 21.

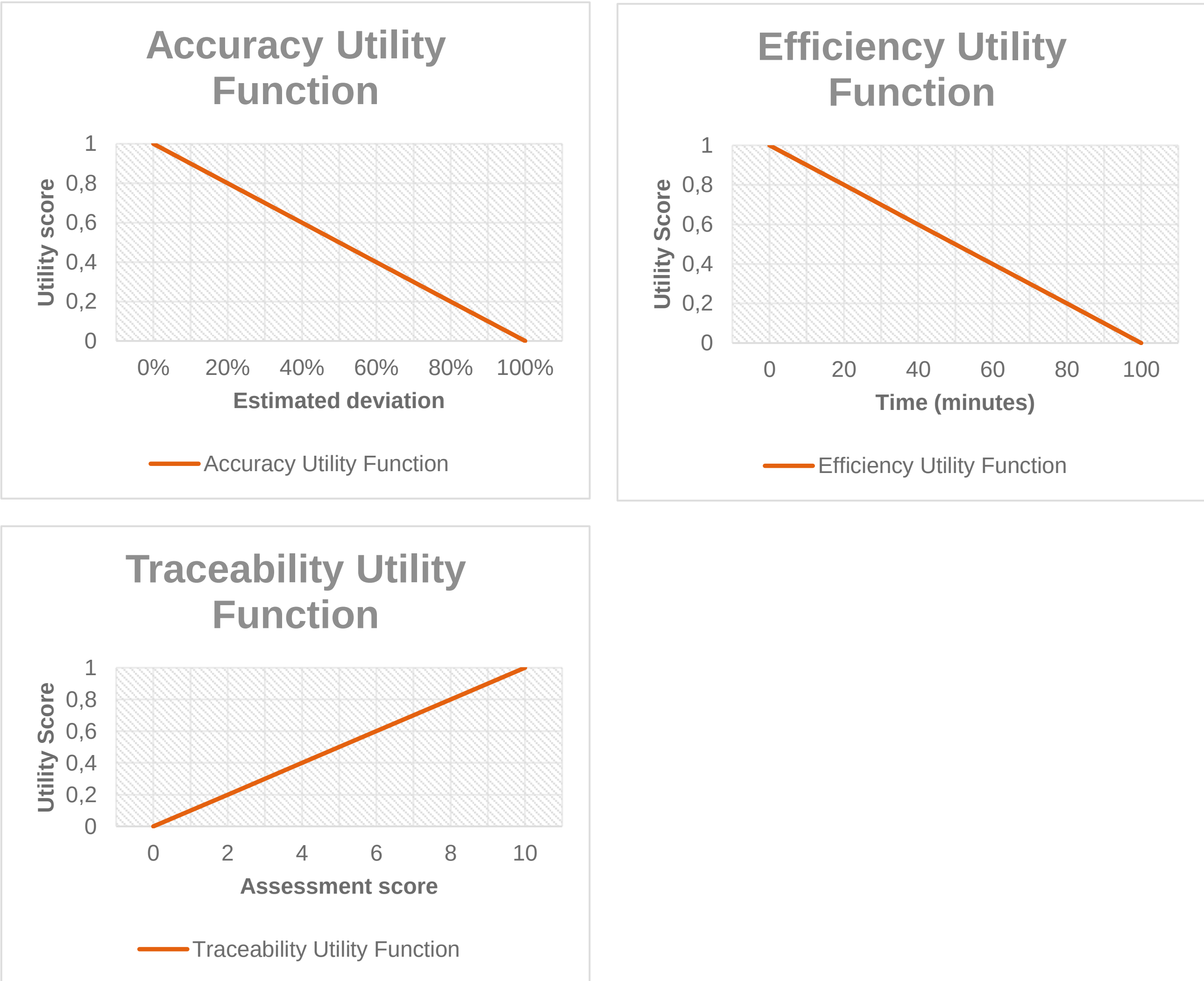

Figure 21: Utility functions for verification

The overall performance using MAUT was determined by multiplying the weights and utility scores and can be seen in Table 18. The overall performance of the quantity estimation methods using MAUT has the same result as using the SMART method, namely, the BIM-viewer has the highest overall performance, followed by BIM-based QTO. According to both multi-criteria decision analysis methods the alternative with the highest overall performance is the BIM-viewer. Therefore, this study verified the result.

Table 18: Overall performance

Manual quantity estimation	BIM-viewer	BIM-based QTO
0,71	0,92	0,82

4.4 Validation

The final result, i.e. overall performance, was validated by cost engineers assessing the value of the quantity estimation methods after the workshop. Table 19 displays the ranking of the quantity estimation methods, 1 is the preferred alternative and 3 is the alternative that is considered least useful. The substantiation of Table 19, i.e. the results of the workshop, can be found in Appendix F.

The result of the validation was that all cost engineers preferred using the BIM-viewer to estimate quantities. The BIM-viewer is an unanimously decided winner; however, there is not unanimously decided what quantity estimation method is least preferred. Some cost engineers preferred manual quantity estimation over BIM-based QTO and vice versa. The main reason why the BIM-viewer is preferred by the cost engineers is because of the direct visualization of the object to which the quantity belongs. Furthermore, an advantage mentioned often was that the quantity appeared directly in the cost estimation. The result is uniform and therefore, the quantity estimation method with the highest overall performance has been validated.

Table 19: Preferred quantity estimation method by cost engineers

Participant	Manual quantity estimation	BIM-viewer	BIM-based QTO
Cost engineer 1	3	1	2
Cost engineer 2	3	1	2
Cost engineer 3	3	1	2
Cost engineer 4	2	1	3
Cost engineer 5	2	1	3
Cost engineer 6	3	1	2
Average	2,67	1	2,33

5 DISCUSSION

This study compared three early-stage quantity estimation methods, namely: manual quantity estimation using 2D drawings, using a BIM-viewer and BIM-based QTO. The BIM-viewer is a tool to display a three-dimensional model including the dimensions of the objects in the project. BIM-based QTO involves the automatic extraction of object quantity information of three-dimensional models. The early-stage quantity estimation methods are compared using three criteria, namely: traceability, accuracy and efficiency. The criteria are described in more detail in paragraph 3.2.4.

Five aspects are discussed in this section, namely this section discusses: (1) the results compared to other scientific BIM literature, (2) the lack of literature regarding comparing a BIM-viewer with other quantity estimation methods, (3) the difference between early-stage designs and detailed designs, (4) the practical approach of this study compared to the theoretical approach of other scientific literature and (5) the gap in literature regarding comparing early-stage quantity estimation methods.

The first aspect discussed is the result of this study. This study shows that quantities estimated using a BIM-viewer are most traceable. Cost engineers consider the quantities estimated using the BIM-viewer traceable, because all quantities are connected to objects. Clicking on the quantity highlights the object to which the quantity belongs. Therefore, cost engineers and clients can quickly see to what objects the quantities belong, making the quantities traceable. In contrary to the BIM-viewer, the quantities estimated using BIM-based QTO are not considered traceable by the cost engineers. The cost engineers mentioned that it is difficult to understand to what objects the quantities belong. It is possible to use the element ID to see to what object the quantity belongs, however the cost engineers did not consider this traceable. Since not every cost engineer or client is experienced with Revit, it is not possible for everyone to see to what object the quantity belongs. The quantities estimated manually are considered more traceable than the quantities estimated using BIM-based QTO and less traceable than quantities estimated using the BIM-viewer. Cost engineers mentioned that the quantities are traceable, because you can use a bill of quantities in which you state how the quantities are estimated; however, it is time consuming to trace the object to which the quantity belongs. Traceability was not the only criterium used in this study. This study also compared the accuracy and efficiency of the quantity estimation methods. Scientific BIM literature often states that BIM-based QTO is accurate and efficient (Whang and Park, 2016; Bryde et al., 2013; Chou and Chen, 2017). This literature focuses on either detailed designs or the complete construction process. Therefore, this study is different, because it focuses on early-stage designs. However, this study confirms the scientific BIM literature regarding the accuracy and efficiency of BIM-based QTO. According to this study and the literature, BIM-based QTO is more accurate and efficient compared to manual quantity estimation (Whang and Park, 2016; Bryde et al., 2013; Chou and Chen, 2017). This study also focused on the efficiency and accuracy of the BIM-viewer. The accuracy of the BIM-viewer is similar to the accuracy of BIM-based QTO. It was expected to be similar, because the quantities of both the BIM-viewer and BIM-based QTO are based on the same 3D model created in Revit. Therefore, the quantities are similar. The efficiency of the BIM-viewer and BIM-based QTO differs. BIM-based QTO is faster compared to the BIM-viewer. This was expected, because BIM-based QTO automatically estimates the quantities, for the BIM-viewer the cost engineer must select the objects of which the cost engineer wants the quantities. The overall performance of the BIM-viewer is higher than the overall performance of BIM-based QTO. The better efficiency of BIM-based QTO does not counterbalance the lack of traceability of BIM-based QTO compared to the BIM-viewer, because the difference in traceability is bigger than the difference in efficiency.

The second aspect of the discussion section is the comparing a BIM-viewer with other quantity estimation methods. Most studies regarding the performance of quantity estimation methods do not focus on using a BIM-viewer (Whang and Park, 2016; Bryde et al., 2013; Chou and Chen, 2017). Often BIM-based QTO is proposed as quantity estimation method. Hafez et al. (2015) did focus on an estimation tool where quantities of the individual building components can be read as properties of the component. Hafez et al. (2015) named this tool a BIM-Assisted Detailed Estimating (BADE) tool without a calculation function. The result of the study by Hafez et al. (2015) was that the BADE tool without calculation function performed better than the manual estimation method. Therefore, the visualization of the BADE tool improved the performance of the estimation. However, Hafez et al. (2015) also used a BADE tool with calculation function. This method had a higher performance than the BADE tool without calculation function. The calculation function is a function where the costs of the project are automatically estimated. The result of this study is that the semi-automatic quantity estimation, i.e. BIM-viewer, has a higher overall performance than automatic quantity estimation, i.e.

BIM-based QTO. Therefore, this study does not confirm the result of Hafez et al. (2015). The reason for this difference is where the third point of discussion arises.

The third point of discussion is the difference between early-stage and detailed quantity estimation. The study of Hafez et al. (2015) focused on detailed designs and on costs instead of early-stage designs and quantities. This could be the reason for the different result, because early-stage designs contain less detailed quantity information compared to detailed designs. For early-stage designs other criteria are of importance than for detailed designs, e.g. accuracy is of more importance for a detailed design. Early-stage designs contain a larger bandwidth. Hafez et al. (2015) mentioned that the BADE without calculation function could not estimate all costs, though in this study all quantities could be estimated using the BIM-viewer. This could be due to the fact that Hafez et al. (2015) used a different case study and older software. Furthermore, Hafez et al. (2015) did not use the criterium traceability that this study used. All cost engineers that participated in the workshop of this study assessed traceability of high importance, because otherwise the quantities cannot be verified by the client and other cost engineers. No scientific BIM literature used the criterium traceability to compare the performance of quantity estimation methods, though using traceability as criterium could improve the comparison. This study shows that traceability is of importance for quantity estimation and that traceability can be used as a criterium to compare quantity estimation methods.

The fourth discussion point is that scientific BIM literature (i.e. Whang and Park, 2016; Bryde et al., 2013; Chou and Chen, 2017) often focuses on the efficiency and accuracy of quantity estimation methods, instead of on the traceability. This could be due to the fact that this study used a more practical approach and the scientific literature used a more theoretical approach. This study focused on what cost engineers consider important and the scientific literature focused more on the measurability of the criteria. Therefore, traceability was not taken into account in other scientific BIM literature regarding quantity estimation.

The fifth and last point of this discussion is that scientific BIM literature that proposed early-stage quantity estimation methods did not compare early-stage quantity estimation methods (Soto and Adey, 2016; Nesticò et al., 2017; Cheung et al., 2012; Choi et al., 2015; Barg et al., 2018; Marzouk and Hisham, 2012; Vitásek and Matějka, 2017). Therefore, the result of this study contributes to the scientific literature. Existing scientific BIM literature only proposed early-stage quantity estimation methods instead of comparing, therefore previously it was unknown if using BIM for early-stage quantity estimation is beneficial for organizations that estimate quantities of infrastructure projects. This study shows that using a BIM-viewer to estimate early-stage quantities has the highest overall performance and therefore using BIM to estimate early-stage quantities is beneficial for organizations. Improved early-stage quantity estimations result in improved early-stage cost estimations. Early-stage cost estimations have a high impact on the project performance (Phaobunjong, 2002), which could result in a decreasing rate of failure of contractors (McIntyre, 2007).

This section compared the results to other scientific BIM literature. This study agrees with the scientific literature regarding the accuracy and efficiency of BIM-based QTO (Whang and Park, 2016; Bryde et al., 2013; Chou and Chen, 2017). However, the scientific literature did not use traceability as comparison criteria, though according to this study traceability is of importance for early-stage quantity estimation. Furthermore, this section mentioned that there is a lack of literature regarding comparing a BIM-viewer with other quantity estimation methods. This section also mentioned the difference between early-stage designs and detailed designs and the influence of the level of detail on the quantity- and cost estimation. This section mentioned a possible reason for scientific literature that did not take into account traceability, namely that scientific literature used a theoretical approach and this study a more practical approach. Lastly, the gap in literature regarding comparing early-stage quantity estimation methods is described.

6 CONCLUSIONS

This section first describes the research aim and question of this study, followed by a short description of what has been done to answer the research question. The main results of this study are presented followed by the main conclusions of this study.

The aim of this study was to compare the performance of automatic BIM-based QTO to using a BIM-viewer and manual quantity estimation for early-stage quantity estimation of cost determining objects, and to give a recommendation regarding implementing BIM to estimate product quantities in the work practice of Arcadis. Consequently, the following research question was formulated:

What is the overall performance of the manual quantity estimation method, the BIM-viewer and BIM-based QTO for early-stage quantity estimation?

BIM-based QTO concerns automatically extracting object quantity information of three-dimensional models and the BIM-viewer is a tool that displays a three-dimensional model including the dimensions of the objects in the project. The manual quantity estimation method used 2D drawings to estimate the quantities.

Since there exists not one single best decomposition structure that decomposes construction objects, there is not a clear and uniform method to estimate costs using an early-stage design. This study used cost determining objects, comparison criteria and a MCDA method to compare the overall performance of the quantity estimation methods. Three criteria determined the overall performance of the quantity estimation methods, namely: efficiency, accuracy and traceability. The weights of these criteria are respectively 0.29, 0.38 and 0.33. Therefore, the cost engineers considered accuracy the most important criteria, followed by traceability. The performance of the criteria was determined by using a workshop where cost engineers estimated the quantities of a bridge project using the three early-stage quantity estimation methods. The accuracy was determined by the deviation of the estimated quantity compared to the actual quantity. The efficiency was determined by the required time to estimate the quantities and the traceability was assessed by the cost engineers.

The result of the workshop was that BIM-based QTO and the BIM-viewer are equally accurate. Manual quantity estimation was significantly less accurate than the quantity estimation methods that used BIM. Regarding efficiency, BIM-based QTO performed best, followed by the BIM-viewer. All cost engineers considered the quantities estimated using the BIM-viewer most traceable, because the objects to which the quantities belong are directly visualized and highlighted. The average performance per criterium is displayed in Table 20.

Table 20: Average performance of quantity estimation methods per criterium

Criteria	Manual quantity estimation	BIM-viewer	BIM-based QTO
Accuracy	10,9% deviation	0,9% deviation	1,0% deviation
Efficiency	41,85 minutes	21,21 minutes	11,64 minutes
Traceability	7,08	10,00	6,17

The researcher used the weights and the average performance per criterium displayed in Table 20 to determine the overall performance score. There can be concluded that the BIM-viewer is the quantity estimation method with the highest overall performance according to the workshop. This is mainly because the quantities estimated using the BIM-viewer have a higher traceability compared to the other two quantity estimation methods. There can be concluded that traceability is of importance for quantity estimation, because the cost engineers that participated in the workshop considered traceability more important than efficiency.

Validation and verification were performed to ascertain the alternative with the highest overall performance. All cost engineers preferred using the BIM-viewer to estimate the quantities over the other two quantity estimation methods. Therefore, the quantity estimation method with the highest overall performance is also the alternative the cost engineers preferred. The researcher also verified the result by using a sensitivity analysis and a different MCDA method. The result of the verification was that the BIM-viewer was still the quantity estimation method with the highest overall performance.

The main conclusion is that semi-automatic early-stage quantity estimation using a BIM-viewer has a higher overall performance than quantity estimation using BIM-based QTO and manual quantity estimation. For early-stage quantity estimation of infrastructure projects, using a BIM-viewer has a higher performance, though literature often proposes BIM-based QTO using detailed designs. Using the BIM-viewer for early-stage quantity estimations results in improved early-stage cost estimations. Improved cost estimations lead to enhanced early-stage decision-making contributing to a decreasing rate of failure of contractors. Other BIM literature regarding quantity estimation methods, did not use traceability as comparison criteria to determine the overall performance. Cost engineers that participated in the workshop of this study mentioned the high importance of traceable quantity estimation methods. If the quantity estimation method is not traceable, the client cannot verify the quantities. Furthermore, quantity estimation in a successive design phase will take more time when the quantities are not traceable, because it is unknown how the quantities of the previous design stage were determined.

7 LIMITATIONS AND FUTURE RESEARCH

This section describes the limitations of this research and the possibilities for future research. The first limitation mentioned is the number of cases and participants of the workshop. The second limitation is that the cost engineers were not experienced with using BIM. The possibilities for future research described in this section are: the design time, benchmarking and regression analysis of cost determining objects, developing an object library, researching how to take into account phasing and location of infrastructure projects and research could be performed regarding using the criterium traceability.

Six cost engineers participated in the workshop and this study used one case study. More participants and cases would result in more reliable conclusions. Different cases could be used to determine if the BIM-viewer would have the highest overall performance when using early-stage designs of more complicated projects or different types of projects, e.g. road projects. More participants would lead to more conclusive findings. This research focused on a bridge project, future research can focus on other types of civil engineering structures, e.g. roads. For different types of projects, different complications regarding estimating quantities might exist.

The cost engineers were not experienced with using Autodesk Revit or the BIM-viewer. Therefore, using the methods took more time than it will take in the future. Instructions regarding how to use the methods were provided, otherwise the cost engineers did not know how to use the BIM-viewer and BIM-based QTO. Future research could use cost engineers that participate in the workshop that are experienced with Autodesk Revit and the BIM-viewer.

Future research can be performed regarding the time required to create the design. According to designers at Arcadis, it does not take more time to create 3D models instead of 2D drawings and separating the objects does not take more time (Rapis, 2018). However, this could be researched in more detail.

Automatically estimating the costs of a project could be the next step in using BIM at Arcadis. A complete database should be created to automatically estimate the costs of a project. All objects should have a code that is attached to the object in the cost database and in the 3D model. The unit prices can be multiplied by the quantities to create a cost estimation. However, this cost estimation should always be verified by a cost engineer. Important cost determining factors should always be taken into account, e.g. the location of the project. This information is not always attached to the object or the code of the object. Future research can be performed to determine how to take into account all cost determining factors and how to automatically estimate the costs using BIM. Unit prices differ per quantity. The higher the quantity, the lower the unit price; therefore, research can be performed regarding benchmarking and regression analysis of cost determining objects.

An object library with codes for every object should be created. This object library should be shared with the designers to make the designers understand what information should be stored in the building information model. The object library should also exist of what information the cost engineers need of the objects, e.g. volume and material type. The designers should store the required information in the building information model. The information that should be stored in the building information model could be determined using the BIM basic Information Delivery Manual (IDM). The IDM is used by multiple organizations to exchange information in a uniform way (BIM Loket, 2018).

The location of the project can be of huge influence for the costs of the project. If the project is located at a greenfield site, i.e. an undeveloped site (Carvalho, 2014; Shelton et al., 2015) or a site with existing infrastructure and buildings. Replacing infrastructure means that either the infrastructure will be closed, or the construction should be performed in phases. Constructing in phases has influence on the costs of the project, because the efficiency of construction is lower. Future research can be performed regarding how to take into account the phasing of the project using BIM and how this will influence the costs of a project.

This study mentioned multiple times that traceability of the product quantities is of high importance for early-stage quantity estimation. This study used traceability for comparing early-stage quantity estimation methods; however, traceability could also be used for comparing detailed quantity- and cost estimation methods. Future research could be performed regarding using traceability as criterium for comparing quantity- or cost estimation methods.

8 RECOMMENDATIONS

This section describes the recommendations regarding implementing BIM in the work practice of Arcadis. This section starts by recommending Arcadis to gradually implement BIM in their work practice and not immediately trying to use BIM to automatically estimate the cost. To automatically estimate the costs a complete unit price database is required, which currently does not exist. Furthermore, it is currently not possible to estimate the cost of the location and phasing of a project. Therefore, expertise of the cost engineer is required. This study recommends implementing the BIM-viewer to estimate quantities and creating an object library to define the information the cost engineers require to estimate the costs. Lastly this section recommends making agreements with clients regarding using BIM, because not all clients are experienced with using BIM.

It is not recommended to start automatically estimating the costs using BIM, because the unit price database is not on the required level to automatically estimate the costs. Unit prices of all construction objects should be stored in a database. It is recommended to add a code to all objects in the unit price database and use the same code for the designs. Using the same codes, a connection can be created between the quantities of the building information model and the unit prices of the database. This could be the first step towards automatically estimating the costs. However, it does take time to create a complete unit price database. If the unit price database is on the required level, most product costs can be automatically estimated; however, all costs should be verified by the cost engineer. Therefore, a transition will happen, the cost engineers will focus more on verification instead of on estimation.

The unit price database cannot take into account all cost determining factors of a project, e.g. location and phasing. Therefore, the expertise of a cost engineer is always required to estimate the costs of a project, because automatically estimating the costs will result in mistakes. Expertise is required to for example understand if sheet piles are required based on the water level and to understand if the sheet piles can be taken out afterwards or should stay in the ground. Furthermore, the phasing should be determined by the cost engineer to understand what equipment is required and to find the correct balance between accessibility, i.e. not closing the road, and the costs.

A good first step in implementing BIM in the work practice of Arcadis is by using BIM to estimate the quantities. The main result of this study was that the BIM-viewer has the highest overall performance. Therefore, according to the results of this study, the BIM-viewer is preferred over the manual quantity estimation method and BIM-based QTO for early-stage quantity estimation. This result was validated by cost engineers that determined their preferred quantity estimation method. All cost engineers considered that the BIM-viewer is the best method to estimate quantities of infrastructure projects. Therefore, recommended is that the BIM-viewer will be implemented in the work practice of Arcadis to estimate the quantities of infrastructure projects using early-stage designs.

To use the BIM-viewer to estimate the quantities, the design should be created correctly. Mistakes in the design can cause huge deviations in the total costs of a construction project. Therefore, it is recommended to check the design for mistakes. Furthermore, the required information for the cost engineer should be added to the building information model, e.g. material type and volume. This required information differs for every construction object in a project. Therefore, it is recommended to create an object library that contains the required information for every construction object. This object library should also state what object to separate and at what location of the object it should be separated, e.g. placing asphalt on a bridge has a different unit price than placing the asphalt a few meters before the bridge. Therefore, the road should be separated before the bridge. The designer should add all the required information to the objects, e.g. material type and volume. Different objects require different information. Therefore, the object library can be utilized to make the designer understand the information that should be in the building information model. Currently, a cost engineer estimates the quantities and another cost engineer checks them. In the future, the quantities can be estimated using BIM and a cost engineer checks the quantities. An object library should be created for the designer with all required information of the objects in it.

An interesting discussion that started after a workshop was that not all clients have experience with using BIM. Therefore, some clients might not accept quantities that are estimated by using BIM, because the client cannot check the correctness of the quantities. Some clients might be sceptical regarding using BIM. It is recommended that during tender phase agreements must be made with the client regarding using BIM. Therefore, this study recommends Arcadis to start using the BIM-viewer for early-stage quantity estimation and to create an object library to define the information that cost engineers require to estimate the costs. Furthermore, it is recommended to make agreements with clients regarding using BIM.

REFERENCES

Arcadis. (n.d.). *BIM according to Arcadis*. Retrieved from https://images.arcadis.com/media/5/F/2/%7B5F298123-F67E-4CAD-A01C-03A9C1C0CCFE%7DBIM_According_to_Arcadis_Asia_001.pdf

Bai, Q., Labi, S., & Li, Z. (2008). Trade-off analysis methodology for asset management.

Baker, D., Bridges, D., Hunter, R., Johnson, G., Krupa, J., Murphy, J., & Sorenson, K. (2002). Guidebook to decision-making methods. *Department of Energy, USA*.

Balvert, R. (2016). ILS IN NATIVE SOFTWARE. 25 November 2016. Retrieved from https://www.bimloket.nl/upload/documents/downloads/BIMbasisILS/ILS_Native_Revit.pdf

Barg, S., Flager, F., & Fischer, M. (2018). An analytical method to estimate the total installed cost of structural steel building frames during early design. *Journal of Building Engineering, 15*, 41-50. doi:10.1016/j.jobe.2017.10.010

Barrie, D. S., & Paulson, B. C. (1992). *Professional construction management: including CM, design-construct, and general contracting*: McGraw-Hill Science/Engineering/Math.

Bartholomew, M., Blasen, B., & Koc, A. (2015). *Bridge information modeling (BrIM) using open parametric objects* (No. FHWA-HIF-16-010).

Bhimani, A., & Mülder, P. S. (2001). Managing processes, quality, and costs: a case study. *Journal of cost management, 15*(2), 28-32.

BIM Loket. (2018). BIM basis ILS. Retrieved from https://www.bimloket.nl/BIMbasisILS

Bryde, D., Broquetas, M., & Volm, J. M. (2013). The project benefits of building information modelling (BIM). *International journal of project management, 31*(7), 971-980.

BuildingSMART. (2010). Investing in BIM competence BuildingSMART: a guide to collaborative working for project owners and building professionals. *Endeavour. UK*.

Businessdictionary. (2018). Quantity. Retrieved from http://www.businessdictionary.com/definition/quantity.html

Carvalho, L. (2014). Smart cities from scratch? A socio-technical perspective. *Cambridge Journal of Regions, Economy and Society, 8*(1), 43-60.

Cheung, F. K., Rihan, J., Tah, J., Duce, D., & Kurul, E. (2012). Early stage multi-level cost estimation for schematic BIM models. *Automation in Construction, 27*, 67-77.

Choi, J., Kim, H., & Kim, I. (2015). Open BIM-based quantity take-off system for schematic estimation of building frame in early design stage. *Journal of Computational Design and Engineering, 2*(1), 16-25.

Chou, H.-Y., & Chen, P.-Y. (2017). *Benefit Evaluation of Implementing BIM in Construction Projects.* Paper presented at the IOP Conference Series: Materials Science and Engineering.

Collins. (2018). Definition of 'generality'. Retrieved from https://www.collinsdictionary.com/dictionary/english/generality

Daschbach, J., & Apgar, H. (1988). Design analysis through techniques of parametric cost estimation. *Engineering Costs and Production Economics, 14*(2), 87-93.

De Montis, A., De Toro, P., Droste-Franke, B., Omann, I., & Stagl, S. (2000). Criteria for quality assessment of MCDA methods. *Transitions Towards a Sustainable Europe*, 1-30.

De Soto, B. G. D., & Adey, B. T. (2016). *Preliminary Resource-based Estimates Combining Artificial Intelligence Approaches and Traditional Techniques.* Paper presented at the Procedia Engineering.

Dictionary. (2018). Efficiency. Retrieved from http://www.dictionary.com/browse/efficiency

Eastman, C. M., Eastman, C., Teicholz, P., & Sacks, R. (2011). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*: John Wiley & Sons.

Emmen, W. (2018) *Use of BIM at the infrastructure department of Arcadis/Interviewer: P. van Wee*.

Fragkakis, N., Marinelli, M., & Lambropoulos, S. (2015). Preliminary cost estimate model for culverts. *Procedia Engineering, 123*, 153-161.

Fülöp, J. (2005). *Introduction to decision making methods.* Paper presented at the BDEI-3 workshop, Washington.

Guitouni, A., & Martel, J.-M. (1998). Tentative guidelines to help choosing an appropriate MCDA method. *European Journal of Operational Research, 109*(2), 501-521.

Hafez, S. M., Aziz, R. F., & Eldars, E. A. (2015). Construction Cost Prediction by Using Building Information Modeling. *International Journal of Engineering Research and Applications*.

Hensbroek, R. (2018). *Werkafspraak piramide*. Arcadis. Amersfoort.

Investopedia. (2018). Utility. Retrieved from https://www.investopedia.com/terms/u/utility.asp

ipv Delft. (n.d.). AANBESTEDEN MET SO, VO OF DO? Retrieved from http://ipvdelft.nl/aanbesteden-met-vo/

Karlas, M. F. (2014). *Kostenraming brug Tilburg*. Arcadis. Amersfoort.

Kim, K. J., Kim, K., & Kang, C. S. (2009). Approximate cost estimating model for PSC Beam bridge based on quantity of standard work. *KSCE Journal of Civil Engineering, 13*(6), 377-388.

KPI Working Group. (2000). *KPI Report for the Minister for Construction*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/16323/file16441.pdf

Lee, S.-K., Kim, K.-R., & Yu, J.-H. (2014). BIM and ontology-based approach for building cost estimation. *Automation in Construction, 41*, 96-105.

Marzouk, M., & Hisham, M. (2012). Applications of building information modeling in cost estimation of infrastructure bridges. *International Journal of 3-D Information Modeling (IJ3DIM), 1*(2), 17-29.

Marzouk, M., & Hisham, M. (2014). Implementing earned value management using bridge information modeling. *KSCE Journal of Civil Engineering, 18*(5), 1302-1313.

McIntyre, M. (2007). Why do contractors fail. *Construction Business Owner*, 62-65.

Morren, G. (2001). *Kostenraming fietsviaduct Waalwijk*. Arcadis. Amersfoort.

Nesticò, A., De Mare, G., Frusciante, B., & Dolores, L. (2017) Construction costs estimate for civil works. A model for the analysis during the preliminary stage of the project. In*: Vol. 10408 LNCS. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* (pp. 89-105).

Olsen, D., & Taylor, J. M. (2017). Quantity Take-Off Using Building Information Modeling (BIM), and Its Limiting Factors. *Procedia Engineering, 196*, 1098-1105.

Oxford Dictionaries. (2018). Definition of accuracy in English. Retrieved from https://en.oxforddictionaries.com/definition/accuracy

Oxford Dictionaries. (2018). Definition of expertise in English. Retrieved from https://en.oxforddictionaries.com/definition/expertise

Oxford Dictionaries. (2018). Definition of traceable in English. Retrieved from https://en.oxforddictionaries.com/definition/traceable

Parnell, G. S. (2009). Decision analysis in one chart. *Decision Line*, 21.

Peek, T. (2018) *Use of BIM at the building department of Arcadis/Interviewer: P. Van Wee*.

Phaobunjong, K. (2002). *Parametric cost estimating model for conceptual cost estimating of building construction projects.* (Doctor of philosophy), University of Texas, Austin.

Popham, K. (1996). Cost estimating using historical costs. *AACE International Transactions*, ES141.

Rapis, P. (2018) *Time required to design bridges/Interviewer: P. van Wee*.

Rijkswaterstaat. (2017). *Instructie modelleren op basis van de OTL 2.1*. Retrieved from http://publicaties.minienm.nl/documenten/2-instructie-modelleren-op-basis-van-de-otl-versie-2-1

RISE Research Institutes of Sweden. (2018). The traceability chain - the link to basic quantities. Retrieved from https://www.sp.se/en/index/information/si2/traceability/Sidor/default.aspx

Rossow, M. (2015). *Bridge Inspection (Part 1): Abutments and Wingwalls (BIRM)*. Retrieved from https://www.cedengineering.com/userfiles/Abutments%20and%20Wingwalls%20(Part%201).pdf

Shelton, T., Zook, M., & Wiig, A. (2015). The ‘actually existing smart city’. *Cambridge Journal of Regions, Economy and Society, 8*(1), 13-25.

Tah, J., Carr, V., & Howes, R. (1999). Information modelling for case-based construction planning of highway bridge projects. *Advances in Engineering Software, 30*(7), 495-509.

The Construction Industry Institute. (1995). *Pre-Project Planning Handbook – Special Publication 39-2*. Austin, Texas: Construction Industry Institute, The University of Texas at Austin.

Triantaphyllou, E. (2000). Multi-criteria decision making methods. In *Multi-criteria decision making methods: A comparative study* (pp. 5-21): Springer.

van der Knoop, E. (2018) *Use of BIM at the infrastructure department of Arcadis/Interviewer: P. van Wee*.

Vitásek, S., & Matějka, P. (2017). *Utilization of BIM for automation of quantity takeoffs and cost estimation in transport infrastructure construction projects in the Czech Republic.* Paper presented at the IOP Conference Series: Materials Science and Engineering.

Whang, S.-W., & Park, S. M. (2016). Building Information Modeling (BIM) for Project Value: Quantity Take-Off of Building Frame Approach. *International Journal of Applied Engineering Research, 11*(12), 7749-7757.

APPENDIX A - LITERATURE STUDY

Several studies were performed that are slightly comparable with this study; however, those studies often differ regarding that the research is based on a detailed design instead of a preliminary design or the research only mentions that the quantity estimation method can be applied and does not compare quantity estimation methods. Therefore, this section focuses on the existing literature regarding quantity estimation methods. This section answers the first question of this study, namely determining and understanding the existing literature regarding quantity estimation methods and exploring how the existing literature can be utilized for this study.

The first paragraph describes the existing literature that compares detailed estimation methods. The first paragraph of this appendix is the only paragraph of this appendix that compares estimation methods. The other paragraphs of this appendix describe literature that only apply and propose an estimation method and does not compare it. Furthermore, the existing literature was separated regarding if a building information model has been used and if the design used for the study was detailed or early-stage. This section finishes with a conclusion regarding the most important lessons learned from the existing literature. The literature has been retrieved from the scientific database Scopus.

Comparison of detailed estimation methods

This paragraph describes the studies that focused on the performance of quantity estimation methods using detailed designs instead of preliminary designs. The literature used for this paragraph compares the estimation methods.

The research of Hafez et al. (2015) focused on comparing BIM-assisted detailed cost estimating (BADE). The research focused on comparing three cost estimation methods: 2D drawings, BADE tool without calculation function and a BADE tool with calculation function. The researchers used four evaluation criteria: generality, flexibility, efficiency, and accuracy to determine the performance of the methods. Two case studies were performed, a building and a bridge project. The three estimation methods were applied on both cases. The result of the case studies was the performance of the methods based on the four criteria. To determine the accuracy, the cost estimation created during the case studies was compared with the actual costs of the project after construction. The efficiency of the methods was based on the time required to estimate the costs using the three cost estimation methods. To determine the generality, the number of trade estimates that can be generated by the method were measured. Flexibility was determined by measuring the number of special design features. To determine the overall performance of the cost estimation methods, a multi-attribute utility model was used. This method took into account all four criteria. For all criteria a utility function was created to determine the utility score, e.g. a high accuracy will result in a high utility score and a long time required to estimate the costs will result in a low utility score. To determine the weights of the criteria, the eigenvector prioritization method was used. For the eigenvector prioritization method, importance factors are required, which were based on authors’ industry experience and related studies. The importance of all criteria was compared with the importance of the other criteria, e.g. the accuracy of the cost estimation methods was five times more important than the flexibility. The importance of the criteria was placed in a matrix and were normalized. The normalized importance factors per row were combined and divided by the number of columns, i.e. the number of criteria. The result was the weights of the comparison criteria. The conclusion of the research was that a BADE tool performed better than traditional estimating methods.

Whang and Park (2016) compared BIM-based QTO with traditional manual quantity estimation using drawings. Whang and Park (2016) used a case project to determine the accuracy of the quantity estimation methods. To determine the accuracy, the deviation of the quantities using both quantity estimation methods are compared with the real input values of the case study. The result of the research was that the accuracy of BIM-based QTO was 95% and of traditional manual quantity estimation 89%. Therefore, BIM-based QTO is more accurate compared to manual quantity estimation according to Whang and Park (2016). The biggest differences regarding accuracy of the two quantity estimation methods were caused by the quantity estimation of difficult construction objects. The beams and slabs of the case study did not have regular geometric forms and therefore the quantities were difficult to estimate manually. BIM-based QTO was more accurate regarding the quantity estimation of difficult construction objects.

Olsen and Taylor (2017) used interviews and questionnaires to compare BIM-based QTO to manual quantity estimation. Most respondents of the questionnaire mentioned that only 50 percent of the required data for

BIM-based QTO is available in the 3D models. Therefore, it is of importance to ascertain that the model contains all data required to perform BIM-based QTO. Olsen and Taylor (2017) mentioned inadequately represented trades for BIM-based QTO, such as earthwork and landscape. However, earthwork and landscape are of great importance for the cost estimation of infrastructure. Therefore, it is not advisable to estimate the quantities of earthwork of an infrastructure construction project. Furthermore, adequately represented trades are mentioned, e.g. concrete and structural steel. During the interviews performed by Olsen and Taylor (2017) there was mentioned that a big advantage of BIM-based QTO is the speed of quantity estimation. Furthermore, mentioned is the accuracy of BIM-based QTO, since the reduced probability of rounding errors and the visualization of the project (Olsen and Taylor, 2017).

Applied preliminary estimation methods without using a building information model

To create an overview of quantity- and cost estimation methods, this paragraph describes estimation methods that were used in scientific literature that do not use a building information model. Several scientific studies mention that building information models can be used to automatically estimate the quantities of objects. However, most of those studies do not compare the method with alternative quantity estimation methods. Therefore, there cannot be concluded that automatic BIM-based QTO has a higher performance compared to alternative quantity estimation methods. This paragraph describes two studies that applied preliminary estimation methods without using a building information model.

De Soto and Adey (2016) used artificial intelligence to estimate the early-stage costs. If a design is available, the construction material quantities are used to estimate the costs, in combination with the unit prices. If there is not yet a design made, the construction material quantities (CMQs) are not known. Therefore, the CMQ should be based on data of structures that are similar to the structure that will be build. Based on historical data of completed projects, the CMQs can be determined. De Soto and Adey (2016) determine the CMQs by using regressions analysis models (RA), neural network models (NN) and case-based reasoning models (CBR) and a combination of the beforementioned models. The research was performed using 148 tall-frame structures built of structural steel and reinforced concrete. The result of the research was that the overall mean absolute percentage error (MAPE) of the separate methods were higher than the MAPE of the combined method, namely the MAPE of the combined method was 2,55%, of CBR 9,30%, of NN 5,84% and of RA 12,01%. Therefore, the performance of the combined methods is higher. However, for using the combined method, a huge database of historical data of similar projects is required, which is not always the case for every type of project.

Nesticò et al. (2017) use three classification systems to break down projects in components. The Italian classification systems UNI 8290 formed the basis and the international standards UNIFORMA II and Elemental standard form of cost analysis (SFCA) were used to complete the UNI 8290. The result was five levels of breakdown, being: (1) class of technological units, (2) technological units, (3) class of technical elements (4) technical elements and (5) work items.
The costs of a construction project can be estimated by multiplying the quantities by the unit prices. Using only the quantities of cost determining objects could lead to an underestimation of the costs. Therefore, the ABC analysis can be used to assign project costs to three classes. Class A represents 70% of the costs and 10% of the quantities, class B represents 20% of the costs and quantities and class C represents only 10% of the costs, though class C represents 70% of the quantities. Therefore, if the quantities of A and B are estimated, 90% of the costs are known by only estimating 30% of the quantities. The additional 10% of the costs can be a percentage over the estimated costs using class A and B.

Applied preliminary estimation methods using a building information model

This paragraph describes three studies that applied preliminary estimation methods by using a building information model. There is often mentioned that using a building information model has advantages, however the studies do not compare BIM-based estimation methods to alternative estimation methods.

Cheung et al. (2012) researched preliminary cost estimation using schematic building information models for the utility sector. Cheung et al. (2012) propose a tool to estimate the costs using a design made with Google SketchUp. The tool is called Low Impact Design Explorer (LIDX) and is a plug-in for the design software

Google Sketch-up. LIDX can be used to estimate the costs of a construction project during different stages. Therefore, the tool can be used for preliminary designs as well as for detailed designs. The advantage is that the cost estimates of an early stage can be updated to a more detailed stage (Cheung et al., 2012). LIDX requires a cost database that comprises of fourteen entries that are required to determine the costs that belong to the materials. The entries are: *"1) element type (element, sub-element or component), 2) element name (e.g. frame), 3) element description (e.g. Timber frame incorporating Structural Insulated Panels), 4) sub-element/element unit (e.g. m2), 5) minimum element unit rate, 6) maximum element unit rate, 7) density of sub-element, 8) reference of density (e.g. GIA), 9) default assumption (yes or no), 10) sundries allowance (low end), 11) sundries allowance (high end), 12) data source reference (e.g. in-house), 13) adjustment remark, and 14) type of rate (e.g. basic or extra over)"* (Cheung et al., 2012). The entries have been used to find the corresponding unit prices.

Choi et al. (2015) suggest using open BIM-based QTO. The process of extracting the quantities of an early-stage building information model exists of four steps: (1) creating an early-stage building information model, (2) verifying the accuracy of the model, (3) verifying the quality of the data, (4) developing or using a method to extract the quantities and estimate the costs. Choi et al. (2015) developed a prototype system able to extract the quantities and estimate the costs of a building frame. Volumes of for example walls are used to determine the amount of concrete, steel and formwork required to estimate the costs. The result of the research was that that the prototype system can be used to improve the reliability of early-stage quantity and cost estimation.

Barg et al. (2018) propose a method called Integrated Steel Design (ISD). This method is able to quickly estimate the costs of a structural steel building frame during early design. The method requires a model that consists of the layout of the frame with preliminary member sizes and connection types. This model is uploaded to a web portal which first details the member connections of the steel frame and afterwards estimates the costs based on unit prices of suppliers of the material. The suppliers have their own web portal to edit the unit prices of the materials to keep the price updated. The ISD method has been compared with other estimation methods on a 1x1 and a 5x5 frame resulting in that the ISD method has lower-cost design alternatives (Barg et al., 2018).

Applied detailed estimation methods using a building information model

This paragraph describes the scientific literature regarding detailed estimation methods that used a building information model. The studies did not compare the estimation methods, but solely applied the methods.

To estimate the costs of the construction of a bridge, Marzouk and Hisham (2012) used a program developed by C# programming language that extracts the quantities of the building information model. The quantities are exported to an Excel file and BOQ numbering is added to the file. The BOQ numbering has been used to connect the quantities with the unit prices and is a codification method. The function VLOOKUP in Excel was used to find the corresponding unit prices for the quantities. The method of Marzouk and Hisham (2012) comprises of five steps: (1) development of the 3D information model of the bridge, (2) visualization of the construction steps, (3) add additional information required for the cost estimation to the bridge information model, (4) export all information, e.g. volume, casting type, length, ID and material type to an Excel spreadsheet and step 5 is estimating the costs automatically by using the program developed by C# language. Marzouk and Hisham (2012) only proposed the method and did not evaluate it.

Vitásek and Matějka (2017) researched how to utilize BIM to estimate the costs of transport infrastructure projects by using QTO. To estimate the costs of an infrastructure project during preliminary stage, the complete design is not required. A schematic design is often incomplete. Therefore, a list of the requirements for the information needed should be created (Vitásek and Matějka, 2017). Vitásek and Matějka (2017) use two case studies of the construction of a motorway in Czech Republic. Vitásek and Matějka (2017) mention that to automatically extract the quantities of building information models, three phases need to be performed: (1) the requirements for the designers should be specified, (2) price databases should be created and implemented in BIM and (3) a software extension is required for the conversion of data from the building information model to the price database.

Summary

Several studies have been performed regarding quantity- and cost estimation. The literature that has been described in this section is mainly focused on BIM and early-stage designs. Most studies focused on cost estimation and to estimate the costs, the construction material quantities are required. Those quantities are multiplied with the corresponding unit prices. To determine the corresponding unit prices information of the construction object is required. This can be done by either a code that was added to the object or by using multiple entries, e.g. element type, element name etc.

Based on the studies, several possible criteria can be used for this research to compare the early-stage quantity estimation methods. Most studies mention accuracy and/or efficiency as advantages of BIM-based QTO. However, other criteria can be used as well, e.g. flexibility and generality.

Literature also mentioned disadvantages and problems of implementing BIM to estimate quantities. For example, earthwork is inadequately represented for BIM-based QTO. Therefore, using BIM-based QTO to estimate quantities and costs of earthwork will create problems. Furthermore, there was mentioned that often only 50% of the required data for automatic quantity extraction is available in the building information model. Therefore, there should be verified that all required data to estimate the costs are available.

To estimate the costs of an early-stage design, the quantities of cost determining objects were used in the research. Only using costs of the cost determining objects leads to an underestimation of the costs and therefore a percentage over the costs of the cost determining objects should be used to estimate the total costs. Nesticò et al. (2017) used an additional percentage of 10% over the costs of the cost determining objects, where cost determining objects are 30% of the quantities. If only 10% of the quantities of a construction project are used to estimate the costs, an additional 30% over the costs of the cost determining objects should be used to estimate the costs.

Vitásek and Matějka (2017) mention three phases must be performed to automatically extract quantities and costs using a building information model, namely: (1) specify the requirements for the designers, (2) create price databases and (3) a software extension is required for the conversion of data from the building information model to the price database. Marzouk and Hisham (2012) mention five steps that are required to automatically estimate the quantities and costs of a construction project using a building information model, namely: (1) developing a 3D information model, (2) visualizing the construction steps, (3) adding additional information required for the cost estimation to the bridge information model, (4) exporting all information, e.g. volume, casting type, length, ID and material type to an Excel spreadsheet and (5) estimating the costs automatically by using a cost database and software. Vitásek and Matějka (2017) and Marzouk and Hisham (2012) both mention developing a building information model and using a cost database and software. Those are the most important steps required to estimate costs of a construction project.

Cheung et al. (2012) mention the information entries that can be used to connect quantities with its corresponding unit price. Fourteen entries were mentioned that belong to the objects and can be used to determine the unit prices, differing from element name to data source reference.

Nesticò et al. (2017) decomposed the construction objects using levels of breakdown. Five levels of breakdown were used: (1) class of technological units, (2) technological units, (3) class of technical elements (4) technical elements and (5) work items. This decomposition structure could be of use for this research.

APPENDIX B - INTERVIEWS

Panteleimon Rapis

Function: Asset & cost management specialist at Arcadis Romania
16 March 2018

For a basic bridge project, the time needed to make a preliminary 2D design of a bridge is 1 week for a designer to prepare all the drawings (top view, sections etc.). For a detailed design (DO phase) it takes 2 weeks for a designer per bridge. For final detailed design (UO phase) it takes 2 days for a designer per bridge for the formwork and 3 days per designer per bridge for the reinforcement.

It takes one week for a designer to prepare a preliminary 3D model (in Autodesk Revit) without separate cost determining objects of a bridge. For detailed design (DO phase) it takes three days per designer to prepare the 3D Model for 1 bridge. For final detailed design (UO phase) it takes one day per designer per bridge for the formwork and approximately 1.5 days per designer per bridge for the reinforcement.

If the designer knows from the beginning the specific requirements that we have for the cost estimation, he can choose from the beginning to create the objects/family of objects etc. in a way that is convenient for the cost extraction. If this choice is made at the beginning it will not have any impact on the time needed for the creation of the model. So practically the time will be the same for creating a design with separate objects as for a design without separate objects and it takes more time to create 2D drawings than creating a 3D model.

Ted peek

Function: Senior cost engineer at the building department of Arcadis Arnhem
29 March 2018

Bouw(kosten)data (BDB) is a cost database that was developed by Arcadis and can be bought by other companies. Arcadis developed BDB to earn money by selling it to others and to use it for their own projects. The unit prices of construction objects of buildings are stored in BDB. Some unit prices of infrastructural objects are also stored in BDB, however not all. BDB started in 2000 and uses data from the start of the 20th century.

The building department at Arcadis started by using Building Information Modelling, otherwise they would lose their position in the market. The competition of Arcadis often works with lower salaries and therefore the competition could complete a work cheaper. Since BIM was implemented at Arcadis, the efficiency of estimating the costs increased with 30%.

The building department at Arcadis does not often estimate the costs of huge projects but often only of one object, a building. The infrastructure department often needs to focus on multiple objects, e.g. a road and a bridge. Furthermore, not often standard objects are used for infrastructure projects, but often customized objects, e.g. an abutment.

The building department at Arcadis uses another decomposition structure compared to the infrastructure department. The decomposition structure used by the building department will be used all over Europe, therefore it would be advantageous if the infrastructure department will use the same. Only the top of the decomposition structure will be used all over Europe. The bottom of the decomposition structure is national, because most countries use different terms and construction methods. An abutment would be in the element level of the decomposition structure, the highest national decomposition level. A bridge in level six.

The building department at Arcadis often estimates the costs using the object level of the decomposition structure, e.g. type of inner wall. The decomposition level under the object level is the STABU codification and the level above is for example the inner walls in general.

The classification method NL/SfB was used at the building department of Arcadis to decompose and specify the decomposition levels. The NL/SfB was customized by Arcadis to suit the needs of the cost engineers.

Excavation and earthwork is not taken into account, the same goes for other special design features. The cost engineer adds the costs of these components by using his expertise.

The building department at Arcadis automatically extract the quantities of the construction object by using an extension in Excel. The codification of the construction objects is added manually in Excel. This codification is linked with the unit prices and therefore, the unit prices can be combined with the quantities.

Edwin van der Knoop

Function: Senior cost engineer at the infrastructure department of Arcadis Amersfoort
25 April 2018

Edwin van der Knoop considers using BIM important, because it is important to keep up with modern changes. Using BIM can be of great advantage for estimating the costs of a construction project. The visualization factor is important, but also the quantity extraction can be of great use for estimating the costs. Estimating the quantities is half the work of estimating the costs and therefore by automatically extracting the quantities, it is easier and faster to estimate the costs of a construction project. It is also possible to automatically estimate the costs of a project; however, a huge cost database is required to automatically estimate the costs, this is currently not available at Arcadis, however Arcadis is making a transition towards storing all unit prices of construction objects in a database using the software GwwCalc.

Edwin van der Knoop does not think it is possible to fully automatically estimate the costs of an infrastructure project, because he considers estimating the costs of an infrastructure project more difficult than estimating the costs of a building. This difference is mainly based on that a building is made on a greenfield location, i.e. there are no existing objects on the project location. For infrastructure projects, it is always important to take into account the location and its environment, because this might determine most of the costs of the project. Phasing a project causes most of the costs of a project. During the construction of a road, it is always important to keep the mobility and accessibility intact. Therefore, for replacing an old road, the old road cannot be closed, or another temporary road must be built causing high costs. For the phasing costs of a project and other factors, a cost engineer is always required, therefore, fully automatically estimating the costs of an infrastructure project is currently not possible according to Edwin van der Knoop.

Cost estimations should always be clear, traceable and transparent according to mister van der Knoop. The quantities in a cost estimation should be traceable, because other cost engineer and the client should be able to verify if they are accurate. The accuracy is also of importance for quantity estimation, however for preliminary cost estimations a small deviation of the quantities is allowed.

Marcel Volleberg

Function: Senior cost engineer at the infrastructure department of Arcadis Amersfoort
30 April 2018

All information should be stored in a building information model and should be retraceable. The requirements, design, quantities, risks, planning etc. should all be stored in a building information model and should be retraceable. Currently, the use of BIM is limited to a 3D model that sometimes can be used to estimate quantities. Marcel Volleberg is involved in a project in Antwerp, the Antwerp ring. For this project a data dump was extracted from the 3D model. However, over 10.000 lines of data were retrieved. This gigantic data dump was impossible to translate to useful information, because it was unknown to what objects the quantities belong. Codes were added to some objects, however not to all objects or sometimes the same type of objects had different codes. It was difficult or sometimes even impossible to translate the data to useful quantities for the cost estimation. There was no alignment between the modelling and the codes added to the objects.

The data required from the 3D model should be correct, however, the design is not always correct, e.g. the wrong thickness of a deck was used in the 3D model used in the project of the Antwerp ring. All cost determining objects are verified manually by determining the quantities manually. When the deviation is more than 3%, the cost determining object in the 3D model will be verified.

Multiple designers modelled the project of the Antwerp ring, this caused that different designers used different codes for the objects and different assumptions, e.g. where the road starts. Two BIM coordinators were used to prevent differences between the designers and to translate the desires of other people involved in the project to the building information model. The BIM coordinators talked with cost engineers about what information they desire from the building information model. However, not all designers translated the desires of the cost engineers to information in the building information model, mainly because of the budget of the project. The project has used a bandwidth of 15%, meaning that the estimated costs can be 15% higher or lower than expected. Therefore, information of the approximate length, width and height of object is in principal enough information to estimate the approximate quantities.

Currently, BIM is mainly used for visualization purposes, which is a big advantage of 3D models, however not the full potential of BIM is used. Sometimes additional information was added to the 3D model, e.g. the requirements and the quantities. However, this is not enough to reach the full potential, all information should be stored. A problem is that the files are big, the building information model of Antwerp ring is over 1gb, therefore the file is slow, causing problems when editing the file or using information from the file.

BIM has an added value for big and small projects, provided that the model is correct. Designers should understand what information cost engineers need from the model for the cost estimation. It is not required to put the costs in the building information model, because you have a separate cost estimation. However, it would be an added value. Clash detection is a huge advantage of BIM, e.g. there can be checked whether a cable clashes with another object.

Marcel Volleberg expects that all project information will be stored using BIM. The old (current) situation should also be modelled, because this is of great influence for the costs. Around 5% of the infrastructure projects at Arcadis focus on greenfield projects, i.e. a project that will be located at a location without objects, i.e. a meadow. Often a new road will be placed on the location of the old road. Therefore, the old road will be split in sections and the work will be phased to keep the traffic going. The phasing of the work should also be stored in BIM, because this is a big part of the costs of the project. The old and new situation should both be made in one model, otherwise the phasing of the work is not possible, and the timeline of the project cannot be shown. The DTM (digital terrain model) is an important model for estimating the costs.

Currently, the quantities and its substantiation are manually put in an Excel file and the cost estimation in a separate file. In the future the quantities used in the cost estimation should be connected with the building information model to visualize from what object the quantities are and what dimensions were used to estimate the quantities. In the future the unit prices of objects that are stored in GwwCalc, cost estimation software, will be used to estimate the costs. GwwCalc will also be used to create the cost estimation and in the end the cost estimation using GwwCalc will be converted to the SSK cost estimation format, because most clients require the SSK format.

The criteria that Marcel Volleberg identifies as important for quantity estimation methods are accuracy, efficiency and traceability. Marcel deemed traceability the most important factor, because all quantities should be retraceable for the client, the cost engineer, and other cost engineers. Therefore, if the quantities acquired from the quantity estimation method are traceable, it would be a big advantage. Accuracy is less important, because this study focuses on a preliminary design and therefore a bandwidth of 30% is often used. If the quantities differ a few percent this would form no harm for the cost estimation. However, a higher accuracy is of course advantageous, and a very low accuracy is not allowed. For other project phases, e.g. detailed cost estimation, the accuracy is of more importance. For the detailed cost estimation, often a bandwidth of 10% is used. This bandwidth is for the total costs, the bandwidth for the quantities is 5%.

The quantities of all three alternatives used for this study are in their way traceable. The manual quantities are traceable, because the dimensions are written down. The quantities retrieved using a BIM-viewer are traceable, because the quantities are connected with the building information model. The quantities retrieved from BIM-based QTO are traceable, because the codes and sub codes are the same in the cost estimation as in the building information model. However, the client might not know how to use the building information software, therefore the client cannot trace the quantities. Therefore, it is of great importance to make agreements before the start of the project regarding the use of building information models. Marcel Volleberg mentioned that not all cost engineers at Arcadis are experienced with using 3D models, therefore to implement BIM, the staff must be trained.

APPENDIX C – OVERVIEW OF THE THEMES AND GOALS

Table 21: Overview of the themes and goals including definition

Theme	Definition	Goal
Accuracy	The degree to which the result of a measurement, calculation, or specification conforms to the correct value or a standard (Oxford Dictionaries, 2018).	Maximize accuracy
Efficiency	Accomplishment of or ability to accomplish a job with a minimum expenditure of time and effort (Dictionary, 2018).	Maximize efficiency
Generality	The condition or quality of being general, or applicable to all (Collins, 2018) In this study it should be possible to estimate all quantities of all general cost determining objects.	Maximize generality
Flexibility	Possibility to differentiate design features (Hafez et al., 2015).	Maximize flexibility
Time predictability	Change between the actual time and the estimated time expressed as a percentage of the estimated time (KPI Working Group, 2000).	Maximize time predictability
Traceability	Ability to be followed on its course or to its origin (Oxford Dictionaries, 2018). In this study the ability to discover information of the origin of the quantities, i.e. to what objects the quantities belong.	Maximize traceability
Staff expertise	Expert skill or knowledge in a particular field (Oxford Dictionaries, 2018). In this study the skills or knowledge of the cost engineers at Arcadis of working with certain quantity estimation methods.	Minimize required staff expertise

APPENDIX D - DECOMPOSITION STRUCTURE

Decomposition by Kim et al. (2009)

Table 22: Decomposition structure by Kim et al. (2009)

Element	Work item for each element
Superstructure	Beam, Deck, Deck finisher, PSC string placing and tensioning, Temporary facility (pier table, key-segment, form traveller, temporary bent, etc.), Steel structure, Painting, Supporting post/scaffolding, Construction joints, Water proofing, Concrete slab finishing/curing, Cover plate, etc.
Substructure	Piers, Abutments, Foundations, Footing, Approach slab (Dowel-bar), Shoes, Supporting post/scaffolding, Construction joints, Water proofing, etc.
Site preparation	Excavation, Refill, Compaction, Ground contouring, Site clearance, Stabilization, etc.
Services & ancillaries	Mechanical and electrical installation, Communications, Protection, Drainage, Guardrails, Fences, Barriers, Median strip, Deck pavement, Expansion joints, Temporary bridge/road, Maintenance facilities, NOTCH, etc.

Decomposition by Rijkswaterstaat (2017)

Table 23: NEN2767-4 Decomposition structure used by Rijkswaterstaat (Rijkswaterstaat, 2017)

Level 5 – Elements	Level 6 – Construction parts
Main load bearing structure	Anchor; Balance bodkin; Beam; Protective layer; Arc; Steps; Tube; Console; Counterweight; Roof; Door; Diagonal (lattice girder); Driving box; Cross carrier; Gate; Pendant (arch bridge); Hanging bar; Heat-resistant coating; Case; Node; Column; Ladder; Stringer; Handrail; Handrail finish; Liège; Pillar; Plate field; Railing; Driving deck; Schedule; Shaft; Slot substructure; Slot construction; Wire construction; Vertical (lattice girder); Joint transition; Wall; Wall finish; Wind bandage; Rubbing.
Support point	Support point, General; Pylon; Pillar; Pole; Loading table; Mounting block; Support bar; Abutment; Column; Yoke; Conduction; Conductive work; Foundation; Diagonal (lattice girder); Bollard; Protective layer; Beam.
Foundation	Beam; Protective layer; Caisson; Pressure piles; Foundation; Soil improvement; H-piles; Piles manufactured in the ground; Pile cap; Open tube piles; Pole; Drawstring; Floor; Floor finish.

Decomposition by Tah et al. (1999)

Table 24: Decomposition structure by Tah et al. (1999)

Main component	Sub-components
Deck	Box deck, beams with infill deck, mono slab and beam deck, slab and beam deck, slab deck
End support	Strutted abutment, sloping abutment, reinforced abutment, skeleton abutment, mass abutment, counterfort abutment, cantilever abutment, tank seat, abutment on fill
Foundation	Caisson foundation, piles foundation, footing foundation
Intermediate support	Frame support, columns support, wall support
Wingwalls	Standard wingwalls, small wings, crib wings, crib walls, double wingwalls, cantilever wingwalls

Decomposition by the Federal Highway Administration (Bartholomew et al., 2015)

Table 25: Decomposition structure by the Federal Highway Administration (Bartholomew et al., 2015)

Major Component Categories	Sub-Component
Abutments piers	Steel H-Pile U-Shaped Footing Stem Wall Backwall Wingwall Cheekwall Bearing Pedestal
Piers	Drilled Shaft Rectangular Footing Rectangular Column Hammerhead Cap Bearing Pedestal
Bearings	Pot Bearing
Concrete Girders	Prestressed Concrete Bulb-T Girder Prestressed Concrete Adjacent Box Girder
Steel Girders & Framing	Steel I-Girder Vertical Stiffener/ Connection Bolted Field Splice Bolted Splice Plate Bolt Bolt Group Shear Stud Shear Stud Placement Cross Frame Type K Bolted Gusset Welded Gusset Cross Frame Layout Plate Diaphragm
Deck	Deck Deck End Beam
Bridge Railings	Traffic Barrier
Miscellaneous	Generic Reinforcing Bar Bend

APPENDIX E - WORKSHOP

This section describes the preparation of the workshop. The workshop had to be structured, otherwise the results would not be representable. Therefore, this section describes the participants of the workshop and the sequence in which they executed the workshop. The research process and data given to the participants has also been described.

Participants

The participants of the workshop were all cost engineers at Arcadis and are experienced in estimating quantities and costs. All participants usually estimate the quantities manually by using 2D drawings. Most cost engineers are not experienced with BIM. Since the cost engineers are not experienced with BIM, some instructions were given to the cost engineers regarding how to estimate the quantities using the BIM-viewer and BIM-based QTO. Cost engineers 1 and 2 have worked with a 3D model made with Autodesk Revit before, though they did not estimate the quantities using the 3D model, they only used a created 3D model for visualization purposes once before.

Six cost engineers participated in the workshop. The participants used all three quantity estimation methods, otherwise the data would be limited, namely only two results per quantity estimation method. To prevent learning effect due to repetition, the cost engineers used a different sequence of quantity estimation methods. The sequence is displayed in Table 26.

Table 26: Sequence of participants

Participant	Started with	Followed by	Finished with
Cost engineer 1	Manual quantity estimation	BIM-viewer	BIM-based QTO
Cost engineer 2	Manual quantity estimation	BIM-based QTO	BIM-viewer
Cost engineer 3	BIM-viewer	Manual quantity estimation	BIM-based QTO
Cost engineer 4	BIM-viewer	BIM-based QTO	Manual quantity estimation
Cost engineer 5	BIM-based QTO	Manual quantity estimation	BIM-viewer
Cost engineer 6	BIM-based QTO	BIM-viewer	Manual quantity estimation

Workshop process

To not make it a competition to be the fastest quantity estimator, the cost engineers took part of the workshop one by one. It was of importance that all workshops were performed the same way, therefore a clear structure was used for the workshop. All workshops took place in the same room at the office of Arcadis Amersfoort. The cost engineers used the prepared laptop of the researcher, because not everyone has the required software (Autodesk Revit and GwwCalc). Using the same laptop created a similar quantity estimation process for all participants. Therefore, by using the same laptop, the time required to estimate the quantities cannot be blamed on the difference in quality of laptops.

The workshop started by a short introduction by the researcher regarding the three quantity estimation methods and the goal of the study. This short introduction was given to help the cost engineer understand his tasks during the workshop. The introduction involved only a short description of the three quantity estimation methods.

The researcher monitored the time it took the cost engineer to estimate the quantities by using a stopwatch. When the cost engineer is finished with one estimation method the researcher stopped the time. The time it took the cost engineer was notated by the researcher. After a short break of approximately 5 minutes, the cost engineer started estimating the quantities using the next quantity estimation method.

After the workshop, the cost engineer was interviewed by the researcher to understand the opinion of the cost engineer regarding the quantity estimation methods and to explore the traceability of the quantity estimation methods.

Data

For the first quantity estimation method, manual quantity estimation, 2D drawings of the bridge project were used. The 2D drawings are based on the 3D model created by a designer of Arcadis and were printed in A0 format. The printed 2D drawings were used by the cost engineers to estimate the quantities of the cost determining objects.

The 3D model was made by the design department at Arcadis. However, the 3D model was not ready for quantity extraction, because not all objects were separated, and no codification was used. Therefore, the researcher prepared the 3D model by adding codes to all objects and by separating objects when required. This was done by the researcher, because the assumption of the study was that the 3D model of the bridge was correct. The aesthetics and dimensions have not been changed by the researcher. In the future the designer should have made a correct design. The 3D model was exported to an IFC file. The IFC file is required when using the BIM-viewer. The researcher exported to Autodesk Revit model to an IFC file, because the assumption is that if the BIM-viewer is implemented in the work practice of Arcadis, the designer performs the export of 3D model to the IFC file and the cost engineer uses the IFC file. The cost engineer retrieved the IFC file and a user account for the BIM-viewer.

The same 3D model was used for the third quantity estimation method, i.e. BIM-based QTO. The 3D model was created in Autodesk Revit and the cost engineer retrieved the Autodesk Revit file of the bridge project with the assumption that the design is correct.

The cost determining objects of which the quantities should be determined are displayed in Table 27. Therefore, the task of the cost engineer is only to estimate the quantities of the cost determining objects and not to determine of what objects the quantities are required.

Table 27: Cost determining objects

Object component	Cost determining object	Required quantities and units
Sub-structure	Piles	Length (m)
	Abutments	Volume (m^3)
	Wing walls	Volume (m^3)
Super-structure	Prefab girders	Area (m^2)
	Concrete topping	Volume (m^3)
	Approach slab	Amount (pcs)
Finishing	Asphalt road surface	Area (m^2)
	Sidewalk	Area (m^2)
	Traffic barrier	Length (m)

Model requirements

The assumption was that the building information model was correct during the workshop. However, the building information model that the researcher received was not ready for (semi)automatic quantity estimation purposes. Not all required quantities could be automatically estimated, because not all parameters were attached to objects. For example, for the piles, the length parameter was not attached, the researcher added this parameter. Furthermore, for all construction objects, the element ID was not visible in the quantity extraction. A Dynamo script was used to add the element ID to the construction objects. Shared parameters were used to add the element ID to the quantity estimation.

For various construction objects, the quantities were not estimated using the required method. For example, the area of the road surface was estimated for every side of the road surface, although only the top surface was required. Therefore, the researcher had to change the method the area was estimated.

Furthermore, not all construction objects were separated, e.g. the concrete pavement and the asphalt road surface were combined. Therefore, the researcher separated the construction objects where needed. Not all names of the construction objects were self-evident; therefore, some names of construction objects were changed.

For this research, the researcher changed the model to meet the requirements for quantity estimation. In the future, the designer should make a design that meets the requirements to estimate the quantities. Therefore, the cost engineer should collaborate with the designer to determine the requirements for estimating the quantities. This can be stated in the Information Delivery Manual (IDM) of Arcadis. The IDM describes how to exchange information in a structured and uniform manner (Balvert, 2016).

Instructions

Because the cost engineers have no experience with using the BIM-viewer and BIM-based QTO instructions regarding how to use both methods were given. The cost engineers are experienced with the manual quantity estimation method, therefore to compensate the experience, some instructions on how to use the BIM-viewer and BIM-based QTO were given. In the future the cost engineers will be experienced with using the preferred quantity estimation method and the instructions are no longer required.

BIM-viewer

Instructions regarding how to upload the IFC file to the BIM-viewer and instructions regarding how to use the BIM-viewer were given. The time required to read the instructions has not been taken into account for the time required to estimate the quantities, because in the future the cost engineers are experienced with the method and no instructions are required. The given instructions are as follows:

- Open ‘GwwBundel’
- Click on ‘GwwCalc’
- Click on ‘Bestand’
- Click on ‘Nieuw’
- Click on ‘Cancel’
- Fill in the general data as follows:
  - Titel: VO raming
  - Opdrachtgever: Arcadis
  - Aanbestedingsdatum: 01-07-2018
  - Type: RAW
  - Jaarversie: 2015-01
  - Contractvorm: Bestek
  - Besteknummer: NAAMLOOS
- Click on ‘OK’

GwwCalc now started.

- Click on ‘Toevoegen’
- Change the ‘Romptekst’ to the name of the cost determining object
- Change ‘Eenheid’ to the required unit
- Click on the quantity box

- Click on ‘F9’
- Login
- Click on ‘Nieuw project’
- Fill in the project data
  - Projectnaam: Brug Zwolle
  - Modelnaam: Brug Zwolle
- Click on ‘Selecteer IFC bestand’
- Select the IFC file located on the desktop
- Click on ‘Aanmaken’
- Open the created project by double clicking on the project

Now the 3D model is displayed on your screen. To add the quantities to the GwwCalc estimation:
- Select the object of which you want the quantity by clicking on the object in the visualization or by using the menu on the left
- Click on ‘Toevoegen’
- Give it the name of the cost determining object
- If you want to add other similar objects, you can do this by clicking on the object and clicking on ‘Toevoegen’
- Drag the required quantity from the menu on the right to the bottom table and click on ‘Toevoegen’
- Click on the required quantity in the table on the bottom of your screen
- Click on ‘Koppel aan GwwBundel’

You can now see the quantity in GwwCalc.
You can now repeat this process for every cost determining object by:
- In GwwCalc adding another object by clicking on ‘Toevoegen’ in the start tab.
- Change the unit to the required unit and quantity can be coupled to the 3D model by selecting the object in the 3D model and making a new ‘Meetstaat’. The required quantity can be coupled with GwwCalc by clicking on ‘Koppel aan GwwBundel’

BIM-based QTO

The cost engineers are not experienced with using BIM-based QTO. Therefore, the researcher gave instructions regarding how to automatically extract the quantities using a building information model. In the future the cost engineers are experienced with the method and no instructions are required. Therefore, this study did not take into account the time used for reading the instructions. The given instructions are as follows:

- Click on the Autodesk Revit file called ‘Bridge Zwolle’ on the desktop
- Click on the arrow next to ‘Schedule’ in the window called ‘View’
- Click on ‘Material takeoff’
  - Click on ‘<Multi-Category>’ and click on ‘OK’
  - Double click on the following fields in this order:
    - ‘Family and type’
    - ‘Material: Name’
    - ‘Material: Volume’
    - ‘Area’
    - ‘Lengte’
    - ‘Element ID‘
  - Select the window Sorting/Grouping
    - ‘Sort by: Material: Name’
    - Select ‘Header, Footer and Blank line’
    - Select ‘then by: Type’
  - Select the window Formatting
    - Select Material: Volume
    - Click on the arrow next to ‘No calculation’ and select ‘Calculate totals’
    - Make sure ‘Rounding’ is on ‘2 decimal places’ and Unit symbol’ on ‘None’ and click on ‘OK’
  - Click on ‘OK’

The table with the quantities has now been created.

To export the schedule:
- Click on ‘File’ in the top left corner
- Click on the arrow next to ‘Export’
- Click on the arrow pointing down
- Click on ‘Reports’
- Click on ‘Schedule’
- Save the file

Now a .txt file is stored on the computer

To open the .txt. file in Excel:
- Start Excel
- Click on ‘Andere werkmappen openen’
- Click on ‘Bladeren’
- Click on ‘Alle bestanden’
- Open the text file that has been stored
- Click on ‘Voltooien’

The result is a quantity take-off in Excel.

The quantities of the railing are missing, to extract those quantities, a new schedule must be made in Autodesk Revit.
- Click on the arrow under ‘Schedule’ in the window called ‘View’
- Click on ‘Schedule/Quantities’
- Double-click on ‘Railings’
- Double-click on the following fields using the following sequence:
  - ‘Type
  - ‘Length’
  - ‘Element ID’
- Click on ‘OK’

The quantities of this schedule can be exported to Excel by using the same steps mentioned before.

Assessment format

This interview format was used at the end of the workshop to assess the performance of the quantity estimation methods regarding traceability and to verify if the result of the study is the same as the expected result by the cost engineers. Directly after the workshop, specific questions were asked to the cost engineers regarding how they estimated the quantities. Those questions were related to the method and why they performed certain tasks when using the method. The questions asked regarding the traceability and preference of the cost engineers were:

- Have you used BIM or 3D models before?
  - For what purposes? (visualisation, estimating quantities etc.)

- How would you assess the traceability of the quantity estimation methods using a scale of 0 to 10, in which:

Assessment score	Description
10	Extremely traceable, all quantities can be easily and quickly traced
8	Very traceable, all quantities can be traced
6	Somewhat traceable, all quantities can be traced; however, this does take time
4	Somewhat untraceable, most quantities can be traced
2	Very untraceable, most quantities can’t be traced
0	Extremely untraceable, no quantities can be traced

- Could you elaborate on why you chose these assessment scores?
- What early-stage quantity estimation method do you prefer and what method do you consider least useful?
    - Could you elaborate?
- Is BIM currently used to estimate quantities and costs at Arcadis?
    - What prevents Arcadis from using BIM to estimate quantities and costs at Arcadis?
- Do you see BIM being used in the future for estimating quantities?
    - Could you elaborate?
- Do you see BIM being used in the future for estimating costs?
    - Could you elaborate?
- For what other features should BIM be used?

APPENDIX F - RESULTS WORKSHOP

This appendix describes the results of the workshop regarding the weight assessment, accuracy of the quantities and the validation.

Weight assessment

Before the start of the workshop, the cost engineers were asked to assess the importance of the three criteria: accuracy, efficiency and traceability. There was mentioned that an importance rating of 100 is twice as important as an importance rating of 50. The results per cost engineer are as follows:

Cost engineer 1

The first cost engineer mentioned that efficiency is the most important criterium during a preliminary design, as long as the accuracy does not deviate too much. The quantities can deviate from the actual quantity, because during preliminary design, a certain deviation is allowed, often 30%. Therefore, the criterium accuracy is the least important criterium. Efficiency is deemed most important, because if you can estimate the quantities very quickly, it is quicker and cheaper to create a cost estimation. Therefore, Arcadis can earn more money and gain more work. The second most important criterium is the traceability of the quantities. It is of importance that the quantities can be verified by the client and by other cost engineers, otherwise it is unknown of what construction object the quantities are and if they are accurate.

Table 28: Importance ratings according to cost engineer 1

Efficiency	Accuracy	Traceability
100	60	80

Cost engineer 2

The second cost engineer believes accuracy is the most important criterium for a quantity estimation method, because otherwise the estimated total costs are incorrect. Even using a preliminary design, the cost estimation should be as accurate as possible. The costs can deviate more during preliminary design; however, it is of importance that the cost estimation is as accurate as possible. Traceability is the second most important criterium, because cost engineer two thinks a project should always be clear, traceable and transparent. Efficiency is considered least important.

Table 29: Importance ratings according to cost engineer 2

Efficiency	Accuracy	Traceability
70	100	80

Cost engineer 3

Cost engineer 3 considers traceability of the quantities the most important criterium, because if the quantities are not traceable, the cost estimation cannot be delivered to the client. The client will reject a cost estimation that is not traceable, because the client cannot verify the quantities. Accuracy is considered second most important, because inaccurate quantities cause inaccurate costs. Efficiency is considered least important, because making a cost estimation takes more time if the estimation must be accurate.

Table 30: Importance ratings according to cost engineer 3

Efficiency	Accuracy	Traceability
60	80	100

Cost engineer 4

Cost engineer 4 considers accuracy by far the most important criterium, because if the quantity estimation process is accurate, the quantities are traceable and there will be worked efficiently. Therefore, according to cost engineer 4, accuracy is significantly more important than traceability and efficiency. Efficiency is not considered important, because if there will be worked quicker, quantities will deviate more from the actual quantities.

Table 31: Importance ratings according to cost engineer 4

Efficiency	Accuracy	Traceability
25	100	25

Cost engineer 5

The fifth cost engineer is of the opinion that accuracy is the most important criterium, followed by traceability and efficiency. Accuracy is considered most important, because inaccurate quantities lead to inaccurate cost estimations. If the cost estimation is inaccurate, problems arise with the client, because the budget of the client might not be sufficient for the project.

Table 32: Importance ratings according to cost engineer 5

Efficiency	Accuracy	Traceability
70	100	90

Cost engineer 6

Cost considers accuracy and traceability the most important criteria, because both criteria and important for the client. The client wants a traceable and accurate cost estimation. Efficiency is also of importance; however, it is important for Arcadis itself. When the cost estimation is made quicker, more work can be gained, and more revenue can be made.

Table 33: Importance ratings according to cost engineer 6

Efficiency	Accuracy	Traceability
80	100	100

Accuracy

In section four, only the deviation was mentioned. This appendix describes the quantities that were estimated during the workshop. Six cost engineers estimated the quantities of nine cost determining objects. The estimated quantities using the manual quantity estimation method are illustrated in Figure 22. The quantities estimated using the BIM-viewer and BIM-based QTO were equal for all cost engineers and are therefore not displayed in this appendix. Figure 22 displays all measured quantities of the cost determining objects. There can be seen that most quantities do not deviate much from the actual quantity. Furthermore, there can be seen that for most cost determining objects some cost engineers estimated quantities higher than the actual quantity and some cost engineers lower. Therefore, there is no trend line regarding deviating quantities. Different types of mistakes were made during the workshop. Sometimes a cost engineer estimated the area instead of the volume. Furthermore, a cost engineer used the depth of the piles instead of the length of the piles and a cost engineer forgot to combine all parts of the asphalt and therefore only estimated the quantity of one part of the asphalt. Furthermore, some mistakes were made when measuring quantities and some assumptions were made when measuring quantities of round objects.

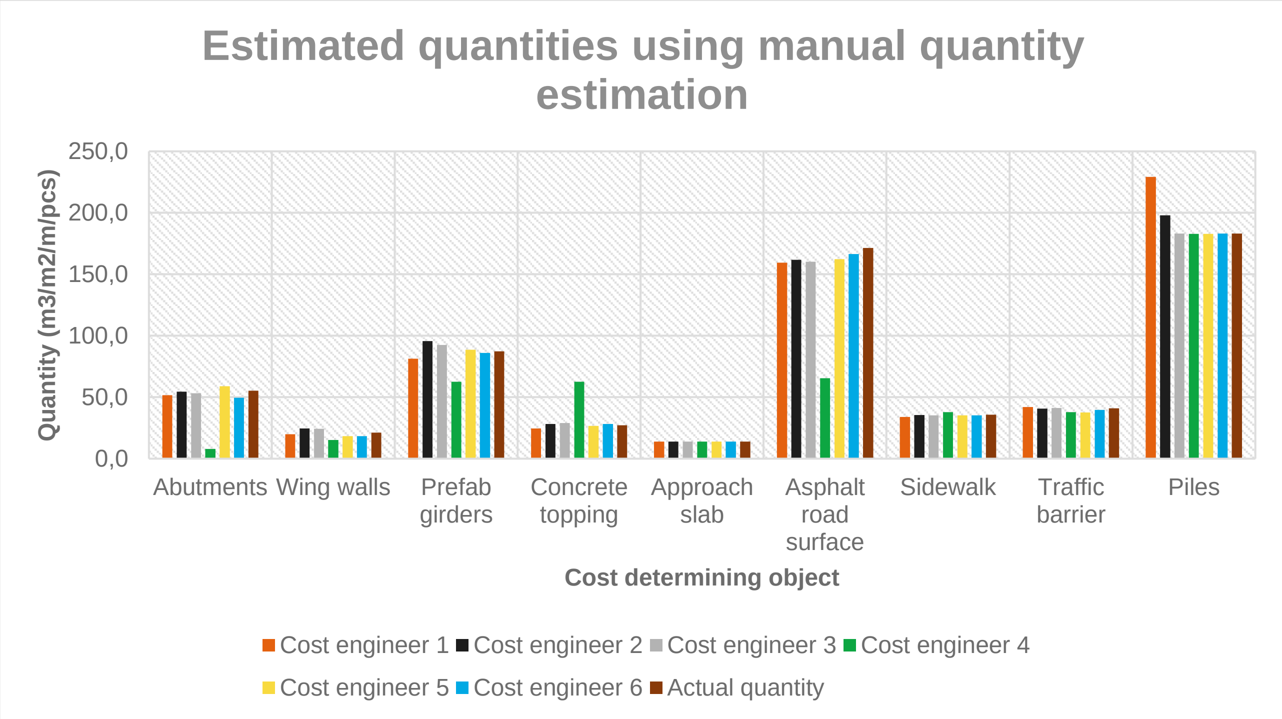

Figure 22: Estimated quantities using manual quantity estimation

A histogram was created to display the frequency of the deviation using the three quantity estimation methods. The histogram is displayed in Figure 23. Since all cost engineers estimated the same quantities using the BIM-viewer and BIM-based QTO, obviously the frequency is a multitude of six, the number of participants of the workshop. There can be concluded that estimating quantities using the BIM-viewer or BIM-based QTO deviates less from the actual quantity compared to manual quantity estimation. Furthermore, manual quantity estimation results in deviations of over 10% in contrast to the BIM-viewer and BIM-based QTO. The quantities estimated using BIM-based QTO or the BIM-viewer deviated 6% for the girders, because Autodesk Revit estimated the gross area and in the detailed cost estimation the net area was used.

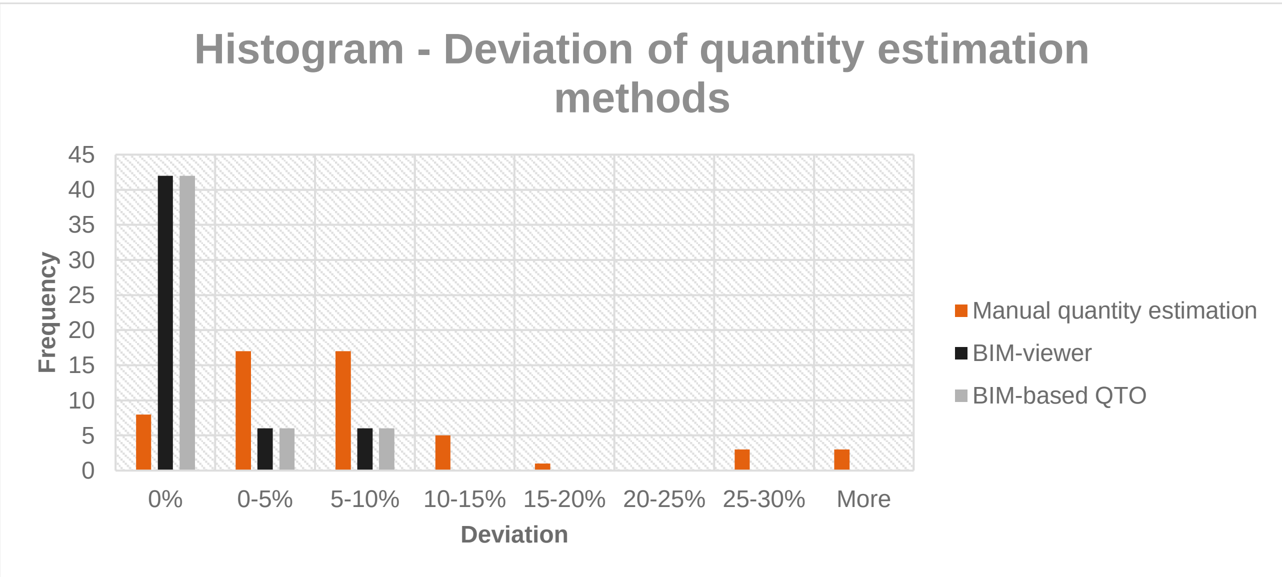

Figure 23: Histogram of deviation of quantity estimation methods

Validation results

At the end of the workshop, the cost engineers were asked to determine their preferred quantity estimation method. Furthermore, questions were asked regarding their experience and expectations of using BIM.

Cost engineer 1

Cost engineer 1 has used BIM before, mainly for visualization purposes and to estimate the quantities by clicking on the object and looking at the properties, this was in BIM360. Estimating the quantities by looking at the properties did not always work, because the design was made in Romania and there were communication problems. Furthermore, not all quantities were possible to estimate, because not all quantities were stored in the properties of the construction objects. Cost engineer 1 has not used Autodesk Revit or GwwCalc before.

Cost engineer 1 preferred the BIM-viewer over BIM-based QTO and manual quantity estimation, because it is clear what you are doing. You still have feeling of what you are doing and what project you are working on. Cost engineer 1 though it was not clear what he was doing when using BIM-based QTO. However, because the quantities are estimated quickly, cost engineer 1 preferred BIM-based QTO over manual quantity estimation. Manual quantity estimation takes time and therefore cost engineer 1 considers it least useful.

Cost engineer 1 thinks BIM should be used in the future. Currently, some projects use 3D models, however using BIM can be improved, because now the 3D models are mostly used for visualization purposes only. The cost engineer does not know what to improve on using BIM, because cost engineer 1 is not experienced with using BIM.

Cost engineer 2

Cost engineer 2 has used BIM before, for visualization and estimating quantities of one project. The 3D model was not correctly modelled, causing problems during quantity estimation. Not the required quantities were available to estimate using the 3D model. Cost engineer 2 mentioned that this has to change. All required quantities to estimate the costs should be stored in the properties of the construction objects. Therefore, the cost engineer should be earlier involved in the project, e.g. in the project start-up (PSU). During the PSU, the cost engineer can tell the designer what quantities he wants and what objects should be separated.

Cost engineer 2 thinks the BIM-viewer is the most useful quantity estimation method, followed by BIM-based QTO. The BIM-viewer has the preference of cost engineer 2, because of the visualization of the objects to which the quantities belong. Manual quantity estimation is considered least useful, because it takes the most time and is less accurate than quantity estimation methods using BIM when the 3D model is correctly made.

Cost engineer 2 mentioned that BIM should be used currently, mainly for visualization and estimating quantities. In the future, not only the quantities, but also the costs should be estimated automatically. Currently, this is not possible, because the database lacks unit prices of all types of construction objects.

Cost engineer 3

Cost engineer 3 has used Autodesk AutoCAD before, however he only created only 2D drawings with it. Cost engineer 3 has not created 3D models before, though he did use visualizations of the model before, by moving through the project and rotating the project.

Cost engineer 3 considers the BIM-viewer the most convenient quantity estimation method, because it is easy to use and directly displays the objects to which the quantities belong. Therefore, cost engineer 3 considers the quantities estimated using the BIM-viewer extremely traceable.

Cost engineer 3 considers BIM a good development and thinks Arcadis should start using it more often. Currently, BIM is not used often enough and not at a high level. BIM offers more than what is utilized currently. BIM could improve by focusing more on infrastructure projects instead of utility project, because it is still difficult to involve the surroundings in BIM.

Cost engineer 4

Cost engineer 4 has not used BIM before the same way as during workshop. Cost engineer 4 only used BIM for visualization purposes to view a project.

Cost engineer 4 prefers using the BIM-viewer to estimate quantities of construction objects, because the quantities can be quickly estimated, and the BIM-viewer makes the project comprehensible as opposed to BIM-based QTO. Cost engineer 4 thinks BIM-based QTO does not make a project comprehensible and considers BIM-based QTO not traceable. The main advantage of the BIM-viewer is that you can see what you are doing and therefore you create a feeling for the project. Cost engineer 4 prefers manual quantity estimation over BIM-based QTO.

According to cost engineer 4 the quantities should be combined with unit prices to automatically estimate the costs; however, the environmental and external factors should be correctly taken into account. Therefore, expertise and experience of cost engineers is always required, because it is not possible to automatically estimate all costs and assume the costs are correct. The environmental and external factors determine a significant part of the costs of a project. There should be started by slowly using BIM. Estimating the quantities using BIM would be a good step towards automatic cost estimation. The transitions towards automatic cost estimation should be done step by step, like learning how to ride a bicycle. Cost engineer 4 does not know at what point the use of BIM is in the organization and therefore does not know where to improve.

Cost engineer 5

Cost engineer 5 has no experience with using BIM, only watching others use 3D models and receiving a picture of a 3D model for visualization purposes.

Cost engineer 5 discussed the possibility of delivering quantities using BIM to the client. Before the start of the project, the delivery should be discussed with the client, because the client might not have experience with using BIM and therefore cannot verify the quantities. Therefore, the quantities are not traceable using BIM if the client cannot work with BIM.

Cost engineer 5 is of the opinion that the BIM-viewer is the least error prone and therefore is the best quantity estimation method. Furthermore, the BIM-viewer is quick, and the quantities are traceable. Cost engineer 5 believes the quantities estimated using the BIM-viewer are less error prone, because less actions are required to estimate the quantities and the quantities are immediately displayed in GwwCalc. BIM-based QTO was least favoured by the cost engineer, because currently not all clients can work with it. The cost engineer believes manual quantity estimation will not be used in the future. After approximately five years the cost engineer expects that manual quantity estimation will stop being used.

BIM should be used in the future, because it is fast and therefore saves time. The cost engineer expects that the phasing of the project and the surroundings are probably not in the building information model in the future. Therefore, it will not be possible to automatically estimate the costs of a complete project in the near future. BIM has advantages, however the risk is that you do not create a feeling for the project, where you do create a feeling for the project when you work with 2D drawings. This mainly applies for BIM-based QTO, because here you do not see the objects of which you estimate the quantities. The BIM-viewer visualizes the construction objects and therefore does create a feeling for the project.

Cost engineer 5 believes that BIM should be implemented in the work practice of Arcadis; however, first the designers should be aware of what quantities are required. Therefore, the cost engineers should teach the designers regarding the required quantities. Often the designers do not estimate all quantities, e.g. designers consider all types of asphalt the same and therefore only estimate the total quantity and not the quantity per type of asphalt. A solution for this problem could be to hand over a cost estimation to the designer to make the designer aware of what quantities are required. This could be a historic cost estimation of a similar project or a new created list of required quantities. This new created list could be used for all similar projects. Therefore, a standard should be created. This should be made during the Project Start Up.

Cost engineer 6

Cost engineer 6 has previously used Autodesk AutoCAD, however only for 2D purposes. Cost engineer 6 has not used 3D models, only seen 3D visualizations of projects and seen others working with 3D design software.

Cost engineer 6 is of the opinion that the BIM-viewer is the most useful method to estimate the quantities, mainly because of the visualization and traceability of the quantity estimation method. Furthermore, the fact that the BIM-viewer can be combined with GwwCalc is an advantage of the method, because GwwCalc is the new method that will be used to create cost estimations. Cost engineer 6 prefers BIM-based QTO over manual quantity estimation, mainly because it is faster and because cost engineer 6 expects that BIM-based QTO is more accurate compared to manual quantity estimation. However, the accuracy depends on the designer.

According to cost engineer 6, BIM should be used to estimate the quantities, mainly because of the speed and accuracy. Fully automatic cost estimation will not be performed in the near future, maybe after 20 years, because it is not possible to estimate all cost factors automatically. It is always important to use the expertise of cost engineers, otherwise mistakes will be made using BIM. It is important to verify the quantities more often, because mistakes can be made using BIM, because the design is made by a designer and the designer can make mistakes.