FEASIBILITY OF BIM IMPLEMENTATION IN TURKISH CONSTRUCTION INDUSTRY

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ABSTRACT

FEASIBILITY OF BIM IMPLEMENTATION IN TURKISH CONSTRUCTION INDUSTRY

Validation of the true benefits of BIM utilization is important for the decision makers of construction industry. Moreover, there are numerous software and technologies available, making it difficult for decision-makers who are not sufficiently knowledgeable about BIM to make the right choices. Therefore, there is a need to extend current state of knowledge in the literature about economic value of BIM and quantitative decision supportive system in order to extend the use of BIM in the AEC industry. To extend the current state of knowledge in the literature about economic value of BIM, a detailed survey is conducted with AEC experts. After that, a multi-criteria decision supportive model is developed for most fitted BIM tool selection to maximize BIM benefits. To develop the decision supportive model, the literature review is conducted, and various costs, benefits and BIM software types are assessed. Subsequently, an ANP model was established and analyzed based on expert opinion. As a result, while contractor firm employees recognize significant benefits of BIM in coordination and design perception, there are areas, particularly in cost management, where further advancements could enhance the overall efficiency and effectiveness of BIM implementations. On the other hand, BIM implementations positively contribute to the capacity and capabilities of design firms, though there are areas for improvement, such as design and analysis integration. Additionally, while the enhanced technological capabilities increase competitive advantage as a reason for preference, the economic benefits are not realized to the same extent. Additionally, according to the ANP analysis results, the highest priority software category for investment to maximize BIM benefits for Turkish design firms is “Modelling Software” followed” by “Collaboration Software”. These two categories represent 76% of software cluster contribution.

ÖZET

TÜRK İNŞAAT SEKTÖRÜNDE BIM UYGULAMASININ FİZİBİLİTESİ

BIM kullanımının gerçek faydalarının doğrulanması, inşaat endüstrisinin karar vericileri için önemlidir. Ayrıca, mevcut çok sayıda yazılım ve teknoloji, BIM hakkında yeterli bilgiye sahip olmayan karar vericilerin doğru seçimler yapmasını zorlaştırmaktadır. Bu nedenle, BIM'in ekonomik değeri ve nicel karar destek sistemi hakkında literatürdeki mevcut bilgi düzeyini genişletmek, BIM'in inşaat endüstrisinde kullanımını artırmak için gereklidir. BIM'in ekonomik değeri hakkındaki literatürdeki mevcut bilgi düzeyini genişletmek amacıyla inşaat sektörü uzmanlarıyla detaylı bir anket yapılmıştır. Daha sonra, BIM faydalarını maksimize etmek için en uygun BIM aracının seçimine yönelik çok kriterli bir karar destek modeli geliştirilmiştir. Karar destek modelini geliştirmek için literatür taraması yapılmış ve çeşitli maliyetler, faydalar ve BIM yazılım türleri değerlendirilmiştir. Ardından, uzman görüşlerine dayanarak bir ANP (Analitik Ağ Süreci) modeli oluşturulmuş ve analiz edilmiştir. Sonuç olarak, yüklenici firma çalışanları BIM'in koordinasyon ve tasarım algısındaki önemli faydalarını fark ederken, maliyet yönetimi gibi bazı alanlarda BIM uygulamalarının genel verimliliğini ve etkinliğini artıracak ilerlemelere ihtiyaç duyulmaktadır. Öte yandan, BIM uygulamaları tasarım firmalarının kapasite ve yeteneklerine olumlu katkılar sağlamaktadır, ancak tasarım ve analiz entegrasyonu gibi alanlarda geliştirme alanları bulunmaktadır. Ek olarak, gelişmiş teknolojik yetenekler rekabet avantajını artırsa da ekonomik faydalar aynı ölçüde gerçekleşmemektedir. ANP analiz sonuçlarına göre, Türk tasarım firmaları için BIM faydalarını maksimize etmek amacıyla yatırım yapılacak en yüksek öncelikli yazılım kategorisi "Modelleme Yazılımı" olup, bunu "İşbirliği Yazılımı" izlemektedir. Bu iki kategori, yazılım kümesi katkısının %76'sını temsil etmektedir.

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LIST OF ACRONYMS/ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
4D	Four Dimensional
ANP	Analytical Network Process
AR	Augmented Reality
BIM	Building Information Modelling
CAD	Computer Aided Design
CDE	Common Data Environment
CMMS	Computerized Maintenance Management Systems
CO	Change Order
COBie	Construction Operations Building Information Exchange
ERP	Enterprise Resource Planning
IFC	Industry Foundation Class
IoT	Internet of Things
LOD	Level of Development
n/a	Non-available
RFI	Request for Information
VR	Virtual Reality

1. INTRODUCTION

1.1. General Information

When compared to other sectors, Teicholz (2004a) demonstrated through his study that while productivity continuously increased in non-construction sectors between 1964-2000, there was a continuous decline in productivity within the construction sector. One of the fundamental reasons for this can be attributed to the inability of industrialization observed in other sectors to be achieved as desired in the construction sector. Undoubtedly, the construction sector faces its own challenges compared to many other sectors, such as being less conducive to mass production and each project having unique qualities that do not allow for repetitive production.

Although the desired adoption in Industry 1.0 and 2.0 could not be achieved in the construction sector, Industry 3.0 with automation technologies and Industry 4.0 with digitalization still appear as significant goals that can be pursued. Especially digitalization, much like in many other sectors, brings about a significant transformation in the construction sector. The advantages of digitalization in the construction sector include elements such as project management, collaboration, resource management, and error reduction. The complexity of construction projects, involving numerous stakeholders and the coordination of different disciplines, further underscores the importance of digitalization. While digitalization in the construction sector shares certain similarities with other sectors such as manufacturing, health, and finance, it also faces specific challenges unique to the industry. Construction projects are generally large-scale, long-term, and complex, necessitating that digitalization strategies be designed to align with these characteristics. Similar to other sectors, the aim of digitalization in the construction sector is to expedite business processes, reduce costs, and enhance accuracy and reliability. However, the unique requirements of construction projects call for digitalization efforts to be supported by industry-specific solutions. At this point, Building Information Modeling (BIM) plays a crucial role in the digitalization process

of the construction sector. The concept of Building Information Modeling contributes significantly to modernizing traditional practices in the industry, making construction projects more successful for the future.

When the computer aided design software are considered, the history goes back to 1957 when Patrick Hanratty, an American computer scientist, developed the first example of CAD code (Weisberg, 2008). In the following years until today, many software has been developed which enable to design in a virtual environment. However, one of the first attempts to oversee today's capabilities can be seen in the research paper "The Use Of Computers Instead of Drawings in Building Design" written by Eastman in 1975" (Quirk, 2012). In this paper, Eastman discussed about what he called Building Description System. He pointed out the opportunities that computers provide in terms of efficient and holistic design process. Some of these opportunities are obtaining 2D drawings from 3D models, providing material take-offs or further analysis using one main 3D model. All these features can be seen as the base of a modern BIM software. In 1984 ArchiCAD derived from Radar CH was created by Graphisoft which can be seen as the first holistic BIM software (Quirk, 2012). Finally, in 1992 Nederveen and Tolman used the term "Building Information Modelling" for the first time in their article entitled "Modelling multiple views on buildings" (van Nederveen and Tolman, 1992). A broad literature review shows that there is a distinction between Building Information Modelling (BIM) and Building Information Model. Eastman *et al.* state that Building Information Modelling (BIM) offers a novel approach to design, construction, and facility management in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in digital format (Eastman *et al.*, 2008). Lee *et al.* define BIM is the "process" of generating and managing building information in an interoperable and reusable way (Lee *et al.*, 2006). Azhar and Brown define BIM as the process of developing computer-generated model of a project which enables to simulate design, planning, construction and operation phases in the virtual environment of that information model (Azhar *et al.*, 2009). On the other hand, Schlueter and Thesseling define Building Information Models as the virtual superposed representation of multi-disciplinary design data (Schlueter and Thesseling,

2009). According to Shen *et al.* a BIM software includes and provides both graphical and non-graphical information of a project during its whole life cycle (Shen *et al.*, 2012). Considering these definitions, the term Building Information Model covers just the digital model containing design data, while the term Building Information Modelling "BIM" covers whole process which includes both software related and managerial issues for collaborative work flow covering entire life-cycle of a project.

Despite the facilitative effect of BIM, the construction industry remains weak in digital transformation (Sokas *et al.*, 2019). The AEC sector is mainly controlled by managers with a majority over 40 years of age and the rate of workers over 55 ages are growing in all occupations (Sokas *et al.*, 2019). Moreover, as one of the oldest professions, construction sector has a very solid and conservative mentality. Therefore, there is a resistance to change in the AEC industry as many researched showed (Won *et al.*, 2013; Gu and London, 2010; Walasek and Barszcz, 2017). However, this resistance does not provide measurable benefits, and under the control of the current mindset, the construction industry's efficiency is continuously declining (Teicholz, 2004a).

Among the barriers preventing the widespread adoption of BIM at the desired level are resistance to change (Won *et al.*, 2013; Gu and London, 2010; Walasek and Barszcz, 2017; Rezgui *et al.*, 2013), high investment costs (Won *et al.*, 2013; Ghaffarianhoseini *et al.*, 2017; Walasek and Barszcz, 2017; Ademci, 2018; Eadie *et al.*, 2013), lack of technical knowledge (Won *et al.*, 2013; Volk *et al.*, 2014; Giel and Issa, 2013). Particularly at the core of financial concerns, it is observed that the return on investment cannot be precisely determined by industry decision-makers (Won *et al.*, 2013; Ghaffarianhoseini *et al.*, 2017; Lu *et al.*, 2014). Breaking down this uncertainty-induced barrier and accelerating transformation in the industry requires not only a change in understanding but also a need for reliable financial analysis and concrete evidence. To calculate the net cost of BIM implementations, it is necessary to determine the required investment amount and the benefits obtained in return, as well as the savings resulting from these benefits. Various benefits are mentioned for BIM application in literature. "Rapid and efficient design process" (Yan *et al.*, 2011; Manning and Mess-

ner, 2008; Petrova *et al.*, 2017; Pollock *et al.*, 2009; Schlueter and Thesseling, 2009; Öktem and Ergen, 2014; Basbagill *et al.*, 2013; Barlish and Sullivan, 2012; Dodge Data and Analytics, 2017; Giel and Issa, 2013), "improved coordination" (Manning and Messner, 2007; Petrova *et al.*, 2017; Öktem and Ergen, 2014; Barlish and Sullivan, 2012; Dodge Data and Analytics, 2017; Giel and Issa, 2013), "less revision and claim" (Manning and Messner, 2007; Petrova *et al.*, 2017; Öktem and Ergen, 2014; Barlish and Sullivan, 2012; Giel *et al.*, 2013; Dodge Data and Analytics, 2017; Giel and Issa, 2013) and "reduced total time" (Öktem and Ergen, 2014; Barlish and Sullivan, 2012; Giel *et al.*, 2013; Li *et al.*, 2014; Dodge Data and Analytics, 2017) are some of the most referred benefits. On the other hand, BIM implementation requires additional investments such as "software and hardware acquisition" (Becerik-Gerber and Rice, 2010; Sacks and Barak, 2008; Walasek and Barszcz, 2017), "staff training and hiring consultancy" (Qian, 2012; Walasek and Barszcz, 2017). These can be counted as direct costs of BIM utilization. Moreover, "temporary reduction in productivity and unlearning old approaches" (Walasek and Barszcz, 2017; Latiffi and Tai, 2017; Raval and Narayana, 2018; Reizgevicius *et al.*, 2018; Li *et al.*, 2009), and "uncertain legal foundation of BIM" (Sebastian, 2011; Elmali, 2018; Tel, 2021) are some of the risks of BIM implementation. These risks can cause indirect costs. All of the direct and indirect costs as well as benefits and savings should be investigated carefully in order to assess true value of BIM. However, determining all these benefits and costs holistically is quite challenging. Contributing factors include the difficulty in maintaining relevant records, the complexity of distinguishing between benefits and costs, and the tendency of firms to withhold data due to its confidential nature. In the absence of comprehensive information, prioritizing areas for investment becomes increasingly difficult.

1.2. Motivation and Problem Statement

In the literature, there are very few studies that propose decision-support methods to guide BIM investments by examining the economic aspects of BIM utilization. In Turkey, the first thesis on BIM appeared in 2009 (Özge, 2009), and an examination of these theses reveals numerous studies on various topics such as BIM adaptation, BIM's

impact on sustainability and green energy, and BIM's contributions to design and collaboration. However, there is a lack of research focusing on the economic aspects of BIM or the development of a decision-support model for BIM investments. This research significantly contributes to the literature by addressing these gaps. It examines the economic aspects of BIM utilization from the perspective of Turkish contractors and design firms and develops a model to guide BIM investments for Turkish design firms.

The research questions of this study are as follows:

- What are the benefits of BIM utilization and what are their economic impacts?
- What are the costs associated with BIM utilization?
- What is the overall economic impact of BIM utilization?
- How efficiently are the benefits of BIM being realized from the perspective of Turkish contractors and designers?
- What are the priorities for BIM software investment for Turkish design firms?

1.3. Aim and Objectives

The main aim of the paper is to extend the current state of knowledge about economic value of BIM utilization and develop a decision supportive model for corporates which have multiple BIM projects, to find best suited BIM software category to invest in order to maximize overall BIM benefit at corporate level.

In order to extend the current state of knowledge about economic value of BIM utilization and develop a decision supportive model, the objectives are followed given below:

- Evaluating the advantages, disadvantages, and classifications of BIM software based on existing literature.
- Organizing a focus group workshop to verify the literature review.

- Conducting a survey to evaluate the significance of Building Information Modeling (BIM) advantages and the economic influence of BIM implementation, as perceived by professionals in the Turkish Architecture, Engineering, and Construction (AEC) industry.
- Developing an Analytical Network Process (ANP) model to identify the most suitable Building Information Modeling (BIM) tools to invest in, in order to maximize the aforementioned benefits of BIM.

1.4. Scope and Limitations

The scope of the research is to assess perception of BIM benefits and economic value of BIM use in Turkey as well as to develop a decision supportive model to determine the best suited BIM software category for Turkish design service providers including civil, electrical, mechanical engineers and architects to maximize benefits of BIM utilization.

While the study offers valuable insights, there are limitations to consider. The number and variety of participants are limited, potentially excluding the perspectives of certain stakeholders. This may have led to overlooking potential benefits and the exclusion of various software types from the analysis. Obviously, there are many parameters which effect economic value of BIM-use in a project. However, some limits should be set due to practical reasons. An extensive literature review is conducted and only the most cited parameters are selected. Therefore, there may be a significant gap that the proposed model cannot cover. Since the validation of research needs company-specific data such as cost and schedule, it is hard to find sufficient amount of companies which voluntarily collaborate to share their project-specific data. Thus, the data obtained from the survey could not be validated with real-case examples. The lack of validation through a case study further restricts the generalizability of the results.

Another limitation is the subjectivity of the formed clusters and the inherent subjectivity of pairwise comparisons within the Analytic Network Process (ANP) raise

questions about the overall objectivity of the findings. Additionally, the multi-criteria analysis was only applied to designers among the stakeholders in the AEC sector. Furthermore, the cost perspective was not considered, with only benefits being used as criteria and the focus was solely on software among the potential areas for investment.

1.5. Methodology

To answer the research questions, a comprehensive literature review was initially conducted. The literature review focused on the benefits, costs, and overall economic impact of BIM utilization.

In the second section, to examine the impact of BIM benefits on the Turkish construction sector and the overall economic impact of BIM utilization, a survey was conducted with experts, managers, or business owners in the AEC sector who have experience with both BIM-utilized and non-BIM-utilized project types. The survey consisted of 5-point Likert scale questions and quantitative questions.

In the third section, a decision-supportive model was developed to assist design firms that have adopted BIM or are considering transitioning to BIM in making more informed investment decisions. To achieve this, a semi-structured workshop was first conducted with a focus group of BIM experts to categorize BIM benefits, BIM costs, and BIM software types. Due to the multi-criteria and alternative nature of the problem, as well as the interactions between components, the ANP method was preferred. Using the benefit and software categories obtained, a relation matrix was determined based on expert opinions, followed by the creation of pairwise comparison matrices. Subsequently, the ANP model was established and analyzed using Super Decisions software. The process is schematically shown in Figure 1.1.

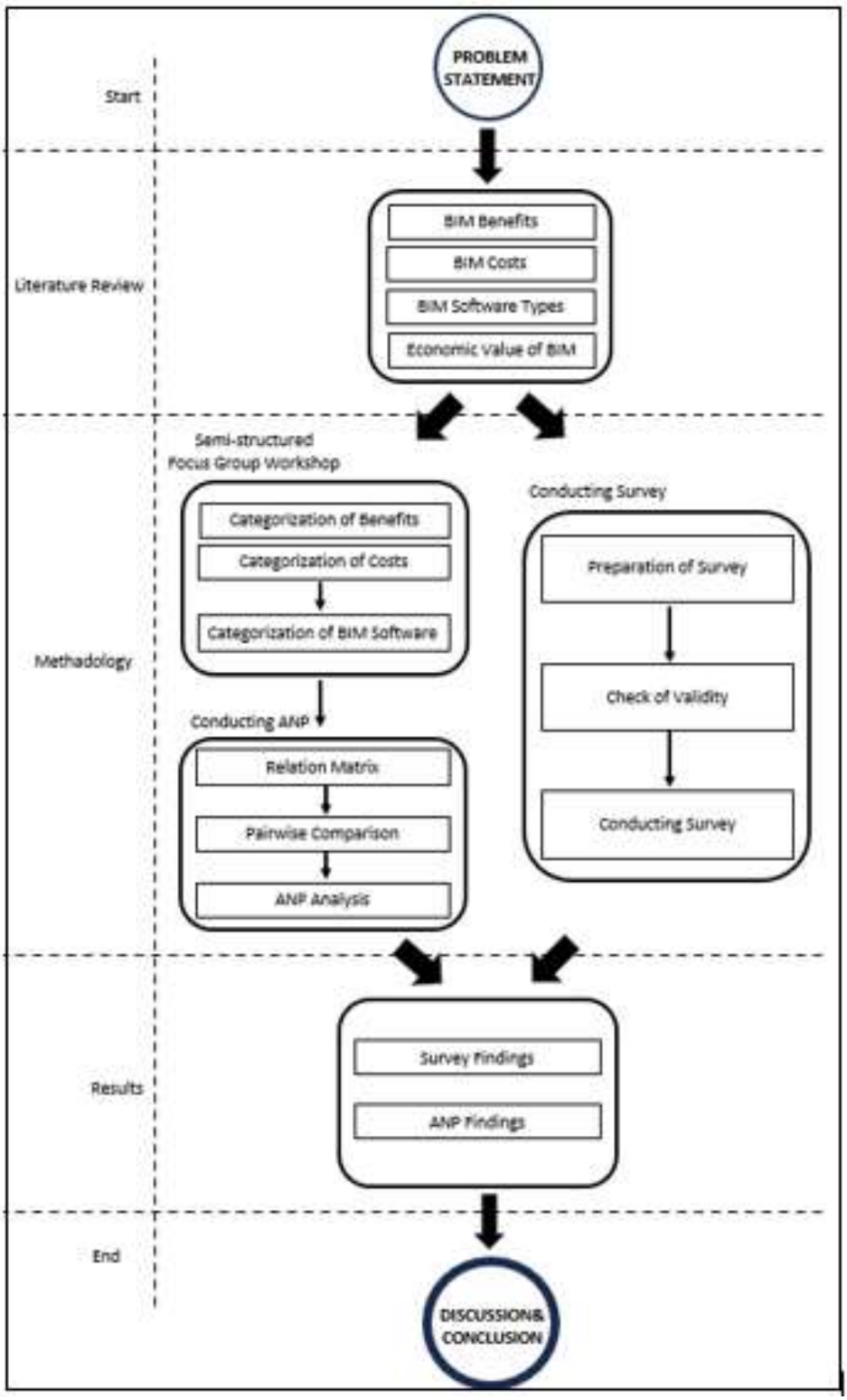

Figure 1.1. Methodology of thesis.

1.6. Thesis Organization

In Chapter 2, a comprehensive literature review on BIM was conducted. This review continued with an exploration of the most frequently cited benefits and cost elements of BIM utilization in the literature. Keywords such as "BIM", "benefits of BIM", "advantages of BIM", "costs of BIM", and "disadvantages of BIM" were used to focus on both the gains and cost impacts of BIM usage. After identifying these benefits, additional literature searches were conducted to determine the economic impacts of each benefit on projects. The leading software types currently used in the BIM ecosystem were then researched among the BIM cost elements. Finally, studies examining the overall economic impact of BIM utilization were investigated using keywords such as "ROI" and "B/C" (benefit to cost ratio).

In Chapter 2, a comprehensive literature review on BIM was conducted. This review continued with an exploration of the most frequently cited benefits and cost elements of BIM utilization in the literature. Keywords such as "BIM", "benefits of BIM", "advantages of BIM", "costs of BIM", and "disadvantages of BIM" were used to focus on both the gains and cost impacts of BIM usage. After identifying these benefits, additional literature searches were conducted to determine the economic impacts of each benefit on projects. The leading software types currently used in the BIM ecosystem were then researched among the BIM cost elements. Finally, studies examining the overall economic impact of BIM utilization were investigated using keywords such as "ROI" and "B/C" (benefit to cost ratio). Chapter 4 first compiles and examines the economic impacts of BIM benefits identified in the literature review. It then presents the results of both the survey and the ANP analysis. Chapter 5 discusses and interprets the findings. In Chapter 6, the conclusion of the thesis is presented along with recommendations for further research.

2. LITERATURE REVIEW

2.1. Background of the Research

A broad literature review shows that, BIM is widely investigated and discussed in terms of benefits, challenges-weaknesses and adoption. Obviously, BIM benefits are popular research topics among academicians. Manning and Messner and Bryde *et al.* emphasize time and cost savings as most important benefits of BIM (Manning and Messner, 2008; Bryde *et al.*, 2013). Barlish and Sullivan and Qian give tables for most mentioned benefits of BIM in literature (Barlish and Sullivan, 2012; Qian, 2009). Moreover, business analysis conducted by Deloitte presents the most mentioned benefits obtained by interviews with experts (Dodge Data and Analytics, 2017).

On the other hand, BIM adoption and utilization in project has also some disadvantages, challenges and extra costs. Manning and Messner state that data transfer, inadequate object library and parametric working are most important weaknesses of BIM (Manning and Messner, 2008). Bryde *et al.* emphasize that software, hardware and training costs are biggest challenges (Bryde *et al.*, 2013). Rizal defines contractual limitations of roles and responsibilities as the main problems which hinders a fully collaborative working environment (Rizal, 2011). Won *et al.* present major challenges for adoption of BIM from literature (Won *et al.*, 2013).

Researches of Won *et al.* and Homayouni *et al.* present critical success factors obtained by surveys (Won *et al.*, 2013; Homayouni *et al.*, 2010). According to these researches, willingness to adopt and interdisciplinary knowledge are most critical factors for successful adoption. Rizal defines 5 success factors for adoption in which communication is most emphasized Rizal,2011). Gu and London develop a framework for BIM adoption and they emphasize data management and technical issues more than communication (Gu and London,2010).

Although BIM has a long history in AEC industry and is known commonly, industry professionals hesitate to work with BIM (Walasek and Barszcz, 2017). Commonsense is that innovative approaches cause extra costs and therefore BIM transition cannot be afforded the cost of small-scale applications. However, BIM has a great potential to spread from complex public projects to any scale and any kind. It is expected that the more the investment on BIM, the higher is the efficiency of BIM. However, this improvement has its limits (McGeorge, 1988). Project specific constraints limit the efficiency improvement, since resources are always limited for all projects. Each project has its own budget, own schedule and own priorities. Therefore, each project needs different level of BIM-use and different aspect of BIM. Even though the value and cost of BIM is investigated separately detailed, there are limited number of research which handle the net value of BIM holistically considering both savings and costs together (Gerbov *et al.*, 2017). Furthermore, there are only limited number of research which investigate cash flow and ROI analysis of BIM projects. Research by Walasek and Barszcz (2017) shows that BIM adoption may also have negative impact on annual revenue (Walasek and Barszcz, 2017). Since research show that BIM has both positive and negative impact on ROI (Lu *et al.*, 2014; Sacks and Barak, 2008) many professionals want to know if BIM is really beneficial and is worth to pay extra fee (Latiffi and Tai, 2017).

On the other hand, the necessity for numerous disciplines to collaborate and conduct various specialized analyses has led to an explosion in the number of software solutions. Within the BIM ecosystem, there are a multitude of disciplines, each containing numerous sub-disciplines, and for nearly every sub-discipline, there are several specialized software alternatives. For instance, most preferred BIM tools by sector professionals are Autodesk Revit®, Autodesk Navisworks®, Trimble TEKLA®, Graphisoft Archicad, Nemetschek ALLPLAN, and Bentley Microstation. Among these software, Revit is the market leader with almost half of the all BIM users' choice (Becerik-Gerber and Rice, 2010; Manning and Messner, 2008). However, each software has its strengths and weaknesses, and factors such as licensing models, costs, and other criteria place each one in a unique market position. Selecting the right software from

such a wide array of options is quite challenging. Consequently, there is a need for a decision support system for BIM software selection (Omar *et al.*, 2014).

2.2. Benefits and Savings of BIM Implementation

Based on extensive literature review, numerous positive contributions associated with BIM implementation have been identified. Some of these contributions appear as tangible benefits (or savings) which defines monetary contributions on projects, while others are identified as intangible benefits which defines non-monetary contributions on projects. Tangible benefits will be considered within this thesis, encompassing both direct monetary contributions through cost savings and indirect contributions through time savings.

The literature review indicates that, while the percentages vary, the use of BIM reduces the overall project cost (including design and construction processes). In a study conducted by Barlish and Sullivan (2012), two separate cases were examined in terms of total design cost, total construction cost, RFI numbers, Change Order numbers, and total project duration. In the first case, a BIM project and a non-BIM project, both constructing similar structures in the same area, were compared. The comparison revealed that the use of BIM reduced the total project cost by 2%. In the other case, four historical building projects were compared, consisting of two BIM projects and two non-BIM projects. The result showed that the use of BIM reduced the total project cost by 1%. In another study conducted by Lu *et al.* (2014), a time-effort analysis was performed on two housing projects in Hong Kong, one using BIM and the other not using BIM. The comparison, based on cost per square meter, revealed that BIM usage decreased the overall cost (including design and construction) by 6.92%. In another research, Bockstael and Issa (2016) developed a methodology to assess the impact of clashes identified in clash tests. In their study, BIM models undergo clash tests using software capable of performing such tests. The test results are initially filtered into relevant and irrelevant clashes. Focusing on relevant clashes, these are organized into smaller groups. Subsequently, a Failure Mode and Effect

Analysis (FMEA) is conducted for each clash group. The likelihood of each clash group occurring and the magnitude of potential damage are determined, establishing a prioritization based on significance. As a result, it has been determined that the use of BIM results in a savings of 0.1% in the total project cost. While the savings amount constitutes a relatively small proportion of the overall budget, BIM implementation still appears to be justified, considering the BIM investments. The Return on Investment (ROI) is found as 127%. In the case of the Nintendo of America Headquarters project, examined in a market report by Dodge Data and Analytics (2015), the use of BIM and Lean project management resulted in a 7% savings in the total budget. The most significant factors contributing to this included completing the planned project three months ahead of schedule, reducing the planned workforce by 37%, and observing a 42% increase in productivity. In addition to these findings, Ham *et al.* (2018) identified a total cost saving of 0.6%, while Rayal and Narayana (2018) found a total cost saving of 3.72%.

While there may not be an abundance of studies which quantifies the direct contribution of BIM usage to the construction schedule, the existing studies indicate that BIM applications have resulted in a reduction of construction duration. According to a market report prepared by Dodge Data and Analytics in 2015, the majority of owners with a rate of 40% reported that BIM utilization facilitates reduction in project duration by at least 5%. Becerik-Gerber and Rice (2010) conducted a survey with 428 professionals in the industry, and the results showed that 58% of the participants believed that BIM usage could reduce the project schedule by up to 50%.

2.2.1. Accuracy in Schedule Planning

BIM enables more detailed and realistic preliminary design. Therefore, more detailed and realistic schedule planning is enabled and less delay is guaranteed. Survey conducted with industry professionals by Becerik-Gerber and Rice (2010) presents that most of the participants think BIM helps project schedules to be reduced up to 50%. Hence, Giel *et al.* (2013) conducted a comparison using two BIM and two non-BIM

projects from a company, examining a total of two cases. In the first case, a comparison was made between one mixed-use BIM project and one mixed-use non-BIM project. The results indicated that BIM utilization enables better schedule estimation with a rate of 80.1%. In the second case, a comparison was made between one warehouse BIM project and one warehouse non-BIM project, revealing that BIM utilization enables better schedule estimation with a rate of 1.92%. In another research conducted by Barlish and Sullivan (2012), two separate cases were examined in terms of total design cost, total construction cost, RFI numbers, Change Order numbers, and total project duration. In the first case, a BIM project and a non-BIM project, both constructing similar structures in the same area, were compared. The comparison revealed that the use of BIM enables better schedule estimation by 10%. In the other case, four historical building projects were compared, consisting of two BIM projects and two non-BIM projects. The result showed that the use of BIM enables better schedule estimation by 8%. Giel and Raja (2013) construct 3 cases with 6 projects in total. According to comparison of each pair of each case, BIM application contributes projects to have more realistic schedule estimation with rates of 1.94%, 15.38% and 80%.

2.2.2. Accuracy in Cost Estimation

BIM enables more detailed and realistic preliminary design. Moreover, BIM software can calculate and store quantity take off data dynamically. Therefore, more detailed and realistic cost estimation is enabled. The potential of BIM applications to increase coordination and allow for a more error-free design and implementation also has the potential to assist in more accurate budget estimates during the planning phase. Poirier *et al.* (2015) suggested examining the actual cost-to-tender cost ratio to quantify this estimation effect. In their study, they investigated two separate cases. In the first case, they analyzed four District Energy Station (DES) projects, three of which employed BIM, while one was selected as a non-BIM project for comparison. The findings revealed that the non-BIM project exceeded the tender budget by 66%, while BIM projects were found to be 28%, 9%, and -17% (under budget), respectively. According to these limited examples, BIM projects have a 23% standard deviation with

a 18% average budget overrun, showing a 48% more accurate performance compared to non-BIM projects. In the second case, they examined four building projects, three of which utilized BIM, while one non-BIM project was chosen for comparison. The analysis indicated that the non-BIM project exceeded the tender budget by 6%, while BIM projects were -23%, -1% (under budget), and -1% (under budget), respectively. According to these limited examples, BIM projects have a 14% standard deviation with a 8% average budget overrun, indicating a 2% poorer performance compared to non-BIM projects. In their research conducted in 2007, Khanzode *et al.* highlighted a case study where they found that the budget overrun for MEP systems in a pilot plant facility, constructed within an existing warehouse for Sequus Pharmaceuticals, was only at the level of 1%. Furthermore, Gilligan and Kunz (2007) also report 3% cost accuracy thanks to BIM based on survey conducted with experts.

2.2.3. More Efficient Design and Delivery Process

Since BIM is a collaborative and integrated process, errors caused by miscommunication can be eliminated more effectively. Moreover, repetitive tasks can be done automatically with the help of BIM software. Thus, design, presentation and delivery processes are expected to be faster.

The literature review has yielded varying results regarding the impact of BIM usage on the total cost of the design team. One group of research has identified an increase in the total design cost. In a study conducted by Barlish and Sullivan (2012), for instance, bids were requested from firms for an existing non-BIM project, and then a second bid was requested for the same project with BIM implementation. The comparison of bids for electromechanical disciplines revealed a 31% increase in design work proposals for the BIM project scenario. In a study conducted by Lu *et al.* (2014), a time-effort analysis was performed on two projects in Hong Kong, one using BIM and the other not using BIM. The comparison, based on cost per square meter, revealed that BIM usage increased the overall cost of design activities by 45.93%. The reason for this increase was attributed to additional investment costs such as software

and hardware, as well as the learning curve experienced by all stakeholders during BIM adoption and the resulting loss of efficiency. In another study, Lu *et al.* (2015) conducted a time-effort analysis on two housing projects, one using BIM and the other not using BIM. By examining the cost per square meter, including both design and construction, throughout the project duration, it was found that BIM implementation increased design costs but, in contrast, reduced the overall project cost. As a result of this study, it was observed that BIM implementation increased design costs by 118% compared to the non-BIM project.

Contrary to studies that found BIM usage increased design costs, another group of research has found that BIM implementations significantly reduced design expenses. As an example, in a study conducted by Sholeh *et al.* (2020), a bid proposal was examined. Two bid proposals were prepared for the same project, one using BIM and the other not using BIM. The comparison of actual costs and durations revealed that BIM usage reduced the total design cost by 52.36%. In another study from Israel, Racks and Barak (2007) found, based on data from an experiment with 3 similar residential and housing projects, that there could be a decrease in man-hours of up to 65% for draftsmen and up to 30% for engineers. The impact of this productivity gain on the total design cost was determined to be in the range of a minimum of 15% to a maximum of 48%.

Although the percentages may vary, the literature review has shown that BIM implementations reduce design durations in terms of total man-hours. Manning and Messner conducted a study where they performed separate design work for two projects, using 2D CAD and BIM for each. In the first case, a hospital project was examined, revealing a 39% reduction in man-hours through BIM usage (Manning and Messner, 2008). In the second case, a laboratory project was investigated, and BIM usage was determined to result in a 20% reduction in man-hours. In another study conducted by Lu *et al.* (2014), a time-effort analysis was performed on two housing projects in Hong Kong, one using BIM and the other not using BIM. The comparison revealed that design phase is found as 41% of total project duration for the non-BIM project.

On the other hand, design phase is found as 33% of total project duration for the BIM project. As a result, it is determined that BIM utilization may facilitate design time to decrease up to 8%. In a study conducted by Sholeh *et al.* (2020), a bid proposal was examined. Two bid proposals were prepared for the same project, one using BIM and the other not using BIM. The comparison of actual costs and durations revealed that BIM usage reduced the total design time decreased by 50%.

Racks and Barak (2007) found, based on data from an experiment with 3 similar residential and housing projects, that there could be a decrease in man-hours of up to 65% for draftsmen and up to 30% for engineers. Productivity gain was obtained by comparing the design durations for the same task between 2D and BIM designs. The productivity gain achieved by BIM utilization was determined to be 61%, 55% and 21% for these projects. Additionally, researchers conducted a student experiment with 2 projects. According to results, 40% and 43% productivity gain may be achieved. In another research, Reizgevičius *et al.* (2018) found that productivity gain as 31% according to the survey they conducted with designers of ten companies adopted to BIM. In addition to that, Shin *et al.* (2022) from South Korea, conducted research with 3 BIM and 3 non-BIM projects of metro lines in South Korea. Considering costs, man-hours and labour forces, researchers determined a productivity gain by 2.9%.

2.2.4. More Effective Learning Process and Improved Adaptation

Since conventional design methods and workflows are commonly known among all parties of the AEC industry, non-BIM projects need less learning time in terms of software and data sharing processes. However here, the term “learning” is used for adaptation of professionals to different project types who do not have experience in that type of project. Each project type has its own typical constraints, solutions and tricks. 2D drawings lack of sufficient visualization and therefore professionals have difficulties to perceive project specific issues. On the other hand, 3D visualization is sufficient in terms of visualization comparatively to 2D design. 2D design also lacks of representation of non-spatial relations and information. Beyond 2D drawings and

3D visualization, BIM offers non-spatial information and also holistic approach which deals time and cost parameter of project. In this way, professionals can easily perceive project specific issues by accessing various aspects of information.

In the research paper by Lu *et al.* (2013), the use of BIM as a learning tool and its potential for facilitating project adaptation, leading to man-hour gains, were examined. Learning curves were generated and analyzed for a selected high rise building project with both BIM and non-BIM approaches. As a result, an average gain of approximately 5.99% was identified. According to market report prepared by Dodge Data and Analytics (2017), half of the industry experts participated in the survey mentioned that improving youngers' staff understanding and participation is one of the top benefits of BIM.

2.2.5. Complex Design Capability

Complex geometries and architectural expressions are hard to realize with traditional 2D design concept since it is challenging to imagine and revise. Many solid-design software enables to create complex 3D forms in terms of visualizing however, they lack enriched object information and involvement of multi-disciplines. On the other hand, BIM software provides a parametric design approach, allowing geometric designs to be guided by mathematical expressions created by the user. Consequently, it offers a more controlled design environment compared to standard modeling software. In their research, Ding *et al.* (2014) demonstrated that BIM applications allow projects to be designed more accurately from a safety perspective through 4D-based analyses, enabling the safer implementation of complex designs.

2.2.6. Improved Design Analysis

For a design to be safely accepted and constructed, it must be validated with advanced engineering analysis. The model-based approach and collaboration philosophy of BIM allow the same model to serve as a substrate for various analyses required by

different disciplines. Thus, different disciplines spend less time setting up their models to perform specialized checks in their areas and can focus their main concentration on conducting complex analyses. Through export models available in various formats from BIM models, a wide range of complex engineering analyses such as structural analysis (Ren *et al.*, 2018), fire simulations (Siddiqui *et al.*, 2021), and energy consumption analysis (Carvalho *et al.*, 2021) can be easily performed using the same model. Smart object-oriented parametric design concept of BIM enables complex designs to be realized, since it aggregates complex 3D form creating with multi-disciplinary design solutions in one model. Therefore, the design environment created by BIM concept, encourages designers to attempt more complex design.

2.2.7. Improved 3D Coordination

Design conflict does not mean only the physical clashes but also technical improprieties and spatial issues. Multidisciplinary 3D visualization and clash detection enable to detect physical and technical design conflicts rapidly and accurately. Two different aspects are seen in literature. First aspect accepts all costs of clashes as potential savings of BIM (Barlish and Sullivan, 2012). Second aspect investigates possibility of missing for each clash and proposes a cost calculation according to their likelihood (Giel and Issa, 2013; Oktem and Ergen, 2014; Won *et al.*, 2016).

As a result of design conflicts faced in the construction phase, design related change orders are given. In the analysis published by Cannistraro company in 2009, the impact of BIM usage on Change Order costs was investigated by examining a total of 408 projects with an approximate total value of $558 million over 6 years. According to their analysis, in 2D projects with a total value of $144 million, there were total Change Order costs of $26.5 million, or proportionally 18.42% of the total cost. In BIM-utilized projects with a total value of $53 million, there were total Change Order costs of $1.4 million, or proportionally 2.68% of the total cost. Comparatively, BIM utilization resulted in a 15.74% reduction in Change Order costs compared to 2D projects. In another research conducted by Barlish and Sullivan (2012), two separate cases were

examined in terms of total design cost, total construction cost, RFI numbers, Change Order numbers, and total project duration. In the first case, a BIM project and a non-BIM project, both constructing similar structures in the same area, were compared. The comparison revealed that the use of BIM reduced the total cost of change orders by 42%. In the other case, four historical building projects were compared, consisting of two BIM projects and two non-BIM projects. The result showed that the use of BIM reduced the total cost of change orders by 70%. Giel *et al.* (2013) conducted a comparison using two BIM and two non-BIM projects from a company, examining a total of two cases. In the first case, a comparison was made between one mixed-use BIM project and one mixed-use non-BIM project. The results indicated that BIM utilization could result in a 9.3% reduction in the total Change Order cost. In the second case, a comparison was made between one warehouse BIM project and one warehouse non-BIM project, revealing that the total Change Order cost could be reduced by 4% through the use of BIM. Bockstael and Issa (2016) developed a methodology to assess the impact of clashes identified in clash tests and 3D coordination. They work on a retail and commercial project in Canada. As a result, BIM implementation can decrease total number of COs up to 7%. They also analyze the cost impact of preventable change orders. According to their analysis, BIM implementation can decrease total cost of COs up to 9%.

2.2.8. Schedule Optimization and Faster Completion

Various research show that BIM enables to optimize project schedule and shorten total completion time since it provides a holistic design environment and defines more effective and collaborative workflow. In addition to that, BIM enables to evaluate different design options easily and fast since each design change effects whole documentation automatically and there is minimized time loss for revising 2D drawings separately. Schedule variations are easier with BIM compared to conventional design methods. Since design data is the initial input of planning, evaluating different design options in terms of total project duration is easier with BIM implementation. In this way, best option can be chosen to guarantee least project duration.

Giel (2009) concludes by comparing similar projects that BIM helps to early completion. In their research, Li *et al.* (2014) examined the 6 disciplines of selected disaster center project, focusing on one of the major advantages of BIM, which is 3D coordination and clash detection. In the scope research, researchers try to optimize project duration with the help of BIM utilization. According to findings, BIM facilitates to mitigate project duration by enabling improved understanding about project and better planning. 26.7% reduction in project scheduling is determined thanks to BIM utilization. In a case reported in the market report conducted by Dodge Data and Analytics (2015), BIM enabled prefabrication in new tower project of Central Washington Hospital reduced construction schedule by 18%.

Moreover, BIM applications, leading to reduced Change Orders and RFIs, enhanced collaboration and coordination, and subsequently increased productivity gains, are believed to assist firms in achieving more earning value within the same specified timeframes. Although there may not be a sufficient number of studies on this topic in the literature, Serhat Kaş (2019) conducted a comparison between two metro projects—one using BIM and the other not. Through this comparison, it was found that, considering the mentioned advantages, the BIM project could achieve 1.5 times more earning value within the same time period.

2.2.9. Reduced Construction Cost

As a collaborative and holistic design environment, BIM offers reducing in design error and misinterpretation. Therefore, reworks at site due to design conflicts can be reduced remarkably. Moreover, design failures due to lack of sufficient spatial and non-spatial information is reduced. All these contributions facilitate construction cost to be mitigated.

The literature review results indicate a clear consensus regarding the impact of BIM usage on construction costs. Accordingly, BIM implementations are seen to reduce construction costs. In a research paper conducted by Barlish and Sullivan (2012),

for instance, bids were requested from firms for an existing non-BIM project, and then a second bid was requested for the same project with BIM implementation. The comparison of bids for electromechanical disciplines revealed a 5% decrease in construction work proposals for the BIM project scenario. In another research, Li *et al.* (2014) examined the MEP design of a selected project, focusing on one of the major advantages of BIM, which is 3D coordination and clash detection. They prioritized the physically detected clashes based on the likelihood of being identified through traditional methods and the potential cost impacts on the project. Among a total of 2000 detected clashes, they isolated the top 500 clashes they considered most significant. Through a cost analysis based on these 500 clashes, they found that BIM usage directly contributed to the construction, reducing the total MEP construction cost by 2.91%. In another study conducted by Lu *et al.* (2014), a time-effort analysis was performed on two housing projects in Hong Kong, one using BIM and the other not using BIM. The comparison, based on cost per square meter, revealed that BIM usage decreased the overall cost of construction stage by 8.61%. In a market report prepared by Dodge Data and Analytics (2015), it was observed that in the analyzed projects, there was a 6% direct savings in total construction work due to BIM-supported prefabrication applications in the SCL Health's new St. Joseph replacement hospital project. The most significant factors contributing to this savings were an 18% reduction in the project schedule, leading to man-hour savings, and increased productivity. In another study by Bebani (2022), BIM applications were found to offer the opportunity to optimize excavation and filling quantities in road projects. A case study demonstrated a reduction and optimization of excavation and filling quantities by 21%, leading to a corresponding reduction in construction costs. Khanzode *et al.* (2008) focused on MEP construction works and found that the application of 3D coordination processes and information management practices through BIM resulted in a direct savings of $500,000 or proportionally 5.56% in a $9 million hospital project. On the other hand, total budget of the MEP systems of the project is about $96.9 million. Total savings for whole MEP parties is about $9 million which is 9.28% of total the budget.

2.2.10. Less Rework

Rework is one of the most important factors which extends project duration and cause project budget to be exceeded. According to Forcada *et al.* (2017), rework is responsible for 50% of project time overruns and costs up to 5-25% of project budgets (Forcada *et al.*, 2017). Love *et al.* states that design related problems are responsible for 50% of total rework (Love *et al.*, 2016). Studies in the literature suggest that BIM usage enhances coordination between the design process and the construction site and reduces rework rates. Hwang *et al.* (2019) found that BIM implementation may reduce rework up to 4.8% (Hwang *et al.*, 2019). The research by Lee *et al.* (2012) focuses on the design phase of a mixed-use project consisting of high-rise and mid-rise buildings, examining clash results. They categorized identified clashes in terms of likelihood and probabilistic approach, calculating their potential costs on the project. Additionally, they considered the costs of subcontractors and in-house BIM coordinators required for BIM usage in the project. The return on investment (ROI) ratio for the investments made in BIM usage was found to be 22%. Moreover, the savings amount achieved in the $583 million project ranged from $1,100,551 to $1,734,640 with the probabilistic approach. Therefore, the potential savings in rework due to BIM usage in the project were found to be between 0.02% and 0.03%. Khanzode *et al.* (2008) focused on MEP construction works of a hospital project and found that the application of 3D coordination processes and information management practices through BIM resulted the rework for mechanical subcontractors decreased by 0.2%.

2.2.11. Increasing Involvement of Prefabrication

Prefabrication is the name of a construction technique that is based on the principle that the building elements are not prepared on-site but prepared and transported to the construction site by being prepared at the factory or another manufacturing site. To increase use of prefabrication, designers must ensure the accuracy and precision of their design. Otherwise rework due to design failures can raise construction cost remarkably and can extend project duration. BIM offers to deal with these needs and

provides the extensive usage of prefabrication. Integrating prefabrication with BIM can yield benefits such as exploring design constraints for fabricators, reduced design errors in the manufacturing phase, reduced production time, and reduced implementation time due to improved coordination (Mostafa *et al.*, 2020).

2.2.12. Waste Mitigation

BIM integrated with numerical control (NC) production systems can optimize material usage since the technology allows more accurate manufacturing. Moreover, BIM provides a more detailed design environment and better simulation of construction phase. Therefore, BIM utilization allows better materialization planning and reduces waste materials. At first, construction sub-contractors enjoy the opportunity however increasing competition will surely cause contract values to decrease in favor of the contractors.

One of the important factors affecting construction costs is construction waste. Construction waste arises due to various reasons such as inaccurate estimation of total material orders and design errors. Both excessive orders and the disposal of generated waste result in economic losses for companies. Construction waste can be divided into recyclable and non-recyclable categories. Non-recyclable waste is naturally a financial burden for companies. The cost of waste can be reduced by economically evaluating recyclable waste. Nevertheless, this impact is in the form of reducing economic losses. Therefore, regardless of its type, reducing total waste is crucial for both the economic interests of companies and the reduction of overall carbon emissions. Construction waste as percentage of total amount of purchased construction material in Brazil is found as between %20 and 30% (Pinto and Agopayan, 1994; Hamassaki and Neto, 1994; Formosso *et al.*, 1993). Bossink and Brouwers (1996) show that construction waste as percentage of total amount of purchased construction material in Netherland is found as between %1and 10% (Bossink and Brouwers, 1996). According to the conducted research, the amount of construction waste per unit area varies. Li *et al.* determined construction waste as 55 kg/m^2 while Wang *et al.* concluded that construction waste

50 kg/m^2 in Shenyang in China (Li *et al.*, 2017; Wang *et al.*, 2016). On the other hand, Llatas found that construction waste is 120 kg/m^2 in Spain (Llatas, 2011).

It is believed that the use of BIM, which helps reduce errors in the design and construction processes through better coordination, can also contribute to the reduction of waste material. In their study, Won *et al.* (2016) quantified the hypothesis that BIM usage reduces waste material by examining two examples. The method involved categorizing design errors detected through 3D coordination and clash tests based on their likelihood and causes, then calculating the potential waste that could be prevented. In the first case, a residential project was examined, and it was observed that BIM usage could reduce waste by 15.2%. In the second case, a baseball sports complex, including a management building and fields, was studied, revealing that BIM usage could reduce waste by 4.3%. In another research, Cheng and Ma (2013) proposed an alternative approach to the contribution of BIM usage to waste reduction. In many projects, contractors dispose of their waste as landfill, incurring costs, as sorting construction waste for resale requires time and resources. However, it is a known fact that valuable materials are present in the waste given to landfills. The researchers developed a Revit add-in to process waste material information on the BIM model and utilize Revit's automatic quantification feature to sort waste materials. As a result, it was observed that waste sorted in this way could reduce landfill disposal costs by up to 70%.

Considering construction waste costs between 1%-10% of total amount of purchased construction material (Bossink and Brouwers, 1996) and BIM implementation mitigates total waste 41.13% on average, BIM implementation may save between 0.41% and 4.1% of total cost of purchased construction material.

2.2.13. Prestige and Reputation

BIM is the rising trend for AEC industry. Most of companies still do not work with BIM. Therefore, companies adopted to BIM are the pioneers of the industry.

Moreover, BIM projects offer less design error. Both of these factors improve company's reputation and help them to extend their business areas.

Bryde *et al.* (2013) state that project's success with 5D BIM promises new business opportunities due to growing reputation. Market report prepared by Dodge Data and Analytics shows that most of the industry experts believe BIM helps them to maintain their business and to gain reputation by improving business quality (Dodge Data and Analytics, 2017).

2.2.14. Energy Efficient Design

Today, buildings account for approximately 20% to 40% of total energy consumption (Perez *et al.*, 2008). Moreover, buildings are responsible for 40% of total CO2 emissions (Schlueter and Thesseling, 2009). Considering the urgent climate crisis and increasing energy costs, it is evident that any improvements in the total energy consumption of buildings throughout their life cycle will make a significant contribution. Using spatial and non-spatial information in BIM models, it is possible to conduct energy analyses. Evaluating this potential from the early stages of design will enable the creation of more sustainable designs. Designers who can quickly analyze the energy performance of different design alternatives gain the ability to select the most energy-efficient option throughout the life cycle of the building (Pollock *et al.*, 2009; Schlueter and Thesseling, 2008).

Furthermore, leveraging BIM models in the retrofit of existing buildings enables a much faster and easier increase in energy efficiency. Moreover, due to the high design fidelity provided by BIM models, interventions can be much more precise. Indeed, in a case study conducted by Zhu, the saving rate for a retrofit project was found to be 22% (Zhu, 2006).

On the other hand, delivering BIM models to end-users allows for the easy tracking of actual energy consumption through the establishment of necessary infrastructure.

Furthermore, by incorporating potential renovations throughout the life-cycle of the building, this model can remain dynamic, enabling more understandable monitoring and analysis of the building's energy performance. Consequently, it is expected that the building's occupants will be more engaged in finding methods to reduce energy consumption, driven by both economic considerations and environmental awareness (Alahmad *et al.*, 2011).

2.2.15. Improved Health and Safety Protocols

Construction accidents on construction sites, accounting for about 90% of incidents, often occur due to inadequate precautions, but they are preventable with proper interventions (Teo *et al.*, 2005) In the traditional working method, the design and planning disciplines progress by communicating with each other through a limited interface within their respective domains. While the design focuses on producing drawings to represent the finished state, the planning discipline concentrates on determining time and cost factors through lists and charts. However, the realization of a design progresses over time, and ensuring minimum safety at each step of construction is essential. Due to shortcomings of traditional methods, capturing safety vulnerabilities that may arise during construction with the traditional method is quite challenging and requires high expertise and attention.

Indeed, the BIM concept, with its model-based approach, integrates design, planning, and construction stages as much as possible, breaking down communication barriers between different disciplines. As a result, improvements can be made in Health and Safety (H and S) protocols. For example, BIM software, which allows for 4D phase planning simulations, enables planning that used to progress independently of the 3D representation of the design and relied on tables to now show the development of the 3D design over time. This makes it much easier to take necessary precautions during the planning stage. Similarly, evolving Augmented Reality (AR) and Virtual Reality (VR) technologies can transform 2D images tracked on screens, which only depict height, depth, and other dimensions, into spatial perceptions, thereby increasing awareness.

Last but not least, it is possible to automatically check rich models for spatial and non-spatial data. Software capable of code checking can automatically and quickly identify many safety vulnerabilities, allowing necessary precautions to be taken easily (Getuli *et al.*, 2017).

2.2.16. Flexibility in Team Composition and Increased Globalization

Indeed, collaborating with individuals and teams from different cultures and countries towards a common goal on the same project is a highly challenging task. Factors such as language barriers and differences in local regulations make collaborative work significantly more difficult. Moreover, communication and collaboration become even more challenging in case of different time zones. In conventional projects, the scarcity of non-spatial data on drawings compared to a BIM project makes it difficult for stakeholders to understand the design and collaborate effectively. However, in BIM projects, the richness of spatial and non-spatial data facilitates and accelerates adaptation to projects. Additionally, software capable of automatic code checking simplifies quality control activities. Furthermore, cloud-based and collaborative technologies allow multiple individuals to work seamlessly on the same file regardless of location and time. All these factors reduce dependence on local workforce in fields such as design and planning, enabling collaboration with experts from around the world for higher expertise and more cost-effective services (Ghafar *et al.*, 2018).

2.2.17. User Satisfaction

Thanks to BIM applications, information is more evenly distributed and more easily understood by non-technical stakeholders. Among the primary non-technical stakeholders are usually the customer and the end-users. Considering that projects are essentially realized according to user needs, meeting user expectations is crucial for a sustainable business model. BIM applications play a key role in the "User Centered Design" (UCD) approach by enhancing communication and increasing planning reliability (Bullinger *et al.*, 2010). Indeed, BIM applications support the design being

better understood by the user during the design phase, receiving positive feedback, and shaping the design according to user needs (Shen *et al.*, 2012). Tools within the BIM ecosystem, such as VR usage, particularly facilitate user involvement in the process (Petrova *et al.*, 2017). Additionally, throughout the lifespan of the structure, integrating live data with BIM supports operational functions like predictive maintenance, helping to meet user needs throughout the lifecycle (Akcamete *et al.*, 2010).

2.2.18. Reduced Number of RFIs

BIM In addition to many other significant contributions, one of the benefits of BIM usage, as shown in the literature, is the reduction in the number of Request for Information (RFI). RFI usage is necessary and unavoidable up to a certain point, but due to insufficient communication among stakeholders and deficiencies in projects, the number of RFIs can increase more than necessary. In such cases, the review and response to RFIs lead to a significant loss of workforce and, consequently, cost. Tara indicates that AECOM estimates the average RFI review cost to be about $1700 for an architect and $2800 for a project manager (Tara, 2018). According to Hughes *et al.* (2013), The Navigant Construction Forum estimates average cost per RFI is $1080 (Forcada *et al.*, 2017). Considering these research, significant reduction in RFIs may mean significant savings in total project cost.

Giel and Issa (2013) construct 3 cases with 6 projects in total. In the first case, 2 similar small tilt-wall projects, one with BIM and one without BIM, are compared. According to comparison, number of RFIs are 34% less in BIM project. However, considering the number change orders which may be preventable by BIM, potential BIM contribution is about 29% for the non-BIM project. In the second case, 2 similar living facility, one with BIM and one without BIM, are compared. According to comparison, number of change orders are 68% less in BIM project. However, considering the number change orders which may be preventable by BIM, potential BIM contribution is about 40.5% for the non-BIM project. In the third case, 2 similar midrise commercial condominium projects, one with BIM and one without BIM, are compared. According

to comparison, number of change orders are 43% less in BIM project. However, considering the number change orders which may be preventable by BIM, potential BIM contribution is about 32.2% for the non-BIM project. Bockstael and Issa (2016) developed a methodology to assess the impact of clashes identified in clash tests and 3D coordination. They work on a retail and commercial project in Canada. As a result, BIM implementation can decrease total number of RFIs up to 4.8%.

On the hand, Papajohn and El-Asmar (2021) found that average number of RFIs is between 1.1 and 2.4 RFI per each million $ of project. Considering cost per RFI is between $1700 and $2800, average number of RFIs is between 1.1 and 2.4 RFI per each million $ of project and BIM implementation may decrease number of RFIs 28.54% on average, BIM implementation can provide saving between minimum of $534 and maximum of $1918 per each million $ of budget which is between 0.05% -0.2%.

2.2.19. Less Dispute and Reduced Number of Change Orders

BIM provides a virtual environment which all participants can understand better what other participants want. Therefore, many research confirm that BIM facilitates to reduce revisions and claims. BIM is especially advantageous for owners since owners usually have limited perception about construction projects and design in terms of spatial relations and construction materials. Without a comprehensive presentation of the project which covers designs of all disciplines, spatial relations, 3D expression of architecture and cost of all options it is hard to imagine end-product for owners. Thanks to BIM, owners face less surprises at the end of construction.

In the literature, one of the most significant contributions of BIM application is shown as the reduced number of change orders. Giel and Raja (2013) construct 3 cases with 6 projects in total. In the first case, 2 similar small tilt-wall projects, one with BIM and one without BIM, are compared. According to comparison, number of change orders are 40% less in BIM project. However, considering the number change orders which may be preventable by BIM, potential BIM contribution is about 30% for the

non-BIM project. In the second case, 2 similar living facility, one with BIM and one without BIM, are compared. According to comparison, number of change orders are 48% less in BIM project. However, considering the number change orders which may be preventable by BIM, potential BIM contribution is about 19% for the non-BIM project. In the third case, 2 similar midrise commercial condominium projects, one with BIM and one without BIM, are compared. According to comparison, number of change orders are 37% less in BIM project. However, considering the number change orders which may be preventable by BIM, potential BIM contribution is about 22% for the non-BIM project.

2.2.20. Efficient Meetings

In the construction industry, since the end product is a 3D structure, discussing the structure based on its 3D representation during design meetings helps reduce communication gaps in meetings. Additionally, evolving online meeting applications create new opportunities. Many design-related issues can be easily resolved online through these applications and BIM models, reducing the need for physical meetings significantly. Another important aspect is that cloud-based sharing systems enable digital feedback on the BIM model, allowing the meeting agenda to be defined much more precisely in advance. Similarly, meeting notes can also be taken on the BIM model during the meeting using cloud software, reducing the likelihood of misunderstandings. Rischmoller *et al.* (2017) found in their case study that BIM model driven meetings can improve coordination, communication and collaboration between stakeholders.

Thanks to benefits mentioned above, all parties have better understanding with the help of BIM, since information is distributed more evenly among all parties of projects. Therefore, less time is wasted for understanding the basics of design during coordination meetings and meeting efficiency is improved (Majumdar *et al.*, 2022). Thus, more effort can be spent for interdisciplinary coordination instead of design basics.

2.2.21. Reduced Hard-Copy Document and Easy Control of Documents

Hard-Copies of drawings are one of the biggest cost sources of design teams. Moreover, it is also a huge source of paper consumption which is very problematic in terms of sustainability. Additionally, it is hard to store hard copies and manage them properly. Cloud technology integrated with BIM and synchronized working on server systems help participants to understand the project better. However, this feature can be used also for non-BIM projects. Main difference of BIM is that it promotes model-based thinking. The core of design process and collaboration is the models itself, therefore BIM projects require less printed document to collaborate. Last but not least, BIM models contain not only geometric information such as volume, surface area or weight but also, they are enriched with non-geometric information such as quantities, cost, time, phases etc. It is possible to reach quantity take-offs and progress information dynamically in the BIM model using schedules and other features provided by software. Thus, Jones *et al.* (2015) found that most of the professionals participated in their survey indicate improvement in document management.

2.2.22. More Efficient Facility Management

Liu and Issa (2013) states that approximately 60% of a project's total life cycle cost is incurred during the operational phase (Liu and Issa, 2013). On the other hand, according to Teicholz operational phase covers 85% of life cycle cost (Teicholz, 2004b), while Lewis *et al.* (2010) determines it as 70% (Levis *et al.*, 2010). Traditionally, design and construction phases are dissociated from operation and management phase. Relation between design documents and operation is not strong. However, Building Information Models can be enhanced with various information such as procurement, maintenance and cost. Therefore, each model object does not only represent its 3D geometry but also can contain data for facility management. By integrating these data with proper facility management software or directly using design software, facility management crews can handle many issues. In this way BIM claims that it covers all the life cycle of a building including operation and demolishment in one common envi-

ronment. Moreover, developing technologies for data tracking and processing provide many new opportunities for efficient facility management such as decreasing energy consumption or better planning.

2.2.23. Improved Coordination and Perception of Design

In most projects, both the owner and the end users are often outside the construction sector. Manning and Messner (2008) conducted a case study about hospitals. Hospitals are used by medical personnel to provide services to patients and are managed by operators specialized in medical facilities. These individuals are familiar with the operational needs of the hospital for it to function effectively. However, they are not knowledgeable about what needs to be done during the construction phase. Furthermore, they often lack experience in reading technical drawings and their competency in this area is limited. In traditional project and construction processes, the connection between the construction team bringing the structure to life and the users with expectations for the building is not strong enough. Moreover, there are insufficient technical means for strengthening this connection and aligning the parties' understanding of the project to similar levels. On the other hand, BIM concept aims to transform traditional information flow structures into a more homogeneous form. This allows for greater involvement of end users in the project from the planning stage to handover. Consequently, it enables the construction of more functional structures with fewer surprises at the end of the project. Similarly, Petrova *et al.* (2017) found that VR implementation integrated with BIM models can significantly improve perception of design by all relevant stakeholders.

2.3. Costs of BIM Implementation

Although BIM implementations bring about numerous benefits and savings, they also entail various direct and indirect costs. BIM implementation results in many additional costs; however, some findings in the literature shed light on what the total BIM investment and cost could be. According to Miller (2012), BIM implementation

brings extra £10.000 cost per staff including hardware, software and training (Miller, 2012). On the other hand, Qian (2009) detailed the investment cost of BIM as follows: $3500 per staff for hardware upgrading, $1500 for software licensing, $3500 for training fees, and a production loss ranging from $6000 to $9000 over a period of two months and determines the total investment cost of BIM between £18.000 - £30.000 per staff (Qian,2009). Garrett and Garside (2003) conducted case study research on two BIM and two non-BIM projects involving historical buildings and found that design services' costs increased by 34% in BIM projects. Additionally, they determined that all BIM expenses accounted for less than 1% of the total cost (Garrett and Garside, 2003). On the other hand, Giel *et al.* (2013) examined four mixed-use projects of a firm and identified the cost of BIM as 0.5% of the contract value. Azhar *et al.* (2008) found the cost of BIM utilization to be 0.2% in their study about a hotel project. Giel and Issa (2013) examined a total of six projects, including two warehouses, two living facilities, and two mid-rise commercial buildings, and found the total cost of BIM to be 0.5% of the contract value. Poirier *et al.* (2015) determined the average actual cost of BIM implementation to be 6.2% for Distinct Energy Projects. In their research, Raval and Narayana (2018) found that the investment on BIM was 3% of the contract value. Ham *et al.* (2018) conclude that investment cost of BIM is 0.23% of total budget, based on their analysis of a high-rise building project. According to a survey conducted by Becerik-Gerber and Rice (2010), training, software upgrades, and hardware maintenance expenses account for less than 0.5% of overall revenue, while software and hardware expenditures range from 0.5% to 2% of overall revenue.

2.3.1. Software Costs

One of challenges of BIM utilization is inadequacy of software. There are two types of software inadequacies. First, each BIM software has its own weaknesses as well as its strong sides. For instance, some software is good at 3D modelling quality where some others good at quantifications or 4D simulation or MEP design.

Since almost every organization relies on limited resources and cannot afford for every software in the market at the same time, they are dependent on the software they choose for their technical capabilities.

Second, BIM software tend to be more expensive than the non-BIM software due to their more complex nature of capability. In addition to that, BIM models need more space in RAM and memory since they produce more data compared to traditional 2D drawings or non-BIM 3D drawings without any non-semantic data. As technology and software develop, document size problem is becoming crucial for companies to keep their competitive advantages. Cloud based solutions are becoming more popular as a solution to this problem. However, working on cloud makes the situation more fragile as it brings new cost and some additional risks such as lack of control on loss of data, semi-owned state of models due to lack of dedicated servers, digital security risks etc. All these factors create a recursive cost cycle.

Similar to other software products, BIM software may be also available with different license types. Depending on project duration and project complexity, different software products with different licence types can be preferred. Each choice means a different level of cost for budget. Furthermore, as a result of software companies strengthening their positions in the market, many products that were previously sold as perpetual licenses are now marketed as annual lease agreements, and they tend to be more expensive. This situation entails ongoing costs for companies rather than a one-time initial investment.

Many software products are available in the market and are part of the BIM ecosystem. These software products can generally be grouped into five main categories: 3D Modeling Software, BIM Design Software, Project Management Software, Computerized Maintenance Management Systems (CMMS), and Data Sharing and Collaboration Platforms. Under these categories, there are numerous software options with various features. Available information for some of the major ones are given in the Appendix-B.

2.3.2. Hardware Costs

The more complex and realistic BIM models become, the more advanced hardware is required. Every BIM software has its own hardware and operation system requirements for the best performance. Detailed information about hardware requirement of various software can be found in Appendix-B. Meeting these needs often entails a high investment and operational cost. Another aspect of this issue is the fact that companies have a need to use multiple software applications concurrently. Considering that each software has its own minimum hardware capacity requirements, hardware costs significantly increase. The result of not operating with the required hardware capacity can lead to unexpected software failures resulting in data and labour loss or, in some cases, freezing issues, leading to a substantial loss of productivity. Another issue is the permanent and reliable storage of digitized documentation. Especially due to the larger data contained in BIM models compared to traditional projects, the cost of storing them is also greater (Wang *et al.*, 2018).

2.3.3. Maintenance Costs

Like every equipment, computers also require maintenance. In addition to the hardware maintenance, the software products also require regular backup, clean up and version upgrade or license renewal. These expense items are also valid for traditional design work-flow. However, most of BIM models have greater file sizes and complexity compared to CAD drawings. Moreover, BIM software are developing continuously. Since software utilization is in the core of competitiveness, these factors together mean more frequent maintenance and higher maintenance cost.

2.3.4. Interoperability Costs

Today, in the market, there are numerous specialized software applications available for various tasks within the Building Information Modelling (BIM) ecosystem. In the construction industry, various disciplines are involved at different stages throughout

the entire project lifecycle. These disciplines include architectural, structural, mechanical, electrical/electronic, infrastructure/process, transportation, geotechnical, geomatics, urban and regional planning, usability and circulation, document management, design management, procurement, planning, cost control, sales/marketing, and facility management. Considering that beneath almost each of these diverse disciplines, there are sub-disciplines that employ different software applications for engineering analysis, visualization, presentations, and other specialized tasks, the seamless utilization of all this data becomes a challenging endeavour. This is where effective and accurate information management becomes paramount.

Interoperability among software applications emerges as a critical component of efficient information management. The ability to transfer data between various software solutions specialized in different domains can prevent redundant and independent work, resulting in significant time savings for design and management processes. Moreover, such data exchange enhances coordination and strengthens control over the final product, consequently increasing satisfaction. To achieve all of this, it is imperative that the aforementioned data exchange is performed with minimal loss. To ensure this, numerous software solutions in the industry provide infrastructure to support import and export in various formats as a feature of their software.

Furthermore, to foster sectoral collaboration and define technical standards, BuildingSmart has introduced the Interoperable Data Exchange Format called the Industrial Foundation Class (IFC), which is continuously developed with new versions. Despite these opportunities and efforts, industry experts often complain about the inadequacy of these data exchange formats. Geometric inaccuracies and omissions in geometric conversion and the loss of non-spatial data are among the most frequently cited issues. This situation is perceived as a significant impediment to achieving complete collaboration among industry stakeholders and is detrimental to efficiency at all stages and levels of a project.

2.3.5. Training Costs

In the industry, BIM still remains a relatively new concept for many firms and individuals. Therefore, for many designers and managers, BIM software may be unfamiliar. When a firm or project aims to transition to BIM system, training is essential for both understanding the general concept and gaining proficiency in the software. Hence, training may take long time (Nurtan Güneş, 2018) and that should be taken into account by decision makers.

Firstly, the content of BIM software training can vary depending on who receives it and their specific roles. For example, designers may only need to learn relevant design programs and some coordination tools. On the other hand, project managers may require proficiency in coordination programs.

Secondly, BIM does not only mean to design with parametric models but it also covers all the processes about collaborative workflow and data sharing. Many international codes have been developed to ensure collaboration. It may be difficult to quickly adopt to all these codes and workflows for a company. Therefore, it's essential to have a training program in place for learning those relevant standards.

On the other hand, there are many different BIM software. Additionally, there are various specialized software for each of different tasks which complement design process. As a result, different companies have different combination of software and somehow different work-flows even if they use same software. Therefore, companies should give importance to train their staff in accordance with their company specific standards if they want to maximize staff's performance. Otherwise, it is really difficult to find employee to fit exactly to needs of company.

2.3.6. Consultancy Costs

BIM adaptation requires expertise in multiple areas and strategic planning aligned with company goals. Each BIM software and its complementary tools have their own expertise and advantages, but they also have shortcomings in different areas. Similarly, different software options offer various licensing choices based on their sales strategies. Another aspect related to software is the observation that different regions adopt different software solutions. Furthermore, there is diversity in the standards and guidelines to be followed when creating workflows.

Choosing software tailored to the target market also requires proper planning of hardware and the diversity of expertise within the team. Therefore, it is essential to identify the software options that align with the company's resources and goals among various factors such as technical capabilities, licensing features, market usage, regional preferences, naming standards prepared by different institutions, and BIM Execution Plans and Guides. Especially for organizations new to BIM, finding individuals with sufficient experience and expertise in all these areas is often not available. As a result, consulting services are necessary in case of lack of internal expertise in BIM (Garcia *et al.*, 2018).

According to survey by Becerik-Gerber and Rice (2010), majority of respondent firms do not hire consulting services for BIM with a rate of 59%. Moreover, 31% of the respondent firms which hire consultants spend between 1% and 5% of project costs.

2.3.7. Staff Salaries

BIM creates its own specialists. Some of top mentioned ones of these new titles are BIM Engineer, BIM Technician, BIM Specialist, BIM Coordinator, BIM Project Manager and BIM Manager. All or some of these professions can work in a BIM project depending on project scope and size.

2.3.8. Increase in Subcontractor Costs

All cost items stated for contractors are also valid for sub-contractors. In addition to that, it is still hard to find a fully integrated company to BIM. Therefore, subcontractors capable of working in BIM ecosystem, demand higher contract values.

2.3.9. Temporary Production Loss

Transition from traditional design methods to BIM takes time to adopt. Therefore, productivity loss and its cost should be predicted for companies which are inexperienced in BIM. Adoption time differs depending on project scope and size.

Walasek and Barszcz (2017) conducted a case study in collaboration with Graph' it Studio, a Polish company, covering a three-year period of data. The study revealed that the annual net income of the company decreased over the three-year period as a result of BIM usage, indicating a negative trend, meaning a loss was incurred. Latiffi and Tai (2017) found, based on the experiences and opinions of experts from four firms, that the use of BIM had a negative impact on ROI during the first three years. In fact, the first two years were identified as the period with the strongest negative impact. By the third year, a break-even point was reached, after which the ROI turned positive. On the other hand, Raval and Narayana, based on their analysis of a housing project in India, identified the break-even point as the second year. Reizgevicius *et al.* (2018) predicted a 50% productivity loss during training based on their computational and conceptual study. Another significant factor is the difficulty of abandoning existing habits. Li *et al.* (2018) highlighted this issue, defining it as 'unlearning cost.

2.3.10. Cost of Developing Internal Workflow

BIM projects, unlike traditional approaches, prioritize the equal distribution of information. In addition, the software used offers many advantages; however, for these advantages to materialize, the software must be used correctly. Therefore, the adoption

of BIM entails various regulations and investments. Internal company habits, workflows, and communication methods also need to be readjusted during this process. Especially, making significant adjustments to enhance internal collaboration, strengthen interdisciplinary communication, and establish a collaborative design philosophy are inevitable. Adaptation of cloud software, setting up server infrastructure, establishing the correct file management system, and organizing communication matrices are crucial tasks. Achieving all of these requires adequate time and resources. Hochsheid and Halin (2019) identified the development of an internal collaborative workflow as one of the most important items in the guide they created for BIM adoption. Similarly, a survey conducted with industry experts for the Smart Market Report by Dodge Data and Analytics (2017) revealed that developing an internal collaborative workflow is seen as one of the top 3 BIM investments. Furthermore, Yanda and Soehari (2019) found that developing an internal collaborative workflow is among the top 5 investments.

In the research mentioned before, while more emphasis has been placed on communication, however standardizing internal digital data transfer is also part of this collaboration. Determining which formats different stakeholders will work with and which data will be transferred to which stakeholders in what format must be reinterpreted with a custom approach tailored to the organization. Joseph Garcia *et al.* (2018) emphasized the importance of such a collaborative internal workflow in creating a consistent 3D model.

2.3.11. Cost of Customization

BIM models are based on an intelligent object-oriented approach. While some of these smart objects are provided within software, a much larger and more significant portion needs to be created from scratch according to the needs of the firm and the project. Depending on the desired geometric and information detail levels (LOD, LOI), this production process requires significant labor. Jin *et al.* (2017) found that 3D custom library is one of the most important BIM investments. Additionally, customization of software export/import standards, national and international naming conventions,

etc., according to the needs of the firm and the project, as well as the determination of standard methodologies to be followed in the model production process and their establishment as internal standards, are also crucial and require great effort. A survey conducted with industry experts for the Smart Market Report by Dodge Data and Analytics (2017) revealed that customization is seen as one of the top investments. Furthermore, Yanda and Soehari (2019) found that customization is among the top 6 investments.

2.3.12. Cost of Legal Issues

The fundamental philosophy of the BIM concept revolves around the central dissemination of information throughout the entire lifecycle of a construction project, with the information model itself serving as a center. Unlike the previous approach, where project components were produced as separate endeavours based on limited information sharing, BIM fosters integrated processes. Such an approach significantly reduces hierarchical differences among stakeholders, promoting equal distribution of information and, in turn, enhancing efficiency through improved coordination. However, the dismantling of this hierarchical structure can give rise to certain legal issues (Chien *et al.*, 2014). Contractual issues, intellectual property concerns, authorship, liability of data and distribution of responsibilities are some of most mentioned problems about BIM implementation (Ghaffarianhoseini, 2017; Walasek and Barszcz, 2017).

Under the new approach, where design, procurement, construction, and operation processes progress in an integrated manner, there are gaps revealed in the existing legal framework. For instance, the fact that the model at the core of the system is collaboratively developed with contributions from all stakeholders can lead to disputes regarding model ownership. (Azhar *et al.*, 2012).

Similarly, certain specialized objects within the model, such as electromechanical equipment, may raise questions about the appropriate Level of Development (LOD) at which they should be utilized. In some cases, the supply of a high-level LOD by

a subcontractor might be viewed as a form of know-how sharing and can be subject to dispute. Another issue concerns the inherent gaps that may exist when defining and requesting the Level of Development (LOD), potentially leading to disputes about whether the responsible party's deliveries comply with contract terms. Furthermore, the main model is continually developed cumulatively with increasing levels of detail. However, many supply items can progress far beyond the intended stages of the project, raising concerns about unfair competition and potential know-how transfer enabled by excessive information contained within the shared model. If efforts are made to address this by removing objects and/or information from the main model, it can lead to disputes related to intellectual property rights in this context. In any case, it is believed that a new approach is necessary to resolve these and similar issues effectively.

Additionally, interoperability issues closely relate to whether there is any data loss during the exchange of data between different stakeholders due to the capacities of the software used (Walasek and Barszcz, 2017). In such cases, any misunderstandings, mistakes, or design failures can often lead to debates about who is responsible. To prevent this, BIM quality processes should be well-defined, and responsibility for this control and any potential errors should be clearly defined.

Identifying all these potential issues in advance and implementing the necessary solutions in a timely manner is crucial. Developing and opting for contract types that encompass the entire process and are compatible with BIM usage is the most prominent solution highlighted in the literature in this regard. From identification to determining solutions, as well as creating the appropriate contract and subsequently ensuring its correct implementation, all these steps should be considered as cost factors.

2.3.13. Cost of Resistance to Change

Digitalization appears as one of the most game changing concepts in today's world. The early stages of digital transformation in the construction industry are evident in Computer-Aided Design (CAD) programs. Before the introduction of com-

mercial computers in the early 1980s, the traditional design process relied on engineers, architects, and technical draftsmen using pen and paper for manual drawings and calculations. As computers became an integral part of life, CAD software began to transform the business world. However, starting from those days, resistance to change has become increasingly evident. One of the primary reasons for this resistance is the rapid advancement of technology, which, as a result, makes it increasingly difficult for experienced professionals to maintain their positions with their existing expertise. As technological capabilities advance, the importance of intellectual capacity diminishes, and the ability to leverage technological capabilities for faster production becomes more critical. This, in turn, exerts pressure to constantly keep abreast of the latest technical and technological developments, primarily in the form of software, in order to maintain competitive edge.

Despite the extensive education and professional development undergone by white-collar workers, the need to remain actively engaged with technological advancements, even with their wealth of experience and capabilities, can be perceived as a threat to their comfort zones. While the importance of experience and skills is undeniable, the continual shift of technological prowess towards younger generations and its significant role in bridging the gap with seasoned personnel contribute to a considerable resistance to change and innovation, particularly among those with extensive experience. The relentless pace of technological progress perpetuates the widening technological divide between generations. Consequently, as this dynamic gradually becomes the norm and is culturally internalized, resistance may eventually diminish. However, as this transitional phase is still underway in today's world, resistance remains observable.

Nevertheless, Nurtan Günes (2018) in research about BIM implementation in IGA project namely New Istanbul International Airport found that site crew of the BIM team have to break unwelcoming environment to them and resistance of site staff. As a result of this resistance, the pace of adaptation and adoption slows down, requiring additional workforce to overcome it.

Therefore, the cost of this extra workforce that will inevitably be expended in transitioning to BIM applications should be taken into account.

2.4. Software Types in BIM Ecosystem

Eastman *et al.* state that Building Information Modelling (BIM) offers a novel approach to design, construction, and facility management in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in digital format (Eastman *et al.*, 2008). The BIM concept is a digital representation encompassing the entire lifecycle of a structure. Consequently, there are software solutions developed and continually being developed for the various stages of this lifecycle: planning, design, construction, operation, and demolition.

2.4.1. BIM Modelling Software

Schlueter and Thesseling define Building Information Models as the virtual superposed representation of multi-disciplinary design data (Schlueter and Thesseling, 2009). According to Shen *et al.* a BIM software includes and provides both graphical and non-graphical information of a project during its whole life cycle (Shen *et al.*, 2012). BIM Modelling software, unlike other software, allows for object-based parametric modelling. One of the most important features of BIM Modelling software is the ability to input information into model objects. In this way, non-spatial information that can be utilized throughout the entire lifecycle can be entered into the objects. BIM software that fits this definition includes Autodesk Revit, Trimble Tekla, Graphisoft Archicad, and Nemetschek Allplan. Each software has its own strengths and weaknesses (Eastman *et al.*, 2011).

2.4.2. CAD Software

Computer-Aided Design, or CAD, is a general term for 2D and 3D drawing programs. While BIM software allows for the virtual representation of all possible aspects

of a building, CAD software enables the creation of objects in 3D or the 2D representations of 3D objects (Azhar *et al.*, 2008). Theoretically, BIM software can perform the functions of CAD software with its 3D solid geometry creation and 2D drawing capabilities. However, in practice, BIM software can be inadequate or fall behind in several aspects when detailed modelling is required. Issues such as file size, geometry creation capability, and practicality are some of these aspects. Therefore, specialized CAD software is still preferred for various areas of the AEC industry. Leading CAD software includes Dassault Systèmes Catia and Autodesk Fusion for machine-equipment parts; Autodesk 3Ds Max and Dassault Systèmes Solidworks for architectural elements such as furniture and sanitary ware; and Autodesk Autocad for 2D drawings.

2.4.3. 3D Laser Scanning and Photogrammetry

Laser scanning is a technology used to collect distance information and define 3D geometric surfaces using laser beams (Wehr and Lohr, 1999; Ebrahim, 2015). Laser scanning has various applications in the AEC industry, including as-built data collection (Haijan and Brandow, 2012), quality inspection (Ma *et al.*, 2015), and construction progress measurement (Alomari *et al.*, 2016). On the other hand, photogrammetry is the science of measurement, positioning, and 3D geometry creation based on photographs (Campbell and Wynne, 2011). Similar to laser scanning, photogrammetry has various applications in the AEC industry, including as-built data collection (Dai and Lu, 2010), use in geotechnical engineering (Cleveland and Wartman, 2006), and construction progress measurement (Kim *et al.*, 2011).

2.4.4. Virtual Reality

Virtual Reality (VR) is a field of information technology that simulates a virtual world using specific devices, aiming to make the experience as realistic as possible by providing feedback to the user (Boas, 2013). VR applications can provide benefits in the AEC sector in areas such as design review, team collaboration, and decision making (Sidani *et al.*, 2021). Additionally, VR has the potential to be used for site

safety (Shiringi *et al.*, 2021), training (Wang *et al.*, 2024), and energy assessment (Kula *et al.*, 2024).

2.4.5. Augmented Reality

Augmented Reality (AR) is a technology that enhances the real-world environment by superimposing virtual information and images onto it using appropriate equipment (Carmigniani and Fuhrt, 2011). In AEC industry, AR can be utilized for educational purposes (Urban *et al.*, 2022), for quality inspection and collaboration in site (Wang *et al.*, 2012), visualization of 4D phase planning (Wang *et al.*, 2012).

2.4.6. Common Data Environment

With the adoption of BIM, information management and coordination have become easier. However, the parallel increase in the amount of information that needs to be managed necessitates a comprehensive approach in this area as well. A well-structured information system is one of the most critical requirements for BIM projects in terms of documentation management, information distribution, and collaboration (Özkan and Seyis, 2021). BS EN ISO 19650 defines a common data environment as an "agreed source of information (3.3. 1) for any given project or asset (3.2. 8), for collecting, managing and disseminating each information container (3.3. 12) through a managed process". Today, cloud-based data sharing and management systems are prominent CDE (Common Data Environment) solutions. In this area, various products such as Autodesk ACC, Oracle Aconex, and Trimble Connect provide CDE solutions for the AEC sector. Some of these platforms stand out for their flexible design collaboration capabilities, while others excel in data organization and documentation.

2.4.7. Digital Twin

VanDerHorn and Mahadevan (2021) define digital twin as "a virtual representation of a physical system (and its associated environment and processes) that is updated

through the exchange of information between the physical and virtual systems". According to Singh *et al.* (2021), characteristics of digital twin are high-fidelity, dynamic, self-evolving, identifiable, multiscale and multiphysical, multidisciplinary and hierarchical. of BIM utilization is inadequacy of software. A digital twin is based on a 3D BIM model but enhances it with sensor data integrated from its physical counterpart and utilizes big data, data integration, machine learning, and data analytics to enabling operational improvement, predictive maintenance, and what-if analysis (Nguyen and Adhikari, 2023).

2.4.8. Engineering Analysis / Evaluation Software

One of the most important components of the design process is engineering analysis. Traditionally, drawing/model/coordination processes and engineering analyses are conducted separately. However, one of the fundamental principles of BIM is the creation of information only once. By using information models, the drawing/model/coordination processes can be integrated with engineering analyses. The ability to conduct these processes together has been facilitated by developments in interoperability, such as IFC, and the capability of various software to perform engineering analyses in addition to information modelling. Numerous engineering analysis tools directly use or are based on information models. Some of these analyses include structural analysis (Ren *et al.*, 2018), fire safety analysis (Siddiqui *et al.*, 2021), energy analysis (Carvalho *et al.*, 2021), circulation and accessibility analysis (Lee *et al.*, 2024), CCTV coverage analysis (Chen *et al.*, 2013), and lighting analysis (Shah *et al.*, 2017).

2.4.9. Computerized Maintenance Management System

A Computerized Maintenance Management System (CMMS) is a specialized type of software for facility management that facilitates to manage a computer database containing information about an organization's maintenance activities and assets (Cato and Mobbley, 2001). To establish the integration between CMMS software and BIM, it is necessary to conduct data exchange procedure. The Construction-Operations Build-

ing Information Exchange (COBie) is the international standard of data exchange format for facility management assets (East and Carrasquillo-Mangual, 2012). The compatibility of CMMS software with the BIM ecosystem is becoming increasingly important. The integration of CMMS and BIM offers several benefits, such as the visualization of maintenance-related data, and the more accurate transfer of maintenance and supplier data from the design phase to the operational phase.

2.4.10. Computational Design

With the integration and digitization of the design process through BIM software, the need to manage the increasing volume of data has grown significantly. With this respect, computational design is the name of process which aims to benefit from computational capacities of design tools. (İşbitiren, 2020; Caetano and Leitão, 2019). Various coding and visual scripting tools are integrated within the BIM ecosystem to automate repetitive tasks, analyze large datasets, and perform complex modelling tasks. These coding tools enable the creation of amorphous geometries in parametric forms, bulk data editing, automation of repetitive tasks and integration with robotics (Anane *et al.*, 2023) all of which can be accomplished using rule-based methods. Consequently, the efficiency of existing BIM software is significantly enhanced. Python for Revit, Dynamo for Revit and Grasshopper for Rhino are some of these applications for various functionalities (Nisztuk and Myszkowski, 2018).

2.4.11. 3D Coordination

3D coordination software are programs where 3D models are brought together and design conflicts can be identified (Rojas *et al.*, 2019). One of the most powerful methods used for this purpose is conducting clash tests. In addition to this, the ability to perform 3D geometric spatial reviews and provide comments are important features. This feature is especially important and useful for executives who are not competent in BIM software. To enhance collaboration from issue management perspective, there is a need for a standard data exchange format. BIM Collaboration Format (BCF) is an

open standard for design collaboration, enabling 3D coordination issue exchange (Van Berlo and Krijnen, 2014).

2.4.12. 4D Simulation and Planning

4D BIM enhances the 3D information model by incorporating the dimension of time, allowing for the visualization of planning activities through simulation (Borges *et al.*, 2018). Applications of simulations created using 4D BIM software include enhancing job site safety (Sulankivi *et al.*, 2010), conducting constructability analysis (Boton, 2018), schedule optimization (Patel *et al.*, 2022), waste mitigation (Ahmadi and Arashpour, 2020), and performing sustainability analysis (Lee and Kim, 2017).

2.4.13. Rendering and Animation

Rendering is the term for computer aided generation of photo-realistic 2D still images from 3D model objects (Dennis, 1990) while animation refers illusion of moving images out of still images. Rendering and animation is widely used in AEC sector mainly for commercial sale purposes (Borkowski and Nowakowski, 2023). However, collaboration improvement and increasing perception of design are some other benefits and reasons of rendering and animations in AEC (Wang *et al.*,2014). Nowadays, there are numerous rendering and animation software available in both online and offline formats. Some of these software work directly as plugins for BIM software, while others operate independently. These software differentiate themselves based on several key parameters, such as speed, quality, ease of use, and data size.

2.4.14. Cost Analysis and Estimation

Due to their object-based and parametric nature, BIM models enable precise quantity take-offs. However, the reliability of these quantity take-offs is directly influenced by the quality of the model, the level of detail, and the compatibility with contractual unit price definitions. Today, there are various specialized software avail-

able for quantity take-offs. These tools can provide geometric and non-geometric information that may not be necessary during the design phase but are crucial during the construction phase. This capability allows for more flexible and precise quantity take-offs than what BIM software alone can offer. Additionally, centering the design around a BIM model from the earliest stages helps reduce uncertainties and enhances project perception among relevant personnel, thereby facilitating more accurate cost estimation and potentially lowering bid costs (Eastman *et al.*, 2008). Additionally, the object-based parametric modeling structure, which allows for data input and analysis, along with its precise quantity take-off capability, facilitates much more accurate progress tracking and cost monitoring. (Elbeltagi *et al.*, 2014).

2.4.15. Design Verification and Code Compliance

As engineering advances, codes and regulations become more complex, making compliance checks increasingly laborious. However, the rich spatial and non-spatial data content of a BIM model provides an ideal infrastructure for automating the code-checking process (Preidel and Borrman, 2018). Indeed, there are now many fully or semi-automated code-checking software solutions available for many codes and regulations. Some of the code checking that can be done by software are checking of urban indexes (Villaschi *et al.*, 2022), construction healthy and safety (Getuli *et al.*, 2017), LEED compliance check (Dubljević *et al.*, 2023), automated structural stability check (Khattra *et al.*, 2022).

2.4.16. Interoperability Tools

The term “interoperability” describes the ability of different programs to exchange data (Amoaha and Nguyenb, 2019). Given the numerous different software applications and their native formats, achieving sectoral collaboration on a digital platform becomes quite challenging. To ensure interoperability between software, the IFC (Industry Foundation Class) format, which uses an open and standardized data set for use across the AEC industry, has been defined (Laakso and Kiviniemi, 2012).

Although the goal is seamless data exchange between different programs, this is often not achievable in practice. Key factors affecting the success of interoperability tools include the performance of format translators, the internal configurations of the software, and the diversity of the data (De Gaetani *et al.*, 2020).

2.4.17. Generative Design Software

Generative design can be defined as a computer-aided iterative design process based on the principle of automatically creating possible design alternatives in a rule-based manner, with pre-defined constraints and parameters (Ma *et al.*, 2021). Its applications include design optimization with respect to multiple criteria (Di Filippo *et al.*, 2021), facilitating the creation of complex forms (Andia, 2012), construction site layout optimization, and energy performance optimization (Touloupaki and Theodosiou, 2017).

2.4.18. Enterprise Resource Planning (ERP) Software

Enterprise Resource Planning (ERP) is an enterprise information system that facilitates the integrated management of many fundamental operations within an organization, such as production, procurement, engineering design, manufacturing, sales, marketing, distribution, accounting, and customer service (Ge and Voβ, 2009).

ERP and BIM integration facilitates project management for construction companies (Hewavitharana and Perera, 2020) and, with the inclusion of real-time data processed through IoT (Internet of Things) technology, assists firms in inventory management, time-cost management, and enterprise revenue management (Sarkar *et al.*,2022).

2.5. Financial Performance Measures of BIM in Literature

Some studies in the literature have examined Return on Investment (ROI) and Benefit to Cost (B/C) ratios regarding BIM implementation. Additionally, some com-

panies share project records detailing the expenses incurred for BIM implementation and the resulting savings. The most famous of these is Holder's Construction Company. In fact, out of the 22-project data found in the literature review, 12 of them belong to this company.

2.6. Related Research

2.6.1. Methods for Quantifying Benefits of BIM

As a result of the literature review, various methods for quantifying the benefits of BIM usage have been identified.

The first among these is the method of comparing two similar projects, one utilizing BIM and the other not utilizing BIM. An example of this method is illustrated by Giel's study conducted in 2009, where the benefits of BIM usage were investigated by comparing two projects in separate cases (Giel, 2009). Two case studies from a medium-sized commercial construction firm labeled "Company X" are outlined. The studies compare projects with and without Building Information Modeling (BIM) through data analysis of Request for Information (RFI) and change order logs, along with personal interviews. The return on investment (ROI) for each project is assessed based on BIM-preventable direct and indirect costs related to reduced schedule overruns and change orders. Case Study One involves small tilt wall construction projects, showing an estimated ROI of 36.7% for the non-BIM project and 16.2% for the BIM-assisted project. For a more detailed examination, in non-BIM project, the return on investment for cost savings potential due to preventable change order (COs) is determined to be 11.37%, while the return on investment for savings potential related to the generation of construction drawings is 12.54%. Furthermore, the return on investment for preventing delays in the project schedule is identified as 12.79%. In BIM project, the return on investment for cost savings potential due to generation of construction drawings is determined to be 9.96%, while the return on investment for preventing delays in the project schedule is identified as 6.24%. Case Study Two focuses on larger condo-

minium projects, with a projected ROI of 1,654% for the non-BIM project and 300% for the BIM-assisted project. For a more detailed examination, in non-BIM project, the return on investment for cost savings potential due to preventable change orders (COs) is determined to be 213.33%, while the return on investment for preventing delays in the project schedule is 1,440.67%. In BIM project, the return on investment for preventing delays in the project schedule is identified as 300%. Conclusions highlight potential savings for owners investing in BIM as an additional service.

The second method identified for quantifying the benefits of BIM usage involves comparing the numbers of Requests for Information (RFI). An example of this method can be found in the study conducted by Giel and Issa in 2013. In this study, two examples were taken for each of three separate categories, one with BIM and one non-BIM project (Giel and Issa, 2013). The first category is a small tilt-wall project, where two projects with values of 7 and 8 million dollars were compared. According to the results, the use of BIM reduces RFI numbers by approximately 34%. The second category is a three-story assisted living facility, where two projects with an approximate value of 11 million dollars were compared. BIM usage, according to the analysis, reduces RFI numbers by approximately 68%. The last category is a mid-rise commercial condominium project, where two projects with an approximate value of 41 million dollars were compared. The analysis indicates that BIM usage reduces RFI numbers by approximately 43%.

The third method used to quantify the benefits of BIM usage involves determining the potential impact of clashes identified through clash tests on the project. For instance, Bockstael and Issa (2016) developed a methodology to assess the impact of clashes identified in clash tests. In their study, BIM models undergo clash tests using software capable of performing such tests. The test results are initially filtered into relevant and irrelevant clashes. Focusing on relevant clashes, these are organized into smaller groups. Subsequently, a Failure Mode and Effect Analysis (FMEA) is conducted for each clash group. The likelihood of each clash group occurring and the magnitude of potential damage are determined, establishing a prioritization based on

significance. Following this, preventive measures are developed. Utilizing all this information, the analysis of potential costs of RFIs (Requests for Information) and COs (Change Orders) that might arise if the issues identified through clash tests were not detected is performed. By determining the cost of conducting clash tests as part of BIM implementation and applying the described savings, the Return on Investment (ROI) of BIM implementation can be calculated.

The fourth method involves the rapid and easy comparison of design alternatives in the conceptual phase through the capabilities provided by BIM software, leading to cost optimization. In their study, Biancardo *et al.* (2022) developed a workflow for the design of the Naples-Bari High-Speed Train Line using Infraworks, Civil3D, and Dynamo software. They compared various parameters such as environmental impacts, initial investment and operational costs, and service capacity for different routes to achieve maximum benefit.

In their research which is published by MDPI under an open access Creative Common CC BY license, Shin *et al.* (2022) conducted in-depth surveys and studies with officials involved in the projects to qualitatively and quantitatively compare the design process of six railway projects in South Korea (Table 2.1), three of which were implemented with BIM and three without BIM. In calculating design costs, they adopted an approach focusing solely on labor-hour costs without considering other expenses such as software, hardware etc.

In their study, they categorized design costs into four main categories: planning, modeling (or drafting), training, and meetings. They elaborated on each category and defined cost calculation methods for each step of the design process (Table 2.2). According to their study, they found that BIM projects had lower average design costs. However, they also observed a 2.9% productivity gain in BIM projects compared to non-BIM projects.

Table 2.1. Survey for quantitative and qualitative measures (Shin *et al.*, 2022).

Quantitative Measures	
Categories	**Areas of Questions**
Planning Stage	Planned budget for design and planning stage
BIM Modeling	Man-hours for creating BIM modeling based on different LOD's
	Error-processing time and labor force required for BIM modeling
	Man-hours and the amount of labor required for the design phase
	Labor charges for BIM coordination
	Man-hours for model checks and quality management
	Total working hours to create BIM models
Education and Support	Hours of education for BIM utilization
	Initial investment for BIM adoption
	Types of software and the cost of maintaining it
Relevant Meetings	Additional meetings required when using BIM
	Meetings required for error and interference checks for BIM models
Qualitative Meetings	
Categories	**Areas of Questions**
Product LOD	LOD of the final model compared to the initial plan
	Final LOD of the BIM model
	LOD for BIM utilizations
Design Errors and Difficulties	Reasons for errors during BIM modeling during design stage
	Expected problems during BIM modeling during design stage
	Coordination issues
Budget Changes during BIM Application	How to achieve a successful BIM working environment
	Satisfaction rate from client side
	Benefits of using BIM compared to a traditional working environment
	Types of BIM experts inside firms
Guidelines	Existence of guidelines for BIM utilization
	Utilization process for BIM in design stage

Table 2.2. Equations for quantitative measures (Shin *et al.*, 2022).

Measurement Equations	
Categories	**Aresa of Questions**
Planning Sage	Planned budget=base cost+ (labor charges xman-hours)
BIM Modeling (Desing of non-BIM)	Drawing and scheduling = labor charges based on LOD X man-hours
	Desing cost = labor charges based on skill level x man-hours
	Modeling cast = labor charges based on skill level x man-hours
	Model check and guality control = labor charges based on skill level x man-hours
Education and support Not applicable to non-BIM	BIM aducation = number of aducation x instructor fees
	BIM initial cost = software charges + hartware charges + upgrade cost
	BIM maintenance cost = (software + hardware maintenance) x namber of years
Relevant Meetings	Emergency meetings = number of unexpected meetings x unit price x number of participants
	Model check meetings = number of unexpected meetings x unit price x number of participants

2.6.2. Research about Economic Value of BIM

There are limited but some ROI research in order to assess value of BIM. However, there are not any research that aims to formulize ROI of BIM by combining costs and benefits. Some of these efforts for formulizing ROI of BIM can be found below:

Firstly, one of the most relevant research papers which gives a ROI formula is the paper "Benefits and ROI of BIM for Multi-Disciplinary Project Management" written by Ang Yu Qian (Qian, 2009). The study is an undergraduate thesis in Singapore. The paper presents key investments and benefits of BIM and introduces the current level of BIM in Singapore and proposes a 5-step model for BIM-implementation and also aims to develop a ROI cash-flow model. ROI formula is developed by implementing steps given below:

- Survey for assessment of changes due to BIM adoption
- BIM-cost assessment
- Formulas from literature review
- Original formula developed by author

By performing surveys and analyzing them statistically, two correlation models are developed which are base for the cash-flow formula. Since these models are regression models, correlation factors between change in cost and pre-defined factors. Each regression model of two models has its own hypothesis. First model focuses on the relation between experience and the change in cost of project. The hypothesis is "benefits and ROI which a company in the construction industry derives through the implementation of BIM is affected by experience level of BIM users and project managers in the company". The formula claims that experience in industry and experience with BIM decreases cost of project with BIM. Moreover, experience in industry is more sensitive than the experience with BIM.

Second model investigates discipline-based benefit differences, therefore focuses on the relation between disciplines and change in cost of project. The hypothesis is "different disciplines in the industry will achieve different benefits and ROI". The formula claims that building owner, architecture, MEP and structural engineering experience a decrease in cost and structural engineering experiences the maximum benefit among disciplines, while quantity surveying, project management and main contractor experience an increase in cost.

As it is given above, the formula considers both costs and benefits. “Cost” covers initial investment cost, maintenance cost and salaries. Initial investment cost consists of hardware, software and training costs. “Benefit” covers forecast growth due to BIM usage and savings with the help of BIM.

Secondly, from Autodesk provides another ROI formula considering cost of hardware and software, monthly labor cost, productivity loss during training and productivity gain after training (Autodesk, 2007).

Similar to the Qian’s formula, in the model proposed by Autodesk (Autodesk, 2007) costs and benefits are defined. “Cost” covers hardware, software, training costs and salaries. “Benefit” covers productivity gain after training due to BIM.

Thirdly, Giel and Issa conduct research about ROI of BIM by gathering data from three case studies on three sets of similar projects (Giel and Issa, 2013). Each case study contains two similar projects, one with- and other without BIM. Authors compare those similar projects and aim to obtain net value of using BIM. Researchers also try to estimate net potential savings and ROI of using BIM for project without BIM implementation. Firstly, a framework for ROI estimation is developed and presented in which benefit and cost of BIM is analysed. In this model RFIs, change orders and delays are investigated for savings due to BIM. Cost of using BIM in the project consists of extra payments for architects and engineers and cost of software and hardware. Furthermore, researchers analyse cost of number of change orders, design errors and schedule then they use these data for potential saving of using BIM. In order to monetarize preventable design errors and change orders, researchers investigate dimensional inconsistencies, documentation discrepancies between disciplines, 2D errors and omissions, grid and column alignment issues and direct clashes. Projects without BIM have schedule overrun problem and extra payment for delay while on the other hand projects with BIM do not have such a schedule overrun problem. As a result, in the 6 projects of three case studies the ROI ratios of implementing BIM are 16.2, 36.7, 109, 299.9, 376, 1653% respectively. Moreover for 3 case studies the total number of RFIs

was reduced by 34% on a small tilt-wall project, 68% on a three-story assisted living facility, and 43% on a midrise commercial condominium project, and the number of change orders was reduced by 40, 48, and 37%, respectively. Furthermore, they have created a roadmap based on their study that allows companies to calculate their ROI for BIM implementation themselves. According to this roadmap, they have divided the avoidable costs resulting from BIM implementation into direct and indirect costs (or savings). Among the direct costs are preventable change orders and RFIs. Indirect costs include project delays that can be avoided with BIM implementation. The total indirect costs are calculated by multiplying the unit costs of the delay, such as utilization cost, design cost, developer fee, and financial cost, by the delayed time. By considering the BIM implementation cost as well, the ROI can be determined. The proposed model can be seen in Figure 2.1 with permission from ASCE (see Appendix F).

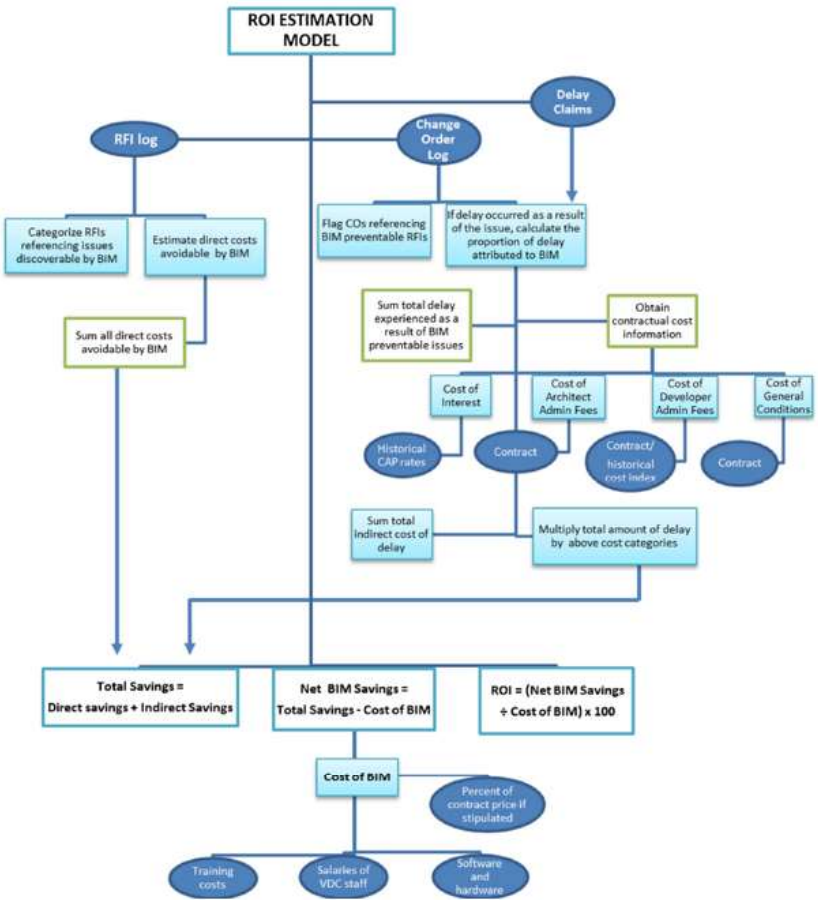

Figure 2.1. ROI estimation flow (Giel and Issa, 2013).

In the master's thesis authored by Koptsopoulou (2020), a cost-benefit analysis of BIM usage was examined. Among various economic analysis methods, the choice of the cost-benefit analysis method was justified by the abundance of intangible benefits in BIM usage. In the study, BIM uses were first identified and grouped under two major headings: 3D Modeling and 4D Planning. Then, BIM costs were listed as software, hardware, and labor-hour. BIM benefits were categorized into tangible and intangible benefits. Tangible benefits included time saving, reduction of waste, prevention of potential failure, and added value. Added value refers to the assumption that BIM usage would lead to a higher contract value. Intangible benefits included trust, supervision, commercial use, quality, and collaboration. As a result, two BIM uses, 3D modeling and 4D phase planning, were compared through cost-benefit analysis using parameters from different projects of a company called BAM. It was observed that 3D modeling had a higher benefit-to-cost ratio (lower C/B). Sensitivity analysis showed that labor cost was the most sensitive factor.

In his master's thesis, Massum (2020) conducted a meta-analysis using BIM cost and net savings reported in six studies identified through literature review. As a result, the saving-to-cost ratio of BIM was found to be 1.7%. Considering BIM costs such as software, hardware, training, and employee salary, and based on assumptions made for these cost items for the year 2020, it is claimed that for BIM usage to be feasible in a project, it should have a minimum size of 15 million Turkish Liras for the year 2020.

2.6.3. Research about Decision Support Systems for BIM Software Selection

In their research, Omar *et al.* (2014) developed a Decision Support System for BIM software selection using the Multi-Criteria Decision-Making method. They identified a total of 24 criteria through a literature review and categorized them into three groups—technical, management, and cost—based on expert interviews. They then identified 44 software alternatives. Finally, they established a decision hierarchy with three main selection criteria and software alternatives for the purpose of BIM software

selection. In a subsequent study by mostly the same team, Nursal *et al.* (2018) utilized the decision hierarchy created in the previous study to conduct a TOPSIS analysis, followed by a case study using the developed model. Like many MCDM problems, this study was fundamentally based on the subjective opinions of decision-makers. According to the participants' weightings, one software was preferred over others, with technical criteria deemed most important by the participants.

In another study, Patel *et al.* (2021) identified Critical Success Factors (CSFs) for software selection through a literature review. They conducted a survey involving experts from various countries to identify the top 15 CSFs. Subsequently, they applied Fuzzy DEMATEL to these 15 factors, finding that 5 of them were causes and the remaining 10 were effects. According to their findings, the five primary causes that should be prioritized in software selection are software functionality, BIM adoption, strategies and processes, interoperability, and staff competencies.

2.7. Gap in the Literature

There is a lack of research focusing on the economic aspects of BIM and the development of a decision-support model for BIM investments. Moreover, evaluations have revealed that the level of savings achieved through BIM implementations is debatable. In fact, it has been observed that in some aspects, BIM implementations may even increase certain costs. Additionally, there is significant fluctuation among the data obtained from studies regarding the overall net benefit of BIM implementations. When examining research on the overall net economic impact of BIM applications, it is evident that calculating the inputs of ROI estimation models is quite challenging. Specifically, the calculation of direct and indirect savings is often insufficiently detailed. On the other hand, the cost factors involved in formulas do not encompass all the cost elements. Last but not least, there is a notable gap in the research concerning both the net economic impact and BIM software selection specific to the Turkish construction industry. Taking all of this into consideration, it is believed that further research is needed on the economic aspects of BIM implementations, and increasing reliability

through more data is essential. Additionally, studies on the economic value of BIM implementations and the impact of BIM benefits on the Turkish construction sector are insufficient. This research aims to contribute to the literature by expanding knowledge in these areas with empirical data. This research significantly contributes to the literature by addressing these gaps.

3. RESEARCH METHODOLOGY

As observed in the literature review, there are few studies addressing the economic benefits of BIM usage. Many of the existing studies do not clearly explain the sources of their data. In the few studies that do provide a transparent methodology and results, the outcomes vary significantly. Additionally, there are even fewer studies and data available concerning costs. Similarly, there is limited research examining the financial impacts of BIM usage on projects, such as cash flow and return on investment. The results of these limited studies also show a wide range of variability.

The high investment cost of BIM adoption and technologies, compared to uncertain returns, is a major reason why many firms hesitate to implement BIM. Therefore, to extend the use of BIM in the construction industry, there is a need for more extensive literature data on the economic impacts of BIM usage and ultimately the development of a quantitative decision support system. To achieve this goal, a survey was conducted with experts from the sector, focusing on the use of BIM in large-scale projects by medium to large-scale firms in Turkey. The study aims to cover designers' and contractors' perspective among various stakeholders of AEC industry. The survey included questions about the direct and indirect benefits of BIM usage in the construction sector, derived from the literature review and expert consultations, and assessed the perceived importance of these benefits by experts. It also included questions aimed at determining the net economic value of BIM utilization. Given the focus on the budgetary impacts of BIM usage, the survey targeted 22 sector experts, including project managers, company owners, and BIM managers.

In addition to the survey study, a decision support model will be established to help industry decision-makers identify their priority areas for investment to maximize the benefits obtained from BIM applications. The study aims to cover large-scale Turkish design firms and focuses only benefit perspective considering only software types of BIM ecosystem. The problem to be addressed, by its nature, is a multi-

criteria decision-making problem. Given the relationships between both the criteria and the alternatives, the Analytical Network Process (ANP) has been employed.

3.1. Data Collection

3.1.1. Sample Selection of Survey

The population of the study consists of engineers (structural, electrical, mechanical) and architects working in the construction sector in Turkey. To accurately understand the population and reach an approximate number, research was conducted using data from various sources, primarily the Union of Chambers of Turkish Engineers and Architects (TMMOB). As of 2023, the relevant professional chambers affiliated with TMMOB have registered: 153,804 civil engineers, 80,789 architects, 8,669 interior architects, 6,905 landscape architects, 127,762 mechanical engineers, and 78,058 electrical engineers (TMMOB, 2024). All civil engineers, architects, interior architects, and landscape architects were considered within this study group. However, since the construction industry is not the primary employment area for mechanical and electrical/electronic engineers, the distribution of employment in the construction sector among these professions was investigated. According to various sources, the employment rate of mechanical engineers in the construction sector ranges from 9.3% to 13% (Kariyer.net, 2024a; Eleman.net, 2024; Yeditepe University, 2019). This corresponds to a range of 11,882 to 16,609 individuals. For electrical engineers, the employment rate in the construction sector varies between 12.87% and 30.63% (TMMOB Elektrik Mühendisleri Odası, 2018; Kariyer.net, 2024b; TOBB ETÜ, 2019). This corresponds to a range of 10,046 to 23,909 individuals.

The sample of the study includes professionals with experience in projects using and not using BIM, capable of qualitatively and quantitatively comparing the differences, and preferably holding managerial positions within the Turkish construction sector. The survey included participants regardless of gender, age, educational background, and race;

- For design and consulting firms, project managers and individuals who have worked or are currently working in roles such as BIM Manager, BIM Coordinator, and BIM Specialist in the field of Building Information Modeling were included in the study.
- For contractor firms, project managers and project coordinators, as well as those who have worked or are currently working in roles such as BIM Manager, BIM Coordinator, and BIM Specialist, were included in the study.
- For facility management firms, project managers and individuals who have worked or are currently working in roles such as BIM Manager, BIM Coordinator, and BIM Specialist could not be reached and were therefore not included in the study. For supplier firms, individuals who have worked or are currently working in roles such as BIM Manager, BIM Coordinator, and BIM Specialist could not be reached and were therefore not included in the study.

The demographic information summary of respondent is given in Table 3.1, while distribution of respondent with respect to total experience, BIM experience, companies' service type, companies' size and their title are shown in Figure 3.1, Figure 3.2, Figure 3.3, Figure 3.4 and Figure 3.5 respectively.

Table 3.1. Demographic information of respondents.

	Role	**Company Code**	**Company Type**	**Company Size (# of employee)**	**Total Experience (Year)**	**BIM Experience (Year)**
R1	BIM Manager	Company-A	Consultancy	201-500	8	8
R2	BIM Manager	Company-B	Design	51-200	21	21
R3	BIM Manager / Company Owner	Company-C	Design	0-20	14	14

Table 3.1 Demographic information of respondents. (cont.)

	Role	**Company Code**	**Company Type**	**Company Size (# of employee)**	**Total Experience (Year)**	**BIM Experience (Year)**
R4	Architect / Company Owner	Company-D	Design	0-20	15	15
R5	Architectural Design Manager	Company-E	Design	201-500	20	12
R6	BIM Manager	Company-F	Design	500+	7	7
R7	BIM Manager	Company-G	Design	500+	12	10
R8	Electrical Engineer / Company Owner	Company-H	Design	0-20	38	5
R9	Structural Engineer / Company Owner	Company-I	Design	0-20	20	7
R10	Mechanical Engineer / Company Owner	Company-J	Design	0-20	11	7
R11	BIM Manager	Company-K	Design	500+	10	10
R12	Design Director	Company-L	Design	51-200	22	6
R13	BIM Manager	Company-M	Contractor	500+	15	12
R14	Project Deputy Manager	Company-N	Contractor	500+	26	16
R15	BIM Manager	Company-O	Contractor	51-200	9	7
R16	BIM Manager	Company-O	Contractor	51-200	14	14
R17	BIM Manager	Company-P	Contractor	500+	14	14

Table 3.1 Demographic information of respondents. (cont.)

	Role	**Company Code**	**Company Type**	**Company Size (# of employee)**	**Total Experience (Year)**	**BIM Experience (Year)**
R18	BIM Manager	Company-R	Contractor	500+	12	8
R19	BIM Manager	Company-S	Contractor	500+	9	9
R20	BIM Manager	Company-T	Contractor	500+	30	20
R21	Technical Office Manager	Company-S	Contractor	500+	13	6
R22	Design Manager	Company-U	Contractor	500+	13	3

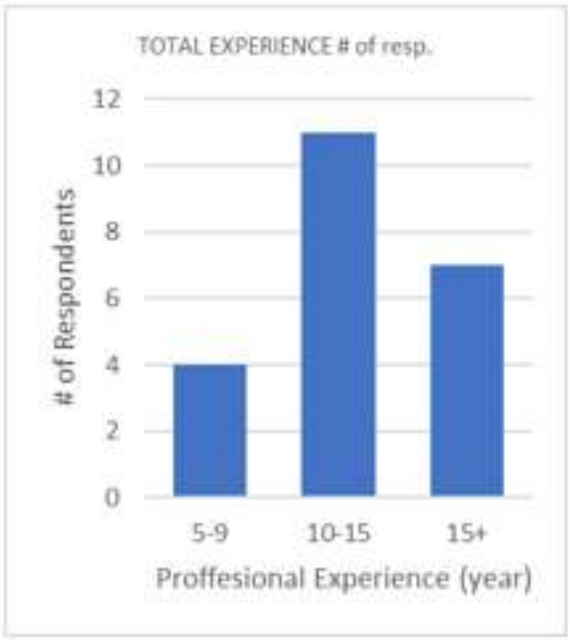

Figure 3.1. Total experience of respondents.

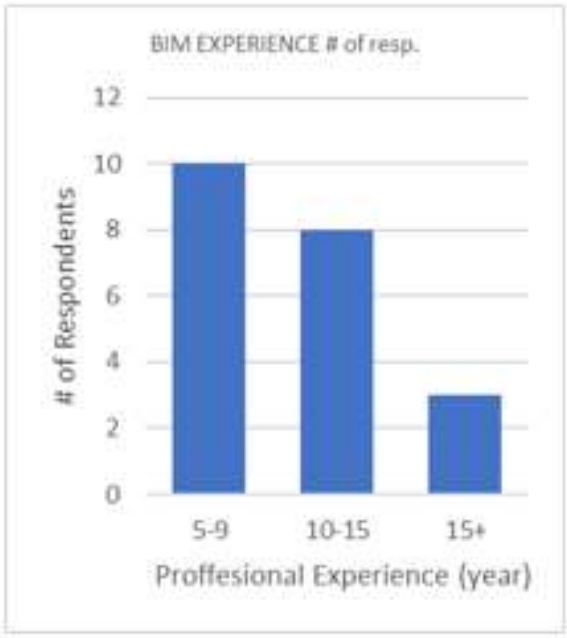

Figure 3.2. BIM experiences of respondents.

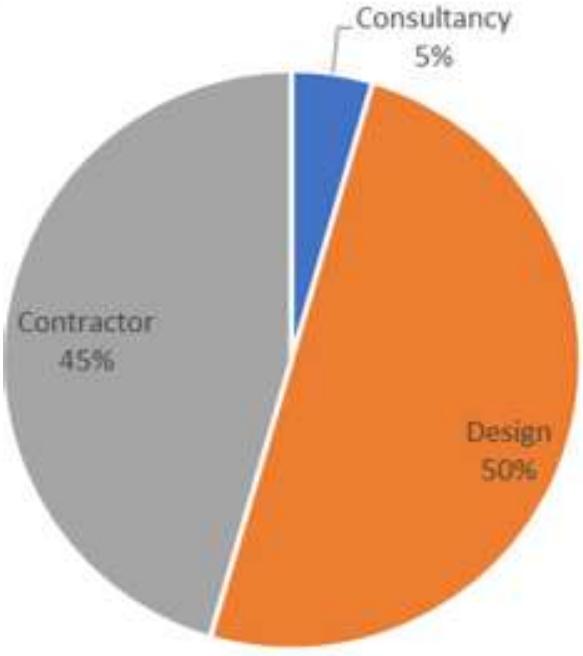

Figure 3.3. Distribution of respondents with respect to their companies' service type.

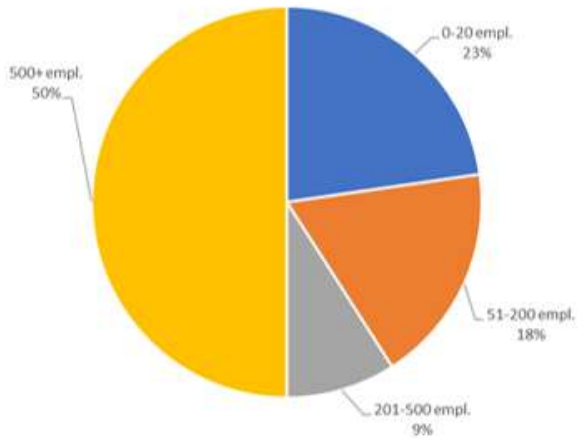

Figure 3.4. Distribution of respondents with respect to their companies' size.

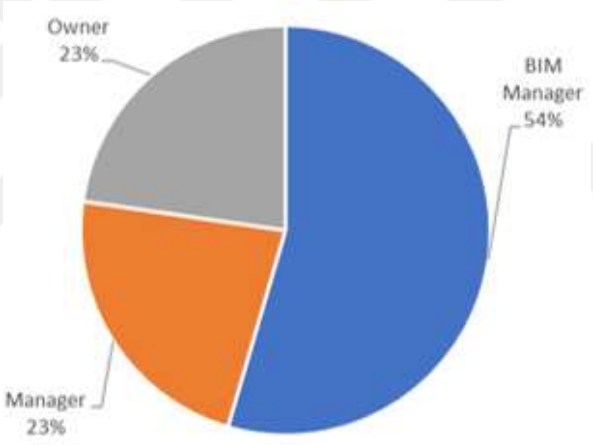

Figure 3.5. Distribution of respondents with respect to their title.

3.1.2. Preparation of Survey

As a result of the literature review, the benefits of BIM utilization were identified. Subsequently, actors in the construction sector were divided into four main groups: Design/Consulting, Contracting, Facility Management, Supplier. To understand the applicability of the benefits identified from the literature review to the Turkish construction sector, 5-point Likert scale questions were prepared for each benefit, tailored to each of the three main actor groups defined above. Numerical scale of judgements for 5-point likert scale is given in Table 3.2. Additionally, quantitative questions were

prepared to understand the net economic impact of combined benefits and costs specific to each actor in the Turkish construction sector.

Table 3.2. Numerical scale of judgements for 5-point likert scale.

Importance	**Definition**
1	Strongly Disagree / None
2	Disagree / Rare
3	Neutral / Sometimes
4	Agree / Frequently
5	Strongly Agree / Always

After preparing the questions and survey, a pilot test was conducted with five individuals who had over minimum five years of experience as BIM managers in medium to large-scale firms in Turkey. Based on the feedback received, the survey flow and questions were finalized (see Appendix-C). Final list of BIM benefits and their source are given in Table 3.3.

Table 3.3. Criteria of survey questionnaires and their sources from literature.

Criteria Code	**Criteria Description**	**Source**
C1	Improved 3D Coordination	Öktem and Ergen (2014); Barlish and Sullivan (2012); Li *et al.* (2014); Won *et al.* (2015); Giel *et al.* (2013); Bockstael and Issa (2016)
C2	Schedule optimization and Faster Completion	Öktem and Ergen (2014); Giel andIssa. (2013); Li *et al.* (2014); Jones and Laquidara-Carr (2017)
C3	Reduced Construction Cost	Manning and Messner (2008); Azhar *et al.* (2008); Lu *et al.* (2014); Jones and Laquidara-Carr (2017); Khanzode *et al.* (2008); Bebani (2022)

Table 3.3 Criteria of survey questionnaires and their sources from literature. (cont.)

Criteria Code	**Criteria Description**	**Source**
C4	Less Rework	Forcada *et al.*, (2017); Love *et al.*, (2016); Hwang *et al.*, (2019); Khanzode *et al.* (2008)
C5	Increasing Involvement of Prefabrication	Becerik-Gerber and Rice (2010); Qian (2012)
D1	More Efficient Design and Delivery Process	Yan *et al.* (2010); Manning and Messner (2008); Petrova *et al.* (2017); Pollock *et al.* (2009); Racks and Barak (2007); Shin *et al.*, (2022); Reizgevičius *et al.* (2018)
D2	More Effective Learning Process and Improved Adaptation	Yan *et al.* (2010); Lu *et al.* (2013)
D3	Complex Design Capability	Ding *et al.* (2014)
D4	Improved Design Analysis	Ding *et al.* (2014); Ren *et al.* (2018); Siddiqui *et al.* (2021); Carvalho *et al.* (2021)
I1	Reduced Number of RFIs	Barlish and Sullivan (2012); Giel andIssa. (2013); Bockstael and Issa (2016)
I2	Less Dispute and Reduced Number of Change Orders	Manning and Messner (2008); Petrova *et al.* (2017); Öktem and Ergen (2014); Barlish and Sullivan (2012); Giel andIssa. (2013); Jones and Laquidara-Carr (2017)

Table 3.3 Criteria of survey questionnaires and their sources from literature. (cont.)

Criteria Code	**Criteria Description**	**Source**
I3	Efficient Meetings	Rischmoller *et al.* (2017); Majumdar *et al.* (2022)
I4	Reduced Hard-Copy Document and Easy Control of Documents	Qian (2012); Jones and Laquidara-Carr (2017)
I5	More Efficient Facility Management	Akcamete *et al.* (2010)
I6	Improved Coordination and Perception of Design	Manning and Messner (2008); Petrova *et al.* (2017); Öktem and Ergen (2014); Barlish and Sullivan (2012); Jones and Laquidara-Carr (2017); Giel *et al.* (2013)
P1	Accuracy in Schedule Planning	Öktem and Ergen (2014); Basbagill *et al.* (2013); Giel andIssa. (2013); Li *et al.* (2014)
P2	Accuracy in Cost Estimation	Forgue *et al.* (2012); Li *et al.* (2014); Jones and Laquidara-Carr (2017)
S1	Waste Mitigation	Li *et al.* (2014); Qian (2012); Won *et al.* (2015)
S2	Prestige and Reputation	Jones and Laquidara-Carr (2017); Bryde *et al.* (2013)
S3	Energy Efficient Design	Pollock *et al.* (2009); Azhar *et al.* (2008); Shlueter and Thesseling (2008); Akcamete *et al.* (2010); Basbagill *et al.* (2013); Alahmad *et al.* (2011); Zhu (2005)

Table 3.3 Criteria of survey questionnaires and their sources from literature. (cont.)

Criteria Code	Criteria Description	Source
S4	Improved H and S Protocols	Ding *et al.* (2014); Teo *et al.*, (2005); Getuli *et al.*, (2017)
S5	Flexibility in Team Composition and Increased Globalisation	Bryde *et al.* (2013); Ghafar *et al.*, 2018
S6	User Satisfaction	Petrova *et al.* (2017); Akcamete *et al.* (2010); Bullinger *et al.* (2010); Shen *et al.* (2012)

3.1.3. Collection of Survey Responses

The survey was sent to 30 professionals via email between January 2, 2024, and April 30, 2024, and 23 responses were received. One of these responses was excluded from the evaluation due to incomplete data, leaving 22 survey forms accepted for assessment.

3.2. Data Analysis

3.2.1. Determination of Clusters

The benefits and costs of BIM implementation as well as software types obtained through literature review were grouped through a two-stage process involving four experts among 22 respondents participating in the survey study who have been working in BIM management positions in large-scale design and construction firms for more than five years.

In the first stage, each participant was asked to categorize the benefits according to their own perspectives under overarching headings. The different overarching categories obtained from each expert in the first stage were collectively evaluated, organized, and refined to create a comprehensive proposal. In the second phase, an online meeting was organized to bring the experts together, during which the proposal created in the first round was evaluated and a consensus was reached. Demographic structure of participating experts is given in Table 3.4.

Table 3.4. Demographic structure of experts contributing two-stage workshop for determination of clusters.

Expert	**Role**	**Company Code**	**Company Type**	**Company Size (# of employee)**	**Total Experience (Year)**	**BIM Experience (Year)**
R2	BIM Manager	Company-B	Design	51-200	21	21
R6	BIM Manager	Company-F	Design	500+	7	7
R7	BIM Manager	Company-G	Design	500+	12	10
R11	BIM Manager	Company-K	Design	500+	10	10

3.3. ANP Model Development

In decision-making problems, one of the foremost methods used is the Analytical Hierarchy Process (AHP). The Analytic Hierarchy Process (AHP) was identified by Myers and Alpet in 1968 and was developed into its current form as a decision-making method by Saaty in 1977 (Saaty, 1977). AHP is primarily used to determine the hierarchical relationship between factors influencing a decision by using both qualitative and quantitative data; in other words, it identifies the weight each factor holds in the decision-making process. AHP can be applied to a variety of decision-making prob-

lems, including planning, resource allocation, prioritization, and alternative selection (Yılmaz, 2022).

The Analytic Network Process (ANP) is also developed by Saaty as a generalized form of the Analytic Hierarchy Process (AHP) (Saaty, 1996). In AHP, interactions among criteria within a cluster are not considered. In ANP, not only the hierarchical structure is taken into account, but also the relationships among the criteria are considered. In this respect, ANP uses a network structure instead of clusters (Saaty, 2005). However, similar to AHP, pairwise comparisons and dominance are central to this method as well. The essence of pairwise comparison lies in estimating the values and relative superiority of the compared elements. Therefore, using an absolute number scale as the scale for pairwise comparisons is appropriate. Indeed, Saaty (2005) prefers an absolute number scale ranging from 1 to 9 for the pairwise comparison scale. In scope of thesis 9-point scale is preferred and their definition are given in Table 3.5.

Table 3.5. Fundamental scale of absolute numbers according to Saaty, 2005.

Importance	**Definition**
1	Equal Importance
2	Weak or Slight
3	Moderate Importance
4	Moderate Plus
5	Strong Importance
6	Strong Plus
7	Very Strong or demonstrated importance
8	Very, very Importance
9	Extreme Importance

According to Kheybari *et al.* (2020) steps of ANP implementation can be summarized as follows:

- Defining the problem and creating a network structure representing relationships
- Conducting pairwise comparisons to determine priorities
- Creating a super matrix and transforming it into a weighted super matrix
- Calculating the limit super matrix to aggregate all weighted super matrix elements
- Identifying the best option

One of the fundamental principles of the AHP and ANP methods is inconsistency. According to Saaty (2005), inconsistency is an indicator of the contribution of our results to the existing literature on the subject under investigation. A very high inconsistency value decreases the reliability of the study and its conclusions, while a very low inconsistency value indicates that the study has not contributed significantly to the existing body of knowledge. Therefore, a certain amount of inconsistency is a targeted outcome for AHP and ANP studies. According to Saaty, the threshold value should be set at less than or equal to 10% (Saaty, 2005). According to Saaty (2005), if group decision making is applied in an ANP model, the way to derive a single outcome from experts with different judgments is by using the geometric mean.

According to Dikmen *et al.* (2010), there is no minimum number of participants required for ANP studies. However, it is generally expected that reliability will increase as the number of participants increases. The principle of conducting ANP with a minimum of 3 or more participants is widely accepted (Çomu *et al.*, 2021). Some research for AEC conducted ANP with less than 10 participants are shown in Table 3.6.

Table 3.6. Descriptives statistics of participants.

Authors who used ANP Method	**Purpose of study**	**Number of participants for ANP Method**
Aydoğan and Köksal, 2013	Construction risk factors on partner selection	8
Yi, 2014	Construction project risk evaluation	10
Erdem and Özorhon, 2015	Assessing real estate project success factors	8
Çomu *et al.*, 2021	Risk assessment of commercial real estate development projects	5
Bayesteh *et al.*, 2022	To evaluate factors influencing construction labor productivity	9

One of the basic elements of the ANP method is the super matrix. Super matrix is a combined matrix where local priorities and inter-cluster priority matrices are collected for each cluster used in ANP model analysis. The matrix obtained by entering the local

priority values obtained as a result of pairwise comparison is called unweighted super matrix. In case there is more than one cluster, the matrix obtained by multiplying the relative priorities of the clusters with each relevant element is called weighted super matrix. The limit matrix is the matrix in which the values at which the relative importance values of the components converge are obtained by taking the limit of the weighted matrix because the problem involves feedback. (Yurdakul and Yıldırım, 2013). In a Limit Super Matrix, each column is identical, and the sum of each column equals one. The final values for decision-making problems are derived from this matrix.

3.3.1. Framework of ANP Model Development

A decision support model will be established to help industry decision-makers identify their priority areas for investment to maximize the benefits obtained from BIM applications. The study aims to cover large-scale Turkish design firms and focuses only benefit perspective considering only software types of BIM ecosystem. The problem to be addressed, by its nature, is a multi-criteria decision-making problem. Given the relationships between both the criteria and the alternatives, the Analytical Network Process (ANP) has been employed. ANP model will be analyzed by following these steps:

- Conducting a literature review to identify the expected/obtained benefits from BIM uses and the software types within the BIM ecosystem.
- Validating the expected/obtained benefits from BIM utilization and the software types within the BIM ecosystem through a focus group composed of BIM experts.
- Grouping and consolidating the expected/obtained benefits from BIM uses and the software types within the BIM ecosystem under certain overarching headings with the help of a focus group of BIM experts.
- Formulating hypotheses and creating the ANP model.
- Developing the Relation Matrix with a focus group of BIM experts.
- Having experts fill in the weight relationships between Criteria and Alternatives.
- Analyzing the ANP Model and identifying alternatives' hierarchy.

3.3.2. Constructing Network Model

Super Decisions software will be used for the analysis of the ANP study to be carried out within the scope of this thesis. Super Decisions software is a free educational software, and its development is sponsored by the Creative Decisions Foundation, which was founded in 1996 by Thomas L. Saaty, the inventor of ANP, and his wife.

Within the Super Decisions software, it is possible to create clusters to enable the establishment of the ANP model, to create subnetworks at various levels within them, and to define one-way or two-way interaction between and within the clusters.

There are 3 network model types that can be installed in the Super Decisions software. These can be listed as simple network, two-level network and complex network. Simple network does not contain any sub-networks and each of the clusters is also an alternative. Two-level network is a model in which each cluster contains one level of subnetwork. Complex network is the situation where clusters contain more than one subnetwork, and in theory there is no upper limit.

After the clusters are formed, a network is created within Super Decisions according to the relationships defined in the relation matrix. Once the relationships between elements and clusters are defined, the Super Decisions software automatically generates the pairwise comparisons. The relative priorities obtained through the pairwise comparisons are then entered into the program to populate the unweighted Super Matrix. For elements that do not have a relationship, the value in the Super Matrix will automatically be set to 0.

Criteria and alternatives used in ANP model and their abbreviations are given in the Table 3.7. The resulting model and its details will be given in the “3.3.5 ANP Model with Super Decisions Software” section.

Table 3.7. Criteria and alternatives used in ANP model.

Cluster	**Abbr.**	**Description**
Criteria	C1	Accurate Planning
	C2	High-quality Design
	C3	Efficient Construction Process
	C4	Improved Sustainability
	C5	Enhanced Information Management
Alternatives	A1	Modelling Software
	A2	Visualization and Simulation Software / Techs
	A3	Evaluation / Analysis Software
	A4	Collaboration Software / Platforms
	A5	Data Management Software/ Platforms

3.3.3. Developing Relation Matrix

At the core of ANP is pairwise comparison. The matrix used to identify the elements to be compared is called the relation matrix. In the relation matrix, all components of the model are listed in the left column and the top row to form a matrix. Each element on the left side is then evaluated for its influence on each element at the top.

Within the scope of the study, a two-round online workshop was conducted with three experts among 22 respondents who have minimum 10 years of experience in BIM management. Demographic structure of experts contributing two-stage workshop for ANP relation matrix is given in Table 3.8.

Table 3.8. Demographic structure of experts contributing two-stage workshop for ANP relation matrix.

Expert	**Role**	**Company Code**	**Company Type**	**Company Size (# of employee)**	**Total Experience (Year)**	**BIM Experience (Year)**
R2	BIM Manager	Company-B	Design	51-200	21	21
R7	BIM Manager	Company-G	Design	500+	12	10
R11	BIM Manager	Company-K	Design	500+	10	10

In the first round, the online survey is shared and results are evaluated. For the parts that showed differences among the experts, a collective online meeting was held in the second round to reach a consensus. The relation matrix obtained from this study is provided in Table 3.9:

Table 3.9. Relation Matrix.

Criteria						
		Accurate Planning	High-quality Design	Efficient Construction Proces	Improved Sustainability	Enhanced Information Management
Criteria	Accurate Planning	x	x	x		
	High-quality Design		x	x	x	
	Efficient Construction Process			x	x	
	Improved Sustainability				x	

Table 3.9 Relation Matrix. (cont.)

Criteria						
		Accurate Planning	High-quality Design	Efficient Construction Proces	Improved Sustainability	Enhanced Information Management
	Enhanced Information Management	x	x	x		x
Alternatives	Modelling Software	x	x	x		
	Visualization & Simulation Software / Techs		x	x		x
	Evaluation / Analysis Software		x		x	
	Collaboration Software / Platforms	x	x	x		x
	Data Management Software / Platforms					x
Alternatives						
		Modelling Software	Visualization & Simulation Software	Evaluation / Analysis Software	Collaboration Software / Platforms	Data Management Software/ Platforms
Criteria	Accurate Planning		x			
	High-quality Design		x			
	Efficient Construction Process				x	

Table 3.9 Relation Matrix. (cont.)

Alternatives						
		Modelling Software	Visualization & Simulation Software	Evaluation / Analysis Software	Collaboration Software / Platforms	Data Management Software/ Platforms
	Improved Sustainability					x
	Enhanced Information Management					x
Alternatives	Modelling Software	x	x	x	x	x
	Visualization & Simulation Software / Techs		x			
	Evaluation / Analysis Software			x		
	Collaboration Software / Platforms	x			x	
	Data Management Software / Platforms				x	x

3.3.4. Pairwise Comparisons with Experts

After constructing a relation matrix, an online survey was conducted using pairwise comparison with seven experts among 22 respondents with at least five years of experience in BIM management. Detailed information about participants is given in Table 3.10. As recommended by Saaty (2005), an absolute number scale from 1 to 9 was used for pairwise comparison. Experts were asked to rate which element had more influence for the specified criterion or alternative on a scale of 1 to 9. The detail

of online survey of pairwise comparison can be seen in Appendix-D. The scores given by each participant were then brought together and the final scores were obtained by taking the geometric mean, as recommended by Saaty (2005). When all pairwise comparison results are entered into the Super Decisions Software, the software automatically performs the necessary AHP calculations for all sub-matrices of the super matrix and computes the inconsistency values. Upon review, it was observed that the inconsistency value exceeded 0.1 for two pairwise comparisons. Consequently, participants were asked to reassess these two items. Through brainstorming, a consensus was reached, and the values were adjusted to bring the inconsistency below 0.1. All resulting pairwise comparison matrices are given in Appendix E.

Table 3.10. Demographic structure of experts participating pairwise comparison.

	Role	**Company Code**	**Company Type**	**Company Size (# of employee)**	**Total Experience (Year)**	**BIM Experience (Year)**
R2	BIM Manager	Company-B	Design	51-200	21	21
R3	BIM Manager / Company Owner	Company-C	Design	0-20	14	14
R5	Architectural Design Manager	Company-E	Design	201-500	20	12
R6	BIM Manager	Company-F	Design	500+	7	7
R7	BIM Manager	Company-G	Design	500+	12	10
R11	BIM Manager	Company-K	Design	500+	10	10
R12	Design Director	Company-L	Design	51-200	22	6

3.3.5. ANP Model with Super Decisions Software

Within the scope of the thesis, a two-level network was selected, and a model was established to include a single-level subnetwork with criteria and alternatives. While BIM Benefits grouped in line with expert opinions form the criteria cluster and subnetwork, BIM software categories grouped in line with expert opinions form the alternatives cluster and subnetwork. The relation matrix between these two clusters was again defined in line with expert opinions. By creating relevant clusters in Super Decisions and establishing networks with relations, the ANP model obtained. Obtained model is shown in Figure 3.6 and some examples of pairwise comparisons are given in Figure 3.7, Figure 3.8 and Figure 3.9.

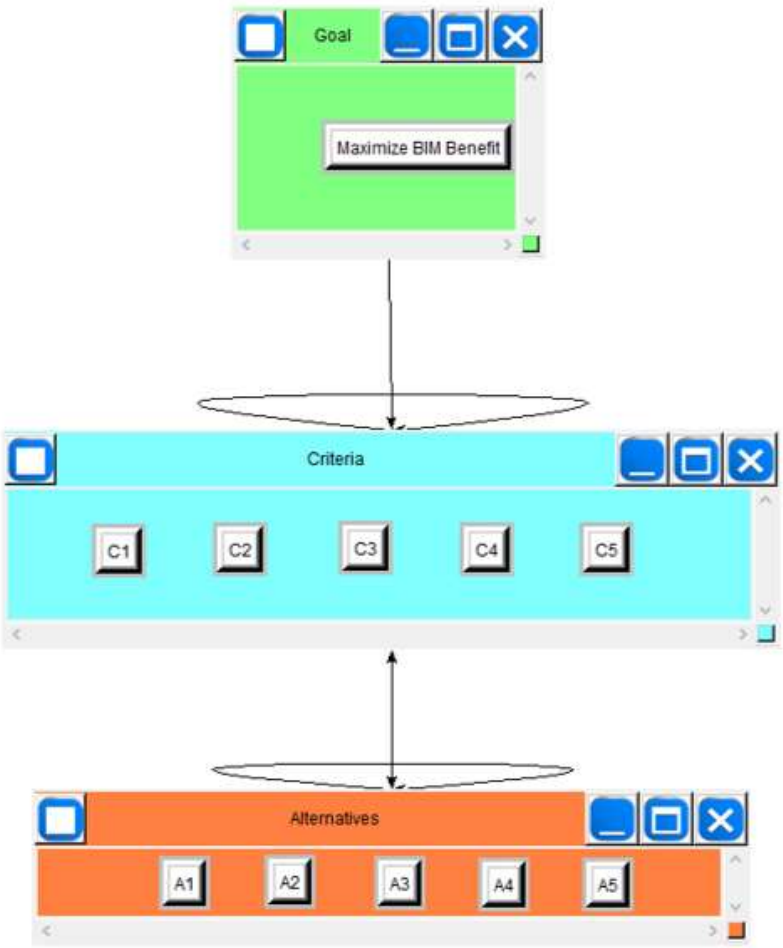

Figure 3.6. ANP model developed in super decisions software.

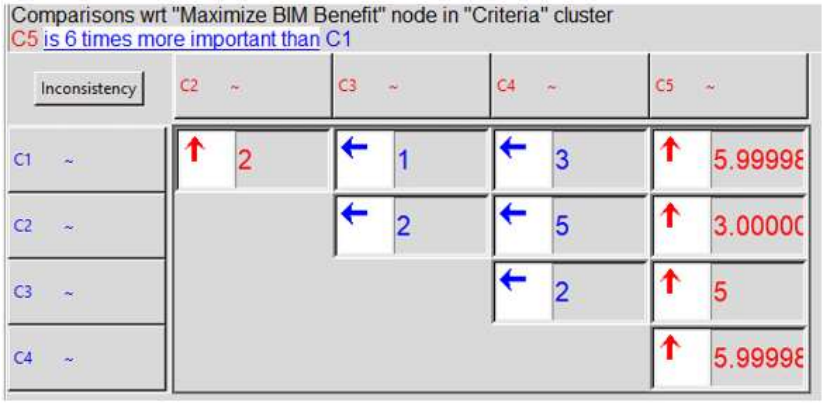

Figure 3.7. Node comparison with respect to goal of maximizing BIM benefit.

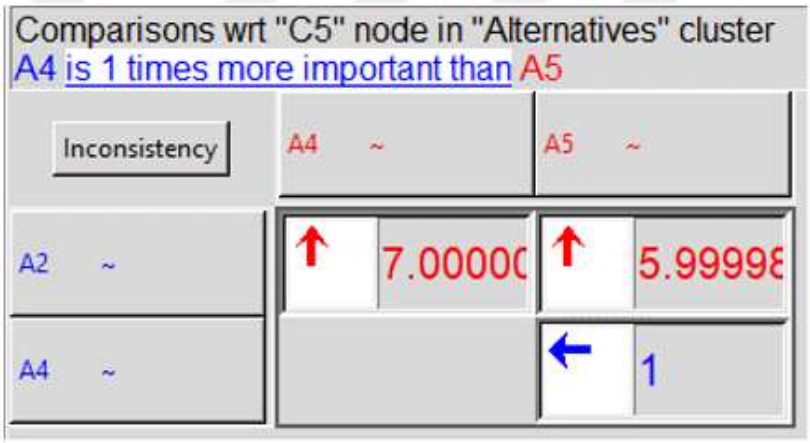

Figure 3.8. Node comparison with respect to enhanced information management criterion in alternatives cluster.

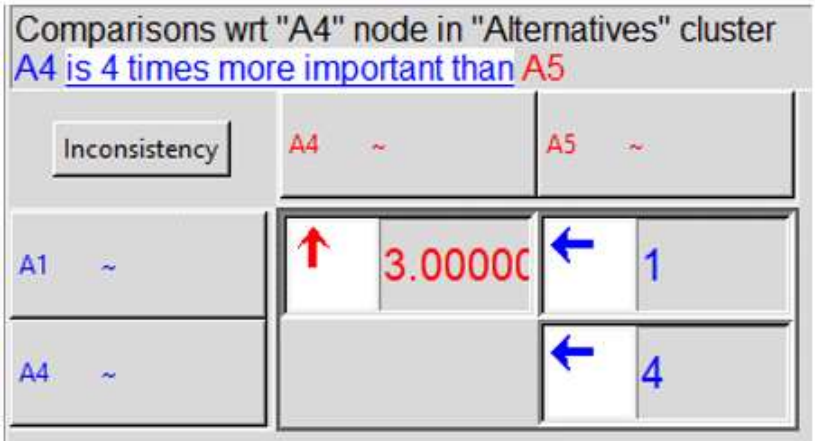

Figure 3.9. Node comparisons with respect to "Collaboration Software" alternative in alternatives cluster.

4. RESULTS

In this section, the results of the survey aimed at measuring the benefits and net economic value of BIM utilization will be presented, along with the results of the ANP analysis, which aims to determine the most suitable types of BIM software to achieve maximum BIM benefits for designers.

4.1. Summary of Literature Review

4.1.1. Summary of Literature Review

In this section, the data obtained from the literature review will be examined and net savings value of BIM utilization will be evaluated.

4.1.2. Benefits of BIM

BIM benefits found in literature review are given in Table A.1. With the incorporation of their final opinions, the benefits of BIM were categorized into a total of 5 main headings: accurate planning, high-quality design, effective construction process, improved sustainability, and improved information management and collaboration. The five BIM benefit clusters and the benefits included in each cluster are shown in Table 4.1.

Table 4.1. Benefit clusters according to expert opinion.

Accurate lanning	Accuracy in Schedule Planning
	Accuracy in Cost Estimation
High-Quality Design	More Efficient Design and Delivery Process
	More Effective Learning Process and Improved Adaptation
	Complex Design Capability
	Improved Design Analysis

Table 4.1 Benefit clusters according to expert opinion. (cont.)

Efficient Construction Process	Improved 3D Coordination in Site
	Schedule optimization and Faster Completion
	Reduced Construction Cost
	Less Rework
	Increasing Involvement of Prefabrication
Improved Sustainability	Waste Mitigation
	Prestige and Reputation
	Energy Efficient Design
	Improved H and S Protocols
	Flexibility in Team Composition and Increased Globalization
	High End-User Gladness
Enhanced Information Management and Collaboration	Reduced Number of RFIs
	Less Dispute and Reduced Number of Change Orders
	Efficient Meetings
	Reduced Hard-Copy Document and Easy Control of Documents
	More Efficient Facility Management
	Improved Coordination and Perception of Design

4.1.3. Savings of BIM

In this section, major savings are presented in detail. Summary of these BIM related savings are given in Table 4.2.

Table 4.2. Summary of BIM savings.

Description	**Source**	**No. of Research**	**Contribution "+" for Positive "-" for negative**
Total Cost Saving	Barlish and Sullivan, 2012; Lu *et al.*, 2013; Lu *et al.*, 2014; Bockstael and Issa, 2016; Jones *et al.*, 2015; Ham *et al.*, 2018; Rayal and Narayana, 2018	7	+

Table 4.2 Summary of BIM savings. (cont.)

Description	**Source**	**No. of Research**	**Contribution "+" for Positive "-" for negative**
Design Cost Saving	Lu *et al.*, 2014; Sacks and Barak, 2008; Sholeh *et al.*, 2020; Barlish and Sullivan, 2012; Lu *et al.*, 2015	5	+/-
Construction Cost Saving	Barlish and Sullivan, 2012; Lu *et al.*, 2014; Dodge Data and Analytics, 2017; Bebani, 2022; Li *et al.*, 2014; Khanzode *et al.*, 2008	6	+
Rework Cost Saving	Lee *et al.*, 2012; Hwang *et al.*, 2019	2	+
Saving in Design-related C.O.	Papajohn and El Asmar, 2021; Giel *et al.*, 2013; Bockstael and Issa, 2013; Barlish and Sullivan, 2012	4	+
Waste Mitigation	Won *et al.*, 2016; Cheng *et al.*, 2013; Jones *et al.*, 2015	3	+
Total Project Time Saving	Lu *et al.*, 2013; Jones *et al.*, 2015	2	+/-
Design Time Saving	Manning and Messner, 2008; Lu *et al.*, 2015; Sholeh *et al.*, 2020	3	+
Learning Time Saving	Lu *et al.*, 2013	1	+
Construction Time Saving	Li *et al.*, 2014; Dodge Data and Analytics, 2017	2	+
Accuracy in Cost Estimation	Poirier *et al.* 2015; Gilligan and Kunz, 2007; Staub-French and Khanzode, 2007	3	+/-
Accuracy in Schedule Estimation	Giel *et al.*, 2009; Giel and Issa, 2013; Barlish and Sullivan, 2012	3	+

Table 4.2 Summary of BIM savings. (cont.)

Description	**Source**	**No. of Research**	**Contribution "+" for Positive "-" for negative**
Reduced Number of RFIs	Giel and Issa, 2013; Barlish and Sullivan, 2012; Jones *et al.*, 2015	3	+
Productivity Gain	Sacks and Barak, 2008; Reizgevičius *et al.*, 2018; Shin *et al.*, 2022	3	+

4.1.3.1. Total Cost Saving of BIM. When examining the data obtained from the literature regarding the total savings provided by BIM usage over the total project budget, there is an undisputed consensus that BIM usage reduces the overall cost. Summary of findings and available details are given in Table 4.3.

Table 4.3. Findings from literature about total cost saving of BIM.

Research	**Detail Information**				**No. of BIM Utilized Project**	**No. of non-BIM Project**	**Cost Change as % of non-BIM case**
	Average Construction Area m^2 (Gross Floor Area)	**Contract Price**	**Type**	**Country / Region**			
Barlish and Sullivan, 2012	n/a	n/a	n/a	n/a	2	2	-1.00%
Barlish and Sullivan, 2012	n/a	n/a	n/a	n/a	1	1	-2.00%
Lu *et al.*, 2013	n/a	n/a	n/a	n/a	n/a	n/a	-5.99%
Lu *et al.*, 2014	47.832,00 m^2	HKD 444.650. 000,00	Housing	Hong Kong	1	1	-6.92%

Table 4.3 Findings from literature about total cost saving of BIM. (cont.)

Research	**Detail Information**				**No. of BIM Utilized Project**	**No. of non-BIM Project**	**Cost Change as % of non-BIM case**
	Average Construction Area m^2 (Gross Floor Area)	**Contract Price**	**Type**	**Country / Region**			
Bockstael and Issa, 2016	3.336,42 m^2	n/a	Retail and commercial	Canada	1	n/a	-0.10%
Jones *et al.*, 2015	35.217,79 m^2	n/a	Hospital	U.S.A.	1	n/a	-7.00%
Ham *et al.*, 2018	661.134,00 m^2	$900.000.000,00	High Rise	South Korea	1	n/a	-0.60%
Rayal and Narayana, 2018	n/a	$13.769.000,00	Residential	India	1	n/a	-3.72%

4.1.3.2. Design Cost Saving of BIM. When examining the impact of BIM utilization on design costs, it is observed that the literature presents a wide range of values. While some studies have found savings at the level of 50%, others have found that total design costs increase further with BIM. Summary of findings and available details are given in Table 4.4.

Table 4.4. Findings from literature about cost saving of design teams.

Research	**Detail Information**				**No. of BIM Utilized Project**	**No. of non-BIM Project**	**Cost Change as % of non-BIM case**
	Average Construction Area m^2 (Gross Floor Area)	**Contract Price**	**Type**	**Country / Region**			
Lu *et al.*, 2014	47.832,00 m^2	HKD 444.650.0	Housing	Hong Kong	1	1	45,93%

Table 4.4 Findings from literature about cost saving of design teams. (cont.)

Research	Detail Information				No. of BIM Utilized Project	No. of non-BIM Project	Cost Change as % of non-BIM case
	Average Construction Area m^2 (Gross Floor Area)	Contract Price	Type	Country / Region			
Sacks and Barak, 2008	24.750,00 m^2	n/a	Housing	Israel	2	2	-48,00%
Sacks and Barak, 2008	9.000,00 m^2	n/a	Faculty (Education)	Israel	1	1	-55,00%
Sholeh *et al.*, 2020	n/a	n/a	n/a	Indonesia	1	1	-52,30%
Barlish and Sullivan, 2012	n/a	n/a	n/a	n/a	2	2	31,00%
Lu *et al.*, 2015	n/a	n/a	n/a	Hong Kong	1	1	118,05%

4.1.3.3. Construction Cost Saving of BIM. When examining the data obtained from the literature regarding the construction cost savings provided by BIM utilization, there is an undisputed consensus that BIM utilization reduces the overall cost. Summary of findings and available details are given in Table 4.5.

Table 4.5. Findings from literature about construction cost saving.

Research	Detail Information				No. of BIM Utilized Project	No. of non-BIM Project	Cost Change as % of non-BIM case
	Average Construction Area m^2 (Gross Floor Area)	Contract Price	Type	Country / Region			
Barlish	n/a	n/a	n/a	n/a	2	2	-5.00%

Findings from literature about construction cost saving. (cont.)

Research	**Detail Information**				**No. of BIM Utilized Project**	**No. of non-BIM Project**	**Cost Change as % of non-BIM case**
	Average Const-ruction Area m^2 (Gross Floor Area)	**Contract Price**	**Type**	**Country / Region**			
and Sullivan, 2012							
Lu *et al.*, 2014	47.832,00 m^2	HKD 444.650. 000,00	Housing	Hong Kong	1	1	-8.61%
Dodge Data and Analytics, 2017	n/a	n/a	Hospital	U.S.A.	1	n/a	-6.,00%
Bebani, 2022	n/a	n/a	Roadwork	Turkey	1	n/a	-21.00%
Li *et al.*, 2014	28.124,00 m^2	n/a	Data Center	China	1	n/a	-2.91%
Khanzode *et al.*, 2008	250.000,00 m^2	$96.900. 000,00	Hospital	U.S.A.	1	n/a	-5.56%

4.1.3.4. Rework Cost Saving of BIM. Only two studies directly provide the proportion of rework cost savings to the total budget. Summary of findings and available details are given in Table 4.6.

Table 4.6. Findings from literature about savings in rework cost.

Research	**Detail Information**				**No. of BIM Utilized Project**	**No. of non-BIM Project**	**Cost Change as % of non-BIM case**
	Average Construction Area m^2 (Gross Floor Area)	**Contract Price**	**Type**	**Country / Region**			
Lee *et al.*, 2012	350.247,00 m^2	HKD 583.000.000,00	Mixed	South Korea	1	n/a	-0.22%
Hwang *et al.*, 2019	250.000,00 m^2	$ 96.900.000,00	Hospital	U.S.A.	1	n/a	-4.8%

4.1.3.5. Saving in Cost of Design Related Change Order BIM. When examining the data obtained from the literature regarding the savings in cost of design related change orders (C.O.) provided by BIM utilization over the total project budget, there is an undisputed consensus that BIM usage reduces the overall cost. However, it is observed that the literature presents a wide range of values. Summary of findings and available details are given in Table 4.7 and Table 4.8.

Table 4.7. Findings from literature about savings in design related change order.

Research	**Detail Information**				**No. of BIM Utilized Project**	**No. of non-BIM Project**	**Cost Change as % of non-BIM case**
	Average Construction Area m^2 (Gross Floor Area)	**Contract Price**	**Type**	**Country / Region**			
Barlish and Sullivan, 2012	n/a	n/a	n/a	n/a	2	2	-5.00%
Lu *et al.*, 2014	47.832,00 m^2	HKD 444.650.000,00	Housing	Hong Kong	1	1	-8.61%

Table 4.7 Findings from literature about savings in design related change order. (cont.)

Research	**Detail Information**				**No. of BIM Utilized Project**	**No. of non-BIM Project**	**Cost Change as % of non-BIM case**
	Average Construction Area m² (Gross Floor Area)	**Contract Price**	**Type**	**Country / Region**			
Dodge Data and Analytics, 2017	n/a	n/a	Hospital	U.S.A.	1	n/a	-6.00%
Bebani, 2022	n/a	n/a	Roadwork	Turkey	1	n/a	-21.00%
Li *et al.*, 2014	28.124,00 m²	n/a	Data Center	China	1	n/a	-2.91%
Khanzode *et al.*, 2008	250.000,00 m²	$96.900.000,00	Hospital	U.S.A.	1	n/a	-5.56%

Table 4.8. Findings from literature about reduction in number of change order.

Research	**Detail Information**				**No. of BIM Utilized Project**	**No. of non-BIM Project**	**Quantity Change as % of non-BIM case**
	Average Construction Area m² (Gross Floor Area)	**Contract Price**	**Type**	**Country / Region**			
Giel and Issa, 2013	9.453,20 m²	$7.986.36,5	Warehouse	U.S.A.	1	1	-40.00%
Giel and Issa, 2013	41.536,33 m²	$43.078.809	Residential	U.S.A.	1	1	-37.00%
Giel and Issa, 2013	8.683,00 m²	$11.250.519	Residential	U.S.A.	1	1	-48.00%
Lu *et al.*, 2013	n/a	n/a	n/a	n/a	n/a	n/a	-40.00%

4.1.3.6. Waste Mitigation of BIM. When examining the data obtained from the literature regarding the waste mitigation provided by BIM utilization, there is an undisputed consensus that BIM utilization contributes to reducing the amount of construction waste. However, it is observed that the literature presents a wide range of values. Summary of findings and available details are given in Table 4.9.

Table 4.9. Findings from literature about waste mitigation.

Research	**Detail Information**				**No. of BIM Utilized Project**	**No. of non-BIM Project**	**Quantity Change as % of non-BIM case**
	Average Construction Area m^2 (Gross Floor Area)	**Contract Price**	**Type**	**Country / Region**			
Won *et al.*, 2016	120.000,00 m^2	n/a	Residential	South Korea	1	n/a	-15.20%
Won *et al.*, 2016	9.995,00 m^2	n/a	Stadium	South Korea	1	n/a	-4.30%
Cheng *et al.*, 2013	n/a	n/a	n/a	n/a	n/a	n/a	-70.00%
Jones *et al.*, 2015	n/a	n/a	n/a	n/a	n/a	n/a	-75.00%

4.1.3.7. Total Project Time Saving of BIM. Only two studies directly provide the proportion of total project time saving. Summary of findings and available details are given in Table 4.10.

Table 4.10. Findings from literature about total time saving of BIM.

Research	Detail Information				No. of BIM Utilized Project	No. of non-BIM Project	Duration Change as % of non-BIM case
	Average Construction Area m^2 (Gross Floor Area)	Contract Price	Type	Country / Region			
Lu *et al.*, 2013	n/a	n/a	High Rise	n/a	1	1	-7.00%
Jones *et al.*, 2015	3.200,00 m^2	n/a	n/a	n/a	n/a	n/a	-5.00%

4.1.3.8. Design Time Saving of BIM. When examining the data obtained from the literature regarding the design time saving provided by BIM utilization, there is an undisputed consensus that BIM utilization contributes to reducing design time. However, it is observed that the literature presents a wide range of values. Summary of findings and available details are given in Table 4.11.

Table 4.11. Findings from literature about design team labor-hour saving.

Research	Detail Information				No. of BIM Utilized Project	No. of non-BIM Project	Duration Change as % of non-BIM case
	Average Construction Area m^2 (Gross Floor Area)	Contract Price	Type	Country / Region			
Manning and Messner, 2008	n/a	n/a	Hospital	U.S.A.	1	n/a	-39%
Manning and Messner, 2008	n/a	n/a	Laboratory	U.S.A.	1	n/a	-20%

Table 4.11 Findings from literature about design team labor-hour saving. (cont.)

Research	Detail Information				No. of BIM Utilized Project	No. of non-BIM Project	Duration Change as % of non-BIM case
	Average Construction Area m^2 (Gross Floor Area)	Contract Price	Type	Country / Region			
Lu *et al.*, 2015	47.832,00 m^2	HKD 444.650.0	Housing	Hong Kong	1	1	-8%
Sholeh *et al.*, 2020	n/a	n/a	n/a	Indonesia	1	1	-50%

4.1.3.9. Learning Time Saving of BIM. Only one research can be found providing ratio for learning data saving which presents learning time saving of 5.9%. Summary of findings and available details are given in Table 4.12.

Table 4.12. Findings from literature about learning time saving.

Research	Detail Information				No. of BIM Utilized Project	No. of non-BIM Project	Duration Change as % of non-BIM case
	Average Construction Area m^2 (Gross Floor Area)	Contract Price	Type	Country / Region			
Lu *et al.*, 2013	3.200,00 m^2	n/a	High Rise	n/a	1	1	-8.9%

4.1.3.10. Construction Time Saving of BIM. Only two studies directly provide the proportion of construction time saving. Summary of findings and available details are given in Table 4.13.

Table 4.13. Findings from literature about construction time saving.

Research	**Detail Information**				**No. of BIM Utilized Project**	**No. of non-BIM Project**	**Duration Change as % of non-BIM case**
	Average Construction Area m^2 (Gross Floor Area)	**Contract Price**	**Type**	**Country / Region**			
Li *et al.*, 2014	28.124,00 m^2	n/a	Data Center	China	1	n/a	-26,7%
Dodge Data and Analytics, 2017	26.729,84 m^2	n/a	Hospital	U.S.A.	1	n/a	-18%

4.1.3.11. Accuracy in Cost Estimation. When examining the data obtained from the literature regarding the accuracy in cost estimation provided by BIM utilization, there is an undisputed consensus that BIM utilization contributes to better estimation. However, it is observed that the literature presents a wide range of values. Summary of findings and available details are given in Table 4.14.

Table 4.14. Findings about accuracy improvement in cost estimation with BIM.

Research	**Detail Information**				**No. of BIM Utilized Project**	**No. of non-BIM Project**	**Net Difference for Cost Deviations**
	Average Construction Area m^2 (Gross Floor Area)	**Contract Price**	**Type**	**Country / Region**			
Poirier *et al.* 2015	20.512,63 m^2	$5.162.500	Building / Various	Canada	3	1	-2.00%
Poirier *et al.* 2015	n/a	$2.150.0	Distinct Energy Station	Canada	3	1	48.00%

Table 4.14 Findings about accuracy improvement in cost estimation with BIM. (cont.)

Research	Detail Information				No. of BIM Utilized Project	No. of non-BIM Project	Net Difference for Cost Deviations
	Average Construction Area m^2 (Gross Floor Area)	Contract Price	Type	Country / Region			
Gilligan and Kunz, 2007	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Staub-French and Khanzode, 2007	12.511,58 m^2	$53.000.0	Various	U.S.A.	2	n/a	n/a

4.1.3.12. Accuracy in Schedule Estimation. When examining the data obtained from the literature regarding the accuracy in schedule estimation provided by BIM utilization, there is an undisputed consensus that BIM utilization contributes to better estimation. However, it is observed that the literature presents a wide range of values. Summary of findings and available details are given in Table 4.15.

Table 4.15. Findings about accuracy improvement in schedule planning with BIM.

Research	Detail Information				No. of BIM Utilized Project	No. of non-BIM Project	Duration Change as % of non-BIM case
	Average Construction Area m^2 (Gross Floor Area)	Contract Price	Type	Country / Region			
Giel *et al.*, 2009	9.453,20 m^2	$7.986.36,5	Warehouse	U.S.A.	1	1	1.92%

Table 4.15 Findings about accuracy improvement in schedule planning with BIM. (cont.)

Research	Detail Information				No. of BIM Utilized Project	No. of non-BIM Project	Duration Change as % of non-BIM case
	Average Construction Area m^2 (Gross Floor Area)	Contract Price	Type	Country / Region			
Giel *et al.*, 2009	41.536,33 m^2	$43.078.809	Residential	U.S.A.	1	1	80.08%
Giel and Issa, 2013	8.683,00 m^2	$11.250.519	Residential	U.S.A.	1	1	15.38%
Barlish and Sullivan, 2012	n/a	n/a	Historical Building	n/a	2	2	10.00%
Barlish and Sullivan, 2012	n/a	n/a	Historical Building	n/a	2	2	8.00%

4.1.3.13. Reduced Number of RFIs. When examining the data obtained from the literature regarding the contribution of BIM to reduce number of RFIs, most of the studies supports the positive contribution while in only one of the cases in one research BIM project shows poorer performance. Summary of findings and available details are given in Table 4.16.

Table 4.16. Findings from literature about change of number of RFIs.

Research	Detail Information				No. of BIM Utilized Project	No. of non-BIM Project	Duration Change as % of non-BIM case
	Average Construction Area m^2 (Gross Floor Area)	Contract Price	Type	Country / Region			
Giel and Issa, 2013	9.453,20 m^2	$ 7.986.36,5	Warehouse	U.S.A.	1	1	-34.00%

Table 4.16 Findings from literature about change of number of RFIs. (cont.)

Research	Detail Information				No. of BIM Utilized Project	No. of non-BIM Project	Duration Change as % of non-BIM case
	Average Construction Area m² (Gross Floor Area)	Contract Price	Type	Country / Region			
Giel and Issa, 2013	41.536,33 m²	$ 43.078.809	Residential	U.S.A.	1	1	-43.00%
Giel and Issa, 2013	8.683,00 m²	$ 11.250.519	Residential	U.S.A.	1	1	-68.00%
Giel and Issa, 2013	3.336,42 m²	n/a	Retail and commercial	Canada	1		-4.80%
Barlish and Sullivan, 2012	n/a	n/a	Historical Building	n/a	2	2	-50.00%
Barlish and Sullivan, 2012	n/a	n/a	Historical Building	n/a	2	2	50.00%
Jones *et al.*, 2015	n/a	n/a	n/a	n/a	n/a	n/a	-50,00%

4.1.3.14. Productivity Gain. When examining the data obtained from the literature regarding the productivity gain provided by BIM utilization, there is an undisputed consensus that BIM utilization contributes to productivity improvement. Summary of findings and available details are given in Table 4.17.

Table 4.17. Findings from literature about productivity gain of design teams.

Research	Detail Information				No. of BIM Utilized Project	No. of non-BIM Project	Duration Change as % of non-BIM case
	Average Construction Area m² (Gross Floor Area)	Contract Price	Type	Country / Region			

Table 4.17 Findings from literature about productivity gain of design teams. (cont.)

Sacks and Barak, 2008	36.500,00 m^2	n/a	Residential	Israel	1	1	61.00%
Sacks and Barak, 2008	9.000,00 m^2	n/a	Faculty (Education)	Israel	1	1	55.00%
Sacks and Barak, 2008	13.000,00 m^2	n/a	Residential	Israel	1	1	21.00%
Sacks and Barak, 2008	18.000,00 m^2	n/a	Commercial	Israel	1	1	40.00%
Sacks and Barak, 2008	8.400,00 m^2	n/a	Residential	Israel	1	1	43.00%
Reizgevičius *et al.*, 2018	n/a	n/a	n/a	n/a	n/a	n/a	25.00%
Shin *et al.*, 2022	n/a	n/a	Subway	South Korea	3	3	2.90%

4.1.4. Cost of BIM

Although there is ample mention of various sub-items contributing to the costs of BIM implementation in the literature, data on the project-specific rates for each individual item could not be found. This may be attributed to the perception of many items (such as software, hardware, etc.) primarily as initial investment costs and the difficulty in establishing a standard average ratio for projects. Nevertheless, there are studies demonstrating the overall impact of BIM implementation on project costs which fluctuates between 0.2% and 6.2% in total.

Additionally, based on the limited number of studies available, it has been observed that as the size of the project budget increases, the proportion of the cost of BIM implementation to the total budget decreases. This may be attributed to the generally more cost-effective pricing offered for bulk purchases of software licenses, hardware, and other equipment, as well as the tendency for the number of white-collar workers

per square meter to decrease as the project grows. Summary of findings and available details are given in Table 4.18.

Table 4.18. Findings from literature about overall cost of BIM.

Research	**Detail Information**				**Cost of BIM as % of total budget**
	Average Construction Area m² (Gross Floor Area)	**Contract Price**	**Type**	**Country / Region**	
Garrett and Garside, 2003	n/a	n/a	n/a	n/a	1%
Giel *et al.*, 2013	n/a	n/a	n/a	n/a	0.5%
Azhar *et al.*, 2008	44.965,00 m²	$46.000.000,00	Hotel	U.S.A.	0.2%
Giel and Issa, 2013	700,00 m²	$8.844.073,00	Warehouse	U.S.A.	0.5%
Poirier *et al.*, 2015	20.512,63 m²	$5.162.500,00	Distinct Energy Project	Canada	6.2%
Rayal and Narayana, 2018	n/a	$13.769.000,00	Residential	India	3%
Ham *et al.*, 2018	661.134,00 m²	$900.000.000,00	High Rise	South Korea	0.23%

The total cost described for BIM implementations actually results from many factors. Moreover, many studies indicate that financial concerns are among the primary barriers to BIM adoption. However, it is observed in the literature that research on the costs of BIM applications tends to be more qualitative compared to research on benefits. Despite the initial investment costs such as software and hardware being more prominent, there are many other significant investment items that need to be taken

into account, and their economic impacts should also be determined. Most stated costs are given in Table A.2.

With the incorporation of their final opinions, the costs of BIM were categorized into a total of 4 main headings: technological costs, labor costs, adaptation costs and indirect costs.

The 4 BIM cost clusters and the cost types included in each cluster are shown in Table 4.19.

Table 4.19. Cost clusters according to expert opinion.

Technological Cost	Software Cost
	Hardware Cost
	Maintenance Cost
	Cost of Interoperability Solutions
Labor Costs	Training Cost
	Consultancy Cost
	Staff Salaries
	Increase in Subcontractor Cost
Adaptation Costs	Temporary Production Loss
	Cost of Developing Internal Workflow
	Cost of Customization
Indirect Costs	Resistance to Change
	Legal Issues

4.1.5. Software Types in BIM Ecosystem

The fundamental BIM software types identified through the literature review are presented in Table A.3.

With the incorporation of their final opinions, the BIM ecosystem software were categorized into a total of 5 main headings: Evaluation and Analysis Software, Data Management Software, Collaboration Software, Modelling Software, Visualization and Simulation Software.

The five BIM software clusters and the software types included in each cluster are shown in Table 4.20.

Table 4.20. BIM Ecosystem software clusters according to expert opinion.

Evaluation / Analysis Software	Engineering Analysis Software
	Design Verification + Code Validation Software
	Cost Analysis and Estimation Software
Data Management Software	Digital Twin Software / IoT
	Computerized Maintenance Management Software
	ERP
Collaboration Software	Common Data Environment / Data Sharing Platforms
	Interoperability Software
	3D Coordination Software
Modelling Software	BIM Modelling Software
	2D / 3D CAD Software
	Laser Scanning / Point Cloud Software
	Computational Design
	Generative Design
Visualization and Simulation Software	VR / AR / MR
	Rendering and Animation Software
	Schedule and Planning Software (4D)

4.1.6. Financial Performance Measures of BIM

When examining the ROI values obtained from the literature review, all studies consistently indicate a positive ROI ratio. This means that the benefits of implementing BIM in a project exceed the costs. However, there is a significant high fluctuation among the data. Summary of findings and available details are given in Table A.4.

The biggest issue with the data presented in the literature is the lack of detail regarding how the figures for both costs and savings are calculated. This is particularly evident in the data from Holder's Construction Company presented by Giel *et al.* (2013), where such information is missing. Additionally, it has been observed that older studies tend to report much higher ROI rates (Giel *et al.*, 2013; Giel and Issa, 2013). One potential reason for this could be that these studies were conducted at a time when there was a stronger emphasis on promoting the understanding of BIM usage. Based on this consideration, when the same analysis was repeated using examples from 2018 and beyond, it is observed that values fluctuate in narrower range.

4.2. Survey Findings

In this section, the results obtained for each criterion investigated in the survey will be presented. The summary of the results obtained separately for designers and contractor company employees is provided in Table 4.21 and Table 4.22, respectively.

Table 4.21. Summary of likert questions for designers.

Ranking #	**Criteria Code**	**Description**	**Average**	**No. of Ratings over 4**	**No. of Ratings 3**	**No. of Ratings under 3**
1	S2	Prestige and Reputation	4.83	12	-	-
2	I3	Efficient Meetings	4.58	11	-	1
3	I2	Less Dispute and Reduced Number of Change Orders	4.50	11	1	-
4	D3	Complex Design Capability	4.42	11	1	-
5	I6	Improved Coordination and Perception of Design	4.08	8	4	-
6	D1	More Efficient Design and Delivery Process	3.75	8	2	2
7	D2	More Effective Learning Process and Improved Adaptation	3.58	5	6	1
8	S5	Flexibility in Team Composition and Increased Globalisation	3.45	6	2	3
9	I1	Reduced Number of RFIs	3.33	7	-	5
10	S4	Improved H and S Protocols	3.25	5	5	2
11	D4	Improved Design Analysis	2.33	varies	varies	varies
12	S3	Energy Efficient Design	1.88	3	2	7

Table 4.22. Summary of likert questions for contractors.

Ranking #	Criteria Code	Description	Average	No. of Ratings over 4	No. of Ratings 3	No. of Ratings under 3
1	I6	Improved Coordination and Perception of Design	4.60	9	1	-
2	D3	Complex Design Capability	4.30	7	3	-
3	S2	Prestige and Reputation	4.30	9	-	1
4	I3	Efficient Meetings	4.00	8	2	-
5	I4	Reduced Hard-Copy Document and Easy Control of Documents	4.00	6	3	1
6	D2	More Effective Learning Process and Improved Adaptation	3.80	8	1	1
7	C1	Improved 3D Coordination in Site	3.70	6	2	2
8	I1	Reduced Number of RFIs	3.50	5	4	1
9	S5	Flexibility in Team Composition and Increased Globalisation	3.50	6	1	3
10	I2	Less Dispute and Reduced Number of Change Orders	3.40	3	6	1
11	C5	Increasing Involvement of Prefabrication	2.10	-	4	6

4.2.1. C1 – Improved 3D Coordination in Site

Criterion C1 was asked only to the contractor team due to their direct involvement in the relevant process. According to the results, out of the 10 respondents, 4 (or 40%) strongly agreed that the use of BIM reduces design-related issues on site. Two respondents agreed, two were neutral, one disagreed, and one strongly disagreed. Distribution of expert ratings is illustrated in Figure 4.1.

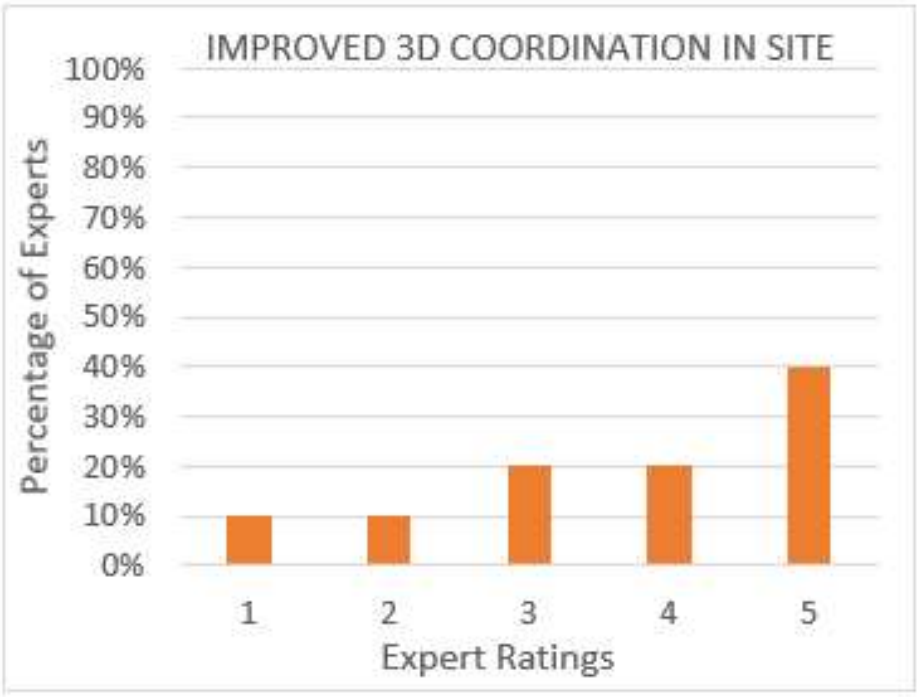

Figure 4.1. Expert ratings for improved 3D coordination in site.

4.2.2. C2 – Schedule Optimization and Faster Completion

Criterion C2 was asked to both contractor and design firm employees. According to the results, regarding the question about the contribution of BIM usage to schedule optimization, 9 out of 12 experts from design firms indicated that BIM contributes to schedule optimization, while 3 expressed a negative opinion. For the same criterion, 9 out of 10 experts from contractor firms responded, with 1 selecting the "No idea" option. Among the 9 respondents, 8 indicated that BIM contributes to schedule optimization, while 1 expressed a negative opinion. Distribution of expert ratings is illustrated in Figure 4.2.

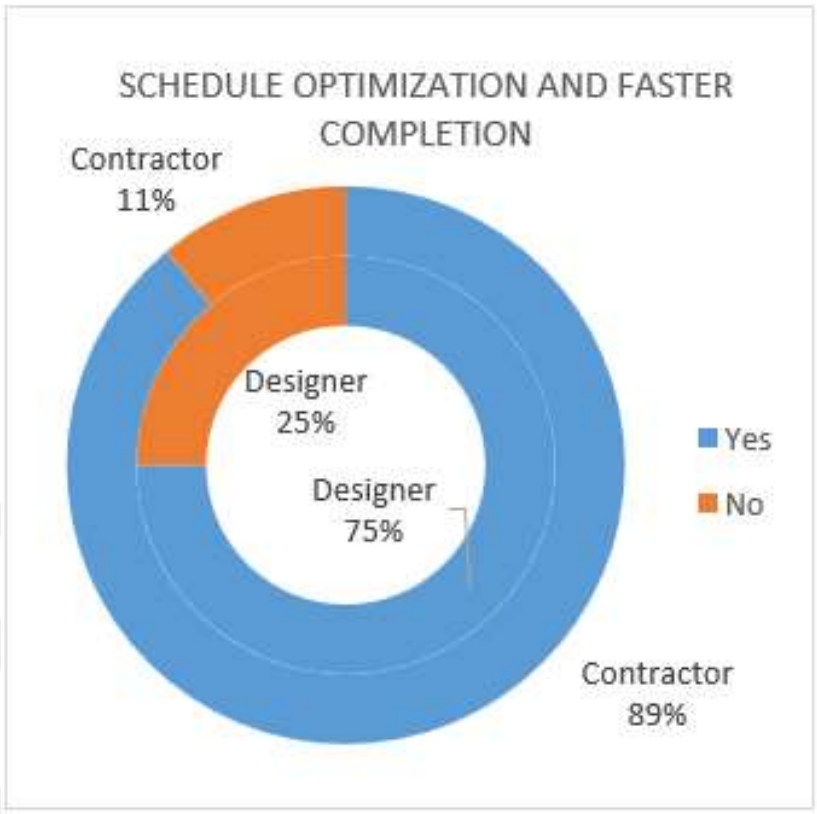

Figure 4.2. Expert ratings for schedule optimization.

When asked about the impact of BIM on "Project Duration", all 12 experts from design firms responded, providing a range of opinions: 3 experts reported a 10-25% reduction in project duration, 2 experts reported a 0-10% reduction, 2 experts stated there was no change, 2 experts reported a 0-10% increase, 1 expert reported a 10-25% increase, and 1 expert reported a 50-75% increase. Regarding the impact of BIM on "Project Duration", all 10 experts from contractor firms responded, with the majority indicating a reduction: 1 expert reported a 25-50% reduction in project duration, 2 experts reported a 10-25% reduction, 3 experts reported a 0-10% reduction, and 4 experts stated there was no change. Distribution of expert ratings is illustrated in Figure 4.3.

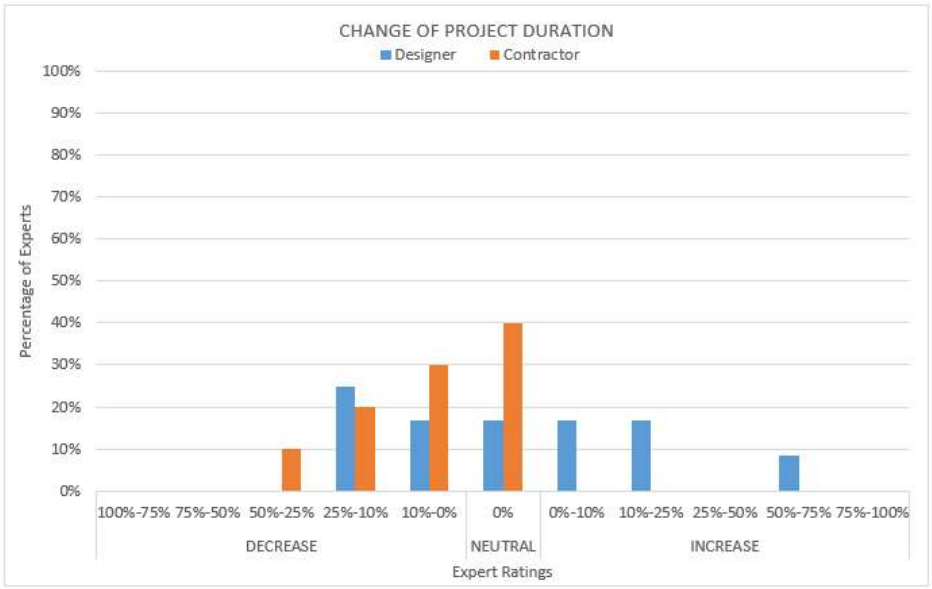

Figure 4.3. Expert ratings for project duration.

4.2.3. C3 – Change of Overall Project Cost

Criterion C3 was asked to both contractor and design firm employees. According to the results, all 12 experts from design firms responded to the question regarding the impact of BIM usage on overall project cost. The responses included a range of opinions on both cost increases and decreases: 1 expert reported a 10-25% cost decrease, 3 experts reported a 0-10% cost decrease, 2 experts reported no change, 1 expert reported a 10-25% cost increase, 2 experts reported a 25-50% cost increase, 1 expert reported a 50-75% cost increase, and 1 expert reported a 75-100% cost increase. Similarly, responses from 10 contractor firm participants on the same question were as follows: 2 experts reported a 10-25% cost decrease, 5 experts reported a 0-10% cost decrease, 2 experts reported no change, and 1 expert reported a 10-25% cost increase. Distribution of expert ratings is illustrated in Figure 4.4.

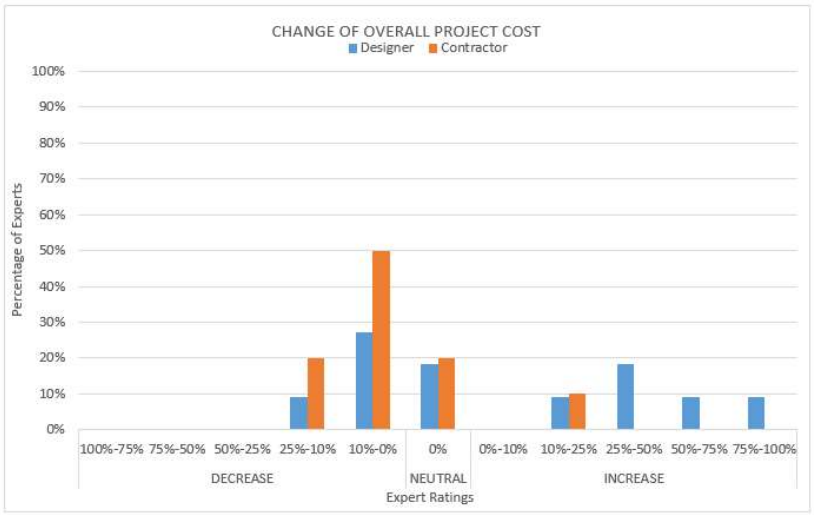

Figure 4.4. Expert ratings for change of overall project cost.

4.2.4. C4 – Less Rework

Criterion C4 was asked only to the contractor team due to their direct involvement in the relevant process. According to the results, 4 out of 10 respondents reported a 25-50% reduction in rework, 4 respondents reported a 10-25% reduction in rework, 1 respondent reported a 0-10% reduction in rework, and 1 respondent indicated that there was no change. Distribution of expert ratings is illustrated in Figure 4.5.

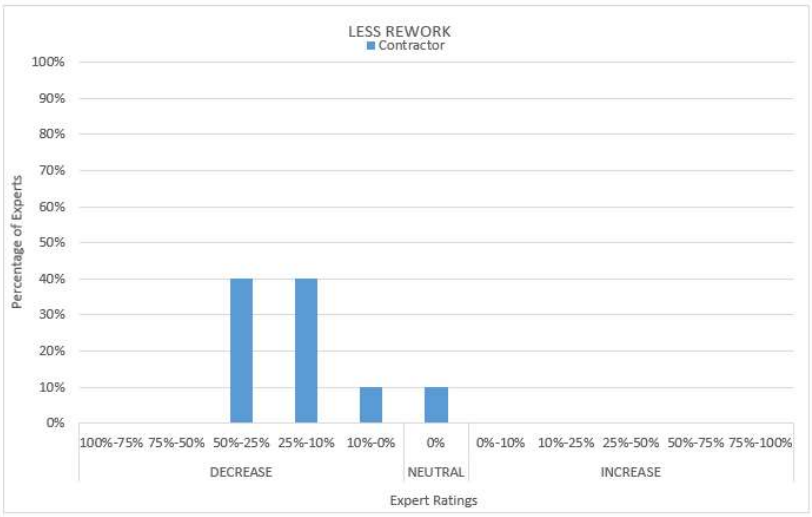

Figure 4.5. Expert ratings for change of overall project duration.

4.2.5. C5 – Increasing Involvement of Prefabrication

Criterion C5 was asked only to the contractor team due to their direct involvement in the relevant process. According to the results, 4 out of 10 respondents indicated that BIM usage had no effect on increasing the use of prefabrication, 3 respondents disagreed with the statement, and 3 respondents strongly disagreed with the statement. Distribution of expert ratings is illustrated in Figure 4.6.

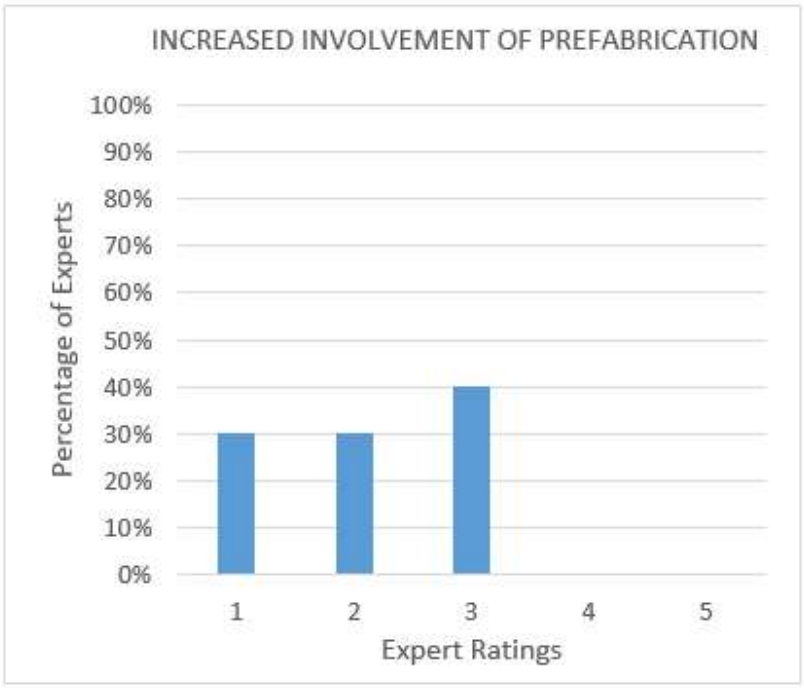

Figure 4.6. Expert ratings for increased involvement of prefabrication.

4.2.6. D1 – More Efficient Process of Design and Delivery

Criterion D1 was directed solely to the design team due to their direct involvement in the relevant process. According to the results, 3 out of 12 respondents strongly agreed that BIM usage contributes to a more effective design and delivery process, 5 respondents agreed with the statement, 2 respondents indicated that BIM usage had no effect, and 2 respondents disagreed with the statement. Distribution of expert ratings is illustrated in Figure 4.7.



Figure 4.7. Expert ratings for more efficient process of design and delivery.

4.2.7. D2 – More Effective Learning Process and Improved Adaptation

Criterion D2 was posed to both contractor and design firms' employees. According to the results, regarding the question about the impact of BIM usage on learning and adaptation, among the 12 experts from design firms, 4 strongly agreed, 1 agreed, 6 were neutral, and 1 strongly disagreed. Among the 10 respondents from contractor firms, 7 agreed, 1 strongly agreed, 1 indicated no effect, and 1 disagreed. Distribution of expert ratings is illustrated in Figure 4.8.



Figure 4.8. Expert ratings for more effective learning process and improved adaptation.

4.2.8. D3 – Complex Design Capability

Criterion D3 was posed to both contractor and design firms' employees. According to the results, regarding the question about the contribution of BIM usage on complex design capability, among the 12 experts from design firms, 6 strongly agreed, 5 agreed, 1 were neutral. Among the 10 respondents from contractor firms, 6 strongly agreed, 1 agreed, 3 indicated no effect. Distribution of expert ratings is illustrated in Figure 4.9.



Figure 4.9. Expert ratings for complex design capability.

4.2.9. D4 – Improved Design Analysis

To clarify various aspects of the relevant criterion, nine types of analyses commonly used in engineering processes were selected, and their frequency of use was queried among design team participants. According to the results, the majority reported that they never used any of the analysis types except for circulation analysis.

For circulation analysis, a slight majority indicated that they occasionally used it. Distribution of expert ratings grouped with respect to ratings and analysis types are illustrated in Figure 4.10 and Figure 4.11 respectively.

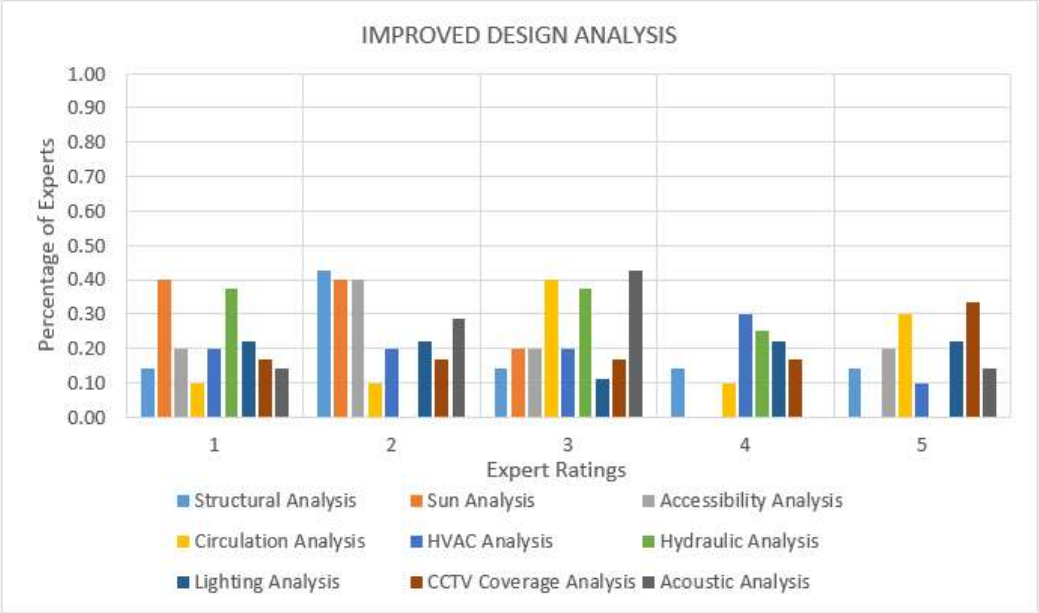

Figure 4.10. Expert ratings for improved design analysis – grouped by ratings.

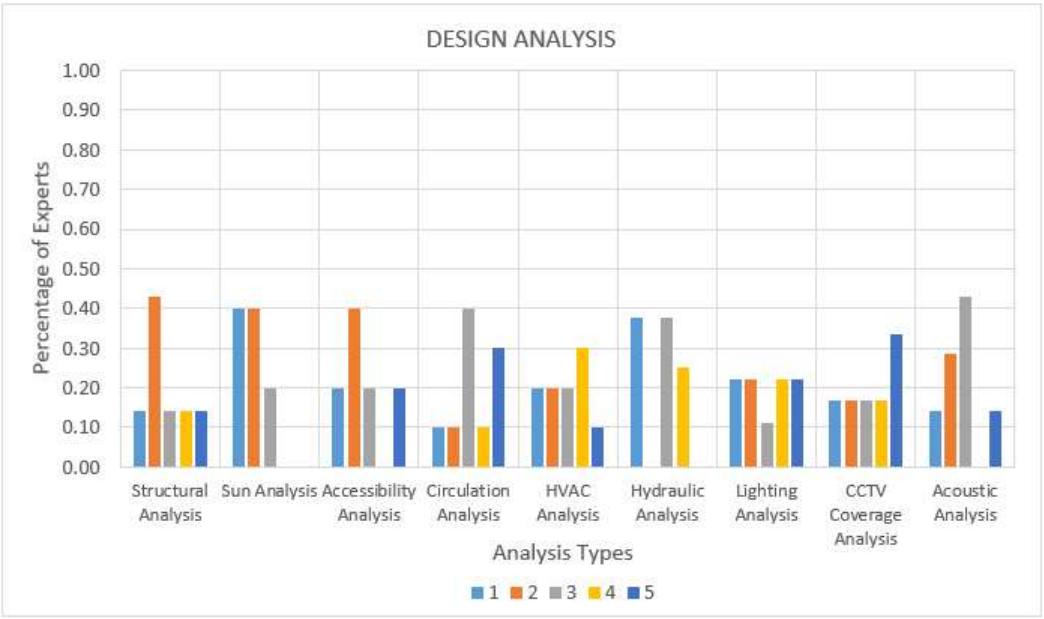

Figure 4.11. Expert ratings for improved design analysis – grouped by analysis types.

4.2.10. I1 – Reduced Number of RFIs

Criterion I1 was posed to both contractor and design firms' employees. According to the results, regarding the question about the contribution of BIM usage on reduced number of RFIs, among the 12 experts from design firms, 3 strongly agreed, 4 agreed, 4 disagreed and 1 strongly disagreed. Among the 10 respondents from contractor firms, 1 strongly agreed, 4 agreed, 4 indicated no effect and 1 disagreed. Distribution of expert ratings is illustrated in Figure 4.12.

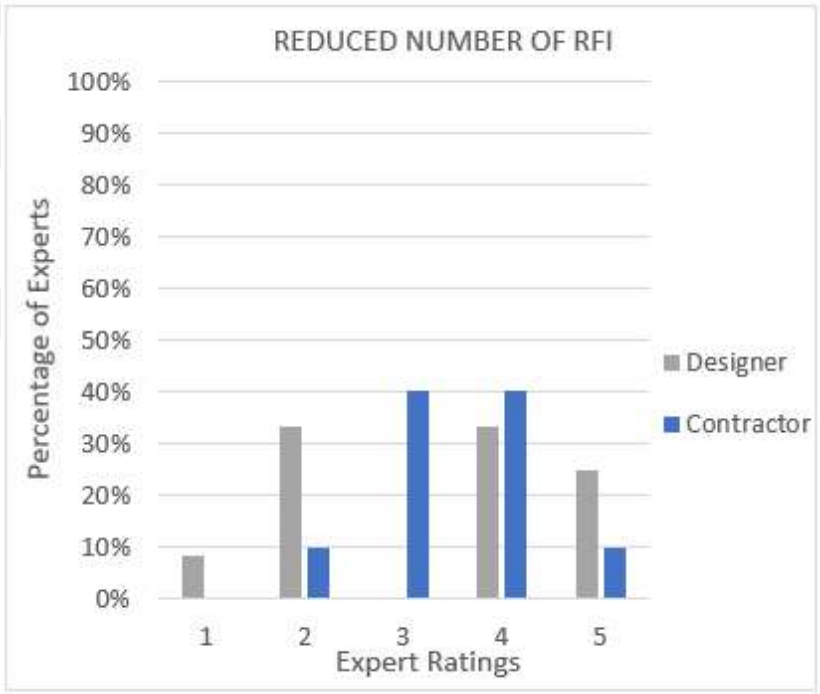

Figure 4.12. Expert ratings for reduced number of RFIs.

4.2.11. I2 – Less Dispute and Reduced Number of Change Orders

Criterion I2 was posed to both contractor and design firms' employees. According to the results, regarding the question about the effects of BIM usage on disputes and change orders, among the 12 experts from design firms, 7 strongly agreed, 4 agreed, 1 indicated no effect. Among the 10 respondents from contractor firms, 2 strongly agreed, 1 agreed, 6 indicated no effect and 1 disagreed. Distribution of expert ratings is illustrated in Figure 4.13.

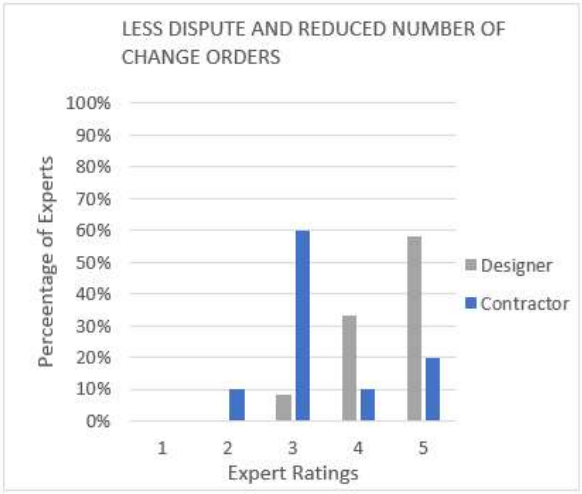

Figure 4.13. Expert ratings for less dispute and reduced number of change orders.

4.2.12. I3 – Efficient Meetings

Criterion I3 was posed to both contractor and design firms' employees. According to the results, regarding the question about the contribution of BIM usage on efficient meeting, among the 12 experts from design firms, 9 strongly agreed, 2 agreed, 1 disagreed. Among the 10 respondents from contractor firms, 2 strongly agreed, 6 agreed, 2 indicated no effect. Distribution of expert ratings is illustrated in Figure 4.14.

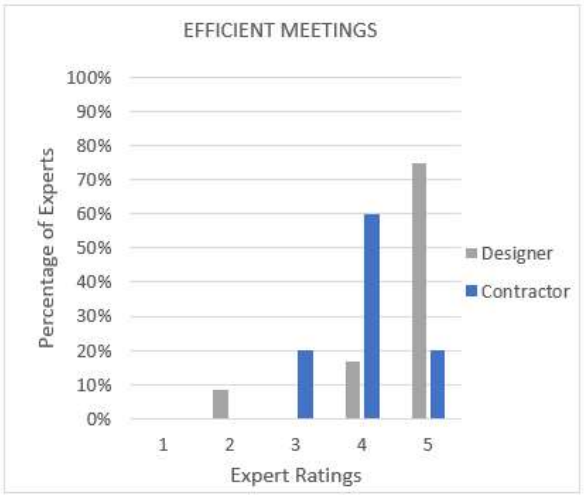

Figure 4.14. Expert ratings for efficient meetings.

4.2.13. I4 – Reduced Hard Copy Document and Easy Control of Documents

Criterion I4 was asked only to the contractor team due to their direct involvement in the relevant process. According to the results, regarding the question about the contribution of BIM usage on reduced hard-copy and easy control of documentation, among the 10 experts from contractor firms, 5 strongly agreed, 1 agreed, 3 indicate no effect and 1 disagreed. Distribution of expert ratings is illustrated in Figure 4.15.



Figure 4.15. Expert ratings for reduced hard copy document and easy control of documents.

4.2.14. I5 – More Efficient Facility Management

Due to the inability to reach any facility management experts working in enterprises utilizing BIM, the survey could not be conducted.

4.2.15. I6 – Improved Coordination and Perception of Design

Criterion I6 was posed to both contractor and design firms' employees. According to the results, regarding the question about the contribution of BIM usage on coordination and perception of design, among the 12 experts from design firms, 5 strongly agreed, 3 agreed, 4 indicated no effect. Among the 10 respondents from contractor firms, 7 strongly agreed, 2 agreed, 1 indicated no effect. Distribution of expert ratings is illustrated in Figure 4.16.



Figure 4.16. Expert ratings for improved coordination and perception of design.

4.2.16. P1 – Accuracy in Schedule Planning

Criterion P1 was asked only to the contractor team due to their direct involvement in the relevant process. 9 out of 10 experts from contractor firms responded, with 1 selecting the "No idea" option. According to the results, regarding the question about the contribution of BIM usage to schedule planning accuracy, 7 out of 10 experts from design firms indicated that BIM contributes to accuracy of planning, while 2 expressed a negative opinion. Distribution of expert ratings is illustrated in Figure 4.17.

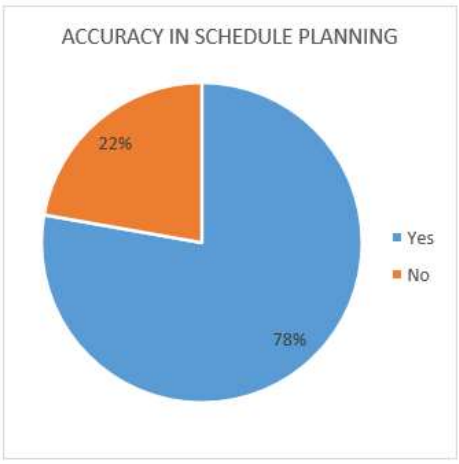

Figure 4.17. Expert opinions for Accuracy in Schedule Planning.

4.2.17. P2 – Accuracy in Cost Estimation

Criterion P2 was asked only to the contractor team due to their direct involvement in the relevant process. 8 out of 10 experts from contractor firms responded, with 2 selecting the "No idea" option. According to the results, regarding the question about the contribution of BIM usage to cost estimation accuracy, 6 out of 10 experts from contractor firms indicated that BIM contributes to accuracy of cost estimation, while 2 expressed a negative opinion. Distribution of expert ratings is illustrated in Figure 4.18.

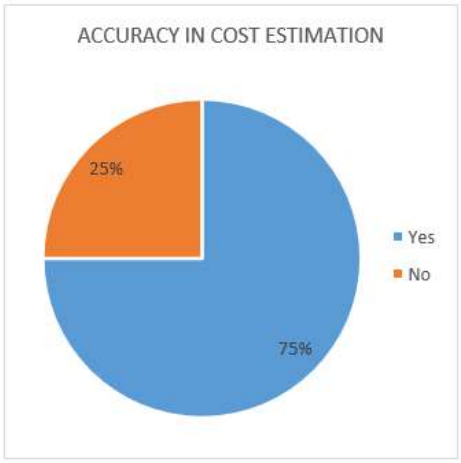

Figure 4.18. Expert opinions for accuracy in cost estimation.

4.2.18. S1 – Waste Mitigation

Criterion S1 was asked only to the contractor team due to their direct involvement in the relevant process. 8 out of 10 experts from contractor firms responded, with 2 selecting the "No idea" option. According to the results, regarding the question about the contribution of BIM usage to waste mitigation, 4 out of 10 experts from contractor firms indicated that BIM contributes to waste mitigation, while other 4 expressed increase in waste due to BIM. Distribution of expert ratings is illustrated in Figure 4.19.



Figure 4.19. Expert ratings for waste mitigation.

4.2.19. S2 – Prestige and Reputation

Criterion S2 was asked to both contractor and design firm employees. According to the results, regarding the question about the contribution of BIM usage to preference, 11 out of 12 experts from design firms indicated that positive contribution, while 1 expressed a negative opinion. For the same criterion, 7 out of 10 experts from contractor firms indicated positive contribution, while 3 expressed a negative opinion. Distribution of expert ratings is illustrated in Figure 4.20.

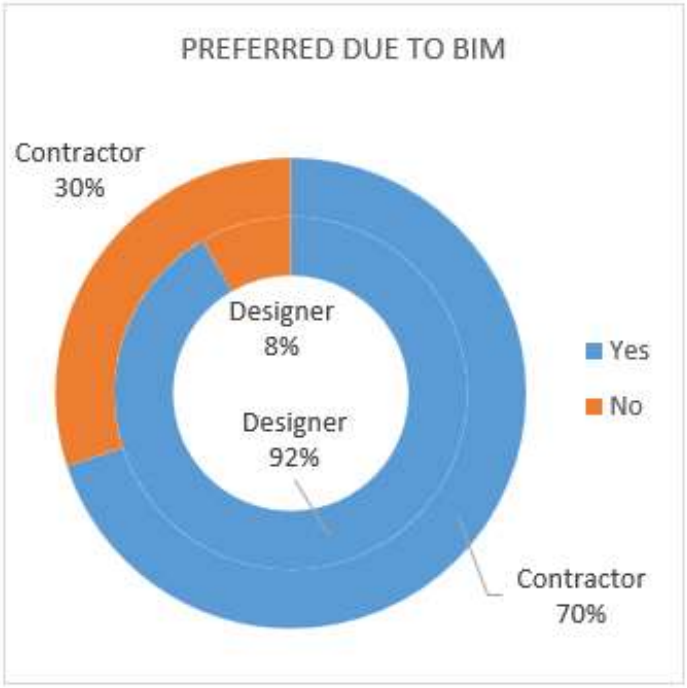

Figure 4.20. Findings about client preferences due to BIM.

When asked about the impact of BIM on "Prestige and Reputation", all 12 experts from design firms responded, providing a range of opinions: 10 strongly agreed, 2 agreed. Among the 10 respondents from contractor firms, 6 strongly agreed, 3 agreed, 1 disagreed. Distribution of expert ratings is illustrated in Figure 4.21.

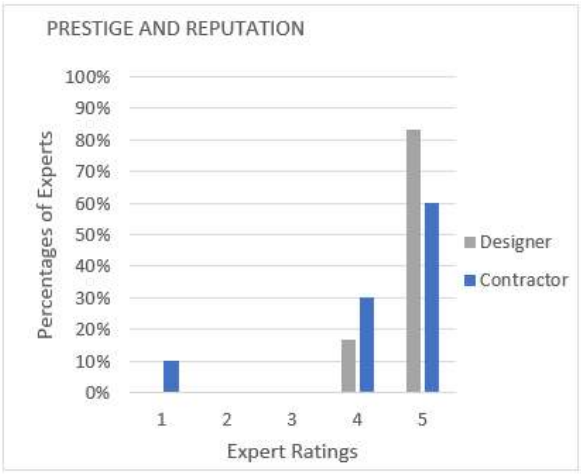

Figure 4.21. Expert ratings for prestige and reputation.

4.2.20. S3 – Energy Efficient Design

Criterion S3 was asked only to the design team due to their direct involvement in the relevant process. According to the results, regarding the question about the contribution of BIM usage on energy efficient design, among the 12 experts from design firms, 3 agreed, 2 indicate no effect, 3 disagreed and 4 strongly disagreed. Distribution of expert ratings is illustrated in Figure 4.22.

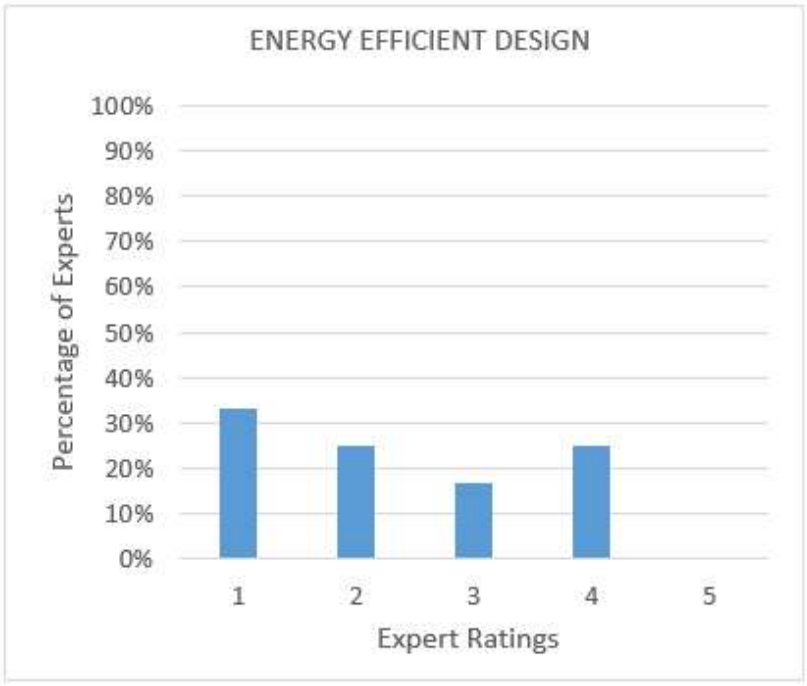

Figure 4.22. Expert ratings for implementation frequency of energy efficient design.

4.2.21. S4 – Improved H and S Protocols

Criterion S4 was posed to both contractor and design firms' employees. According to the results, regarding the question about the contribution of BIM usage on health and safety improvement, among the 12 experts from design firms, 1 strongly agreed, 4 agreed, 5 indicated no effect, 1 disagreed and 1 strongly disagreed. Among the 10 respondents from contractor firms, 1 strongly agreed, 4 agreed, 3 indicated no effect, 1 disagreed and 1 strongly disagreed. Distribution of expert ratings is illustrated in Figure 4.23.

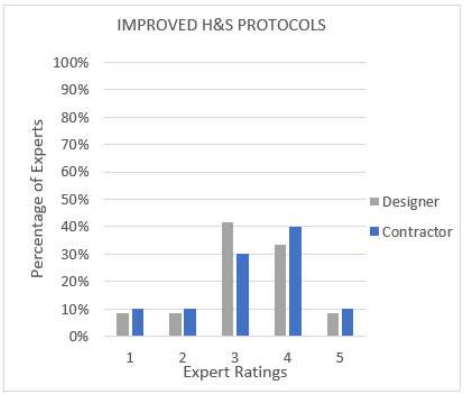

Figure 4.23. Expert ratings for improved H and S protocols.

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4.2.22. S5 – Flexibility in Team Composition and Increased Globalization

Criterion S5 was posed to both contractor and design firms' employees. According to the results, regarding the question about the contribution of BIM usage on flexibility in team composition, among the 12 experts from design firms, 3 strongly agreed, 4 agreed, 2 indicated no effect, 2 disagreed and 1 strongly disagreed. Among the 10 respondents from contractor firms, 3 strongly agreed, 3 agreed, 1 indicated no effect, 2 disagreed and 1 strongly disagreed. Distribution of expert ratings is illustrated in Figure 4.24.



Figure 4.24. Expert ratings for flexibility in team composition and increased globalisation.

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4.2.23. S6 – User Satisfaction

Due to the inability to reach any facility management experts working in enterprises utilizing BIM, the survey could not be conducted.

4.2.24. Change of Contract Value

Change of contract value was asked to both contractor and design firm employees. According to the results, 9 out of 12 experts from design firms responded to the question regarding the impact of BIM usage on contract value. The responses included a range of opinions on both cost increases and decreases: 1 expert reported a 10-25% value decrease, 4 experts reported no change, 4 experts reported a 10-25% value increase. Similarly, responses from 7 out of 10 contractor firm participants on the same question were as follows: 2 experts reported a 0-10% cost decrease, 2 experts reported no change, and 3 experts reported a 0-10% cost increase. Distribution of expert ratings is illustrated in Figure 4.25.

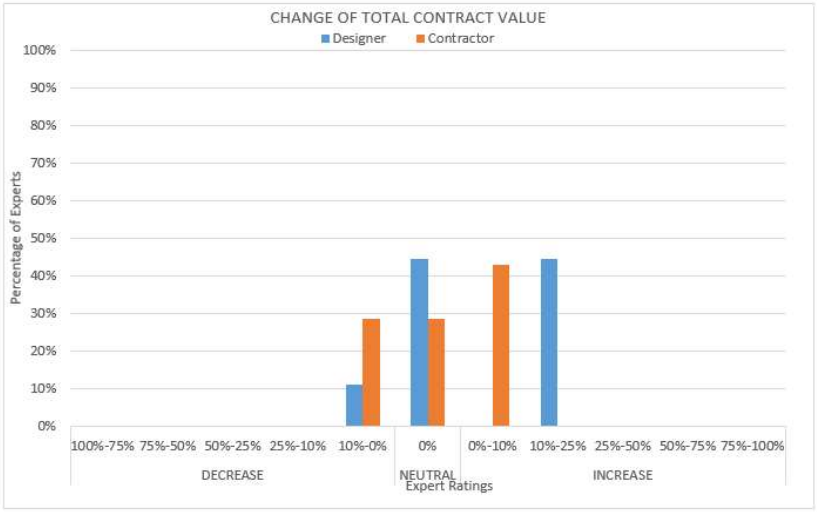

Figure 4.25. Expert ratings for change of total contract value.

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4.2.25. Change of Profitability

Change of Profitability was asked to both contractor and design firm employees. According to the results, 10 out of 12 experts from design firms responded to the question regarding the impact of BIM usage on profitability. The responses included a range of opinions on both cost increases and decreases: 2 experts reported a 25-50% profitability decrease, 3 experts reported no change, 5 experts reported a 0-10% profitability increase. Similarly, responses from 6 out of 10 contractor firm participants on the same question were as follows: 2 experts reported no change, 3 experts reported 0-10% profitability increase and 1 expert reported a 10-25% cost increase. Distribution of expert ratings is illustrated in Figure 4.26.

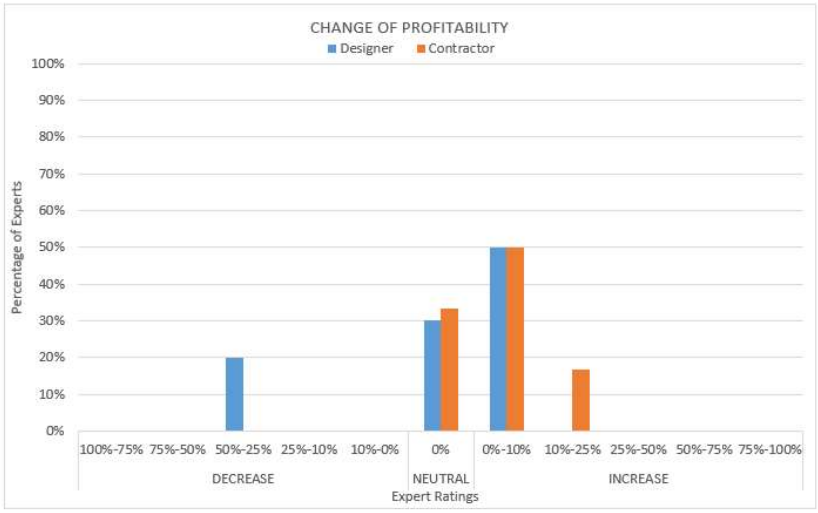

Figure 4.26. Expert ratings for change of profitability.

4.3. ANP Analysis Results

4.4. Unweighted Super Matrix

The priority values obtained from the pairwise comparisons are used to fill in sub-matrices for each node and cluster. Each submatrix is solved using the AHP method to determine the AHP weights, which are then entered into the appropriate positions in the super matrix, resulting in the unweighted super matrix. Since Super Decisions

software is used, the unweighted super matrix is automatically generated by the software once the pairwise comparisons are entered. Resulting unweighted super matrix which reflects pairwise comparison results is shown in Table 4.23.

Table 4.23. Unweighted super matrix.

	C1	**C2**	**C3**	**C4**	**C5**	**A1**	**A2**	**A3**	**A4**	**A5**	Max. BIM Benefit
C1	0	0	0	0	0.2	0.16667	0.11169	0	0.12827	0	0.11094
C2	0	0	0	0	0.8	0	0.26159	0	0.27635	0.49339	0.21148
C3	1	0	0	0	0	0	0.10083	0	0	0.1958	0.10394
C4	0	0.14286	0	0	0	0	0	0	0	0.31081	0.05307
C5	0	0.85714	0	0	0	0.83333	0.52588	1	0.59538	0	0.52057
A1	0.19192	0.0	0.25	0.75	0.333333	0.2	0.17862	0	0.51219	0	0
A2	0	0	0	0	0.66667	0	0.11252	0.0716	0.09764	0	0
A3	0	0	0.75	0	0	0	0	0	0.24403	1	0
A4	0.63371	0	0	0.25	0	0.8	0.70886	0.47612	0.14614	0	0
A5	0.17437	0.8	0	0	0	0	0	0.45227	0	0	0
Max. BIM Benefit	0	0	0	0	0	0	0	0	0	0	0

4.4.1. Weighted Super Matrix

The Weighted Super Matrix is obtained by multiplying the values in the Unweighted Super Matrix by the priority values of their respective clusters. Following this, each cell in a column is divided by the total of that column to normalize it, resulting in the Normalized Weighted Matrix. Since equal priority is evaluated for clusters, priority coefficients are equal and 0.50. Cluster matrix and resulting normalized weighted super matrix are given in Table 4.24 and Table 4.25 respectively.

Table 4.24. Cluster matrix.

Cluster Node Labels	**Alternatives**	**Criteria**	**Goal**
Alternatives	0.50	0.50	0.00
Criteria	0.50	0.50	1.00
Goal	0.00	0.00	0.00

Table 4.25. Normalized weighted super matrix.

	C1	**C2**	**C3**	**C4**	**C5**	**A1**	**A2**	**A3**	**A4**	**A5**	Max. BIM Benefit
C1	0	0	0	0	0.1	0.08333	0.05585	0	0.06413	0	0.11094
C2	0	0	0	0	0.4	0	0.13079	0	0.13817	0.24669	0.21148
C3	0.5	0	0	0	0	0	0.05042	0	0	0.0979	0.10394
C4	0	0.07143	0	0	0	0	0	0	0	0.15541	0.05307
C5	0	0.42857	0	0	0	0.41667	0.26294	5	0.29769	0	0.52057
A1	0.09596	0.1	0.25	0.75	0.16667	0.1	0.08931	0	0.2561	0	0
A2	0	0	0	0	0.33333	0	0.05626	0.0358	0.04882	0	0
A3	0	0	0.75	0	0	0	0	0	0.12202	0.5	0
A4	0.31685	0	0	0.25	0	0.4	0.35443	0.23806	0.07307	0	0
A5	0.08719	0.4	0	0	0	0	0	0.22614	0	0	0
Max. BIM Benefit	0	0	0	0	0	0	0	0	0	0	0

4.4.2. Limit Super Matrix and Rankings

The Limit Super Matrix is obtained by multiplying the Normalized Weighted Super Matrix by itself until it converges to a stable value. The Super Decisions software generates this matrix automatically. The final values for decision-making problems are

derived from this matrix. Resulting limit super matrix and final priorities of nodes are shown in Table 4.26 and Table 4.27 respectively.

Table 4.26. Limit super matrix.

	C1	C2	C3	C4	C5	
C1	0.0121	0.0121	0.0121	0.0121	0.0121	
C2	0.03142	0.03142	0.03142	0.03142	0.03142	
C3	0.12258	0.12258	0.12258	0.12258	0.12258	
C4	0.00859	0.00859	0.00859	0.00859	0.00859	
C5	0.18028	0.18028	0.18028	0.18028	0.18028	
A1	0.25754	0.25754	0.25754	0.25754	0.25754	
A2	0.02233	0.02233	0.02233	0.02233	0.02233	
A3	0.03251	0.03251	0.03251	0.03251	0.03251	
A4	0.23112	0.23112	0.23112	0.23112	0.23112	
A5	0.10153	0.10153	0.10153	0.10153	0.10153	
Max. BIM Benefit	0	0	0	0	0	
	A1	A2	A3	A4	A5	Max. BIM Benefit
C1	0.0121	0.0121	0.0121	0.0121	0.0121	0.0121
C2	0.03142	0.03142	0.03142	0.03142	0.03142	0.03142
C3	0.12258	0.12258	0.12258	0.12258	0.12258	0.12258
C4	0.00859	0.00859	0.00859	0.00859	0.00859	0.00859
C5	0.18028	0.18028	0.18028	0.18028	0.18028	0.18028
A1	0.25754	0.25754	0.25754	0.25754	0.25754	0.25754
A2	0.02233	0.02233	0.02233	0.02233	0.02233	0.02233
A3	0.03251	0.03251	0.03251	0.03251	0.03251	0.03251
A4	0.23112	0.23112	0.23112	0.23112	0.23112	0.23112
A5	0.10153	0.10153	0.10153	0.10153	0.10153	0.10153
Max. BIM Benefit	0	0	0	0	0	0

Table 4.27. Priorities of nodes.

	Abbr.	Name	Normalized By Cluster	Limiting	Ranking
CRITERIA	**C5**	Enhanced Information Management	0.50788	0.180283	1
	C3	Efficient Construction	0.34532	0.122579	2
	C2	High-quality Design	0.08852	0.031424	3
	C1	Accurate Planning	0.03409	0.012102	4
	C4	Improved Sustainability	0.02419	0.008587	5
ALTERNATIVES	**A1**	Modelling Software	0.39927	0.257541	1
	A4	Collaboration Software	0.3583	0.231116	2
	A5	Data Management Software	0.15741	0.101531	3
	A3	Evaluation / Analysis Software	0.0504	0.03251	4
	A2	Visualization and Simulation Software	0.03462	0.022328	5

5. DISCUSSIONS

5.1. Evaluation of Survey Findings

The main aim of the paper is to extend the current state of knowledge about economic value of BIM utilization and develop a decision supportive model to find best suited BIM software category to invest.

The scope of the research is to assess perception of BIM benefits and total economic value of BIM use in Turkey as well as to develop a decision supportive model to determine the best suited BIM software category for Turkish designers to maximize benefits of BIM utilization.

The research questions of this study are as follows:

- What are the benefits of BIM utilization and what are their economic impacts?
- What are the costs associated with BIM utilization?
- What is the overall economic impact of BIM utilization?
- How efficiently are the benefits of BIM being realized from the perspective of Turkish contractors and designers?
- What are the priorities for BIM software investment for Turkish design firms?

To answer the research questions, a comprehensive literature review was initially conducted. The literature review focused on the benefits, costs, and overall economic impact of BIM utilization.

To examine the impact of BIM benefits on the Turkish construction sector and the overall economic impact of BIM utilization, a survey was conducted with experts, managers, and business owners in the AEC sector who have experience with both BIM-utilized and non-BIM-utilized project types. The survey consists of questions

investigating how BIM benefits are experienced by Turkish designers and contractors, as well as questions measuring the overall durational and economic impacts of BIM utilization on projects. The questions regarding BIM benefits were prepared based on the benefits identified through the literature review, aiming to understand the extent to which these benefits are realized in the Turkish construction sector. Since the benefit of increased design capability encompasses several subtopics, multiple questions related to various engineering analyses were asked to address this benefit comprehensively. In the survey questions related to BIM benefits, the 5-point Likert scale is used to determine positive and negative contributions. However, for the questions D4-Improved Design Analysis and S3-Energy Efficient Design, the focus is on determining the frequency of use. To investigate the economic impacts of BIM usage, questions were asked about reputation, competitive advantage, and the proportional changes in total budget, profitability, and costs that constitute cash flow. For durational impacts, questions were asked about the proportional changes in planning success, total duration, and delays in order to have a comprehensive perception.

Lastly, a decision-supportive model was developed to assist design firms that have adopted BIM or are considering transitioning to BIM in making more informed investment decisions. To achieve this, a semi-structured workshop was first conducted with a focus group of BIM experts to categorize BIM benefits, BIM costs, and BIM software types. Due to the multi-criteria and alternative nature of the problem, as well as the interactions between components, the ANP method was preferred. Using the benefit and software categories obtained, a relation matrix was determined based on expert opinions, followed by the creation of pairwise comparison matrices. Subsequently, the ANP model was established and analyzed using Super Decisions software.

5.2. Contractor Companies' Perspective

From the perspective of contractor firm employees, the highest score was awarded to I6 – Improved Coordination and Perception of Design. This is aligned with the literature as expected which indicates a strong positive contribution (Manning and

Messner, 2008; Petrova *et al.*, 2017). The second highest score was given to D3 – Complex Design Capability. This is aligned with the literature as expected which indicates increasing capability and variability of engineering analysis (Ren *et al.*, 2018; Siddiqui *et al.*, 2021; Carvalho *et al.*, 2021). Evaluating these two results together suggests that, for contractor firm employees, BIM implementations significantly contribute to the integration between the site and the design team.

Moreover, one of the highest-rated benefit experienced was prestige and reputation (S2). Considering that the expectation from construction firms is to deliver high-quality with low price in time, BIM usage has become a significant factor in their selection due to its strengths in visualization, contribution to collaboration and enhancement of design quality. These findings support the views in the literature that BIM applications enhance companies' prestige and create new business opportunities (Bryde *et al.*, 2013; Dodge Data and Analytics, 2017).

In terms of site-related benefits, relatively low degree of contribution is seen. Multidisciplinary 3D visualization and clash detection enable to detect physical and technical design conflicts rapidly and accurately. Many research indicate reduction of physical clashes resulting significant cost and time saving (Barlish and Sullivan, 2012; Giel and Issa, 2013, 2014; Won *et al.*, 2016). The contribution of BIM to 3D coordination in site related works (C1) is rated relatively low by contractor employees, with an average score of 3.7 and a high standard deviation. Despite indicated positive contribution, negative ratings beside positive ratings suggests that the benefits of BIM are not fully realized on-site in Turkey as it is in developed countries and that addressing inefficiencies could significantly enhance overall benefits. Prefabrication (C5) holds substantial potential benefits for the construction sector, including design freeze at early stages, better supervision, reduced construction costs, shortened construction time, and improved sustainability (Tam *et al.*, 2007). Furthermore, integrating prefabrication with BIM can yield benefits such as exploring design constraints for fabricators, reduced design errors in the manufacturing phase, reduced production time, and reduced implementation time due to improved coordination (Mostafa *et al.*, 2020).

However, survey results indicate that none of the contractor respondents believe that BIM supports the increase in prefabrication usage, as reflected by an average score below 3, making it one of the lowest-rated items. Considering the dynamic conditions of the global construction market and rising green concerns, BIM-prefabrication integration could support prefabrication usage and enhance sustainability. On the other hand, research suggest that BIM usage enhances coordination between the design process and the construction site and reduces rework. Hwang *et al.* (2019) found that BIM implementation may reduce rework up to 4.8% (Hwang *et al.*, 2019). The research by Lee *et al.* (2012) reports potential savings in rework due to BIM usage in the project were found to be between 0.02% and 0.03%. Moreover, it is believed that the use of BIM, which helps reduce rework, can also contribute to the reduction of waste material (Won *et al.*, 2013; Cheng and Ma, 2013). Indeed, the benefits C4 – Less Rework and S1 – Waste Mitigation were positively experienced by almost all participants as expected which indicates construction process is positively affected by BIM utilization.

In the literature, one of the most significant contributions of BIM application is shown as the reduced number of change orders. Indeed, in various research, findings indicate that BIM facilitates to decrease both of number of change order (Papajohn and El Asmar, 2021; Giel *et al.*, 2013, Barlish and Sullivan, 2012) as well as costs related to them (Giel and Issa, 2013; Lu *et al.* ; 2013). Controversially, I2 – Less Dispute and Reduced Number of Change Orders received a relatively low average score, placing it among the lowest-ranked benefits. Considering that improved coordination and perception of design were rated the highest by contractor firm employees, this appears contradictory. One possible explanation is that designs, which used to be modified mostly during construction, are now better understood due to enhanced capabilities and face significantly more revision requests during the design phase itself. Indeed, the benefits C4 – Less Rework and S1 – Waste Mitigation were positively experienced by almost all participants, supporting the notion that the mentioned change orders and disputes are more related to the design process than the construction process.

Looking at the impact of BIM implementations on schedule and time management, the majority of contractor firm employees provided positive feedback across all metrics assessed in the survey, including total duration, planning success (P1), and schedule optimization (C2). Specifically, 89% of participants believed that BIM positively impacts schedule optimization, while 78% felt that BIM usage leads to more successful schedule planning. Although opinions on the overall impact on total duration were less strongly positive, no participants expressed negative opinion. Collectively, these findings indicate that BIM implementations are effective in ensuring accurate planning and execution which supports literature findings indicating time saving during construction phase (Li *et al.*, 2014; Dodge Data and Analytics, 2017), improved accuracy in schedule estimation (Giel *et al.*, 2009, Barlish and Sullivan, 2012) and schedule optimization (Li *et al.*, 2014).

BIM enables more detailed and realistic preliminary design. Moreover, BIM software can calculate and store quantity take off data dynamically. Therefore, more detailed and realistic cost estimation is enabled. Thus, many research positive effect on cost estimation in preliminary design phase (Poirier *et al.*, 2015; Gilligan and Kunz, 2007; Staub-French and Khanzode, 2007). As a collaborative and holistic design environment, BIM offers reducing in design error and misinterpretation, facilitating construction cost to be mitigated. The literature review results indicate a clear consensus regarding the impact of BIM usage on construction cost saving (Barlish and Sullivan, 2012; Lu *et al.*, 2014; Dodge Data and Analytics, 2017, Bebani, 2022; Li *et al.*, 2014, Khanzode *et al.*, 2008). Regarding the impact of BIM implementations on cost management, the majority of contractor firm employees expressed positive opinions across all metrics, including total project cost (C3), accuracy of cost estimation (P2), profitability, and contract value changes. However, there were also some negative opinions regarding the direct economic impact on the three metrics of total project cost, contract value changes, and profitability. This contrast, not seen in time management metrics and literature, may indicate a comparatively lower contribution to cost management in Turkey. Another possible reason could be that budget deviations are harder to pinpoint due to various factors in inflationist business environment of Turkish con-

struction market and weaker business culture in terms of recording project data which leads more subjectively assessments. Despite 75% of participants reporting a positive impact on planning, the less clear-cut impact on overall effectiveness suggests areas for improvement in site-technical office integration in terms of cost management.

In terms of information management, literature review indicates that BIM contributes to efficient meetings, enhanced document management and reducing RFIs. In the construction industry, since the end product is a 3D structure, discussing the structure based on its 3D BIM model during design meetings helps reduce communication gaps in meetings (Rischmoller *et al.*, 2017; Majumdar *et al.*, 2022). Moreover, promoting model-based thinking, BIM projects require less printed document to collaborate and BIM enhances document management (Jones *et al.*, 2015). According to survey results, both meeting efficiency (I3) and the reduction in the need for hard copies (I4) leading to more effective information management received high scores from most participants which support literature findings as expected. However, there is relatively weak contribution regarding the number of RFIs (I1) whereas many research show that BIM contributes on mitigating number of RFIs (Giel and Issa, 2013; Barlish and Sullivan, 2012). This suggests that while BIM strengthens the coordination between active stakeholders—such as designers, contractors, and clients—throughout the project, it may not deliver the expected benefits in Turkey, particularly in areas involving suppliers where BIM adoption is still low unlike developed countries research are conducted. Consequently, this supports the notion that for BIM to yield maximum efficiency, it must be embraced by all stakeholders.

BIM is thought to disseminate technical knowledge, thereby reducing the need for specialized expertise and experience. Thus, Ghafar *et al.*, 2018 states that BIM implementation reduces dependence on local workforce in fields such as design and planning, enabling collaboration with experts from around the world for higher expertise and more cost-effective services. Additionally, Lu *et al.* (2013) show the use of BIM as a learning tool and its potential for facilitating project adaptation leads to man-hour gains. However, when considering the survey findings there are no strong

positive feedbacks in terms of adaptation (D2) and the expansion of the subcontractor portfolio (S5). One possible explanation for this is that both firms and employees have not yet achieved the desired level of BIM adaptation. Indeed, many research indicate lower adoption of BIM for small and medium size subcontractors (Franco *et al.*, 2015; Hosseini *et al.*, 2016) while one of the most cited adoption barriers is lack of technical knowledge (Won *et al.*, 2013; Volk *et al.*, 2014; Giel and Issa, 2013). Therefore, BIM adaptation itself poses a barrier, reducing potential benefits before the project's adaptation can take place. This indicates that while BIM has significant potential to improve coordination and information management, its full benefits are not yet realized due to insufficient adoption among all parties involved in the construction ecosystem. To maximize BIM's effectiveness, comprehensive adoption and integration across all project stakeholders are necessary.

Briefly, while contractor firm employees recognize significant benefits of BIM in coordination and design perception, there are areas, particularly in cost management, where further advancements could enhance the overall efficiency and effectiveness of BIM implementations. Summary of findings and comparisons with literature are given in Table 5.1.

Table 5.1. Summary of survey findings for contractors.

Aggregated benefit	**Control criteria**			**Point of departure contractors' perspective**	**Literature**	**Accordance with literature and possible explanation**
	Criterion Code	**Description**	**Rating**			
Site-design team integration	I2	Less Dispute and Reduced Number of C.O.	3.4	Strong positive in construction phase / moderately positive in preliminary design	Strong positive (e.g. Hwang *et al.*, 2019)	Unrealistic expectations / misuse of technological advance
	D3	Complex Design Capability	4.3			

Table 5.1 Summary of survey findings for contractors. (cont.)

Aggregated benefit	**Control criteria**			**Point of departure contractors' perspective**	**Literature**	**Accordance with literature and possible explanation**
	Criterion Code	**Description**	**Rating**			
	I6	Improved Coordination and Perception of Design	4.6			
	C4	Less Rework	+			
	S1	Waste Mitigation	+			
Time management	C2	Schedule Optimization	89% Positive	Strong positive	Strong Positive (e.g. Li *et al.*, 2013)	In accordance
	C2	Change of Project Duration	+			
	P1	Accuracy in Schedule Planning	78% Positive			
Economical	S2	Prestige	4.3	Strong positive for reputation and profitability; both (comparatively more) positive and negative f or costs and contract value	Strong Positive (e.g. Lu *et al.*, 2014)	Lack of transparency and recordings / fragile economy and fluctuations
	C3	Change of Project Cost	+/-			
	-	Change of Contract Value	+/-			
	-	Change of Profitability	+			
	P2	Accuracy in Cost Estimation	75% Positive			
Information management	I1	Reduced Number of RFIs	3.5	Strong positive in design perception / moderately positive in subcontractor integration / moderately positive in design-site	Strong Positive (e.g. Majumdar *et al.*, 2022)	Lack of bim adoption in Turkey / unrealistic expectations / misuse of technological advance
	I2	Less Dispute and Reduced Number of C.O.	3.4			
	I3	Efficient Meetings	4			

Table 5.1 Summary of survey findings for contractors. (cont.)

Aggregated benefit	**Control criteria**			**Point of departure contractors' perspective**	**Literature**	**Accordance with literature and possible explanation**
	Criterion Code	**Description**	**Rating**			
	I4	Reduced Hard-Copy Document and Easy Control of Documents	4	integration		
	I6	Improved Coordination and Perception of Design	4.6			
Ease and flexibility in team formation	D2	More Effective Learning Process and Improved Adaptation	3.8	Moderately positive	Strong Positive (e.g. Ghafar *et al.*, 2018)	Lack of bim adoption in Turkey
	S5	Flexibility in Team Compositon and Increased Globalisation	3.5			
Site capability	C1	Improved 3D Coordination in Site	3.7	Moderately positive / low integration of prefabrication	Strong Positive (e.g. Barlish and sullivan, 2012)	Lack of bim adoption in Turkey / lack of prefabrication
	C4	Less Rework	+			
	C5	Increasing Involvement of Prefabrication	2.3			
	D3	Complex Design Capability	4.3			
	S1	Waste Mitigation	+			

5.2.1. Design Companies' Perspective

From the perspective of design firm employees, the highest-rated benefit experienced was prestige and reputation (S2). Considering that the primary task of design firms is the production of geometric and non-geometric information, BIM usage has become a significant factor in their selection due to its strengths in visualization, contribution to information distribution, and enhancement of design quality. These findings support the views in the literature that BIM applications enhance companies' prestige and create new business opportunities (Bryde *et al.*, 2013; Dodge Data and Analytics, 2017). BIM usage appears to contribute positively to the more successful implementation of higher-quality designs on-site. BIM software enable more control on design compromising complex geometry with spatial and non-spatial data. In this way, complex analysis can be conducted (Ren *et al.*, 2018; Siddiqui *et al.*, 2021; Carvalho *et al.*, 2021) and complex designs can be safely realized (Ding *et al.*, 2014). Moreover, in various research, findings indicate that BIM facilitates to decrease both of number of change order (Papajohn and El Asmar, 2021; Giel *et al.*, 2013, Barlish and Sullivan, 2012) as well as costs related to them (Giel and Issa, 2013; Lu *et al.* ; 2013). BIM models can significantly improve perception of design by all relevant stakeholders via better visualization and cutting-edge technology integration such as VR (Petrova *et al.*, 2017) and transforming information distribution into a more homogeneous form for greater involvement of end users in the project from the planning stage to handover (Manning and Messner, 2008). Three related benefits-namely I2 (Less Dispute and Reduced Number of Change Orders), D3 (Complex Design Capability), and I6 (Improved Coordination and Better Perception of Design)-all received high ratings, indicating a positive impact and accordance with literature as expected.

In terms of information management, literature indicates positive contribution of BIM. Discussing the structure based on its 3D BIM model during design meetings helps reduce communication gaps in meetings (Rischmoller *et al.*, 2017; Majumdar *et al.*, 2022). RFI usage is necessary and unavoidable up to a certain point, but due to insufficient communication among stakeholders and deficiencies in projects, the num-

ber of RFIs can increase dramatically. Fortunately, research show that BIM can reduce number of RFIs significantly (Giel and Issa, 2013; Bockstael and Issa, 2016). Survey findings indicate that improved meeting efficiency (I3) received the second-highest rating while the contribution to the number of RFIs (I1) was relatively weaker. This suggests that while BIM significantly enhances meeting efficiency, its impact on reducing RFIs is not as pronounced. This suggests that while BIM strengthens the coordination between active stakeholders—such as designers, contractors, and clients—throughout the project, it may not deliver the expected benefits, particularly in areas involving suppliers. This could be due to the weaker BIM integration among suppliers. Consequently, this supports the notion that for BIM to yield maximum efficiency, it must be embraced by all stakeholders.

Since BIM is a collaborative and integrated process, errors caused by miscommunication can be eliminated more effectively. Moreover, repetitive tasks can be done automatically with the help of BIM software. Thus, design, presentation and delivery processes are expected to be faster. The literature review has yielded varying results regarding the impact of BIM usage on the total cost of the design team indicating both of cost increase (Lu *et al.*, 2014; Barlish and Sullivan, 2012; Lu *et al.*, 2015) as well as cost decrease (Sacks and Barak, 2008; Sholeh *et al.*, 2020). When examining the benefits related to design quality and efficiency, it is observed that respondents from design companies experienced relatively weaker contributions. Moreover, BIM applications enhance companies' prestige and create new business opportunities (Bryde *et al.*, 2013; Dodge Data and Analytics, 2017) facilitating to win higher priced contracts. Regarding the impact of BIM implementations on cost perspective, the majority of design firm employees expressed both positive and negative opinions across all metrics, including total project cost (C3), profitability, and contract value changes. Given the ability of BIM software and ecosystems to create a design much faster and present it more richly compared to traditional systems (D1), this might seem contradictory. However, the project's increased perception and accessibility by all stakeholders has led to a rise in revision and alternative study requests. This, combined with the misconception that design work has become simpler due to advanced technology, has resulted in a

diminished appreciation for design. Due to fragile economy and extremely competitive market conditions in Turkey, workload of designers is extremely high. This discrepancy can explain why the theoretical increase in speed and efficiency is not equally experienced in practice by Turkish designers which also support literature findings. Consequently, as evidenced in the findings, many designers have faced increased costs while profitability and project fees have declined. However, designers who work with clients that recognize the value of their work and who have successfully optimized their internal processes have economically benefited from BIM implementations. Moreover, model-based approach and collaboration philosophy of BIM allow the same model to serve as a substrate for various analyses required by different disciplines. Thus, different disciplines spend less time setting up their models to perform specialized checks in their areas and can focus their main concentration on conducting complex analyses. Through export models available in various formats from BIM models, a wide range of complex engineering analyses such as structural analysis (Ren *et al.*, 2018), fire simulations (Siddiqui *et al.*, 2021), and energy consumption analysis (Carvalho *et al.*, 2021) can be easily performed using the same model. However, all questions related to engineering analyses (D4) received the lowest scores in average indicating weak utilization. Each one of analysis types asked to experts scored below an average of 3, indicating a general perception that the integration of engineering analysis processes into BIM workflows is lacking across the industry. Given that integrated engineering analyses within BIM processes are expected to be faster and more accurate, the disconnect between these processes' points to a significant current inefficiency and an area of focus for future improvement. Particularly, the low integration of energy analyses (S3) within BIM processes suggests that the Turkish construction sector may not be adequately prepared for the rising trends in green economy and green funding. Moreover, BIM applications enhance companies' prestige and create new business opportunities (Bryde *et al.*, 2013; Dodge Data and Analytics, 2017) facilitating to win higher priced contracts.

Literature indicates both positive contribution of BIM implementation regarding time management. While Li *et al.*, 2014 state positive effect of BIM for schedule op-

timization, many research indicates significant time saving for design teams (Manning and Messner, 2008; Lu *et al.*, 2015; Sholeh *et al.*, 2020). According to survey findings, regarding impact of BIM implementations on time management, both positive and negative experiences are observed. While 75% of designer participants expressed a positive view on schedule optimization, opinions were mixed on the effect on the overall project duration (C2). It is believed that the increased technological capabilities can sometimes be exploited by other stakeholders, disproportionately increasing the workload on designers. Due to fragile economy and extremely competitive market conditions in Turkey, workload of designers is extremely high.

Ghafar *et al.*, 2018 states that BIM implementation reduces dependence on local workforce in fields such as design and planning, enabling collaboration with experts from around the world for higher expertise and more cost-effective services. Additionally, Lu *et al.* (2013) show the use of BIM as a learning tool and its potential for facilitating project adaptation leads to man-hour gains. Considering the benefits of adaptation (D2) and the expansion of the subcontractor portfolio (S5), there was no strong positive feedback. One possible explanation for this is that both firms and employees have not yet achieved the desired level of BIM adaptation. Therefore, BIM adaptation itself poses a barrier, reducing potential benefits before the project's adaptation can take place. This indicates that while BIM has significant potential to improve coordination and information management, its full benefits are not yet realized due to insufficient adoption among all parties involved in the construction ecosystem. To maximize BIM's effectiveness, comprehensive adoption and integration across all project stakeholders are necessary. This is also consistent with contractors' findings.

In summary, BIM implementations positively contribute to the capacity and capabilities of design firms, though there are areas for improvement, such as design and analysis integration. Additionally, while the enhanced technological capabilities increase competitive advantage as a reason for preference, the economic benefits are not realized to the same extent. Summary of findings and comparisons with literature are given in Table 5.2.

Table 5.2. Summary of survey findings for designers.

Aggregated benefit	**Control criteria**			**Point of departure contractors' perspective**	**Literature**	**Accordance with literature and possible explanation**
	Criterion Code	**Description**	**Rating**			
Site-design team integration	I2	Less Dispute and Reduced Number of C.O.	4.5	Strong positive	Strong positive (e.g. Hwang *et al.*, 2019)	In accordance
	D3	Complex Design Capability	4.42			
	I6	Improved Coordination and Perception of Design	4.08			
Time management	C2	Schedule Optimization	75% positive	Moderately positive in general / both positive and negative according to adoption level and clients' attitude	Strong Positive (e.g. Sholeh *et al.*, 2020)	Lack of bim adoption in Turkey unrealistic expectations / misuse of technological advance
	C2	Change of Project Duration	n/a			
Economical	S2 C3	Prestige Change of Project Cost	4.83 +/-	Strong positive for reputation and contract value / both positive and (comparatively more) negative for costs and profitability according to adoption level and clients' attitude	Both (comparatively more) positive and negative for costs and profitability (e.g. Lu *et al.*, 2015; sholeh *et al.*, 2020)	Lack of bim adoption in Turkey / fragile economy and fluctuations / extreme competition
	-	Change of Contract Value	+			
	-	Change of Profitability	+/-			

Table 5.2 Summary of survey findings for designers. (cont.)

Aggregated benefit	**Control criteria**			**Point of departure contractors' perspective**	**Literature**	**Accordance with literature and possible explanation**
	Criterion Code	**Description**	**Rating**			
Information management	I1	Reduced Number of RFIs	3.33	Strong positive in design-site integration / moderately positive in subcontractor integration	Strong positive (e.g. Majumdar *et al.*, 2022)	Lack of bim adoption in Turkey
	I2	Less Dispute and Reduced Number of C.O.	4.5			
	I3	Efficient Meetings	4.58			
	I6	Improved Coordination and Perception of Design	4.08			
Ease and flexibility in team formation	D2	More Effective Learning Process and Improved Adaptation	3.75	Moderately positive	Strong positive (e.g. Ghafar *et al.*, 2018)	Lack of bim adoption in Turkey
	S5	Flexibility in Team Composition and Increased Globalisation	3.45			
Design capability	D1	More Efficient Design and Delivery Process	3.75	Moderately positive in design capability and pace / weak in design analysis integration	Strong positive (e.g. Aladag *et al.*, 2016)	Lack of bim adoption in Turkey
	D3	Complex Design Capability	4.42			
	D4	Improved Design Analysis	2.33			
	S3	Energy Efficient Design	1.88			

5.3. Evaluation of ANP Results

When comparing the benefit categories based on the number of research references to the benefits comprising them, "Efficient Construction" and "Improved Sustainability" have received the most citations. They are closely followed by "High-Quality Design" and "Enhanced Information Management". The "Accurate Planning" cluster, however, ranks last in terms of citations. On the other hand, comparing the software categories based on the number of research references to the benefits comprising them, "Visualization and Simulation Software" received the most citations. It is followed by "Evaluation / Analysis Software", "Modelling Software", "Collaboration Software" and "Data Management Software" respectively.

According to the results of the pairwise matrix, the criterion that influences the most factors is "Enhanced Information Management", while the alternative influencing the most factors is "Modelling Software". The analysis results also indicate that the criterion with the most significant overall impact is Enhanced Information Management and the most impactful alternative is Modelling Software. When looking at the influence rates of the criteria, Enhanced Information Management accounts for 50.8% and Efficient Construction for 34.5%, collectively comprising 85.3% of the total benefit obtained from criteria cluster. Other benefits are relatively minor. From the designers' perspective, it is noteworthy that High-Quality Design remains at a low 8.8%, while Efficient Construction is significantly more prominent. Considering the overall benefit, the substantial portion of the projects in terms of budget, duration and environmental impact occur during the construction phase, which gives this result its significance. Regarding the influence rates of the alternatives, Modelling Software accounts for 39.9%, Collaboration Software for 35.8%, and Data Management Software for 15.7%, making these top three alternatives collectively 91.5% influential on total benefit obtained from alternative cluster. Given the critical role of information sharing in both design and construction processes and its contribution to increasing benefits, this result is expected.

The low impact of Engineering Analysis Software, a fundamental tool in design processes, at only 5%, indicates that the integration of engineering analyses into the BIM ecosystem has not yet reached the desired level.

These results differ significantly from the importance ranking given in the literature. A possible explanation for this discrepancy is that researchers may be more interested in areas where BIM applications are still developing, rather than in areas where BIM is already widely adopted. In contrast, AEC stakeholders have ranked the areas based on the benefits they have most frequently experienced.

6. CONCLUSION AND FUTURE RESEARCH

6.1. Conclusion Based on Research Findings

The survey results indicate some important findings. In Turkey, prestige is the most positively influencing benefit of adopting BIM. This suggests a growing awareness of the BIM concept and an emerging market demand in this direction. While BIM significantly enhances the integration of site-design teams, there remains room for improvement in this area. A key advantage of BIM is its strong enhancement of information management, which is identified as the most critical factor for achieving maximum benefit.

Furthermore, BIM positively impacts design capabilities, although there is a need to strengthen the integration of engineering analysis. Despite the major barrier of a lack of widespread BIM adoption, BIM slightly improves the opportunity for ease and flexibility in team formation.

Economically, BIM has a positive impact on Turkish contractors, improving their financial outcomes and time management processes. However, for Turkish designers, the impact of BIM has both positive and negative effects on their economic performance and time management.

Overall, while BIM presents numerous benefits and opportunities for the Turkish construction and design industry, ongoing efforts are needed to address its integration and adoption challenges to fully realize its potential.

According to the results of the pairwise matrix, the criterion that influences the most factors is “Enhanced Information Management”, while the alternative influencing the most factors is “Modelling Software”. The analysis results also indicate that the criterion with the most significant overall impact is Enhanced Information Man-

agement, and the most impactful alternative is Modelling Software. These findings support the view that information modeling and information management form the foundation of BIM.

The second most important benefit identified is "Efficient Construction". When looking at the influence rates of the criteria, Enhanced Information Management accounts for 50.8% and Efficient Construction for 34.5%, collectively comprising 85.3% of the total benefit. Other benefits are relatively minor. From the designers' perspective, it is noteworthy that High-Quality Design remains at a low 8.8%, while Efficient Construction is significantly more prominent. Considering the overall benefit, the substantial portion of the project's budgetary, temporal, and environmental impacts occur during the construction phase, which gives this result its significance.

The second most important alternative identified is "Collaboration Software". Regarding the influence rates of the alternatives, Modelling Software accounts for 39.9%, Collaboration Software for 35.8%, and Data Management Software for 15.7%, making these top three alternatives collectively 91.5% influential on total benefit. Given the critical role of information sharing in both design and construction processes and its contribution to increasing benefits, this result is expected. The low impact of Engineering Analysis Software, a fundamental tool in design processes, at only 5%, indicates that the integration of engineering analyses into the BIM ecosystem has not yet reached the desired level.

The benefits grouped under the "Enhanced Information Management" heading, with an average higher than that of all other benefit clusters, emerged as the most highly experienced cluster. Within the ANP analysis, the benefit with the highest priority in terms of overall impact was also found to be Enhanced Information Management. This indicates that the strongest aspect of BIM implementations for Turkish design firms is the improvement in information management.

Excluding "improved design analysis", the "High-Quality Design" cluster, which includes five benefits, had the second-highest average among the clusters. The fact that these two clusters, where design plays a significant role, are highly positively rated, while clusters where construction site processes are relatively less rated, suggests that BIM adaptation in the Turkish construction sector is stronger in design offices. In contrast, site integration has not yet reached its full potential.

6.2. Recommendations

6.2.1. Organizational Recommendations

A significant portion of designers have experienced negative impacts of BIM usage on both profitability and total costs. In post-research interviews conducted to evaluate these results, designers who experienced negative impacts cited repeated work and increased workload as the primary reasons. Despite the increased job volume and higher total contract values due to enhanced prestige, the increase in expenses outweighs these benefits. Additionally, one of the most striking findings of the study is that designers are weak in adapting engineering analyses to BIM processes. Many firms stick to traditional workflows, setting up models from scratch for analysis programs and manually tracking and correcting revisions. This leads to significant time loss and consequently higher costs, as well as weakened interdisciplinary coordination, threatening design quality. In contrast, current technology and software infrastructures increasingly support data transfer between specialized software for different disciplines. This allows for the seamless use of the geometric, spatial, and non-spatial data content of the BIM model for various engineering analyses, making the processes more reliable and faster.

According to research findings, the most effective benefit identified was information management, and the second most effective software type was collaboration software. Therefore, for design firms, investing in cloud-based Common Data Environment (CDE) and design management software is crucial for increasing internal efficiency and reducing issues with stakeholders.

Considering the significant number of participants experiencing negative financial impacts, integrating engineering analyses into BIM processes would positively affect reducing internal costs. The main reasons for the weak adaptation are the lack of technical knowledge and resistance to change. To overcome these and enhance the integration of engineering analyses into the BIM ecosystem, the following are recommended:

- Investment in Collaboration Software: Invest in collaboration software, particularly CDE software, and ensure its effective use within the organization.
- Basic BIM Training for Specialists: Provide basic training on BIM concepts and the capabilities of BIM software used within the organization to employees specialized in engineering analyses.
- Training for Drawing and Coordination Specialists: Train employees specialized in drawing and coordination on the basic operating principles and input requirements of the analysis software used within the organization, ensuring these requirements are considered during modeling.
- Data Exchange Format Evaluation: Research and evaluate the data exchange formats among the used software and determine the most suitable exchange format for each workflow.
- Standardization of Export and Import Settings: Standardize the export and import settings to use the chosen exchange format most efficiently.
- Process Monitoring and Continuous Improvement: Monitor processes to identify effective and problematic areas, and ensure lessons learned are documented to continuously improve workflows.
- Following Technological Developments: Stay updated on technological advancements to maintain and enhance technical capabilities.

6.2.2. Decision Framework for Software Selection

There are many specialized software in the market for various domains, making it increasingly challenging to master them all and choose the most technically and economically suitable software for a firm's needs.

To address this issue analytically, significant findings have been reached within the scope of this thesis. Based on these findings, a framework has been developed for design firms (architectural, structural, electrical, mechanical, etc.) operating in the Turkish construction market to determine which software to invest.

Initially, the budget for software infrastructure investment is determined which is out of the scope of this thesis. Once the budget is set, it is allocated across software clusters based on the ratios found in the research.

For each software cluster, the number of users is determined. For example, coordination software may be assigned to everyone, while modeling software may be assigned to modelers, and analysis software is assigned to specialists in relevant fields. Next, software suitable for the defined software clusters is identified.

Annex-A can be used as a reference however, it is essential to identify the most up-to-date status due to the dynamic nature of technology. Based on the identified number of users for each software cluster, software that fits within the budget is selected. When evaluating software that serves multiple groups, its primary functions are considered.

Finally, the shortlisted software is assessed based on its technical capacity to make the final selection.

The framework described above is depicted in Figure 6.1. By following this framework, design firms can systematically and effectively choose the most appropriate software investments, ensuring both technical adequacy and economic feasibility.

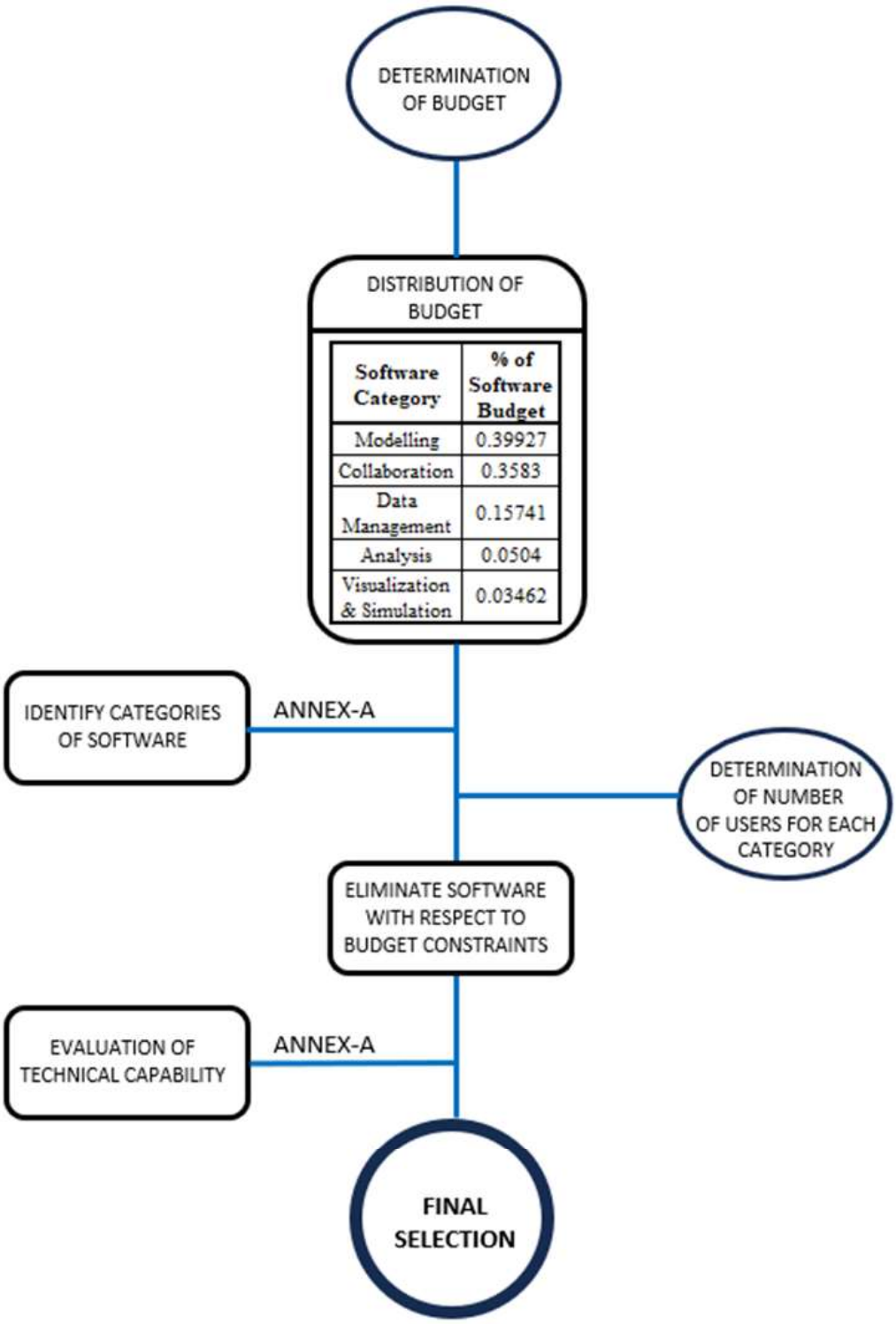

Figure 6.1. Framework for software selection.

6.3. Future Research

If the scope of this study can be expanded to include all stakeholders and cost items, a comprehensive decision analysis encompassing all AEC sector decision-makers and all aspects of BIM usage can be conducted. Figure 6.2 illustrates the proposed network model for each stakeholder. This network model can be applied to all stakeholders, including designers, consultants, contractors, facility managers, and suppliers, to determine the weight of maximum benefit for investment areas specific to each stakeholder. Consequently, the cost-performance relationship for BIM investments can be better understood, and investments can be made more accurately.

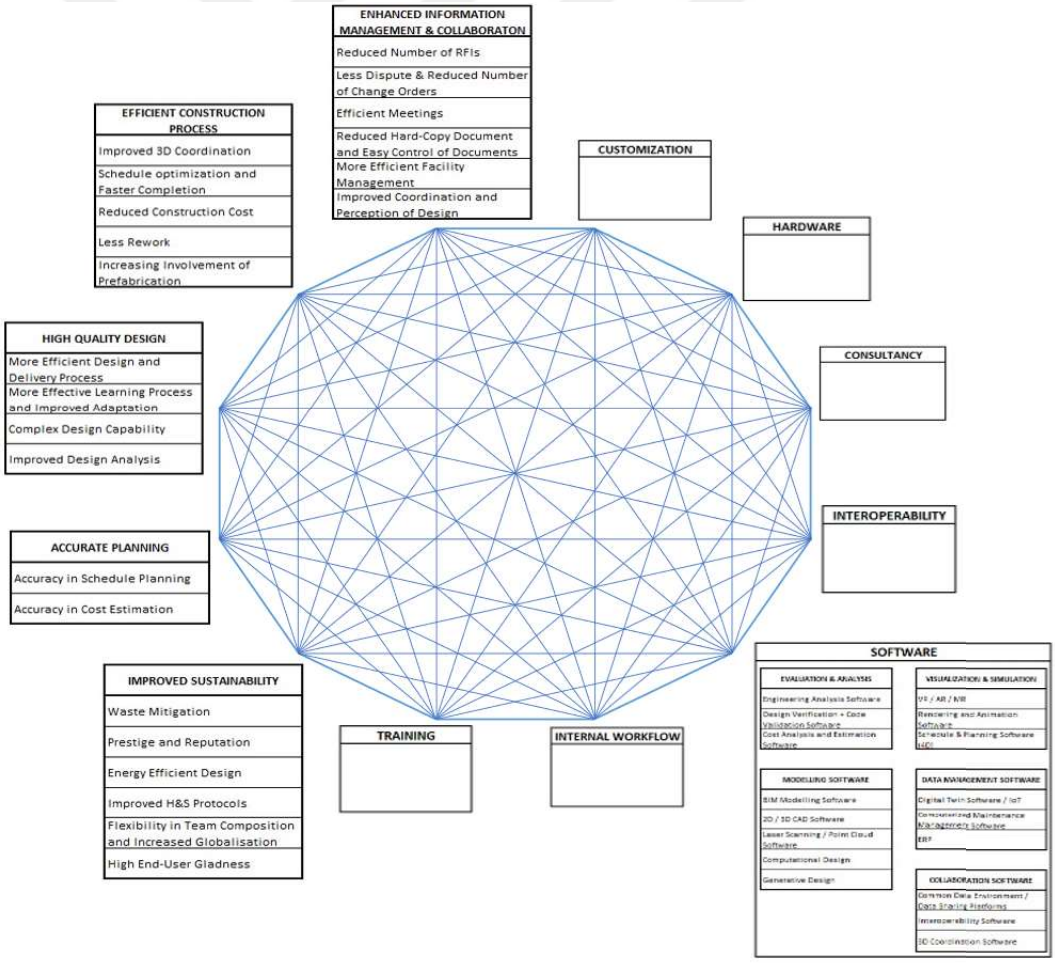

Figure 6.2. Comprehensive ANP model proposal for further research.

In summary, while contractor firm employees recognize significant benefits of BIM in coordination and design perception, there are areas, particularly in cost management, where further advancements could enhance the overall efficiency and effectiveness of BIM implementations. On the other hand, BIM implementations positively contribute to the capacity and capabilities of design firms, though there are areas for improvement, such as design and analysis integration. Additionally, while the enhanced technological capabilities increase competitive advantage as a reason for preference, the economic benefits are not realized to the same extent. Additionally, according to the ANP analysis results, the highest priority software category for investment to maximize BIM benefits for Turkish design firms is "Modelling Software". It is hoped that the results obtained and the information gathered will expand the current state of BIM knowledge in the literature, particularly for the Turkish construction sector.

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APPENDIX A: LITERATURE REVIEW LISTS

Benefits and costs and ROI of BIM implementation as well as BIM software types obtained from literature review are given below:

Table A.1. Benefits of BIM from literature.

Criteria Description Research	Improved 3D Coordination in Site	Schedule optimization and Faster Completion	Reduced Construction Cost	Less Rework	Increasing Involvement of Prefabrication
Yan *et al.* -2010					
Manning and Messner -2008			x		
Petrova *et al.* -2017					
Pollock *et al.* -2009					
Azhar *et al.* -2008			x		
Shlueter and Thesseling -2008					
Öktem and Ergen -2014	x	x			
Akcamete *et al.* -2010					
Basbagill *et al.* -2013					
Barlish and Sullivan -2012	x				
Ren *et al.*, -2018					

Table A.1 Benefits of BIM from literature. (cont.)

Criteria Description Research	Improved 3D Coordination in Site	Schedule optimization and Faster Completion	Reduced Construction Cost	Less Rework	Increasing Involvement of Prefabrication
Lu *et al.* -2013					
Lu *et al.* -2014			x		
Forgue *et al.* -2012					
Giel and Issa. -2013		x			
Becerik-Gerber and Rice -2010					x
Li *et al.* -2014	x	x			
Qian -2012					x
Jones and Laquidara-Carr -2017		x	x		
Won *et al.* -2015	x				
Giel *et al.* -2013	x				
Alahmad *et al.* -2011					
Siddiqui *et al.*, -2021					
Zhu -2005					
Bryde *et al.* -2013					

Table A.1 Benefits of BIM from literature. (cont.)

Criteria Description Research	Improved 3D Coordination in Site	Schedule optimization and Faster Completion	Reduced Construction Cost	Less Rework	Increasing Involvement of Prefabrication
Bullinger *et al.* -2010					
Shen *et al.* -2012					
Ding *et al.* -2014					
Racks and Barak -2007					
Shin *et al.*, -2022					
Reizgevičius *et al.* -2018					
Bockstael and Issa -2016	x				
Khanzode *et al.* -2008			x	x	
Bebani -2022			x		
Forcada *et al.*, -2017				x	
Love *et al.*, -2016				x	
Hwang *et al.*, -2019				x	
Teo *et al.*, -2005					
Getuli *et al.*, -2017					
Ghafar *et al.*, -2018					

Table A.1 Benefits of BIM from literature. (cont.)

Criteria Description Research	Improved 3D Coordination in Site	Schedule optimization and Faster Completion	Reduced Construction Cost	Less Rework	Increasing Involvement of Prefabrication
Rischmoller *et al.*, -2017					
Majumdar *et al.*, -2022					
Carvalho *et al.*, -2021					
Yan *et al.* -2010	x	x			
Manning and Messner -2008	x				
Petrova *et al.* -2017	x				
Pollock *et al.* -2009	x				
Azhar *et al.* -2008					
Shlueter and Thesseling -2008	x				
Öktem and Ergen -2014	x				
Akcamete *et al.* -2010					
Basbagill *et al.* -2013	x				
Barlish and Sullivan -2012	x				x
Ren *et al.*, -2018				x	

Table A.1 Benefits of BIM from literature. (cont.)

Criteria Description Research	More Efficient Design and Delivery Process	More Effective Learning Process and Improved Adaptation	Complex Design Capability	Improved Design Analysis	Reduced Number of RFIs
Lu *et al.* -2013		x			
Lu *et al.* -2014	x				
Forgue *et al.* -2012					
Giel and Issa. -2013					x
Becerik-Gerber and Rice -2010					
Li *et al.* -2014					
Qian -2012					
Jones and Laquidara-Carr -2017	x				
Won *et al.* -2015 **Giel *et al.* -2013**	x				
Alahmad *et al.* -2011					
Siddiqui *et al.*, -2021				x	
Zhu -2005					
Bryde *et al.* -2013					

Table A.1 Benefits of BIM from literature. (cont.)

Criteria Description Research	More Efficient Design and Delivery Process	More Effective Learning Process and Improved Adaptation	Complex Design Capability	Improved Design Analysis	Reduced Number of RFIs
Bullinger *et al.* -2010					
Shen *et al.* -2012					
Ding *et al.* -2014			x	x	
Racks and Barak -2007	x				
Shin *et al.*, -2022	x				
Reizgevičius *et al.* -2018	x				
Bockstael and Issa -2016					x
Khanzode *et al.* -2008					
Bebani -2022					
Forcada *et al.*, -2017					
Love *et al.*, -2016					
Hwang *et al.*, -2019					
Teo *et al.*, -2005					
Getuli *et al.*, -2017					
Ghafar *et al.*, -2018					

Table A.1 Benefits of BIM from literature. (cont.)

Criteria Description Research	More Efficient Design and Delivery Process	More Effective Learning Process and Improved Adaptation	Complex Design Capability	Improved Design Analysis	Reduced Number of RFIs
Rischmoller *et al.*, -2017					
Majumdar *et al.*, -2022					
Carvalho *et al.*, -2021				x	
Yan *et al.* -2010					
Manning and Messner -2008	x				x
Petrova *et al.* -2017	x				x
Pollock *et al.* -2009					
Azhar *et al.* -2008					
Shlueter and Thesseling -2008					
Öktem and Ergen -2014	x				x
Akcamete *et al.* -2010				x	
Basbagill *et al.* -2013					
Barlish and Sullivan -2012	x				x
Ren *et al.*, -2018					
Lu *et al.* -2013					

Table A.1 Benefits of BIM from literature. (cont.)

Criteria Description Research	Less Dispute and Reduced Number of Change Orders	Efficient Meetings	Reduced Hard-Copy Document and Easy Control of Documents	More Efficient Facility Management	Improved Coordination and Perception of Design
Lu *et al.* -2014					
Forgue *et al.* -2012					
Giel and Issa. -2013	x				
Becerik-Gerber and Rice -2010					
Li *et al.* -2014					
Qian -2012			x		
Jones and Laquidara-Carr -2017	x		x		x
Won *et al.* -2015					
Giel *et al.* -2013	x				x
Alahmad *et al.* -2011					
Siddiqui *et al.*, -2021					
Zhu -2005					
Bryde *et al.* -2013					
Bullinger *et al.* -2010					

Table A.1 Benefits of BIM from literature. (cont.)

Criteria Description Research	Less Dispute and Reduced Number of Change Orders	Efficient Meetings	Reduced Hard-Copy Document and Easy Control of Documents	More Efficient Facility Management	Improved Coordination and Perception of Design
Shen *et al.* -2012					
Ding *et al.* -2014					
Racks and Barak -2007					
Shin *et al.*, -2022					
Reizgevičius *et al.* -2018					
Bockstael and Issa -2016					
Khanzode *et al.* -2008					
Bebani -2022					
Forcada *et al.*, -2017					
Love *et al.*, -2016					
Hwang *et al.*, -2019					
Teo *et al.*, -2005					
Getuli *et al.*, -2017					
Ghafar *et al.*, -2018					
Rischmoller *et al.*, -2017		x			

Table A.1 Benefits of BIM from literature. (cont.)

Criteria Description Research	Less Dispute and Reduced Number of Change Orders	Efficient Meetings	Reduced Hard-Copy Document and Easy Control of Documents	More Efficient Facility Management	Improved Coordination and Perception of Design
Majumdar *et al.*, -2022		x			
Carvalho *et al.*, -2021					
Criteria Description Research	Accuracy in Schedule Planning	Accuracy in Cost Estimation	Waste Mitigation	Prestige and Reputation	Energy Efficient Design
Yan *et al.* -2010					
Manning and Messner -2008					
Pollock *et al.* -2009					x
Azhar *et al.* -2008					x
Shlueter and Thesseling -2008					x
Öktem and Ergen -2014	x				
Akcamete *et al.* -2010					x
Basbagill *et al.* -2013	x				x
Barlish and Sullivan -2012					
Ren *et al.*, -2018					
Lu *et al.* -2013					

Table A.1 Benefits of BIM from literature. (cont.)

Criteria Description Research	Accuracy in Schedule Planning	Accuracy in Cost Estimation	Waste Mitigation	Prestige and Reputation	Energy Efficient Design
Petrova *et al.* -2017					
Lu *et al.* -2014					
Forgue *et al.* -2012		x			
Giel and Issa. -2013	x				
Becerik-Gerber and Rice -2010					
Li *et al.* -2014	x	x	x		
Jones and Laquidara-Carr -2017		x		x	
Won *et al.* -2015			x		
Giel *et al.* -2013					
Alahmad *et al.* -2011					x
Siddiqui *et al.*, -2021					
Zhu -2005					x
Bryde *et al.* -2013				x	
Bullinger *et al.* -2010					
Shen *et al.* -2012					

Table A.1 Benefits of BIM from literature. (cont.)

Criteria Description Research	Accuracy in Schedule Planning	Accuracy in Cost Estimation	Waste Mitigation	Prestige and Reputation	Energy Efficient Design
Qian -2012			x		
Ding *et al.* -2014					x
Racks and Barak -2007					
Shin *et al.*, -2022					
Reizgevičius *et al.* -2018					
Bockstael and Issa -2016					
Khanzode *et al.* -2008					
Bebani -2022					
Love *et al.*, -2016					
Hwang *et al.*, -2019					
Teo *et al.*, -2005					
Getuli *et al.*, -2017					
Ghafar *et al.*, -2018					
Rischmoller *et al.*, -2017					
Majumdar *et al.*, -2022					
Carvalho *et al.*, -2021					

Table A.1 Benefits of BIM from literature. (cont.)

Criteria Description Research	Improved H&S Protocols	Flexibility in Team Composition and Increased Globalisation	User Satisfaction		
Yan *et al.* -2010					
Manning and Messner -2008					
Petrova *et al.* -2017			x		
Pollock *et al.* -2009					
Azhar *et al.* -2008					
Shlueter and Thesseling -2008					
Criteria Description Research	Accuracy in Schedule Planning	Accuracy in Cost Estimation	Waste Mitigation	Prestige and Reputation	Energy Efficient Design
Öktem and Ergen -2014					
Akcamete *et al.* -2010			x		
Basbagill *et al.* -2013					
Barlish and Sullivan -2012					
Criteria Description Research	Improved H&S Protocols	Flexibility in Team Composition and Increased Globalisation	User Satisfaction		
Ren *et al.*, -2018					

Table A.1 Benefits of BIM from literature. (cont.)

Criteria Description Research	Improved H&S Protocols	Flexibility in Team Composition and Increased Globalisation	User Satisfaction		
Lu *et al.* -2013					
Lu *et al.* -2014					
Forgue *et al.* -2012					
Giel and Issa. -2013					
Becerik-Gerber and Rice -2010					
Li *et al.* -2014					
Qian -2012					
Jones and Laquidara-Carr -2017					
Won *et al.* -2015					
Giel *et al.* -2013					
Alahmad *et al.* -2011					
Siddiqui *et al.*, -2021					
Zhu -2005					
Bryde *et al.* -2013		x			
Bullinger *et al.* -2010			x		

Table A.1 Benefits of BIM from literature. (cont.)

Criteria Description Research	Improved H&S Protocols	Flexibility in Team Composition and Increased Globalisation	User Satisfaction		
Shen *et al.* -2012			x		
Ding *et al.* -2014	x				
Racks and Barak -2007					
Shin *et al.*, -2022					
Reizgevičius *et al.* -2018					
Bockstael and Issa -2016					
Khanzode *et al.* -2008					
Bebani -2022					
Forcada *et al.*, -2017					
Love *et al.*, -2016					
Hwang *et al.*, -2019					
Teo *et al.*, -2005	x				
Getuli *et al.*, -2017	x				
Ghafar *et al.*, -2018		x			
Rischmoller *et al.*, -2017					

Table A.1 Benefits of BIM from literature. (cont.)

Criteria Description Research	Improved H&S Protocols	Flexibility in Team Composition and Increased Globalisation	User Satisfaction		
Majumdar *et al.*, -2022					
Carvalho *et al.*, -2021					

Table A.2. Cost factors from literature review.

RESEARCH COSTS	Won *et al.*, 2013	Gu and London, 2010	Giel *et al.*, 2013	Becerik-Gerber and Rice, 2010	Ghaffarinhoseini *et al.*, 2017	Qian, 2009	Dodge Data and Analytics, 2017
Software Cost	x	x	x	x	x	x	x
Training Cost	x	x	x	x	x	x	
Hardware Cost	x	x		x	x	x	x
Cost of Inter-Operability Solutions	x				x		x
Cost of Developing Internal Workflow	x	x			x		x
Temporary Production Loss						x	
Legal Issues		x			x		
Maintenance Cost	x			x		x	x

Table A.2 Cost factors from literature review. (cont.)

RESEARCH COSTS	Won *et al.*, 2013	Gu and London, 2010	Giel *et al.*, 2013	Becerik-Gerber and Rice, 2010	Ghaf-Farina-hoseini *et al.*, 2017	Qian, 2009	Dodge Data and Analytics, 2017
Staff Sallaries			x			x	
Cost of Customization							x
Consultancy Cost				x	x		
Resistance to Change	x						
Increasing Cost of Subcontractor							
RESEARCH COSTS	Walasek and Barszcz, 2017	Latiffi and Tai, 2017	Raval and Narayana, 2018	Reiz-Gevicius *et al.*, 2018	Sholeh *et al.*, 2020	Yanda *et al.*, 2019	Li *et al.*, 2009
Software Cost		x		x	x	x	
Training Cost		x		x		x	
Hardware Cost		x		x	x	x	
Cost of Inter-Operability Solutions	x			x		x	x
Cost of Developing	x			x		x	
Internal Workflow							
Temporary Production Loss	x	x	x	x			x
Legal Issues	x						
Maintenance Cost	x						
Staff Sallaries	x	x		x	x		

Table A.2 Cost factors from literature review. (cont.)

RESEARCH COSTS	Walasek and Barszcz, 2017	Latiffi and Tai, 2017	Raval and Narayana, 2018	Reiz-Gevicius *et al.*, 2018	Sholeh *et al.*, 2020	Yanda *et al.*, 2019	Li *et al.*, 2009
Cost of Customization				*x*		*x*	
Consultancy Cost				*x*			
Resistance to Change							
Increasing Cost of Subcontractor				*x*			
RESEARCH COSTS	**Joseph Garcia *et al.*, 2018**	**Nurtan Günes, 2018**	**Wang *et al.*, 2018**	**Hochsheid and Halin, 2019**	**Jin *et al.*, 2017**	**Chien *et al.*, 2014**	**Azhar *et al.*, 2012**
Software Cost	*x*		*x*		*x*	*x*	*x*
Training Cost	*x*	*x*	*x*	*x*	*x*		*x*
Hardware Cost			*x*		*x*	*x*	*x*
Cost of Inter-Operability Solutions	*x*		*x*		*x*	*x*	*x*
Cost of Developing	*x*			*x*		*x*	
Internal Workflow							
Temporary Production Loss							*x*
Legal Issues			*x*		*x*	*x*	*x*
Maintenance Cost			*x*				
Staff Sallaries							
Cost of Customization	*x*				*x*		

Table A.2 Cost factors from literature review. (cont.)

RESEARCH COSTS	Joseph Garcia *et al.*, 2018	Nurtan Günes, 2018	Wang *et al.*, 2018	Hochsheid and Halin, 2019	Jin *et al.*, 2017	Chien *et al.*, 2014	Azhar *et al.*, 2012
Consultancy Cost	*x*						
Resistance to Change		*x*			*x*		*x*
Increasing Cost of Subcontractor			*x*				

Table A.3. Software Types of BIM Ecosystem from literature review.

RESEARCH SOFTWARE TYPES	Bouška, 2016	Jensson, 2017	Eastman *et al.*, 2008	Wu, 2022	Sidani, 2019	Herrera *et al.*, 2021	Chong *et al.*, 2016	Zhang *et al.*, 2021
Common Data Environment		*x*						
3D Coordination Software (Clash Test, 3D Coordination)	*x*	*x*	*x*	*x*		*x*	*x*	
Interoperability Tools								
Digital Twin Platforms / IoT								*x*
Computerized Maintanence Management Systems (CMMS)	*x*		*x*					
Enterprise Resource Planning (ERP) Software								

Table A.3 Software Types of BIM Ecosystem from literature review. (cont.)

RESEARCH SOFTWARE TYPES	Bouška, 2016	Jensson, 2017	Eastman *et al.*, 2008	Wu, 2022	Sidani, 2019	Herrera *et al.*, 2021	Chong *et al.*, 2016	Zhang *et al.*, 2021
Engineering Analysis	*x*	*x*	*x*	*x*		*x*	*x*	
Cost Analysis and Estimation Software (QTOs, 5D Analysis)	*x*	*x*	*x*	*x*		*x*	*x*	
Design Verification / Quality Check and Assurance			*x*			*x*		
BIM Modelling Software	*x*	*x*	*x*					
CAD Software (2D Drawing / 3D Modelling)		*x*						
Laser Scanning / Point Cloud / Photogrametry			*x*				*x*	
Computational Design Software								
Generative Design Software								
Virtual Reality (VR)			*x*		*x*			
Augumented Reality (AR)								

Table A.3 Software Types of BIM Ecosystem from literature review. (cont.)

RESEARCH SOFTWARE TYPES	Bouška, 2016	Jensson, 2017	Eastman *et al.*, 2008	Wu, 2022	Sidani, 2019	Herrera *et al.*, 2021	Chong *et al.*, 2016	Zhang *et al.*, 2021
Scheduling, Phase Planning and 4D Simulation Software	*x*	*x*	*x*	*x*		*x*	*x*	
Rendering and Animation		*x*						
RESEARCH SOFTWARE TYPES	Shringi *et al.*, 2023	Ogunrinde *et al.*, 2024	Özkan and Seyis, 2021	Wang *et al.*, 2012	Wang and Piao, 2019	Lavy *et al.*, 2019	Luo and Chen, 2018	
Common Data Environment			*x*					
3D Coordination Software (Clash Test, 3D Coordination)								
Interoperability Tools								
Digital Twin Platforms / IoT		*x*						
Computerized Maintanence Management Systems (CMMS)						*x*		
Enterprise Resource Planning (ERP) Software								
Engineering Analysis								

Table A.3 Software Types of BIM Ecosystem from literature review. (cont.)

RESEARCH SOFTWARE TYPES	Bouška, 2016	Jensson, 2017	Eastman *et al.*, 2008	Wu, 2022	Sidani, 2019	Herrera *et al.*, 2021	Chong *et al.*, 2016	Zhang *et al.*, 2021
Cost Analysis and Estimation Software (QTOs, 5D Analysis)						*x*		
Design Verification / Quality Check and Assurance								
BIM Modelling Software		*x*				*x*		
CAD Software (2D Drawing / 3D Modelling)						*x*		
Laser Scanning / Point Cloud / Photogrametry		*x*						
Computational Design Software								
Generative Design Software								
Virtual Reality (VR)	*x*	*x*						
Augumented Reality (AR)		*x*		*x*	*x*			

Table A.3 Software Types of BIM Ecosystem from literature review. (cont.)

RESEARCH SOFTWARE TYPES	Bouška, 2016	Jensson, 2017	Eastman *et al.*, 2008	Wu, 2022	Sidani, 2019	Herrera *et al.*, 2021	Chong *et al.*, 2016	Zhang *et al.*, 2021
Scheduling, Phase Planning and 4D Simulation Software						*x*	*x*	
Rendering and Animation								
RESEARCH SOFTWARE TYPES	Hua and Wang, 2018	De Gaetani *et al.*, 2020	Anane *et al.*, 2023	Nisztuk and Myszkowski, 2018	Di Filippo *et al.*, 2021	Andia, 2012	Sarkar *et al.*, 2022	
Common Data Environment								
3D Coordination Software (Clash Test, 3D Coordination)								
Interoperability Tools Digital Twin Platforms / IoT		*x*						
Computerized Maintanence Management Systems (CMMS)								
Enterprise Resource Planning (ERP) Software							*x*	

Table A.3 Software Types of BIM Ecosystem from literature review. (cont.)

RESEARCH SOFTWARE TYPES	Hua and Wang, 2018	De Gaetani *et al.*, 2020	Anane *et al.*, 2023	Nisztuk and Myszkowski, 2018	Di Filippo *et al.*, 2021	Andia, 2012	Sarkar *et al.*, 2022	
Engineering Analysis								
Cost Analysis and Estimation Software (QTOs, 5D Analysis)	*x*							
Design Verification / Quality Check and Assurance								
BIM Modelling Software								
CAD Software (2D Drawing / 3D Modelling)								
Laser Scanning / Point Cloud / Photogrametry								
Computational Design Software			*x*	*x*				
Generative Design Software					*x*	*x*		
Virtual Reality (VR)								
Augumented Reality (AR)								

Table A.3 Software Types of BIM Ecosystem from literature review. (cont.)

RESEARCH SOFTWARE TYPES	Hua and Wang, 2018	De Gaetani *et al.*, 2020	Anane *et al.*, 2023	Nisztuk and Myszkowski, 2018	Di Filippo *et al.*, 2021	Andia, 2012	Sarkar *et al.*, 2022	
Scheduling, Phase Planning and 4D Simulation Software	*x*							
Rendering and Animation								

Table A.4. Findings from literature about ROI of BIM.

Research	**Detail Information**		**No. of observations**	**ROI**
	Type	**Country / Region**		
Ham *et al.*, 2018	High Rise	South Korea	1	94.4%
Giel *et al.*, 2013		U.S.A.	1	2600.0%
Giel *et al.*, 2013	Data Center	U.S.A.	1	140.0%
Giel *et al.*, 2013	Hotel	U.S.A.	1	11560.0%
Giel *et al.*, 2013	Library	U.S.A.	1	640.0%
Giel *et al.*, 2013	Hotel	U.S.A.	1	940.0%
Giel *et al.*, 2013	Hotel	U.S.A.	1	780.0%
Giel *et al.*, 2013	n/a	U.S.A.	1	5160.0%
Giel *et al.*, 2013	Data Center	U.S.A.	1	240.0%

Table A.4 Findings from literature about ROI of BIM. (cont.)

Research	Detail Information		No. of observations	ROI
	Type	Country / Region		
Giel *et al.*, 2013	n/a	U.S.A.	1	39900.0%
Giel *et al.*, 2013	Laboratory	U.S.A.	1	32900.0%
Giel *et al.*, 2013	n/a	U.S.A.	1	36.7%
Giel *et al.*, 2013	n/a	U.S.A.	1	16.2%
Giel and Issa, 2013	n/a	U.S.A.	1	376.0%
Giel and Issa, 2013	n/a	U.S.A.	1	1653.0%
Giel and Issa, 2013	n/a	U.S.A.	1	109.0%
Giel and Issa, 2013	n/a	U.S.A.	1	299.0%
Lee *et al.*, 2012	Mixed Use	South Korea	1	63.0%
Reizgevičius *et al.*, 2018	n/a	n/a	1	20.0%
Gilligan and Kunz, 2007	Hotel	U.S.A.	1	667.0%
Shin *et al.*, 2018	Railway	South Korea	1	36.0%
Raval and Narayana, 2018	Residential	India	1	24.3%

APPENDIX B: BIM SOFTWARE LISTS

Some of most commonly used BIM software and their available information are presented below:

Table B.1. BIM software lists.

NAME	**DEV-EL-OPER**	**CATE-GORY**	**TYPE**
Bexel Manager	Bexel Consulting	COLLA-BORA-TION	3D COOR-DINA-TION
RIB iTWO	RIB Software	COLLA-BORA-TION	3D COOR-DINA-TION
Navisworks Manage 2024	Autodesk	COLLA-BORA-TION	3D COOR-DINA-TION
Solibri	Nemetschek	COLLA-BORA-TION	3D COOR-DINA-TION
ASTA Power Project	Elocosoft	COLLA-BORA-TION	3D COOR-DINA-TION
BIM Track	BIM Track	COLLA-BORA-TION	3D COOR-DINA-TION
BIM-Collab	BIM Collab	COLLA-BORA-TION	3D COOR-DINA-TION
BIM 360	Autodesk	COLLA-BORA-TION	CDE

Table B.1 BIM software lists. (cont.)

NAME	**DEV-EL-OPER**	**CATE-GORY**	**TYPE**
Project Wise	Bentley	COLLA-BORA-TION	CDE
Viewpont for Projects	Trimble	COLLA-BORA-TION	CDE
Asite	Asite Solu tions	COLLA-BORA-TION	CDE
Trimble Connect	Trimble	COLLA-BORA-TION	CDE
Allplan Bimplus	Allplan	COLLA-BORA-TION	CDE
Bimsync	Catenda	COLLA-BORA-TION	CDE
Dalux Box	Dalux	COLLA-BORA-TION	CDE
Axxerion	Axxe rion Inc.	DATA MANA-GEMENT	CMMS
QFM BIMi	Service Works Global	DATA MANA-GEMENT	CMMS
You	You	DATA	CMMS
BIM	BIM	MANA-GEMENT	
Spacewell	Space well	DATA MANA-GEMENT	CMMS
BIM 360 OPS	Auto desk	DATA MANA-GEMENT	CMMS
Planon	Planon	DATA MANA-GEMENT	CMMS
ARCHI BUS	Eptura	DATA MANA-GEMENT	CMMS

Table B.1 BIM software lists. (cont.)

NAME	**DEV-EL-OPER**	**CATE-GORY**	**TYPE**
IBM Maximo	IBM	DATA MANA-GEMENT	CMMS
Eco Domus	Siemens	DATA MANA-GEMENT	CMMS
CAFM Explorer	idox	DATA MANA-GEMENT	CMMS
eFacility fm: systems	SIERRA ODC Private Limited Johnson Controls	DATA MANA-GEMENT DATA MANA-GEMENT	CMMS CMMS
Cintoo Cloud	Cintoo	DATA MANA-GEMENT	DIGI-TAL TWIN
SIMULIA by Dassault Systèmes	Dassault Systèmes	DATA MANA-GEMENT	DIGI-TAL TWIN
Altair Smart Works	Altair	DATA MANA-GEMENT	DIGI-TAL TWIN
Hexagon Smart Digital Realities	Hexagon	DATA MANA-GEMENT	DIGI-TAL TWIN
PTC Thing Worx	PTC	DATA MANA-GEMENT	DIGI-TAL TWIN
AVEVA	AVEVA	DATA MANA-GEMENT	DIGI-TAL TWIN
IBM Maximo Asset Monitor	IBM	DATA MANA-GEMENT	DIGI-TAL TWIN

Table B.1 BIM software lists. (cont.)

NAME	**DEV-EL-OPER**	**CATE-GORY**	**TYPE**
IBM Maximo	IBM	DATA MANA-GEMENT	CMMS
Ansys Twin Builder	ANSYS Inc	DATA MANA-GEMENT	DIGI-TAL TWIN
Bentley iTwin	Bentley	DATA MANA-GEMENT	DIGI-TAL TWIN
GE Digital Twin Software	GE Vernova	DATA MANA-GEMENT	DIGI-TAL TWIN
Azure Digital Twins	Microsoft	DATA MANA-GEMENT	DIGI-TAL TWIN
Siemens Digital Twin	Siemens	DATA MANA-GEMENT	DIGI-TAL TWIN
Tandem	Auto desk	DATA MANA-GEMENT	DIGI-TAL TWIN
Revizto	Revizto	EVALU-ATION / ANAL-YSIS	DES-IGN VERIF-ICAT-ION
Simp lebim	Simp lebim	EVALU-ATION / ANAL-YSIS	DES-IGN VERIF-ICAT-ION
BIM Assure	Invicara	EVALU-ATION / ANAL-YSIS	DES-IGN VERIF-ICAT-ION
BIM collab ZOOM	BIM Collab	EVALU-ATION / ANAL-YSIS	DES-IGN VERIF-ICAT-ION

Table B.1 BIM software lists. (cont.)

NAME	**DEV-EL-OPER**	**CATE-GORY**	**TYPE**
Autocad 2024	Auto desk	MODEL-LING	2D CAD
Rhino ceros	McNeil & Friend	MODEL-LING	3D CAD
Sketch Up	Trimble	MODEL-LING	3D CAD
Solid Works	Dassault Systeme	MODEL-LING	3D CAD
Vector works Archi tect	Nemet schek	MODEL-LING	3D CAD
Autodesk Revit	Auto desk	MODEL-LING	BIM
Bentley Micro Station	Bentley	MODEL-LING	BIM
Graphi sopft Archi cad	Grap hisoft	MODEL-LING	BIM
Nemet schek Allplan	Nemet schek	MODEL-LING	BIM
Trimble Tekla Struc tures	Trimble	MODEL-LING	BIM
Civil 3D	Autodesk	MODEL-LING	BIM
Grass hopper		MODEL-LING	COMPU-TATI-ONAL DESIGN
Brics CAD	Bricsys	MODEL-LING	POINT CLOUD
FARO-SCENE 3D Point Cloud Software	Faro	MODEL-LING	POINT CLOUD

Table B.1 BIM software lists. (cont.)

NAME	**DEV-EL-OPER**	**CATE-GORY**	**TYPE**
Leica Cyclone	Leica	MODEL-LING	POINT CLOUD
Trimble Real Works	Trimble	MODEL-LING	POINT CLOUD
Synchro 4D	Bentley	VISUA-LIZA-TION & SIMU-LATION	4D PLAN-NING
Synchro PRO	Bentley	VISUA-LIZA-TION & SIMU-LATION	4D PLAN-NING
Vico Office		VISUA-LIZA-TION & SIMU-LATION	4D PLAN-NING
AR Mapper	Immotef	VISUA-LIZA-TION & SIMU-LATION	AR
GAM MA AR	GAMMA Techn ologies S.à r.l.	VISUA-LIZA-TION & SIMU-LATION	AR
Smart Reality	Smart Reality	VISUA-LIZA-TION & SIMU-LATION	VR
Visi draft	Visidraft	VISUA-LIZA-TION & SIMU-LATION	VR

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
COOR-DINA-TION, CLASH TEST	https:// bexel manager. com/	Annualy: Dolar2400	IFC, BCF
COOR-DINA-TION, CLASH TEST	https:// www. rib-software. co.uk/itwo	n/a	RVT (Converter plug-in), IFC, CPIXML
COOR-DINA-TION, CLASH TEST, 4D PLAN-NING	mhttps:// www. autodesk. com/ products/ navisworks/ overview	3-Year: Dolar8220 Annualy: Dolar2740 Monthly: Dolar345	IFC
COOR-DINA-TION, CLASH TEST	https:// www. solibri. com/	Monthly: Euro280 Annualy: Euro1870	IFC, SMC, SMCT, IFCZIP, DWG, PDF, XLS/ XLSX
COOR-DINA-TION, CLASH TEST, 4D PLAN-NING	https:// www. elecosoft. com/ software/ asta-power project-home/ asta-power project/	Pound1,380.00 excludes VAT	Primavera P6 (.xer), MS Project (.xml), Microsoft Excel (.xlsx)

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
ERROR TRAC-KING, CLASH TEST	https:// bimtra ck.co/	Dolar 140.00 /ay Price for 10 users, unlimited projects, unlimited issues, unlimited storage	
ERROR TRAC-KING	https:// www. bimcollab. com/en	https:// www. bimcollab. com/ en/plans/ bimcollab-cloud	
DATA SHARE	https:// www. autodesk. com/ bim-360/	Dolar 3,274	
DATA SHARE	https:// www. viewpoint. com/en-gb/ products/ viewpoint-for-projects? Redirec ted=y	Dolar 20,000/ 4-lisans	
DATA SHARE, CLASH TEST DATA SHARE	https:// www. asite. com/ https:// connect. trimble. com/	Dolar 375/ ay Başlangıç fiyatı: 10 Dolar/ay/ Kullanıcı Kişisel:	

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
		ÜCRETSİZ İşletme: 10 Pound/ay/ kullanıcı Business Premium: 250 Pound/ yıl/ kullanıcı	
DATA SHARE	https:// www. bentley. com/ en/ products/ brands/ project wise	?	
DATA SHARE	https:// www. allplan. com/ products/ allplan-bimplus/	Basic: Ücretsiz Standart: Pound 169.20/ Kişi Profes yonel: Pound 296.00/ Kişi Enter prise: ?	
DATA SHARE	https:// bimsync. com/	Dolar 270/ ay	
DATA SHARE	https:// www. dalux. com/ dalux-box/		
FM, CMMS	https:// spacewell. us/	n/a	

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
FM, CAFM, SCAN2 BIM	https:// www. swg.com/	USD Dolar 828.00 per year	
FM	https:// www. youbim. com/	n/a	
FM	https:// spacewell. com/	Euro 3500 Per Year	
FM	https:// ops. bim360 ops.com/ authen-tication	Dolar 29 (Monthly)	
FM	https:// planon-software. com/us/	200.000,00 Dolar	
FM	https:// lp.eptura. com/ppc-archibus? utm-source #AD? &utm-medium= ppc&utm-campaign= Archibus-Brand-DE&utm-content= Archibus %20-%20 Gen&utm-term= archibus-20%	n/a	

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
	software &gad-source =1&gclid= Cj0KCQjw 6auyBh DzARIs ALIo6v-qS1U1uh UGP12jtw-74Fnttvw LFel0ua-tsljbWD qkfGJAp6 ex1d8a AucXEAL w-wcB		
FM	https:// www. siemens. com/ global/en/ products/ buildings/ digital-building-lifecycle/ ecodomus-software. html	n/a	
FM	https:// www. idoxgroup. com/ solutions/ computer-aided-facilities-manage ment/	2.000,00 Pound	
FM, CMMS	https:// www. efacility. in/	800 Dolar/ user/m	

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
FM	https:// fmsystems. com/	n/a	
FM	https:// www. ibm. com/ products/ maximo? utm- content #AD? WW& p1= Search &p4= 43700	USD Dolar 250.00	
	7521 1096 036&p5= p&p9= 5870 82 7884 7426& gad- source= 1& gclid= Cj0KCQj w6auyBh DzARI sAL Io6v8 NJIJ worRHBB huel9Cg8, w2eB1J6r Ke5uRR zizIlsV5 MY76j ANjU8a Ah6- EALw- wcB&gc lsrc=aw.ds		

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
DIGI-TAL TWIN DIGI-TAL TWIN	https://cintoo.com/ https://www.3ds.com/products/simulia	n/a https://www.3ds.com/terms/price	
DIGI-TAL TWIN DIGI-TAL TWIN	https://altair.com/ https://hexagon.com/	n/a n/a	
DIGI-TAL TWIN	https://www.ptc.com/en/products/thingworx	https://shop.inneo.de/category/Produktentwicklung/Produktdatenmanagement-PDMPLM/Navigate	
DIGI-TAL TWIN	https://www.aveva.com/	Dolar 20	
DIGI-TAL TWIN	https://www.ibm.com/docs/en/mapms/1-cloud?topic=product-overview-features	250 Dolar	
DIGI-TAL TWIN	https://www.ansys.com/products/digital-twin/	n/a	

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
	ansys-twin-builder		
DIGI-TAL TWIN	https://www.bentley.com/software/itwin-platform/	https://developer.bentley.com/pricing/	
DIGI-TAL TWIN	https://www.ge.com/digital/applications/digital-twin		
DIGI-TAL TWIN	https://azure.microsoft.com/en-us/products/digital-twins/?ef-id=-k-Cj0KCQjw6auyBhDzARIsALIo6v8NXi9iikzt3NAV3bApJ7voTIwquq4QHOZf3PcTbiMkZq4f6Wlx4q4aAg0oEALw-wcB-k-&OCID=AIDcmmzzaokddl-	n/a	

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
	SEM–k-Cj0KCQjw6auyBhDzARIsALIo6v8NXi9iikzt3NAV3bApJ 7voTIwquq4QHOZf3		
	PcTbiMkZq4f6Wlx4q4aAg0oEALw-wcB-k-&gad-source=1&gclid=Cj0KCQjw6auyBhDzARIsALIo6v8NXi9iikzt3NAV3bApJ7voTIwquq4QHOZf3PcTbiMkZq4f6Wlx4q4aAg0oEALw-wcB		
DIGI-TAL TWIN	https://www.sw.siemens.com/de-DE/digital-twin/	n/a	
DIGI-TAL TWIN ERROR TRAC-KING	https://revizto.com/en/	Dolar 500.00/ yıl/kullanıcı	

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
QUAL-ITY CONT-ROL	https:// simplebim. com/	1250 Euro / license annually	
QUAL-ITY CONT-ROL	https:// invicara. com/ technology/ bim-assure/	n/a	
QUAL-ITY CONT-ROL	https:// www. bimcollab. com/ en/ products/ bimcollab-zoom	Euro600/ Lisans	
2D MODEL-LING, 3D MODEL-LING	https:// www. autodesk. com/ products/ autocad/ overview	3-Year: Dolar 6090 Annualy: Dolar2030 Monthly: Dolar255 Single User Perpetual: Euro995 10-User Perpetual: Euro9950 50-User Perpetual: Euro49750	
3D MODEL-LING	https:// www. sketchup. com/	SketchUp Go Annualy: Dolar119 SketchUp Pro Annualy: Dolar349	.dwg, .dxf, .jpg, .png, .tif, .bmp, .psd, .tga,

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
		SketchUp Studio Annualy: Dolar749	.pdf, .eps, .dae, .3ds, .dem, .ddf
3D MODEL-LING	https:// www. solidworks. com/	Annualy: Dolar2580	IGES (*.igs, *.iges) STEP AP203 /214 (*.step, *.stp) ACIS (*.sat) VDAFS (*.vda) SLDXML (*.sldxml)
3D MODEL-LING	https:// www. vector-works. net/en-US/ architect	n/a	.dwg, .dxf, .dwf, .w2d, .dwfx, , .c4d, .eps, .bmp, .gif, .jpg, .jpeg, .jp2, .png, .tif, .ico, .wdp, .dds, .sgi, .tga, .exr, .psd, .icns,

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
			.mac, .icns, .emf, .emf, .pct, .pct, .txt, .csv, .dif,
			.slk, .txt, .vss, .vs, .py, .pyc, .xxt, .mpc, .igs, .iges, .obj, .sat, .stp, .step, .stl, .3dm, .X-T, .hdr, .exr, .ies, .skp, .ifc, .ifcXML, .ifcZIP, .rvt, .rfa, .pdf, .3DS, .skp, .laz, .las, .pts, .e57,

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
			.xyz, .shp, .txt, .csv, .csv, .bcfzip, .bpw, .jgw, .pgw, .tfw, .gfw, .wld, .ecw, .txt, .txt
3D MODEL-LING, CLASH TEST, QUAN-TITY TAKE-OFFs	https:// www. autodesk. com/ products/ revit/ overview	Monthly: Dolar365 Annualy: Dolar2910 3-Year: Dolar8730 (Kullanıcı Başına)	RVT, RFA, RTE, RFT DGN, DWF, DWG, DXF, IFC, SAT, SKP. BMP, PNG, JPG, JPEG, TIF, ODBC, HTML, TXT, gbXML.
3D MODEL-LING, Scan to BIM	http:// www. bentley. com/en-US/ Products/ Micro Station/	Annualy: Dolar2284	DWG, DXF, FBX, STL, SKP, JT, IGES, Parasolid XMT, ACIS

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
			SAT, CGM, STEP AP203, STEP AP214, Acute3D (.3mx), Terrain Model Land XML, Image (JPG, BMP, TIF, GIF, and others), TXT, IFC, RFA (read Only),
3D MODEL-LING	http:// www. graphisoft. com/ archicad/	Monthly: Dolar 153.80	.pln, .pla, .bpn, .tpl, .mod, .2dl, .bimproject, .twtravel, .bimlibrary, .bcmb, .bcsb, .lcf, .gsm, .gdl, .pmk, .lbk, .dwg, .dxf,

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
			.dgn, .ifc, .ifcxml, .ifczip, .bcf, .c4d, .3dm, .3ds, .kml, .kmz, .skp, .dae, .stl, .pdf, .dwf, .bmp, .dib, .rle, .jpeg, .jpg, .jpe, .jfif, .jp2, .gif, .tiff, .tif, .png, .pct, .ico, .hdr, .exif, .lwi, .wmf, .emf, .xyz, .e57, .xls, .xlsx, .txt, .lic, .lis

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
2B MODEL-LEME, 3D MODEL-LING, QUAN-TITY TAKE-OFFs	http:// www. allplan. com/	Monthly: Euro333	.dxf, .dwg, .dwt, .dxb, .dgn, .pdf, .ifc, .ifcXML, .ifcZIP, .c4d, .skp, .3dm, .stl, .wrl, .xml, .plt, .hp, .hpg, .hpl, .prn, .re1, .reb, .re2, .asc, .lin, .lpr, .qpr, .xml, .asf, .sin, .nkb
3D MODEL-LING	https:// www. tekla. com/ products/ tekla-structures	Pound 10000 + Annualy Pound 800	Autodesk (.dwg), Autodesk (.dxf), Bentley ISM, BIM Collabor-Ationfor-Mat (.bcf), Cadma-Ticmo-

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
			Dels (.3dd), CIS/ 2LPM5 /LPM6 analy-tical (.stp, .p21, .step), CIS/ 2LPM5/ LPM6 design (.stp, .p21, .step), DSTV (.nc, .stp, .mis), DSTV (.nc, .stp, .mis), Elema-tic-ELiP-LAN, ELiPOS (.eli), Fabsuite (.xml), Fab-Trol-MISXml (.xml), High-Level-Interface-File (.hli), IFC2x2 (.ifc),

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
			IFC2x3 (.ifc), IFC4 (.ifc), IFCXML 2X3 (.ifcXML), IFCZIP 2x3 (.ifcZIP), Initial-Graphics-Exchange-Specification-(IGES) (.iges, .igs), Land XML (.xml), Microsoft-Project (.xml), Microstation (.dgn), Oracle-Primavera-P6 (.xml), SAP, Oracle, ODBC, etc., Sketch-Up(.skp), Staad ASCII-file(.std), Steel-Detailing-Neutral-Format

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
			(.sdf, .sdnf, .dat), STE-PAP203 (.stp, .step), STEPAP-214 (.stp, .step), Stru-M.I.S, Tekla-BIM-Sight-Projectfile (.tbp), Tekla-Collabor-ationfile (.tczip), Tekla-Structural-Designer-neutralfile (.cxl), Tekla-Structur-esshape (.tsc), Trimble-Field-Link.tfl, Trimble-LM80 (.txt, .cnx)

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
2D MODEL-LING, 3D MODEL-LING	https:// www. autodesk. com/ products/ civil-3d/ overview? us-oa= dotcom-us&us-si=ae43e733-9ebd-47d7-ab07-fdbffa255d3d& us-pt= CIV3D & us-at= Civil 203% D&term =1-YEAR &tab= Subsc-ription& plc=CIV3D	Dolar 1,785/ year for 1 user	
PARA-METRIC MODE-LING SCAN-2BIM	https:// www. grasshopper 3d.com/ https:// www. bricsys. com/ en-eu	Dolar 24/ay https:// www. bricsys. com/ en-eu/ store/ bricscad? ld=12	

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
SCAN-2BIM	https:// www. faro. com/en/ Products/ Software/ SCENE-Software	150 Euro	
SCAN-2BIM	https:// shop. leica-geosy stems. com/gb/ leica-blk/ software/ leica-cyclone-3dr/buy	Dolar 4,16	
SCAN-2BIM	https:// geospatial. trimble. com/ en/ products/ software/ trimble-realworks	Dolar 4,765.00	
COORD-INATION, 4D PLAN-NING	http:// www. bentley. com/en-US/ Products/ Micro Station/	Annualy: Dolar 4280	ACIS, Alias Wavefront, Auto CAD, Autodesk, Autodesk 3DS, Autodesk FBX, Autodesk Inventor, Bentley iModel,

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
			Bentley iModel 2.0, Bentley MicroStation, CATIA V4, CATIA V5/V6, Collada, Dassault Interchange Format, GL Transmission Format, HOOPS stream file, I-deas, IFC, IGES part files, Navisworks, Parasolid, ProE/Creo, Revit, Rhino, SketchUp, Solid Edge, Solid Works, STEP part files, Stereo Lithography, UGS JT,

Table B.1 BIM software lists. (cont.)

USE	**WEB LINK**	**PRICE**	**IMPORT FILE FOR-MATS**
			Unigraphics NX, Universal 3D, VDA-FS, VRML files, 3D PDF, PRC
4D SIMUL-ATION	https:// www. bentley. com/ en/ products/ brands/ synchro	Dolar 2995.00/ yıl/ kullanıcı	
4D SIMUL-ATION	https:// vicooffice. dk/en/		
AR	https:// apps. apple. com/ us/app/ ar-mapper/ id 147424 1221	Free	
AR	https:// gamma-ar.com/	Dolar 86.00/ month	
VR	https:// smart-realty.io/	n/a	
VR	pair3d. com	n/a	

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
IFC	Processor: Intel i5 quad-core processor or AMD equivalent or better. Memory: 16GB RAM. Graphics: A dedicated graphics card that supports Open GL 2.0 at least (e.g. NVIDIA Ge Force GTX 1050 or AMD equivalent or better). The application is best viewed at 1920×1080 resolution or higher. Storage: The setup	Windows 7 SP1, Windows 8.Oca or Windows 10 (version 1607 or newer).	

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
	requires around 500MB of free disk space. For faster loading times, 128GB or larger SSD is recommended to be used for storing BEXEL Manager projects. Network: Internet connection is required during the installation and update process. Also, it is required at the software startup or closing or when using features based on cloud/ web services.		

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
n/a	Operating system Windows® 10.Kas Pro, Enterprise CPU 1x Intel Dual Core processor/ AMD Phenom II (3 GHz) RAM As from 8 GB RAM, 16 GB RAM recommended, for big 5D models 64 GB Monitor At least 22”, at least a resolution of 1920x1080 Hard disc At least 10 GB hard disc space, depending on the number of performed projects Printer All	MS .NET Framework 4.Ağu or higher, MS Windows Installer 4.5, MS Visual C++ 2013 2015 Redistributable, MS Power Shell 4.0, MS Edge Web View2, MS SQL Server 2016 Express Edition and upwards (only with individual workplace installation)	

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
	supported by Windows® General For single user installation 1 free USB slot for USB dongle. RIB iTWO model-based workstations with 3D-Viewer: Graphics card with DirectX, OpenGL 2.1 support. Umlauts and special characters are not supported with computer name and login name.		
FBX, PNG	CPU Intel® Pentium® 4 or AMD Athlon™ 3.0 GHz (or higher) with SSE2 technology RAM	Microsoft® Windows® 10 (64-bit) on the Semi Annual Channel servicing option.	

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
	2 GB RAM (minimum) DISK SPACE 15 GB free disk space for installation GRAPHICS Direct3D 9® and OpenGL® capable graphics card with Shader Model 2 (minimum) DISPLAY 1280 x 800 VGA display with true color (1920 x 1080 monitor and 32-bit video display adapter recommended) POINTING DEVICE Microsoft Mouse-compliant pointing device BROWSER Microsoft Internet Explorer® 8.0 or later		

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
IFC, SMV, JPG, PNG	Windows: Intel® Pentium® processor or compatible processor or better Microsoft® Windows® XP 32bit, Vista 32bit, 7 or 8 32bit MAC: MAC OS X 10.5.x. (Leopard) 2 GB RAM	Windows: 2 GB RAM 200 MB of available hard disk space OpenGL 1.1 Graphics card with OpenGL support and reasonable 3D performance. Up-to-date video card driver Wheel mouse or similar functionality MAC: 200 MB of available hard disk space Graphics card with OpenGL support and reasonable 3D performance. Wheel mouse or similar functionality	

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
Primavera P6 (.xer), MS Project (.xml), Microsoft Excel (.xlsx)			
.dwg, .dxf, .jpg, .png, .tif, .bmp, .psd, .tga, .pdf, .eps, .dae, .3ds, .fbx, .kmz, .obj, .wrl, .xsi, .ifc	Windows: Windows 10, Windows 8+ and Windows 7+ MAC: Mac OS 10.15+ (Catalina), Mac OS 10.14+ (Mojave), and Mac OS 10.13+ (High Sierra)	Windows: 1 GHz Processor 4GB RAM 500MB of free hard-disk space 3D class video card with 512 MB of memory or higher and support for hardware acceleration. Please ensure t hat the video card driver supports OpenGL 3.1 or higher and is up to date. MAC: 2.1+ GHz Intel™ Processor 4GB RAM 500MB	

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
		of available hard-disk space. 3D class video card with 512 MB of memory or higher and support for hardware acceleration. Please ensure that the video card driver supports OpenGL version 3.1 or higher and up to date. 3-button, scroll-wheel mouse.	
3D XML, ACIS, Adobe Illustrator, Adobe Photoshop, Adobe Portable Document	Processor 3.3 GHz or higher RAM 16 GB or More PDM Contributor/ Viewer or Electrical	Windows 10, 64-bit Windows Server 2019 Windows Server 2016 macOS Mojave (10.14) macOS	

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
Format, CATIA Graphics, eDrawings, Highly Compressed Graphics, HOOPS, IDF 2.0, 3.0, 4.0 (Circuit Works), IFC, IGES, JPEG, PADS (*.asc) (Circuit Works), Parasolid, PDF, Pro/ ENGINEER, ProStep EDMD (*.idx) (Circuit Works), Scan To3D, STEP, STL, TIFF, VDAFS, Viewpoint, VRML, XPS	Schematic: 8 GB or More Graphics Certified cards and drivers Drives SSD drives recommended for optimal performance	Catalina (10.15)	

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
.dwg, .dxf, .dwf, .w2d, .dwfx, .txt, .csv, .dif, .slk, .eps, .hdr, .bmp, .gif, .jpg, .jpeg, .png, .tif, .wdp, .dds, .jp2, .tga, .exr, .psd, .emf, .pdf, .txt, .py, .vss, .vs, .txt, .csv, .dif, .slk, .c4d, .dae, .fbx, .igs, .iges, .obj, .jpg, .html, .js, .sat,	Windows: 64-bit Intel Core i5 (or AMD equivalent), Intel Xeon E4 series or better. OpenGL 2.1 compatible graphics card with minimum 1GB, recommended 2GB-4GB VRAM. A dedicated graphics card is highly recommended. 1440 x 900 minimum at least 4GB, better 8GB or more 32 Bit Double-Layer- DVD MAC: 64-bit Intel Core i5 (or AMD equivalent), Intel Xeon E4 series or better. OpenGL 2.1 compatible graphics card with minimum	Windows: 64-bit Intel Core i5 (or AMD equivalent), Intel Xeon E4 series or better. OpenGL 2.Oca compatible graphics card with minimum 1GB, recommended 2GB-4GB VRAM. A dedicated graphics card is highly recommended. at least 1440 x 900 at least 4 GB, better 8 GB or more 32 Bit Double- Layer-DVD MAC: OS X 10.9 or later	

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
.stp, .step, .stl, .3dm, .X-T, .vwx, .ifc, .ifcXML, .ifcZIP, .3ds, .pdf, .kml, .vgx, .html, .js, .bpw, .jgw, .pgw, .tfw, .gfw, .wld, .shp, .bcfzip, .txt, .txt, .esc	1GB, recommended 2GB-4GB VRAM. A dedicated graphics card is highly recommended. at least 1440 x 900 at least 4 GB, better 8 GB or more 32 Bit Double-Layer-DVD		
DWG, DXF, DGN, ACIS SAT, DWF/ DWFx, FBX, NWC, gbXML, IFC, ADSK, gbXML, Microsoft Access, Microsoft Excel, Microsoft SQL	1280 x 1024 with true color Maximum: UltraHigh (4k) Definition Monitor Basic Graphics: Display adapter capable of 24-bit color Advanced Graphics: DirectX®	Microsoft Windows 10 64-bit Windows 10 Enterprise Windows 10 Pro Note: Microsoft Windows 7 SP1 64-bit, Enterprise, Ultimate, and Professional are supported but not	

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
Server, Walkthrough – AVI, Solar Study – AVI, Images, JPEG, TIFF, BMP, TARGA, PNG, Delimited text (.txt)	11 capable graphics card with Shader Model 3 30 GB free disk space	recommended.	
DWG, DXF, FBX, STL, SKP, JT, IGES, Parasolid XMT, ACIS SAT, CGM, STEP AP203, STEP AP214, Acute3D (.3mx), VRML World, SVG, OBJ, Luxology (LXO), Google Earth (KML), Collada	Windows 10 (64-bit) – Home, Pro, Enterprise, and Education Windows 8 (64-bit) – Standard, Pro, and Enterprise Windows 8.1 (64-bit) – Standard, Pro, and Enterprise Windows 7 SP1 (64-bit) – Home Basic, Home Premium, Professional, Enterprise, and Ultimate	Intel Pentium-based or AMD Athlon based processor 2.0 GHz or greater 1 GB minimum, 2 GB recommended, (more memory typically results in better performance) 1.25 GB minimum free disk space	

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
(DAE), U3D	Windows Server 2008 R2 SP1 (64 bit) – Standard and Enterprise Windows Server 2012 (64 bit)		
.pln, .pla, .tpl, .mod, .2dl, .bimx, .bimproject, .twtravel, .bimlibrary, .bcmb, .bcsb, .lcf, .gsm, .gdl, .pmk, .support, .twsupport, .dwg, .dxf, .dgn, .ifc, .ifcxml, .ifczip, .bcf, .nwc, .smc, .c4d, .3dm, .3ds, .atl, .kml,	Windows 8 Windows 7 Mac OS X 10.Eki Yosemite	64-bit processor with two cores 8 GB 5 GB or more is required for the installation OpenGL 2.0 compatible graphics card A resolution of 1366 x 768 or higher	

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
.kmz, .skp, .dae, .epx, .fact, .obj, .stl, .u3d, .fbx, .wrl, .pdf, .dwf, .bmp, .jpeg, .gif, .tiff, .tif, .png, .wmf, .emf, .mp4, .mov, .doc, .xls, .xlsx, .txt, .plt, .phpp, .gbxml			
.dxf, .dwg, .dwf, .dgn, .pdf, .ifc, .ifcXML, .c4d, .skp, .cpixml, .3dm, .wrl, .dae, .kmz,	Intel processor or compatible with AVX support 4 GB RAM 10 GB free hard disk space	Windows 10 64 bit, version 1909 Windows 8.1, 64 bit Windows Server 2019 Standard- Edition (for Citrix)	

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
.stl, .u3d .plt, .hp, .hpg, .hpl, .prn, .svg, .3ds, .xlsx, .docx, .pdf .xml, .re1, .reb, .re2, .asc, .lin, .lpr, .qpr, .asc, .sin, .abs, .tec, .tek, .xml .jpg, .jff, .jtf, .tif, .bmp, .eps, .tga, .pct, .pcx, .png, .psd	OpenGL 2.2 compatible graphics board, 2 GB RAM, resolution 1280 x 1024	Windows Server 2016, Standard- Edition (for Citrix) Windows Server 2012 R2, Standard- Edition (for Citrix)	

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
aSa (.TEK), Autodesk (.dwg), Autodesk (.dxf), Bentley ISM, BIM Collaboration Format (.bcf), BVBS (.abs), Cadma-ticmodels (.3dd), CIS/ 2LPM5/ LPM6 Analytical (.stp, .p21, .step), CIS/ 2LPM6 Manufac-turing (.stp, .p21, .step), CPIxml, EJE, Elematic ELiPLAN, ELiPOS (.eli), EPC, Fabsuite (.xml), Fab Trol Kiss	16+ GB 240-480 GB, SSD Intel® Core™ i5 CPU 2+ GHz Two monitor support e.g. NVIDIA GeForce RTX 2060/2070 Two 27” 1920x1200 Each External hard drive 100 Mbit/s IPv4 or IPv6	Windows 10 (64-bit)	

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
File (.kss), Fab Trol MISXml (.xml), High Level Interface File (.hli), HMS (.sot), IBBB Etsy (.fa, .f, .ev), IFC2x3 (.ifc), IFCX ML2X3 (.ifcXML), IFCZIP 2x3 (.ifcZIP), Initial Graphics Exchange Specification (IGES) (.iges, .igs), Microsoft Project (.xml), Microstation (.dgn), Oracle Primavera P6 (.xml),			

Table B.1 BIM software lists. (cont.)

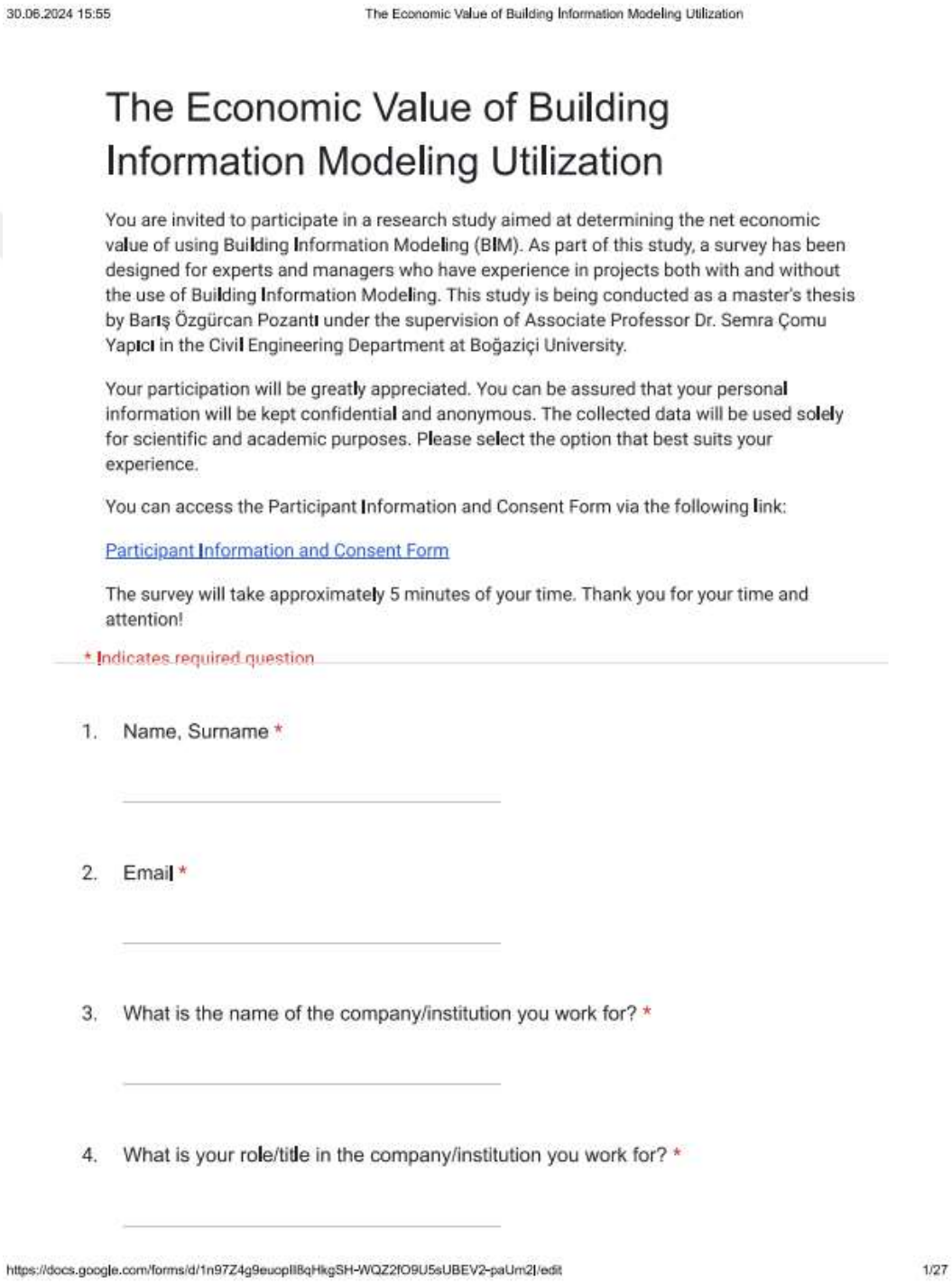
EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
Plant Design Management System (.pdms), SAP, Oracle, ODBC, etc., Sketch Up (.skp), Staad ASCII File (.std), Steel Detailing Neutral Format (.sdf, .sdnf, .dat), Steel 12000 STEPAP 214 (.stp, .step), Stru M.I.S, Tekla BIM Sightproject File (.tbp), Tekla Collabora Tionfile (.tczip), Tekla-Fab Trol Report (.xsr),			

Table B.1 BIM software lists. (cont.)

EXPORT FILE FOR-MATS	**MINIMUM HARD-WARE REQUIR-EMENTS**	**MINIMUM SYSTEM REQUIR-EMENTS**	
Tekla Structural Designer Neutralfile (.cxl), Tekla Structure Sshape (.tsc), Trimble Field Link. tfl, Trimble LM80 (.txt, .cnx), Tube NC (.xml), Unitechnik (.uni, .cam)			
Asta Powerproject (.mpxj), Excel (.xlsx), Microsoft Project (.xml), IFC 2x3 (.ifc), Primavera P6 (.xer)	Processor Requirements: 2.8GHz Dual Core minimum; 3.33GHz Dual Core recommended; 4.0GHZ Quad Core enterprise specification; only 64-bit (x64) processors are supported.	Supported Browsers: Microsoft Windows 7, Microsoft Windows 8/8.1, Microsoft Windows 10, Microsoft Windows Server	

APPENDIX C: WEB QUESTIONNAIRE SURVEY

The online survey conducted in the scope of this thesis is given below:



30.06.2024 15:55 The Economic Value of Building Information Modeling Utilization

The Economic Value of Building Information Modeling Utilization

You are invited to participate in a research study aimed at determining the net economic value of using Building Information Modeling (BIM). As part of this study, a survey has been designed for experts and managers who have experience in projects both with and without the use of Building Information Modeling. This study is being conducted as a master's thesis by Barış Özgürcan Pozantı under the supervision of Associate Professor Dr. Semra Çomu Yapıcı in the Civil Engineering Department at Boğaziçi University.

Your participation will be greatly appreciated. You can be assured that your personal information will be kept confidential and anonymous. The collected data will be used solely for scientific and academic purposes. Please select the option that best suits your experience.

You can access the Participant Information and Consent Form via the following link:

Participant Information and Consent Form

The survey will take approximately 5 minutes of your time. Thank you for your time and attention!

* Indicates required question

1. Name, Surname *

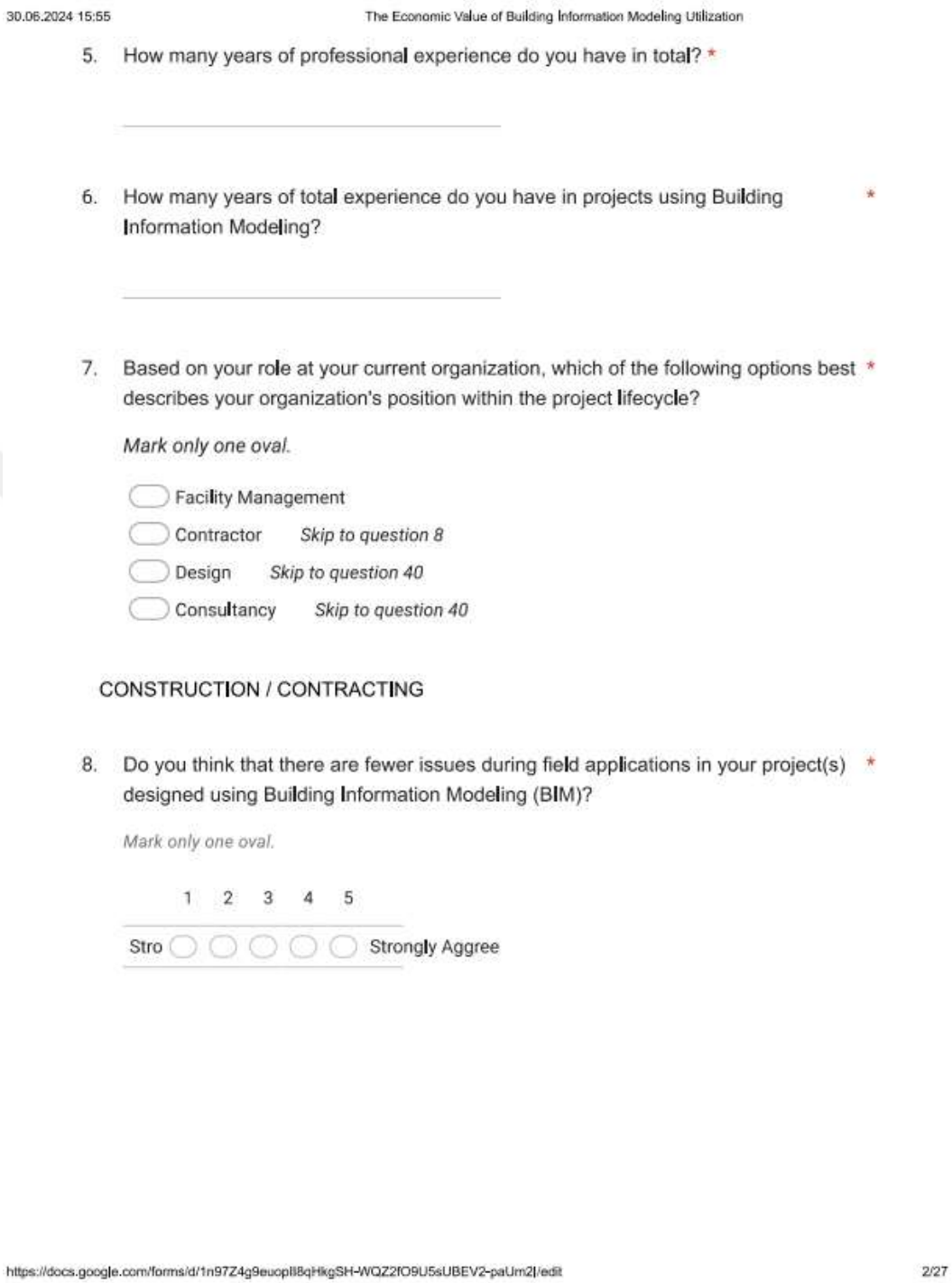
2. Email *

3. What is the name of the company/institution you work for? *

4. What is your role/title in the company/institution you work for? *

https://docs.google.com/forms/d/1n97Z4g9euopIIBqHkgSH-WQZ2fO9U5sUBEV2-paUm2I/edit 1/27

Figure C.1. WEB questionnaire survey 1.



30.06.2024 15:55 The Economic Value of Building Information Modeling Utilization

5. How many years of professional experience do you have in total? *

6. How many years of total experience do you have in projects using Building Information Modeling? *

7. Based on your role at your current organization, which of the following options best describes your organization's position within the project lifecycle? *

Mark only one oval.

- Facility Management
- Contractor *Skip to question 8*
- Design *Skip to question 40*
- Consultancy *Skip to question 40*

CONSTRUCTION / CONTRACTING

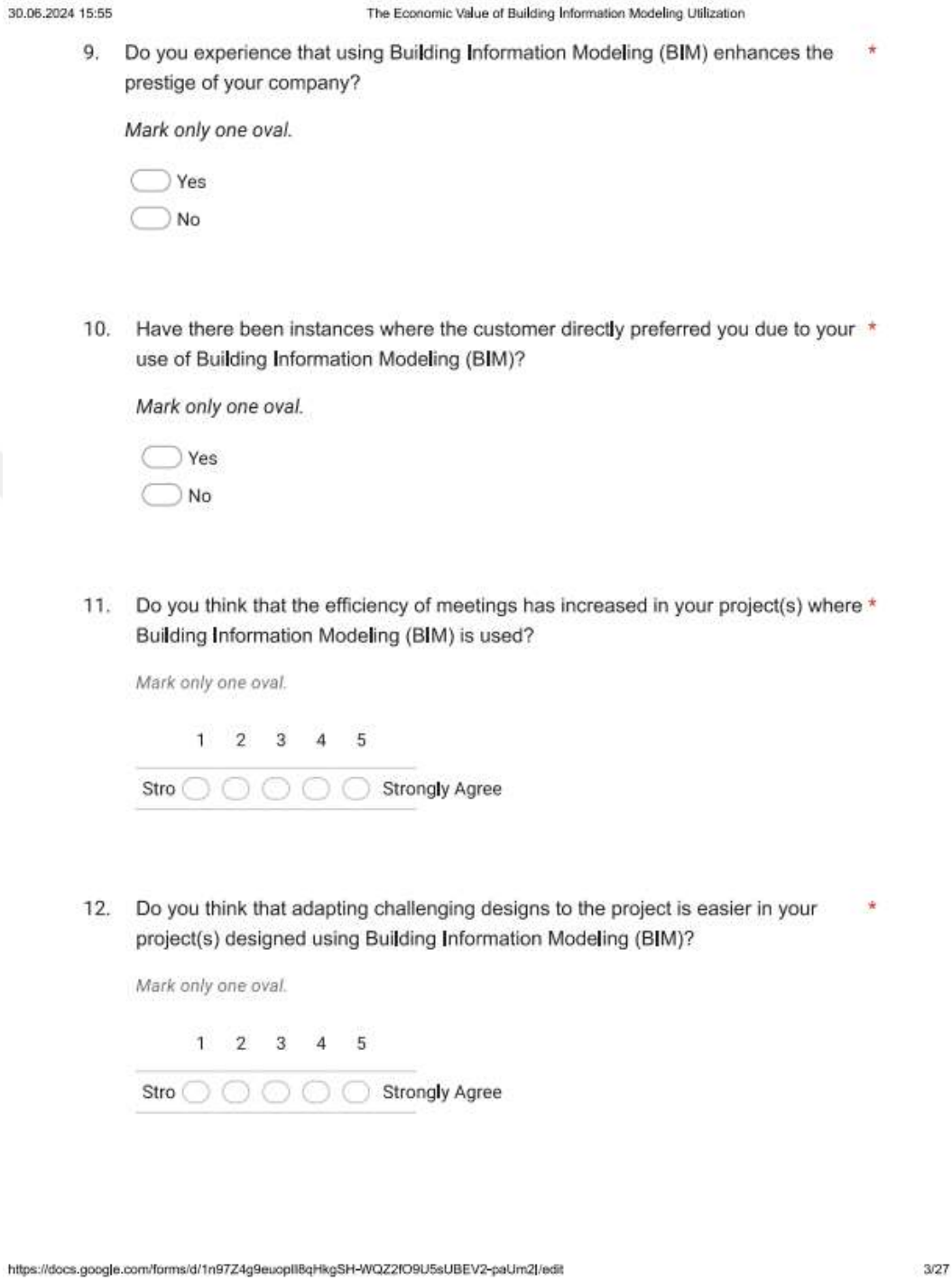
8. Do you think that there are fewer issues during field applications in your project(s) designed using Building Information Modeling (BIM)? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Aggree

https://docs.google.com/forms/d/1n97Z4g9euopll8qHkgSH-WQZ2fO9U5sUBEV2-paUm2I/edit 2/27

Figure C.2. WEB questionnaire survey 2.



9. Do you experience that using Building Information Modeling (BIM) enhances the prestige of your company? *

Mark only one oval.

- Yes
- No

10. Have there been instances where the customer directly preferred you due to your use of Building Information Modeling (BIM)? *

Mark only one oval.

- Yes
- No

11. Do you think that the efficiency of meetings has increased in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

12. Do you think that adapting challenging designs to the project is easier in your project(s) designed using Building Information Modeling (BIM)? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

Figure C.3. WEB questionnaire survey 3.

13. Do you think that document management is easier in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

14. Do you think that you can track the design process better in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

15. Do you think that the use of Building Information Modeling (BIM) helps new technical personnel in your team adapt more easily to projects? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

16. Do you think that using Building Information Modeling (BIM) helps you design more safely in terms of Occupational Health and Safety (OHS) during the construction process? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

Figure C.4. WEB questionnaire survey 4.

17. Do you think that using Building Information Modeling (BIM) helps globalize your pool of subcontractors? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

18. In your project(s) designed using Building Information Modeling (BIM), do you use more prefabricated and precast elements thanks to BIM? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

19. Do you think that the use of Building Information Modeling (BIM) in your project(s) has reduced the number of Requests for Information (RFIs) submitted to and received from your client and subcontractors? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

Figure C.5. WEB questionnaire survey 5.

20. Do you think that more realistic cost estimation and budgeting can be done in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

- ◯ Yes
- ◯ No
- ◯ I don't know / No opinion

21. Do you think that more realistic project scheduling can be done in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

- ◯ Yes
- ◯ No
- ◯ I don't know / No opinion

22. How do you think design change orders (regardless of the source) have changed in your project(s) designed using Building Information Modeling (BIM)? *

Mark only one oval.

- ◯ Increasing
- ◯ Decreasing
- ◯ Neutral (No effect)
- ◯ I don't know / No opinion

Figure C.6. WEB questionnaire survey 6.

23. Do you think that using Building Information Modeling (BIM) helps in optimizing the project schedule? *

Mark only one oval.

- ◯ Yes
- ◯ No
- ◯ I don't know / No opinion

24. How do you think using Building Information Modeling (BIM) has affected the overall project duration? *

Mark only one oval.

- ◯ Negative (Increases it) *Skip to question 25*
- ◯ Positive (Decreases it) *Skip to question 26*
- ◯ Neutral (No effect) *Skip to question 27*
- ◯ I don't know / No opinion *Skip to question 27*

Skip to question 27

CONSTRUCTION / CONTRACTING

25. By how much has the total project duration increased on average due to your use of Building Information Modeling (BIM)? *

Mark only one oval.

- ◯ Up to %10
- ◯ Between 10% and 25%
- ◯ Between %25-%50
- ◯ Between %50-%75
- ◯ Between %75-%100
- ◯ Over %100

Skip to question 27

Figure C.7. WEB questionnaire survey 7.

CONSTRUCTION / CONTRACTING

26. By how much has the total project duration decreased on average due to your use of Building Information Modeling (BIM)? *

Mark only one oval.

- ◯ Up to %10
- ◯ Between 10% and 25%
- ◯ Between %25-%50
- ◯ Between %50-%75
- ◯ Between %75-%100

Skip to question 27

CONSTRUCTION / CONTRACTING

27. How has the total contract value changed as a result of your use of Building Information Modeling (BIM)? *

Mark only one oval.

- ◯ Negative (decrease in cost) *Skip to question 28*
- ◯ Positive (increase in cost) *Skip to question 29*
- ◯ Neutral (No effect) *Skip to question 30*
- ◯ I don't know / No opinion *Skip to question 30*

Skip to question 30

CONSTRUCTION / CONTRACTING

Figure C.8. WEB questionnaire survey 8.

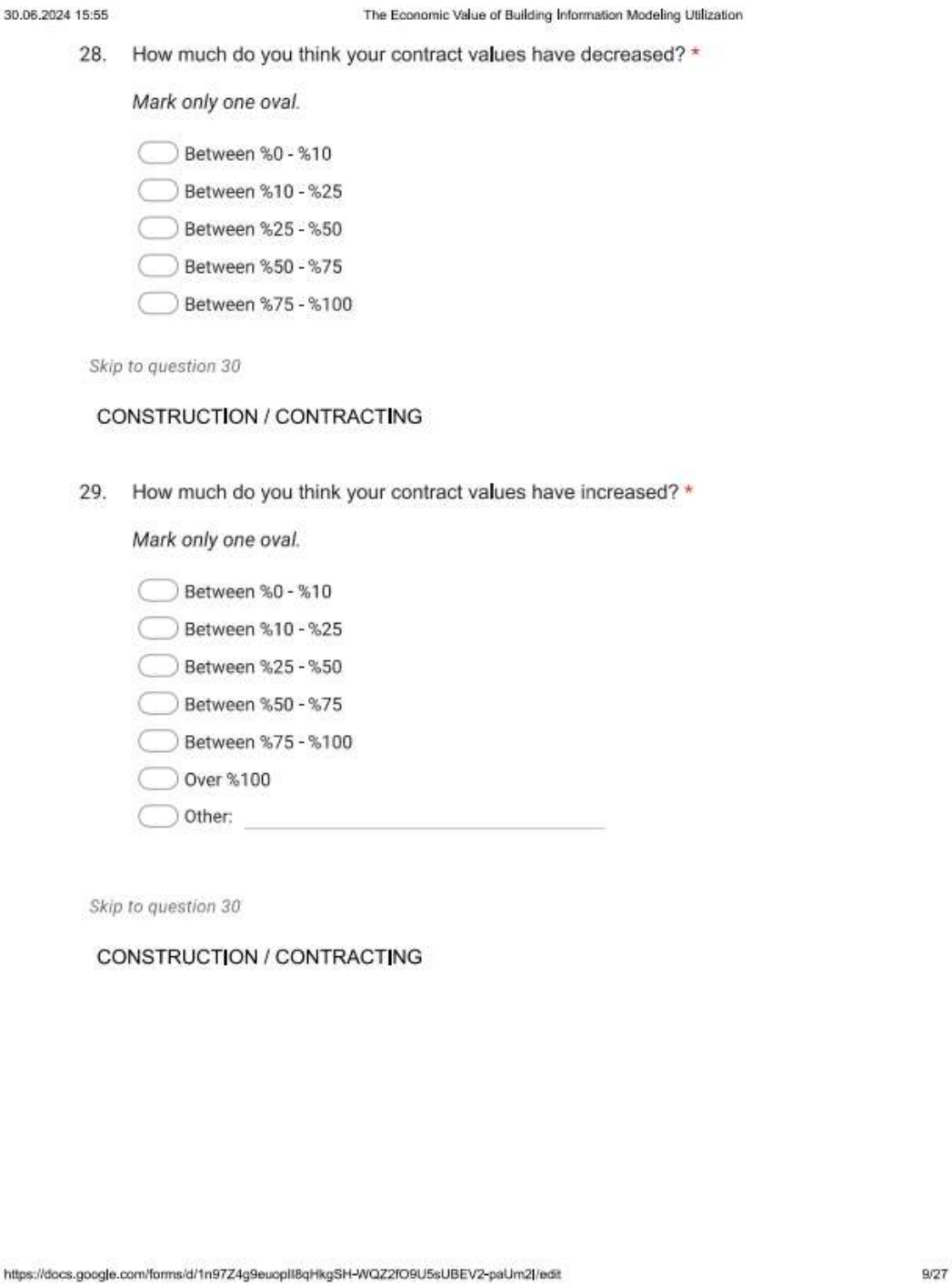


Figure C.9. WEB questionnaire survey 9.

30. How do you think your construction costs (excluding design fees) have changed in your project(s) designed using Building Information Modeling (BIM)? *

Mark only one oval.

- ◯ Negative (cost increase) *Skip to question 31*
- ◯ Positive (cost decrease) *Skip to question 32*
- ◯ Neutral (No effect) *Skip to question 33*
- ◯ I don't know / No opinion *Skip to question 33*

Skip to question 33

CONSTRUCTION / CONTRACTING

31. How much do you think your total construction cost has increased? *

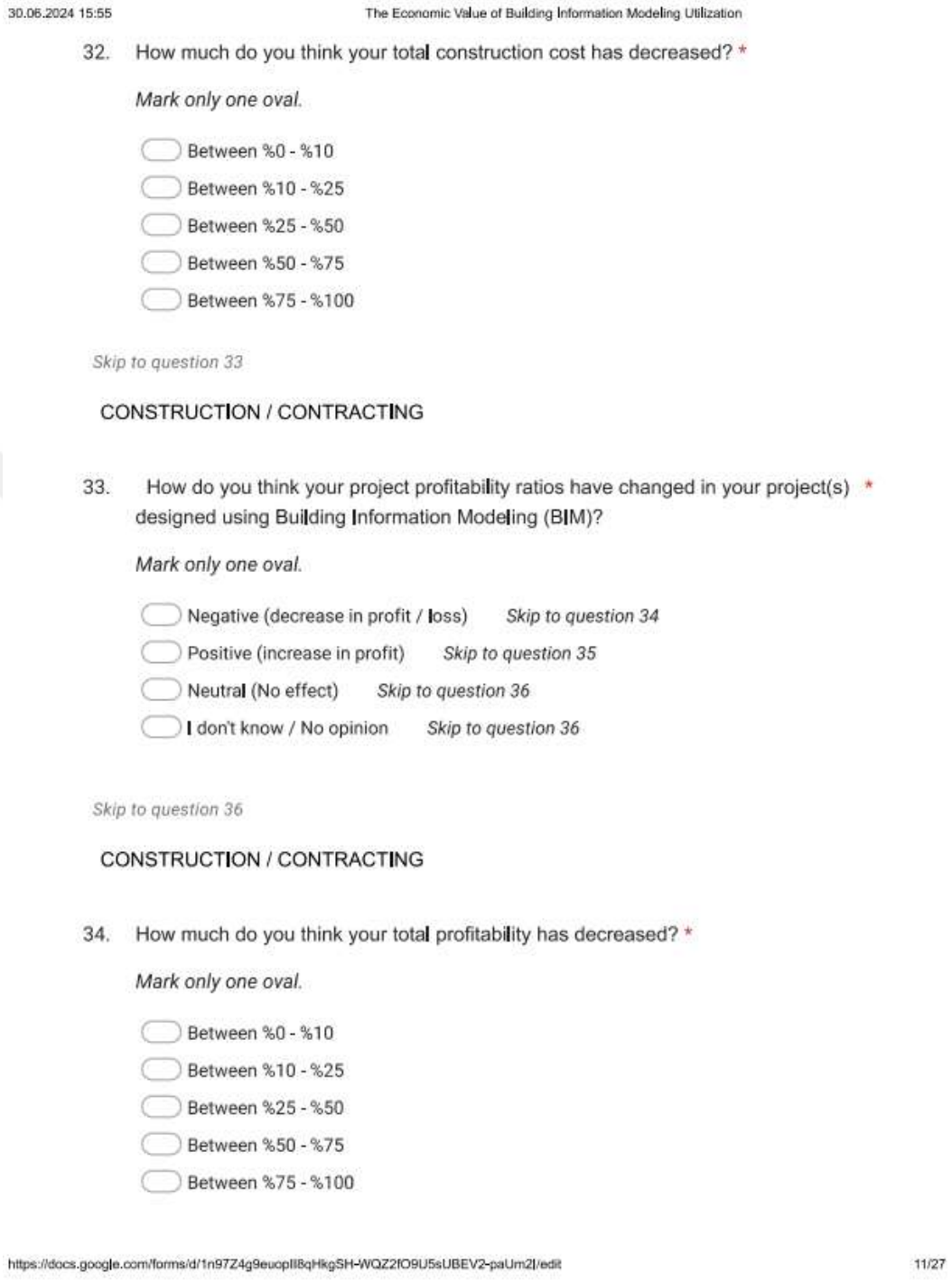
Mark only one oval.

- ◯ Between %0 - %10
- ◯ Between %10 - %25
- ◯ Between %25 - %50
- ◯ Between %50 - %75
- ◯ Between %75 - %100
- ◯ Over %100
- ◯ Other: _____

Skip to question 33

CONSTRUCTION / CONTRACTING

Figure C.10. WEB questionnaire survey 10.



32. How much do you think your total construction cost has decreased? *

Mark only one oval.

- Between %0 - %10
- Between %10 - %25
- Between %25 - %50
- Between %50 - %75
- Between %75 - %100

Skip to question 33

CONSTRUCTION / CONTRACTING

33. How do you think your project profitability ratios have changed in your project(s) designed using Building Information Modeling (BIM)? *

Mark only one oval.

- Negative (decrease in profit / loss) *Skip to question 34*
- Positive (increase in profit) *Skip to question 35*
- Neutral (No effect) *Skip to question 36*
- I don't know / No opinion *Skip to question 36*

Skip to question 36

CONSTRUCTION / CONTRACTING

34. How much do you think your total profitability has decreased? *

Mark only one oval.

- Between %0 - %10
- Between %10 - %25
- Between %25 - %50
- Between %50 - %75
- Between %75 - %100

Figure C.11. WEB questionnaire survey 11.

Skip to question 36

CONSTRUCTION / CONTRACTING

35. How much do you think your total project profitability has increased? *

Mark only one oval.

- ◯ Between %0 - %10
- ◯ Between %10 - %25
- ◯ Between %25 - %50
- ◯ Between %50 - %75
- ◯ Between %75 - %100
- ◯ Over %100
- ◯ Other: _____

Skip to question 36

CONSTRUCTION / CONTRACTING

36. How do you think the amount of rework has changed in your project(s) designed using Building Information Modeling (BIM)? *

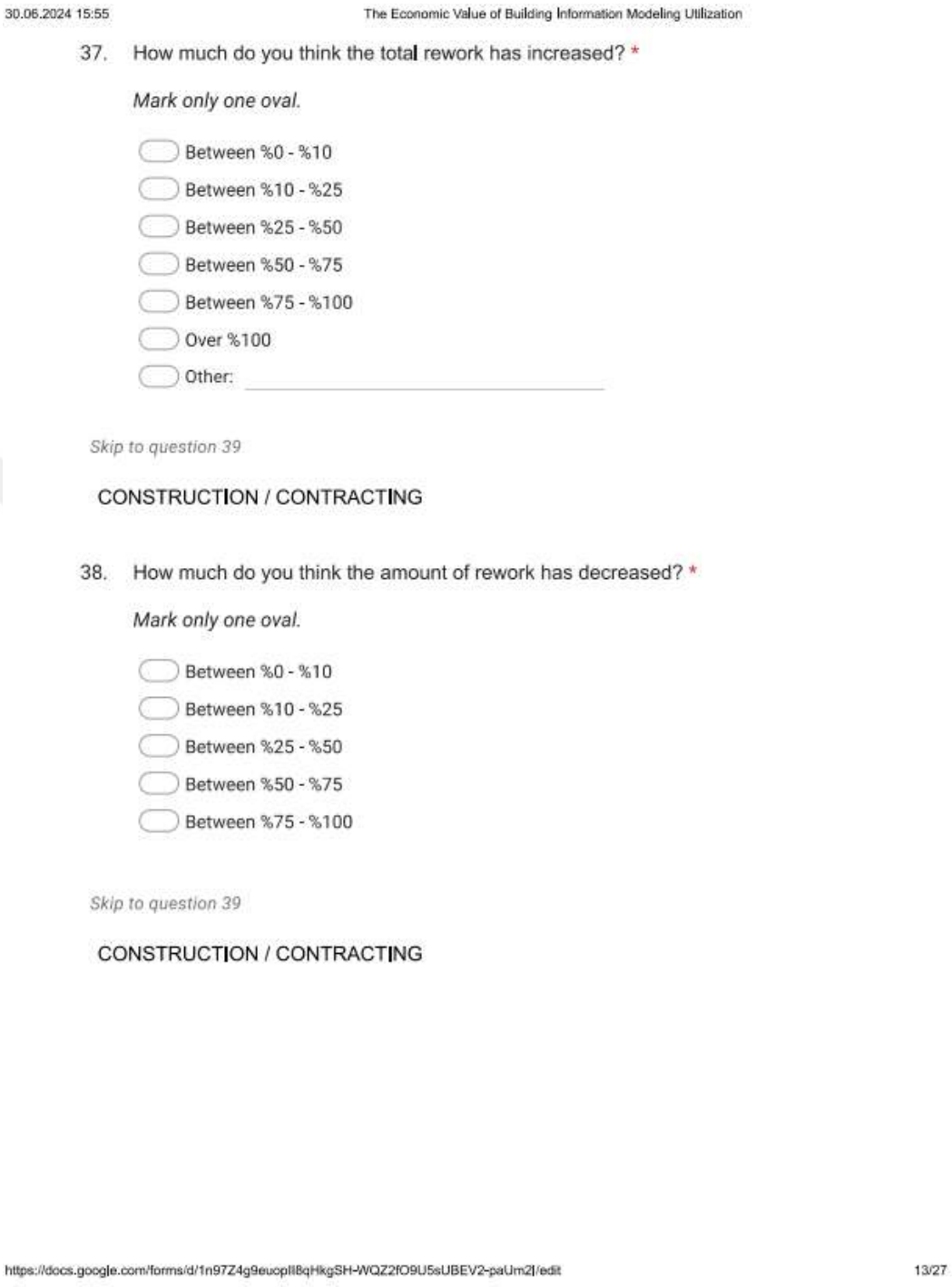
Mark only one oval.

- ◯ Negative (increase in rework) *Skip to question 37*
- ◯ Positive (decrease in rework) *Skip to question 38*
- ◯ Neutral (No effect) *Skip to question 39*
- ◯ I don't know / No opinion *Skip to question 39*

Skip to question 39

CONSTRUCTION / CONTRACTING

Figure C.12. WEB questionnaire survey 12.



37. How much do you think the total rework has increased? *

Mark only one oval.

- Between %0 - %10
- Between %10 - %25
- Between %25 - %50
- Between %50 - %75
- Between %75 - %100
- Over %100
- Other: _____

Skip to question 39

CONSTRUCTION / CONTRACTING

38. How much do you think the amount of rework has decreased? *

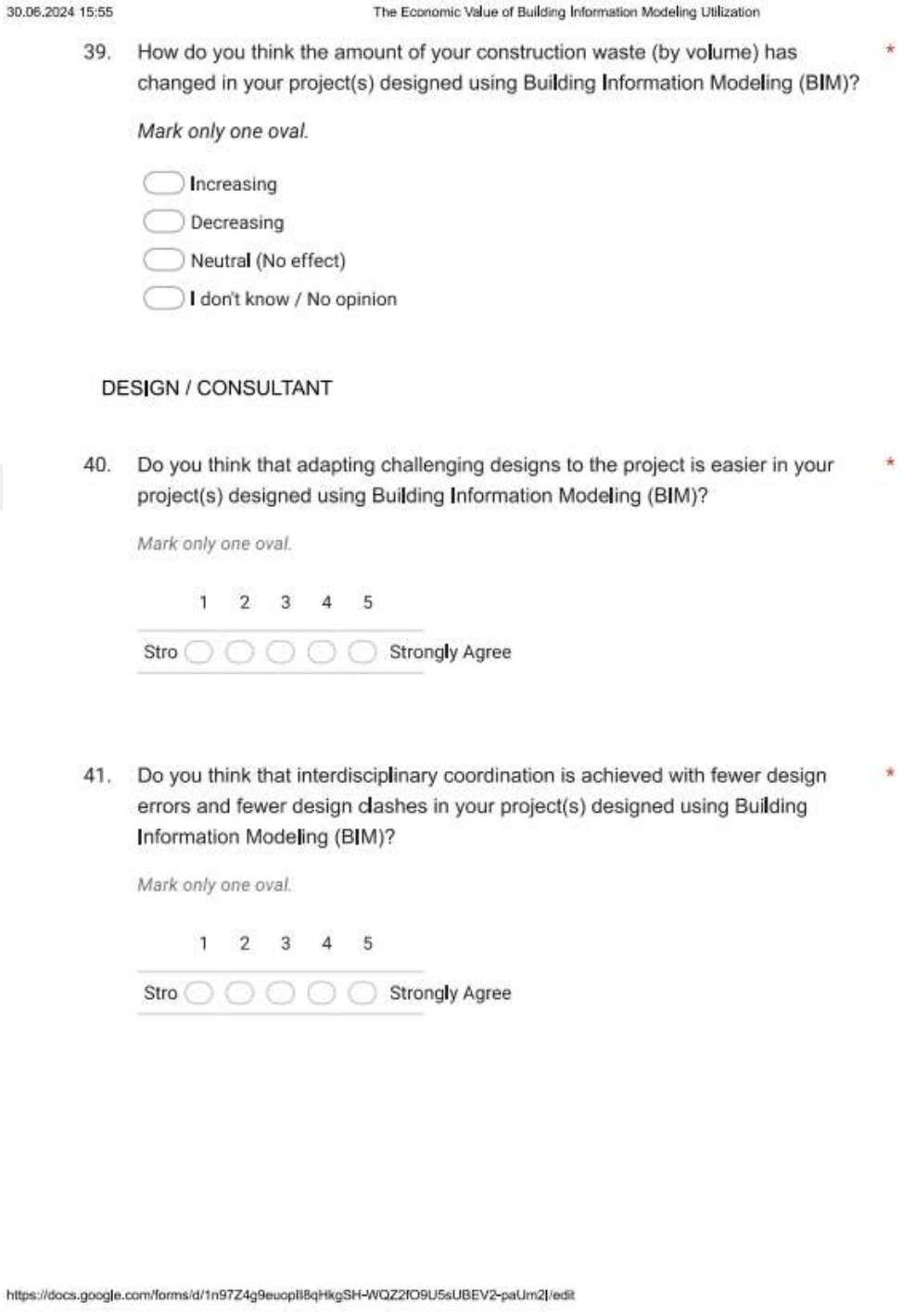
Mark only one oval.

- Between %0 - %10
- Between %10 - %25
- Between %25 - %50
- Between %50 - %75
- Between %75 - %100

Skip to question 39

CONSTRUCTION / CONTRACTING

Figure C.13. WEB questionnaire survey 13.



30.06.2024 15:55 The Economic Value of Building Information Modeling Utilization

39. How do you think the amount of your construction waste (by volume) has changed in your project(s) designed using Building Information Modeling (BIM)? *

Mark only one oval.

- Increasing
- Decreasing
- Neutral (No effect)
- I don't know / No opinion

DESIGN / CONSULTANT

40. Do you think that adapting challenging designs to the project is easier in your project(s) designed using Building Information Modeling (BIM)? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

41. Do you think that interdisciplinary coordination is achieved with fewer design errors and fewer design clashes in your project(s) designed using Building Information Modeling (BIM)? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

https://docs.google.com/forms/d/1n97Z4g9euopli8qHkgSH-WQZ2fO9U5sUBEV2-paUm2I/edit 14/27

Figure C.14. WEB questionnaire survey 14.

42. How often do you use the building information model for conducting structural analyses in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Nev	◯	◯	◯	◯	◯	Always / In all projects

43. How often do you use the information model for conducting solar exposure / shading analysis in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Nev	◯	◯	◯	◯	◯	Always / In all projects

44. How often do you use the information model for conducting energy consumption and sustainability analyses in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Nev	◯	◯	◯	◯	◯	Always / In all projects

Figure C.15. WEB questionnaire survey 15.

45. How often do you use the information model for conducting accessibility analysis in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Nev	◯	◯	◯	◯	◯	Always / In all projects

46. How often do you use the information model for conducting user circulation analysis in normal and emergency situations in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Nev	◯	◯	◯	◯	◯	Always / In all projects

47. How often do you use the information model for conducting passive and active climate control analyses in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Nev	◯	◯	◯	◯	◯	Always / In all projects

Figure C.16. WEB questionnaire survey 16.

48. How often do you use the information model for conducting hydraulic analysis of your structure in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Nev	◯	◯	◯	◯	◯	Always / In all projects

49. How often do you use the information model for conducting lighting analysis in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Nev	◯	◯	◯	◯	◯	Always / In all projects

50. How often do you use the information model for conducting coverage analysis of closed-circuit television (CCTV) systems in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Nev	◯	◯	◯	◯	◯	Always / In all projects

Figure C.17. WEB questionnaire survey 17.

51. How often do you use the information model for conducting acoustic analysis in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Nev	◯	◯	◯	◯	◯	Always / In all projects

52. Do you think that meeting efficiency has increased in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

53. Do you think that presentation and delivery tasks conducted throughout the design process are faster and easier in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

54. Do you think that the design process can be better perceived and followed by the customer in your project(s) where Building Information Modeling (BIM) is used? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

Figure C.18. WEB questionnaire survey 18.

55. Do you think that the use of Building Information Modeling (BIM) helps new technical personnel in your team adapt more easily to projects? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

56. Do you think that using Building Information Modeling (BIM) helps you design more safely in terms of Occupational Health and Safety (OHS) during the construction process? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

57. Do you think that using Building Information Modeling (BIM) helps globalize your pool of subcontractors? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

Figure C.19. WEB questionnaire survey 19.

58. Do you think that the use of Building Information Modeling (BIM) in your project(s) has reduced the number of Requests for Information (RFIs) submitted by you to your client and received from your client? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

59. Do you experience that using Building Information Modeling (BIM) enhances the prestige of your company? *

Mark only one oval.

	1	2	3	4	5	
Stro	◯	◯	◯	◯	◯	Strongly Agree

60. Have there been instances where the customer directly preferred you due to your use of Building Information Modeling (BIM)? *

Mark only one oval.

◯ Yes
◯ No

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Figure C.20. WEB questionnaire survey 20.

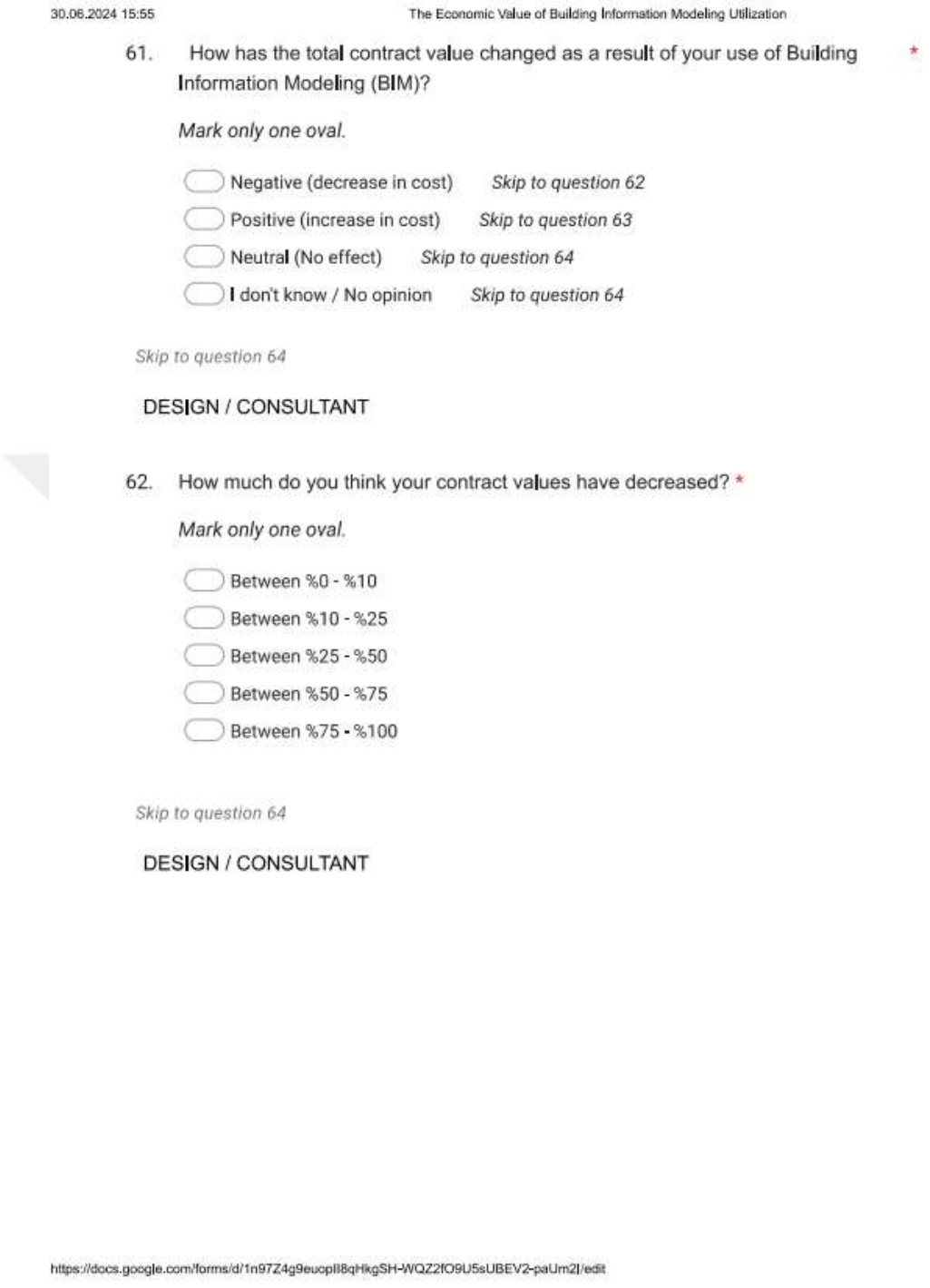

Figure C.21. WEB questionnaire survey 21.

63. How much do you think your contract values have increased? *

Mark only one oval.

- ◯ Between %0 - %10
- ◯ Between %10 - %25
- ◯ Between %25 - %50
- ◯ Between %50 - %75
- ◯ Between %75 - %100
- ◯ Over %100
- ◯ Other: _____

Skip to question 64

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64. Do you think that using Building Information Modeling (BIM) helps in optimizing the project schedule? *

Mark only one oval.

- ◯ Yes
- ◯ No
- ◯ I don't know / No opinion

65. What impact do you think using Building Information Modeling (BIM) has on the total project duration? *

Mark only one oval.

- ◯ Negative (Increase) *Skip to question 66*
- ◯ Positive (Decrease) *Skip to question 67*
- ◯ Neutral (No effect) *Skip to question 68*
- ◯ I don't know / No opinion *Skip to question 68*

Skip to question 68

Figure C.22. WEB questionnaire survey 22.

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66. By how much has the total project duration increased on average due to your use of Building Information Modeling (BIM)? *

Mark only one oval.

- Between %0 - %10
- Between %10 - %25
- Between %25 - %50
- Between %50 - %75
- Between %75 - %100
- Over %100
- Other: _____

Skip to question 68

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67. By how much has the total project duration decreased on average due to your use of Building Information Modeling (BIM)? *

Mark only one oval.

- Between %0 - %10
- Between %10 - %25
- Between %25 - %50
- Between %50 - %75
- Between %75 - %100

Skip to question 68

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Figure C.23. WEB questionnaire survey 23.

68. In your project(s) designed using Building Information Modeling (BIM), in which direction do you think your project cost has changed? *

Mark only one oval.

- ◯ Negative (cost increase) *Skip to question 69*
- ◯ Positive (cost decrease) *Skip to question 70*
- ◯ Neutral (No effect) *Skip to question 71*
- ◯ I don't know / No opinion *Skip to question 71*

Skip to question 71

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69. How much do you think your total project cost has increased?

Mark only one oval.

- ◯ Between %0 - %10
- ◯ Between %10 - %25
- ◯ Between %25 - %50
- ◯ Between %50 - %75
- ◯ Between %75 - %100
- ◯ Over %100
- ◯ Other: _____

Skip to question 71

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Figure C.24. WEB questionnaire survey 24.

70. How much do you think your total project cost has decreased?

Mark only one oval.

- ◯ Between %0 - %10
- ◯ Between %10 - %25
- ◯ Between %25 - %50
- ◯ Between %50 - %75
- ◯ Between %75 - %100

Skip to question 71

DESIGN / CONSULTANT

71. In your project(s) designed using Building Information Modeling (BIM), which direction do you think your project profitability have changed?

Mark only one oval.

- ◯ Negative (decrease in profit / loss) *Skip to question 72*
- ◯ Positive (increase in profit) *Skip to question 73*
- ◯ Neutral (No effect)
- ◯ I don't know / No opinion

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72. How much do you think your total profitability has decreased?

Mark only one oval.

- ◯ Between %0 - %10
- ◯ Between %10 - %25
- ◯ Between %25 - %50
- ◯ Between %50 - %75
- ◯ Between %75 - %100

Figure C.25. WEB questionnaire survey 25.



Figure C.26. WEB questionnaire survey 26.



Figure C.27. WEB questionnaire survey 27.

APPENDIX D: PAIRWISE COMPARISON SURVEY

The online questionnaire about pairwise comparisons of ANP analysis is given below:

Table D.1. Pairwise comparison survey 1.

Information about Expert	
Expert's Name/ Surname	
Job Title	
Work Experience(years)	
BIM Experience(years)	

Table D.2. Pairwise comparison survey 2.

Code	**Linguistic variables**
1	Equal Importance
2	Weak or Slight
3	Moderate Importance
4	Moderate Plus
5	Strong Importance
6	Strong Plus
7	Very Strong or demonstrated importance
8	Very, very Importance
9	Extreme Importance

Table D.3. Pairwise comparison survey 15.

Example Code Selection for Criteria																		
																		Criteria 2 is **Very strongly preferred** than Criteria 1
Criteria 1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Criteria 2**
Criteria 3 is **Strongly to very strongly preferred** than Criteria 4																		
Criteria 3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Criteria 4**

Table D.4. Pairwise comparison survey 4.

Pairwise comparison of Criteria with respect to Maximum BIM Benefit																		
High-quality Design (X2)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Accurate Planning (X1)
Efficient Construction (X3)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Accurate Planning (X1)
Improved Sustainability (X4)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Accurate Planning (X1)
Enhanced Information Management (X5)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Accurate Planning (X1)
Efficient Construction (X3)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	High-quality Design (X2)
Improved Sustainability (X4)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	High-quality Design (X2)
Enhanced Information Management (X5)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	High-quality Design (X2)
Improved Sustainability (X4)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Efficient Construction (X3)
Enhanced Information Management (X5)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Efficient Construction (X3)
Enhanced Information Management (X5)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Improved Sustainability (X4)

Table D.5. Pairwise comparison survey 5.

Pairwise comparison of Criteria with respect to Accurate Planning (X1)																		
Enhanced Information Management (X5)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Accurate Planning (X1)

Table D.6. Pairwise comparison survey 6.

Pairwise comparison of Criteria with respect to High-quality Design (X2)																		
High-quality Design (X2)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Accurate Planning (X1)
Enhanced Information Management (X5)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Accurate Planning (X1)
Enhanced Information Management (X5)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	High-quality Design (X2)

Table D.7. Pairwise comparison survey 7.

Pairwise comparison of Criteria with respect to Efficient Construction (X3)																		
High-quality Design (X2)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Accurate Planning (X1)
Efficient Construction (X3)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Accurate Planning (X1)
Enhanced Information Management (X5)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Accurate Planning (X1)
Efficient Construction (X3)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	High-quality Design (X2)
Enhanced Information Management (X5)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	High-quality Design (X2)
Enhanced Information Management (X5)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Efficient Construction (X3)

Table D.8. Pairwise comparison survey 8.

Pairwise comparison of Criteria with respect to Improved Sustainability (X4)																		
Efficient Construction (X3)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	High-quality Design (X2)
Improved Sustainability (X4)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	High-quality Design (X2)
Improved Sustainability (X4)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Efficient Construction (X3)

Table D.9. Pairwise comparison survey 9.

Pairwise comparison of alternatives with respect to Accurate Planning (X1) in Alternatives Cluster																		
Modelling Software (Y1)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Collaboration Software (Y4)

Table D.10. Pairwise comparison survey 10.

Pairwise comparison of alternatives with respect to High-quality Design (X2)																		
Collaboration Software (Y4)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Engineering Analysis Software (Y3)
Modelling Software (Y1)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Engineering Analysis Software (Y3)
Visualizing and Simulation Software (Y2)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Engineering Analysis Software (Y3)
Modelling Software (Y1)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Collaboration Software (Y4)
Visualizing and Simulation Software (Y2)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Collaboration Software (Y4)
Visualizing and Simulation Software (Y2)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Modelling Software (Y1)

Table D.11. Pairwise comparison survey 11.

Pairwise comparison of alternatives with respect to Efficient Contstruction (X3)																		
Modelling Software (Y1)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Collaboration Software (Y4)
Visualizing and Simulation Software (Y2)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Collaboration Software (Y4)
Visualizing and Simulation Software (Y2)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Modelling Software (Y1)

Table D.12. Pairwise comparison survey 12.

Pairwise comparison of alternatives with respect to Enhanced Information Management (X5)																		
Visualizing and Simulation Software (Y2)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Collaboration Software (Y4)
Visualizing and Simulation Software (Y2)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data Management Platforms (Y5)
Collaboration Software (Y4)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data Management Platforms (Y5)

Table D.13. Pairwise comparison survey 13.

Pairwise comparison of alternatives with respect to Modelling Software (Y1)																		
Collaboration Software (Y4)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Modelling Software (Y1)

Table D.14. Pairwise comparison survey 14.

Pairwise comparison of alternatives with respect to Visualizing and Simulation Software (Y2)																		
Visualizing and Simulation Software (Y2)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Modelling Software (Y1)

Table D.15. Pairwise comparison survey 15.

Pairwise comparison of alternatives with respect to Engineering Analysis Software (Y3)																		
Modelling Software (Y1)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Engineering Analysis Software (Y3)

Table D.16. Pairwise comparison survey 16.

Pairwise comparison of alternatives with respect to Collaboration Software (Y4)																		
Modelling Software (Y1)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Collaboration Software (Y4)
Modelling Software (Y1)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data Management Software (Y5)
Collaboration Software (Y4)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data Management Software (Y5)

Table D.17. Pairwise comparison survey 17.

Pairwise comparison of alternatives with respect to Data Management Software (Y5)																		
Modelling Software (Y1)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Data Management Software (Y5)

Table D.18. Pairwise comparison survey 18.

Pairwise comparison of alternatives with respect to Visualization and Simulation Software (Y2)																		
High-quality Design (X2)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Accurate Planning (X1)

Table D.19. Pairwise comparison survey 19.

Pairwise comparison of alternatives with respect to Data Management Software (Y5)																		
Improved Sustainability (X4)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Enhanced Information Management (X5)

APPENDIX E: PAIRWISE COMPARISON MATRICES

The resulting pairwise matrices calculated by Super Decision software are presented below:

Table E.1. Pairwise comparison matrix 1.

Max. BIM Benefit	C1	C2	C3	C4	C5
C1	1	1/2	1	3	1/6
C2	2	1	2	5	1/3
C3	1	1/2	1	2	1/5
C4	1/3	1/5	1/2	1	1/6
C5	6	3	5	6	1

Table E.2. Pairwise comparison matrix 2.

C1	C1	C5
C1	1	1/5
C5	5	1

Table E.3. Pairwise comparison matrix 3.

C1	A1	A4
A1	1	1/4
A4	4	1

Table E.4. Pairwise comparison matrix 4.

C2	C1	C2	C5
C1	1	1/2	1/5
C2	2	1	1/2
C5	5	2	1

Table E.5. Pairwise comparison matrix 5.

C2	A1	A2	A3	A4
A1	1	5	2	4
A2	1/5	1	1/2	1/2
A3	1/2	2	1	2
A4	1/4	2	1/2	1

Table E.6. Pairwise comparison matrix 6.

C3	C1	C2	C3	C5
C1	1	1/2	1	1/5
C2	2	1	3	1/2
C3	1	1/3	1	1/5
C5	5	2	5	1

Table E.7. Pairwise comparison matrix 7.

C3	A1	A2	A4
A1	1	2	1/5
A2	1/2	1	1/5
A4	5	5	1

Table E.8. Pairwise comparison matrix 8.

C4	C2	C3	C4
C2	1	2	2
C3	1/2	1	1/2
C4	1/2	2	1

Table E.9. Pairwise comparison matrix 9.

C5	A2	A4	A5
A2	1	1/7	1/6
A4	7	1	1
A5	6	1	1

Table E.10. Pairwise comparison 10.

A1	A1	A4
A1	1	3
A4	1/3	1

Table E.11. Pairwise comparison 11.

A2	C1	C2
C1	1	1/4
C2	4	1

Table E.12. Pairwise comparison 12.

A2	A1	A2
A1	1	1/2
A2	2	1

Table E.13. Pairwise comparison 13.

A3	A1	A3
A1	1	1/3
A3	3	1

Table E.14. Pairwise comparison 14.

A4	A1	A4	A5
A1	1	1/3	1
A4	3	1	4
A5	1	1/4	1

Table E.15. Pairwise comparison 15.

A4	C4	C5
C4	1	1/6
C5	6	1

Table E.16. Pairwise comparison 16.

A5	A1	A5
A1	1	1/4
A5	4	1

Table E.17. Pairwise comparison 17.

A5	C4	C5
C4	1	1/6
C5	6	1