Model-based cost estimation for infrastructure projects: a case study

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Abstract
The architecture, Engineering, and Construction industry faces an ongoing digitalization. This study investigates how infrastructure projects practice cost estimation, what is hindering automated cost estimation, and how automated cost estimation can be further developed. A case study with integrated project delivery was studied. The collected data were categorized and analyzed after three cornerstones for digital transformation: people, process, and technology. This study finds current practices time-consuming, error-prone, and inefficient. However, model-based cost estimation can result in higher efficiency and fewer errors. Concerning people, relevant training and mindset identified crucial elements. Concerning process, increased workload due to integrated project delivery, time pressure, and problems with attaching correct classification codes to objects in BIM resulted in incomplete models hindering automated cost estimation. The identified hinders concerning technology were not worth mentioning. Suggested improvements include relevant training and alignment between today's object-oriented BIM and the process-oriented standard specification of work for infrastructure projects.

Keywords: Digitalization, Cost estimation, BIM, Model-based, Infrastructure projects

1 Introduction

Our society faces an ongoing digitalization. Tihinen et al. (2016) introduced digitalization as a major stream of alternating future affairs in society and industry. Degryse (2016) describes it as the fourth industrial revolution. Digital transformation results from accepting and adopting digitalization by organizations and refers to changes at different levels (Parviainen et al., 2017). Along with other components, several publications introduced people, process, and technology as the three main cornerstones of digital transformation within organizations. Bonnet and Nandan (2011), Westerman et al. (2014a) mention the necessity of a reliable connection between these three cornerstones.

As one of the world's largest sectors, the Architecture, Engineering, and Construction (AEC) industry is exposed to this transformation. Feng et al. (2010) and Webb (2017) identified several reasons to encourage the AEC industry to enable digitalization. According to them, construction time, quality of the product, environmental concerns, and social impacts increase digitalization demand. Consequently, within a short period, Building Information Modeling (BIM) as a digital representation of projects has been promoted as the leading technology for digitalization in the AEC industry (Kulasekara et al., 2013, Whang and Park, 2016). Several studies revealed higher efficiency and effectiveness due to BIM use (Whang and Park, 2016), even though there are more benefits that can be unleashed (Fürstenberg and Lædre, 2019). According to Kunz and Fischer (2012), BIM has a tremendous impact on the AEC industry.

Cost estimation can be essential for a project's success, especially in the AEC industry (Elbeltagi et al., 2014, Ma and Liu, 2014). As mentioned by Choi et al. (2015), cost estimation is an effective tool for decision-making in both the early and detailed design phases of AEC projects. Several publications addressed the need for accurate cost estimation and stressed its vital role in the AEC industry (Allison et al., 2018, Andersen et al., 2016, Ebrahimi and Dowlatabadi, 2019, Ismail et al., 2016, Welde and Odeck, 2017). However, cost estimation can be a manual, time-consuming, and error-prone process (Eastman et al., 2011, Holm, 2005, Ma and Liu, 2014, Monteiro and Martins, 2013). This process involves taking off quantities from either drawings or models and copy-pasting the quantities into spreadsheets or cost estimation software. As projects become larger and more complex, quantity takeoff becomes even more time-consuming, and errors occur more often (Babatunde et al., 2019, Olsen and Taylor, 2017). While BIM shows great potential to solve these issues, Shou et al. (2015) report that studies on BIM mainly focus on buildings and not on infrastructure.

Considering the potential benefits of automated quantity takeoff and the absence of practical research on infrastructure projects, model-based cost estimation for infrastructure projects is investigated through the following research questions:

- How is cost estimation practiced in infrastructure projects?
- What is hindering automated cost estimation?
- How can automated cost estimation be further developed?

This study has some limitations. First, it investigates the quantity takeoff part of cost estimation and not unit pricing. Second, only one project with the Norwegian classification codes for the specification of work was studied. The third limitation is that only the early phase – before detailed design – was investigated.

Finally, it is worth mentioning that the investigated case is the first infrastructure project in Norway to use Integrated Project Delivery (IPD). In Norway, IPD is only applied once before, as described by Aslesen et al. (2018) and Simonsen et al. (2019). The novelty of this project delivery method may confines the validity of some of the discussed experiences and challenges.

2 Previous work described in literature

Digitalization, one of the most significant trends changing our society with notable impacts on human life, is compared to industrial revolutions in several publications. Its fast spread sets enormous changes in all knowledge fields (Degryse, 2016, Tihinen et al., 2016). Several different definitions depending on the context have been presented for digitalization during past decades. The simplest and common one is the transformation from analog to digital. According to the studies of Gassmann et al. (2014) and Henriette et al. (2015), digitalization is known as the "Ability to turn existing products or services into digital variants, and thus offer advantages over tangible product". Moore (2015) mentioned new value creation as the result of digitalization; in his idea, only improving without any new creation was not enough. However, in some studies, digitalization is defined as the connection of people, process, and data. According to Westerman et al. (2014b), digital transformation means "The use of technology to radically improve the performance of reach of enterprises". Digital transformation is more about changing roles and ways of working. Digital transformation results from accepting and adopting digitalization and digital technologies (Parviainen et al., 2017). Feng et al. (2010) and Webb (2017) identified several reasons encouraging the construction industry to enable digitalization. According to them, construction time, quality of the product, environmental concerns, and social impacts increase digitalization demand.

Lee et al. (2014) defined cost estimation as "the process of predicting project cost and resource requirements". Cost estimation is a manual and repetitive task prone to human errors (Firat et al., 2010). This uncertain and error-prone nature resulted in uncertainty about the results and a reduction in its reliability. In this study, we used the definition of Messner et al. (2019) for model-based cost estimation. They defined it as "a process in which BIM can be used to assist in the generation of accurate quantity takeoff and cost estimation throughout the lifecycle of the project". Quantity takeoff is one of the critical components in cost estimation, according to Monteiro and Martins (2013). It can be defined as the process of measuring and counting building elements. Several publications stressed that precise quantity takeoff is necessary for reliable cost estimation in different project phases (Liu et al., 2016, Monteiro and Martins, 2013, Whang and Park, 2016).

Traditional quantity takeoff is a manual process based on drawings or models. In this approach, estimators need to go through each different drawing sheet or 3D model and determine the quantities. Since it is based on human interpretation, wrong inputs and interpretations are common due to the task's complexity (Monteiro and Martins, 2013). This process is time-consuming, error-prone, and based on human interpretation. The dependency on human interpretation can result in different results among different quantity surveyors (Elbeltagi et al., 2014, Holm, 2005, Monteiro and Martins, 2013, Sacks et al., 2018). Whang and Park (2016) described that the designer and contractor’s quantity surveyor could come up with different quantities despite following the same documents. Interestingly, Arayici et al. (2011) compared the qualification of quantity surveyors and design teams, and found that quantity surveyors are often less qualified than the design team. Jadid and Idrees (2007) showed that linking DWG files with the bill of quantities gave more reliable and accurate results than traditional methods.

Building Information Modeling (BIM) is important for digital transformation in the AEC industry. According to Sacks et al. (2018), BIM can be defined as "a new approach to design, construction, and facilities management, in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in digital format". During the past decade, BIM has been broadly adopted in the AEC industry. BIM is using for coordinated, consistent and computable building information management in all phases – from design and implementation to maintenance (Lee et al., 2014). Following the emergence of BIM, it has been realized that implementing BIM can result in more efficiency (Wu et al., 2014).

Sattineni and Bradford (2011) mentioned a rising application rate of BIM within the AEC industry. They stated automated quantity takeoff as one of the important BIM uses in cost estimation. According to their results, most organizations suffer from not having skilled employees in BIM with sufficient experience in cost estimating. Nagalingam et al. (2013) report an 80% reduction in spent time due to adopting BIM for cost estimation. Sacks et al. (2018) describe BIM-based quantity takeoff as a new approach. They believe that this approach can provide more accurate results and decrease the time and costs required to do the quantity takeoff. Fürstenberg (2021) in their study described this method more in detailed for a road project. According to him, this process includes creating a dynamic link between design software and cost estimation software. They introduced an IFC file with coded property set as the dynamic link.

3 Method and Case Description

This study investigates model-based cost estimation in a Norwegian road project through a literature review, a document study, and a case study. As Snyder (2019) described, a literature review is crucial for creating the theoretical framework and building conceptual models. The literature review was used to establish knowledge, create the theoretical framework, find the knowledge gap, define the research questions, structure an interview guide and discuss findings.

A case study followed the literature review. Several publications mention the potential benefits of case study (Fürstenberg, 2020). Gerring (2004) defined a case study as “an intensive study of a single unit with an aim to generalize across a larger set of units”. Feagin et al. (1991) introduced a case study as an ideal methodology for a thorough investigation. The studied case was a 7 km four-lane highway project. The case was the first Norwegian infrastructure project with Integrated Project Delivery (IPD). The designer, client, and contractor collaborated closely from the early phases of the project. They were co-located in the project office to improve collaboration. The case was selected because the client had high digital ambitions and expected a mainly model-based design and construction process. The use of drawings should be reduced.

Semi-structured interviews are broadly used as a data collection methodology within qualitative research (McIntosh and Morse, 2015). This research used open-ended semi-structured interviews despite their resource-demanding nature. The semi-structured open-ended questions allowed an in-depth response from interviewees by enabling the researchers to ask probing questions. The possibility to ask probing questions is mentioned by Turner III (2010) as a potential benefit of semi-structured open-ended interviews. The open-ended questions let the participants express their viewpoints. All interviews were through the Microsoft team. Due to the global pandemic worldwide, there were no possibilities for in-person interviews.

The interviewees included representatives from the designer, the contractor, and the client:

- Three project managers from all three parts
- BIM manager
- Four discipline leaders (road, construction, electrical, and water and sewer)
- Three quantity surveyors from the client-side
- Four discipline BIM coordinators (road, construction, electrical, and water and sewer)

4 Findings

This study considers people, processes and technology to be the three main cornerstones of digital transformation. It answers three questions, namely: how do infrastructure projects cost estimate cost, what are hindering automated cost estimation and how can automated cost estimation be further developed.

4.1 People

In the investigated case, semi-automated cost estimation was practiced. The estimation involved extracting quantities from models, entering them in spreadsheets and multiplying them with unit prices. A few quantities were manually calculated. While all four investigated disciplines had a predefined workflow for quantity takeoff, they practiced it differently. The workflow was even practiced differently within the disciplines. Often the disciplines applied the workflow they were most familiar with due to time restriction.

Two challenges hindering an automated model-based cost estimation were identified. The first challenge was little experience with model-based quantity takeoff. The second challenge was lack of a digital mindset. These challenges were a restricting a fully automated estimation, especially for two of the disciplines. Time limitation was explained to cause incomplete models and a shift towards a traditional mindset.

4.2 Process

Concerning processes, a semi-automated cost estimation was noticed. Time pressure and unprecise mapping of prescribed cost classification codes for model objects were the main challenges. There were clear indications that the Integrated Project Delivery method (IPD) caused an increased workload and thereby time pressure in the early phases of the project. For an IPD, an agreed target price based on a sound evaluation of several alternatives is important. According to the respondents, the workload due to evaluating several alternatives prevented automated model-based cost estimation. Traditional workflow was used instead of spending time on developing automated workflows.

A mismatch between mapping of the prescribed cost classification codes to model objects was identified. While BIM is predominantly object-based, the cost classification system is process-oriented. This resulted in problems with mapping the correct classification codes to the corresponding model objects.

4.3 Technology

Regarding technology, the software used by different stakeholders in different disciplines was investigated. The design team and the contractor used different software for quantity takeoff resulting in approximately 10 % deviation. The software used by the contractor was regarded to be better suited, and the contractor became responsible for the quantity takeoff after the project's early phase. Except for this, there were no identified technology challenges worth mentioning.

5 Discussion

5.1 People

In this case, the main challenge was little experience with BIM combined with a traditional mindset. This, directly and indirectly, lead to unmatured and simple models in the early phases. Later, a detailed model suited for automated model-based quantity takeoff was produced.

The importance of education and training was undeniable. Even the respondents themselves mentioned a need. Ali et al. (2016) noted the importance of educating and training quantity surveyors to benefit from 5D BIM. According to their study, educating toward BIM framework for quantity surveyors is fundamental. Their study described the educational framework for quantity surveyors in the context of BIM implementation. Babatunde et al. (2018) also mentioned that education and BIM modeling training are crucial in architecture, engineering, and construction. Not having enough experience with model-based cost estimation result in increased workload and incomplete models. However, the increased workload can also result in unmatured and incomplete models in the early phase facing time limitations. Unmatured and incomplete models are identified as the main restriction hindering automated model-based cost estimation.

Besides training, a change of mindset is necessary. All project participants need to change mindsets and adopt model-based thinking. Lack of experience with model-based cost estimation enhanced the urge to fall back to traditional routines and being unable to take potential advantages of digitalization; the traditional routines are costly, time-consuming, and error-prone.

In this case study, IPD as a new project delivery method for the project team also magnified the importance of relevant training and mindset. A change from traditional mindsets to IPD based mindset will help the project team by saving time and cost.

Implementing and transition toward IPD contracts also requires solving some critical barriers. As Ghassemi and Becerik-Gerber (2011) mentioned, one of these barriers identified from nine case studies is training. All IPD parties need to change their mindsets from a traditional mindset and adopt IPD based thinking. The need for switching from a traditional mindset also applies to cost estimation and quantity takeoff, not just as a requirement for IPD projects but also to be able to move toward automated processes and workflow. As two of the respondents also mentioned this fact, changing mindset from traditional engineering was challenging.

5.2 Process

IPD attempts to improve project outcomes through a collaboration between the different parties, and several projects and studies demonstrated its benefits (Kent and Becerik-Gerber, 2010, Lahdenperä, 2012). Enhanced collaboration was also stressed during interviews. The early involvement of contractors as a feature of IPD resulted in better collaboration and better solutions. However, it increased the design team's workload to find the best solution, especially during the early phases. Increased workload resulting from more concentration toward finding the most cost-optimized solution resulted in simplified and unmatured models before detailed design. This issue makes it hard to adopt automated model-based cost estimation in this phase. All relevant publications on this topic emphasize having a mature and detailed BIM model as a crucial factor to adapt to automated model-based cost estimation.

The respondents believe that the extra workload during the early phases was the main reason hindering automated model-based cost estimation. This issue was also identified as one of the limitations of adopting model-based cost estimation in another study (Naneva et al., 2020).

According to several publications (Matipa et al., 2009, Tiwari et al., 2009, Sunil et al., 2015, Ismail et al., 2018), automated model-based cost estimation is less time and cost-consuming than traditional and semi-automated cost estimation. In this case, the authors believe that the change in project delivery method was challenging regarding the contractor's early involvement and requesting for comparing different alternatives. Increased workload resulted in time limitation in the early phases. The authors believe that this issue can be solved by allowing more time during the early phases. In case of not having sufficient experience, this solution can also cover that issue. Naneva et al. (2020), in their study, also mentioned this limitation. However, in their research, incomplete models were not identified as a result of time limitation directly.

5.3 Technology

Regarding technology, the software used for quantity takeoff represented a challenge. Different software has different approaches and levels of accuracy for quantity takeoff. The software used by the design team and software used by the contractor extracted quantities with an approximate difference of 10 %. Therefore, the responsibility of quantity takeoff was moved from the design team to the contractor. There was a need for software that could extract more accurate quantities and an agreement to use the same software with different parties involved in the project.

6 Conclusion

This study set out to investigate how infrastructure projects practice cost estimation, what are hindering automated cost estimation and how automated cost estimation can be further developed. The findings relate to a infrastructure project using a Norwegian standard for specification of work but are considered relevant for projects in other contexts.

When it comes to findings, current cost estimation practice with manual copy-pasting of quantities from the BIM to a spreadsheet with prices appeared to be time-consuming, error-prone, and not efficient. As an IPD project with a clear need for optimization in terms of productivity (costs) and project value for end users, the designers in this case had to spend resources on evaluation of alternative solutions. The involved disciplines experienced an increased workload compared to what they expected up front. The designers got pressured on time, so they were not able to update the models before quantity takeoff. With incomplete models, an automated cost estimation as originally intended was difficult. However, the project participants saw that automated model-based cost estimation represented a huge potential for fast evaluation of alternative solutions compared to current cost estimation practice.

Hinders for automated cost estimation were related to both people and process. Concerning people, some of the project participants seemed to possess resistance to change their way of working. Surprisingly, they seemed to miss the necessary digital mindset. Concerning process, the increased workload – and time pressure – caused by the IPD arrangement resulted in incomplete models that hindered automated cost estimation. In addition, problems with attaching correct classification codes from the standard specification of work to objects in BIM hindered an automated workflow. The identified technology hinders were not worth mentioning.

Suggested improvements for model-based cost estimation include persistent relevant training since it takes time to get accustomed to new ways of working. Further, model-based cost estimation requires alignment between todays object-oriented BIM and the process-oriented standard specification of work for infrastructure projects. Future studies of automated model-based cost estimation should not concentrate on technology alone but must include the main cornerstones of people and processes.

For future studies it is suggested to investigate projects with different project delivery methods. We also suggest studying next steps of cost estimation and considering unit pricing and considering all life cycle of the projects including detailed design.

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