DEVELOPING A BUILDING INFORMATION MODELING (BIM) EFFECTIVENESS MODEL FOR THE TURKISH CONSTRUCTION INDUSTRY

by

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Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy

Graduate Program in Civil Engineering

Boğaziçi University

2020

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my thesis advisor, Prof. Beliz Özorhon Orakçal for her continuous support, patience, enthusiasm, and immense knowledge. Without her guidance and persistent help, this thesis would not have materialized.

Besides my advisor, I would like to thank the rest of my thesis committee: Assoc. Prof. Ilgın Gökaşar, Assist. Prof. Semra Çomu Yapıcı, Assoc. Prof. Zeynep Işık, and Assoc. Prof. Ümit Işıkdağ for their encouragement and insightful questions. I am gratefully indebted to their constructive comments on the thesis.

I also wish to acknowledge the financial support of Scientific and Technological Research Council of Turkey (TUBITAK) under the BIDEB 2211-A fellowship program.

I owe a very important debt to all the BIM practitioners who participated in the survey and helped me get better quality results. I would like to extend my special thanks to Batıkan Arısoy, Sedef Cebe, and Saniye Öktem for helping me contact the BIM practitioners of certain construction projects.

I am also grateful to the following friends from university: Işık Ateş Kıral, Ahmet Talha Gezgin, Uğur Dündar, Cem Sebzeci, Sadık Yiğit, and Hasan Altun for their unfailing support and assistance. It was fantastic to have the opportunity to study in the same workplace with you.

My deepest appreciation goes to Merve Fercan for all her love and support. I would like to offer my special thanks to my long-lasting friend Buğra Tekin for being the major source of support when things got a bit discouraging.

Finally, I must express my very gratitude to my parents Necati and Birgül Çağlayan, my brother Saygın Çağlayan, and my little nephew Alper Kağan Çağlayan for supporting and encouraging me throughout the thesis period. This accomplishment would not have been possible without them.

ABSTRACT

DEVELOPING A BUILDING INFORMATION MODELING (BIM) EFFECTIVENESS MODEL FOR THE TURKISH CONSTRUCTION INDUSTRY

Project delivery process in the construction industry is highly fragmented and communication is mainly based on 2D drawings. Errors and emissions in the paper documents can cause unexpected costs and delays. Building Information Modeling (BIM) is a path-breaking advancement in the construction industry that can address these issues. This research aims to develop a BIM effectiveness framework for the Turkish construction industry to investigate the BIM implementations in detail. In this context, a BIM effectiveness framework was proposed based on an extensive literature review and expert opinions. The framework mainly included the determinants, measurements, and outcomes. A questionnaire survey was designed and administered to the BIM practitioners of construction projects executed by Turkish construction companies. Structural Equation Modeling (SEM) technique was used as a research tool to validate the proposed framework and assess the model reliability based on 172 responses obtained from 107 different construction projects. The results revealed that (i) effectiveness of BIM implementation is determined mostly by the project-based factors followed by the company-based factors; (ii) industry-based factors do not directly impact the effectiveness of BIM implementation, but they indirectly affect it through exerting influences on the project- and company-based factors; (iii) a very strong association exists between the effectiveness of BIM implementation and the effectiveness of the construction process; and (iv) effectiveness of the construction process directly influences both the project- and company-related benefits, where slightly greater impacts are observed on the project-related benefits.

ÖZET

TÜRK İNŞAAT SEKTÖRÜ İÇİN BİR YAPI BİLGİ MODELLEMESİ (YBM) ETKİNLİK MODELİNİN GELİŞTİRİLMESİ

İnşaat sektöründe proje teslim süreci oldukça dağınıktır ve iletişim çoğunlukla iki boyutlu çizimlerle sağlanmaktadır. Kağıt belgeler üzerindeki hatalar ve unutmalar beklenmedik maliyetlere ve gecikmelere yol açabilmektedir. Yapı Bilgi Modellemesi (YBM) inşaat sektöründeki bu sorunlara çözüm olabilecek çığır açan bir gelişmedir. Bu araştırma Türk inşaat sektörü için bir BIM etkinlik çerçevesi geliştirerek BIM uygulamalarını detaylı olarak incelemeyi amaçlamaktadır. Bu bağlamda, kapsamlı bir literatür taraması ve uzman görüşleri temel alınarak bir BIM etkinlik çerçevesi önerilmiştir. Bu çerçeve başlıca belirleyicileri, ölçümleri ve çıktıları içermektedir. Bir anket çalışması tasarlanmış ve Türk inşaat firmaları tarafından yürütülen inşaat projelerinin BIM'den sorumlu personellerine yönlendirilmiştir. Yapısal Eşitlik Modeli (YEM) tekniği 107 farklı inşaat projesinden elde edilen 172 adet yanıta istinaden önerilen çerçevenin geçerliliğinin onaylanması ve modelin güvenilirliğinin incelenmesi için bir araştırma yöntemi olarak kullanılmıştır. Sonuçlar (i) BIM uygulamalarının etkinliğini en çok proje-bazlı faktörlerin belirlediğini ve bunu firma-bazlı faktörlerin takip ettiğini; (ii) sektör-bazlı faktörlerin BIM uygulamalarının etkinliğini doğrudan etkilemediğini, fakat proje- ve firma-bazlı faktörler üzerine etki ederek BIM uygulamalarının etkinliği üzerinde dolaylı bir etkiye sahip olduğunu; (iii) BIM uygulamalarının etkinliği ile inşaat sürecinin etkinliği arasında çok güçlü bir bağlantının bulunduğunu ve (iv) inşaat sürecinin etkinliğinin projeye- ve firmaya-yönelik faydaların ikisini de doğrudan etkilediğini, ancak projeye-yönelik faydalar üzerindeki etkinin biraz daha fazla olduğunu ortaya çıkarmıştır.

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LIST OF ACRONYMS/ABBREVIATIONS

AMOS	Analysis of Moment Structures
ANOVA	Analysis of Variance
BEP	BIM Execution Plan
BIM	Building Information Modeling
CAD	Computer-Aided Drafting
CFI	Comparative Fit Index
CMR	Construction Manager at Risk
COBiE	Construction Operations Building Information Exchange
DB	Design-Build
DBB	Design-Bid-Build
HVAC	Heating, Ventilating, and Air Conditioning
IFC	Industry Foundation Classes
IPD	Integrated Project Delivery
LOD	Level of Development
MEP	Mechanical, Electrical, and Plumbing
ML	Maximum Likelihood
RMSEA	Root-Mean-Square Error of Approximation
SEM	Structural Equation Modeling
SLAM	Success Level Assessment Model
SPSS	Statistical Package for the Social Sciences
TLI	Tucker-Lewis Index

1. INTRODUCTION

Building Information Modeling (BIM) is considered as a ground-breaking technological advancement in the construction industry. It has therefore been one of the most attractive research topics especially in the last decade, when the number of BIM implementations has significantly increased all over the world. Measuring the effectiveness of BIM implementations in construction projects is essential for discovering the impacts of various parameters on BIM implementation and reflections on the construction process. This research aims to develop a comprehensive BIM effectiveness framework that involves the determinants of BIM effectiveness, the measurement criteria, and the outcomes of BIM implementation. The framework was developed by conducting an extensive literature review and pilot studies. A questionnaire survey was directed to BIM practitioners of construction projects. Structural Equation Modeling (SEM) was used to validate the proposed framework. The research is expected to make both theoretical and practical contribution to the body of knowledge by (i) revealing the factors of the model components, (ii) identifying the interrelations between the model components, and (iii) determining the factor loadings of each factor. Introduction chapter of the thesis is composed of the background of the research, problem definition and statement, related studies, aims and objectives of the research, research methodology, scope and limitations, and organization of the research.

1.1. Background of the Research

BIM is relatively a new concept for the construction industry. Even though the BIM concept goes back to 1970s (Forbes, 2010), BIM implementation started in the construction industry in 2000 (Azhar *et al.*, 2012). Investigation of BIM implementations in construction projects has been a trending research topic. A number of studies have analyzed BIM implementation from various perspectives such as investigation of the success parameters (Son *et al.*, 2015; Ozorhon and Karahan, 2016; Tan *et al.*, 2019), evaluation of the performance (Bin Zakaria *et al.*, 2013; Won and Lee, 2016; Ghaffarianhoseini *et al.*, 2017), and realization of the outcomes (Lu *et al.*, 2014; Fadeyi, 2017;

Olawumi and Chan, 2018). However, there are few studies conducted to analyze BIM implementation by considering these perspectives as a whole. There is a great need to develop a comprehensive framework investigating the BIM effectiveness components and the interrelations between them.

1.2. Problem Definition and Statement

Construction industry includes inefficiencies that mainly stem from its fragmented nature (Stanford *et al.*, 2016). The increasing competition in the international construction market puts pressure on construction companies to enhance their performances (Bajjou *et al.*, 2017). In this respect, BIM is considered as a great opportunity for the companies to sustain their competitiveness globally. The BIM concept has gained popularization over the last two decades by the virtue of certain commercial software. The number of BIM implementations has also gained acceleration in the construction industry. In an attempt to promote effective BIM execution, analyzing the implementations becomes more of an issue. BIM implementations should be analyzed with the objective to identify key parameters for effective BIM implementation, observe how it influences the construction process, and detect the consequences both on the project and the company.

1.3. Related Studies

Investigation of BIM implementations in the construction industry is one of the trend research topics. Majority of the current literature concentrated on critical success/risk factors (Won *et al.*, 2013; Chien *et al.*, 2014; Tsai *et al.*, 2014; Ozorhon and Karahan, 2016), barriers/drivers of BIM (Rogers *et al.*, 2015; Son *et al.*, 2015; Liao and Ai Lin Teo, 2018; Tan *et al.*, 2019), level of BIM implementation (Bin Zakaria *et al.*, 2013; Won and Lee, 2016; Ghaffarianhoseini *et al.*, 2017), impacts on the construction process (Cao *et al.*, 2015; Nadeem *et al.*, 2015; Chang *et al.*, 2017; Liu *et al.*, 2017), and identification/quantification of the benefits (Barlish and Sullivan, 2012; Lu *et al.*, 2014; Zhou *et al.*, 2017; Olawumi and Chan, 2018). Even though these studies investigated the effect of one component on another, none of them considered the components as a whole and specified the interrelations between them. There is a great need for a comprehensive and systematic approach to investigate the BIM effectiveness components and their interactions.

1.4. Aims and Objectives of the Research

This research aims to develop a comprehensive BIM effectiveness framework to investigate BIM implementations in Turkish construction industry. The framework is mainly composed of the determinants (project-, company-, and industry-based factors), measurements (BIM and process effectiveness criteria), and outcomes (project- and company-related benefits). SEM is the statistical analysis technique used to validate the framework and reveal the interactions between the model components based on data collected through a questionnaire survey directed to BIM practitioners. The objectives of the research are (i) to develop of an extensive BIM effectiveness framework, (ii) to unveil the interrelations between the model components, and (iii) to prioritize the factors under each model component.

1.5. Research Methodology

A comprehensive literature review was conducted to specify the BIM effectiveness framework components, their interrelations, and underlying factors. A questionnaire framework was designed and addressed to BIM practitioners to explore BIM implementations in their construction projects. SEM technique was used as a research tool to test (i) the validity of the proposed BIM effectiveness framework and (ii) hypothesis developed for the interrelations between the model components. Findings were discussed and recommendations were provided for construction practitioners to promote BIM effectiveness in Turkish construction industry.

1.6. Scope and Limitations

The scope of this research involves development of a BIM effectiveness framework based on data obtained from the BIM practitioners in Turkish construction industry.

This research is limited to Turkish construction industry because the collected data reflects the opinions and perceptions of Turkish construction professionals. Even though Turkish construction professionals have international experience, another questionnaire could be designed and directed to BIM practitioners from different countries. Another limitation might be the development of hypotheses about the interrelations among the model components and identification of the underlying factors based on literature review and expert opinions, which is subjected to personal judgement to a certain extent.

1.7. Organization of the Research

This research is composed of six chapters. The first chapter presents the background of the research, problem definition and statement, related studies, aims and objectives of the research, research methodology, scope and limitations, and organization of the research. The second chapter introduces the building information modeling concept by providing the definition and main characteristics, explaining the core technologies and software, mentioning the worldwide BIM efforts, and briefly summarizing previous studies on BIM implementation. The research methodology is clarified in the third chapter by introducing the BIM effectiveness framework, explaining the questionnaire survey, and presenting the SEM technique. The research results (descriptive statics and SEM analysis) are reported in the fourth chapter and discussed in the fifth chapter. The sixth chapter summarizes the conclusions. The main observations are stated and recommendations are provided in this chapter. The Appendix section involves the sample questionnaire survey, descriptive statistics, and correlation matrices.

2. CONCEPT OF BUILDING INFORMATION MODELING

2.1. Definition and Main Characteristics

Technological advancement can be measured by means of the improvements in the efficiency of production methods or the raw material consumption. Enhanced productivity decreases costs, increases profits, and provides better living standard by making goods and services affordable. In that regard, construction industry has achieved very little technological advancement (Smith and Tardif, 2009). BIM is one of the most significant technological advancements in the construction industry over the last decades. Although there is no general consensus regarding its definition, it can be described as a model of information about a building that includes all the required information to support the life cycle processes. The model can directly be interpreted by computer applications (Underwood and Isikdag, 2010).

Electronic transfers became alternative to communicating paper drawings with the introduction of computer-aided drafting (CAD). A more radical change that occurred via BIM adoption is the relegation of drawings from information archive to communication medium. When BIM serves as the only archive for building information; paper print-outs (drawings, reports, specifications, etc.) only act as the facilitators of the access to information (Sacks *et al.*, 2018). BIM provides links between three-dimensional geometry and real time databases rather than simply allowing documentation to be drawn in the computer as in CAD (Garber, 2014).

Main difference between 3D CAD and BIM is that the former implies a building with independent 3D views such as sections, plans, and elevations. If one of the views is to be edited, all other views should be checked and updated. This is an error-prone process that results in low quality documents (Azhar *et al.*, 2012). The latter, on the other hand, paves the way for an error-free design process. Having consistent and non-ambiguous data set about a product resolves the problems originating from the inconsistency of information that causes different interpretation by experts or information systems. As the inconsistent and ambiguous information is the primary reason behind many process delays and errors, BIM is expected to make many quality control processes obsolete (Underwood and Isikdag, 2010).

BIM is considered as a new way of working rather than just an improvement in construction process. BIM ensures that a single model can include and coordinate construction documents, visualization, material quantities, cost estimates, construction sequencing, scheduling, and fabrication (Andrews, 1998). Designers can make iterations, simulations, and tests on many aspects of the construction process before the actual construction starts. Correction of inaccuracies virtually prior to construction provides material and time savings (Garber, 2014). Similarly, construction managers and supervisors can simulate the construction process before they commit to the labor and materials. Product and process alternatives can be explored, parts can be changed, and the construction procedures can be adapted in advance. Being able to perform all the activities continuously helps them to deal with the unexpected situations before they emerge (Sacks *et al.*, 2018).

Diffusion of building information modeling has recently gained acceleration worldwide thanks to the government mandates. To illustrate, the main reason behind its outgrowth in United Kingdom is the government's target to have level-2 BIM adoption in the central government sponsored projects by 2016 (Chang *et al.*, 2017). Cultural transformation is the greatest challenge to BIM diffusion within the construction industry. Construction industry needs to change the prevailing legal framework, in particular, dispute resolution. Project parties should focus on identifying and correcting the problems rather than sue each other (Smith and Tardif, 2009). Construction firms planning to adopt BIM in their projects should also be aware of the significant learning curve. Exploitation of the BIM opportunities requires changes in almost every process and business relationships, which makes the transition from drawings to a BIM model quite challenging (Sacks *et al.*, 2018).

BIM is considered as a facilitator of the lean concept. Lean construction focuses on process improvements that enables constructing the buildings and facilities in line with the client' needs and with minimum resource consumption. This requires identification and removal of obstacles and relieving the bottlenecks to smooth the work flow. BIM contributes to the lean construction process in at least four ways: (i) enhancing prefabrication and preassembly, (ii) sharing models, (iii) encouraging teamwork, and (iv) reducing time (Sacks *et al.*, 2018).

2.1.1. Project Delivery Methods

Traditional project delivery process is highly fragmented and the communication is based on 2D drawings. Unexpected costs or delays might occur or even lawsuits may arise between the parties due to the paper documents with errors and omissions. Even though some efforts have been made to address the problem (utilizing 3D CAD tools, implementing different organizational structures, etc.), they could only slightly mitigate the severity of conflicts. The negative side of 2D communication is that it requires considerable amount of time and money to make assessment (energy analysis, cost estimation, structural analysis, etc.) regarding a proposed design. These assessments can be made only after the design is completed, when it unfortunately becomes too late to implement any iterative improvement in design (Sacks *et al.*, 2018).

Project delivery method is the process of determining the contractual responsibilities for the project design and construction. It includes defining the scope, interrelations, responsibilities, and how to manage time, cost, quality, and safety (Carpenter and Bausman, 2016). Project delivery methods mainly differ in two key issues: (i) involvement time of project stakeholders to the project and (ii) contractual relationships between them (El Asmar *et al.*, 2013). Common project delivery methods include design-bid-build, design-build, construction management at risk, and integrated project delivery.

Design-Bid-Build (DBB) is the traditional project delivery method that has been popular since the early twentieth century. Owner contracts with an engineer and a contractor to complete the design and construction works. Once the design documents are completed, the contractor performs the construction works in accordance with the construction drawings and technical specifications at the lowest cost (Sullivan *et al.*, 2017). The total cost of construction is a parameter in the contractor selection (Carpenter and Bausman, 2016).

In *Design-Build* (DB) project delivery method, contractor signs a contract with a single entity that takes the responsibility of both design and construction. The entity is selected based on the criteria included in the selection process. Thus, the candidate with the highest score is selected rather than the lowest bidder (Shrestha and Fernane, 2017). This project delivery method is considered to be superior to the traditional one with regard to time and cost (Xia *et al.*, 2013). The method is becoming popular in the international construction market thanks to its reduced project duration, certainty in cost, and single point of responsibility (Chen *et al.*, 2016).

Construction Management at Risk (CMR) is a project delivery method where an owner contracts with a designer to undertake the design works and with a construction manager to carry out construction management services in both preconstruction and construction stages. Construction management services may cover preparing the bid packages, cost control, scheduling, construction administration, and value engineering. The construction manager guarantees the maximum cost of the project (Sacks *et al.*, 2018). Engagement of the construction manager in the design stage increases the coordination and communication (Francom *et al.*, 2016). The total cost of construction is not a parameter in the contractor selection (Carpenter and Bausman, 2016).

Integrated Project Delivery (IPD) is a delivery model for the execution of construction projects, where a single contract is used for design and construction. The contract is signed by the owners, designers, and builders before the project starts (El Asmar *et al.*, 2015). It gathers architecture, engineering, and construction specialists from multiple companies under a single roof (Hall and Scott, 2019). IPD enables early involvement of the contractor, a multiparty agreement, and alignment the project team's incentives and goals via sharing the risks and rewards; which, in turn, would contribute to the project outcomes (Chang *et al.*, 2017).

Projects executed by IPD and CMR have been reported to be completed faster than the others (Keen and Fish, 2012), which has moved the attention to these alternative project delivery methods, particularly to the IPD (Bilbo *et al.*, 2015). The combination of IPD and BIM can break the restrictions of current linear processes and streamline the information flow (Sacks *et al.*, 2018). BIM and IPD delivery implementations resemble the chicken-and-egg dilemma for the leading professionals in the building industry. It is not possible to take the full advantage of the BIM benefits before the industry completes the transition from current business practices. Until completing the transition, business leaders should determine the extent to which BIM can be efficiently integrated into their operations (Smith and Tardif, 2009).

2.1.2. BIM Utilization Areas

2.1.2.1. Bills of Quantities. The traditional approach to undertake the cost estimation is to multiply the calculated area of materials by the unit cost and installation cost of the material. This approach is unable to provide accurate estimates on complicated or curved shapes. Moreover, the estimated material costs per area are based on experience, meaning that great variations could be observed in the resultant estimations (Garber, 2014). In contrast, cost estimation made in a BIM environment requires significantly less time and effort spent by the cost estimator as the quantified list of materials is automatically generated. The quantity take-off activity is no longer a project responsibility of the cost estimator (McCuen, 2015). Various companies publish online database of construction costs. Linking the information model to such a database can enable making accurate real-time cost estimations.

2.1.2.2. Construction Planning. Adoption of 3D tools broadly in late 1980s enabled the construction organizations to build 4D displays by taking the snapshots of models at critical phases. Evaluation of 4D CAD tools in 1990s facilitated the process by linking 3D geometries to construction activities. Implementation of 4D tools subsequently to BIM models resulted in the existence of many commercially available software tools. Linking the construction schedule to the BIM objects allowed visualization of the sequential construction. Sophisticated 4D tools can optimize the activity sequencing and detailing by incorporating the BIM components and construction method (Sacks *et al.*, 2018).

2.1.2.3. Checking Spatial Conflicts. Coordination of the construction process within the documents and on site is complicated. The architects, being responsible for the design coordination, provide 2D design information to the engineers. However, traditional design documents of various consultants are not necessarily transmitted to another (for example, mechanical design documents to structural consultants). This situation may cause physical conflicts between the building components during the construction phase. With spatial conflict checking within BIM models, such conflicts can be reported and eliminated prior to the construction (Garber, 2014). Modeling the building with sufficient level of detail increases the effectiveness of identifying spatial conflicts.

2.1.2.4. Energy Analysis. Building energy simulation helps predicting the building energy requirements. Parametric BIM allows engineers to simulate the building energy requirement. Examples of energy simulation tools that offer thermal, shading, and daylighting analysis comprise EnergyPlus, TRNSYS, DOE2, IES<VE>, and ESP-r (Kensek and Noble, 2014). Conducting energy analysis requires three datasets: the first one represents the external shell for solar radiation; the second one represents the internal zones and heat generation usages; and the third one represents the heating, ventilation, and air conditioning (HVAC) mechanical plant (Sacks *et al.*, 2018).

2.1.2.5. Shop Drawings. Shop drawings are generally prepared by a specialty subcontractor and reviewed by the architect and general contractor prior to fabrication. The architect becomes responsible for checking and coordinating the shop drawings that are not prepared by the architect. The coordination process results in multiple paper copies distributed with hand notions and signed by each construction professional, which in turn would lead to coordination problems on site. The expansive review process can easily be eliminated by the comments made within the shared BIM model thanks to the promise of attribute data that could be attached to the geometric components (Garber, 2014).

2.1.2.6. Off-Site Fabrication. Off-site fabrication stands for the completion of construction components at a different location to where they are installed. Shortened construction durations, reduced labor costs, and mitigated risks associated with on-site fabrication make the off-site fabrication become increasingly common. The basic requirements for the off-site fabrication are coordination, planning, and exact design information. BIM encourages off-site fabrication process through ensuring detailed information necessary for cheaper and faster off-site fabrication (Sacks *et al.*, 2018).

2.1.2.7. Laser Scanning. Utilization of laser measurement devices helps the contractors to report data directly to BIM tools. It can be used to check whether the columns are located properly. Other uses of laser scanning may include rehabilitation work and capturing as-built details. Laser scanning services are commonly employed worldwide. After scanning the building, the building model representing the scanned components is generated by the operators interactively (Sacks *et al.*, 2018).

2.2. Core Technologies and Software

2.2.1. Level of Development

Level of Development (LOD) stands for the minimum quantitative, qualitative, dimensional, spatial, and other data of a model component. Confusingly, LOD term has also been referred to "level of detail". In both cases, the level represents the richness of components or graphic complexity (Kensek and Noble, 2014). The LOD levels are defined as follows (AIA, 2013):

- LOD 100 (conceptual): The model might include the graphical representations of the model elements such as symbols or other generic representations. However, the requirements of LOD 200 are not satisfied. The information regarding the model element could be obtained from other model elements.

- LOD 200 (approximate geometry): The model includes graphical representations of the model elements as a generic system, assembly, or object having approximate quantities, shape, size, orientation, and location. The model elements may also include non-graphic information.
- LOD 300 (precise geometry): The model includes graphical representations of the model elements as a specific system, assembly, or object having accurate quantities, shape, size, orientation, and location. The model elements may also include non-graphic information.
- LOD 400 (production and assembly): The model includes graphical representations of the model elements as a specific system, assembly, or object having accurate quantities, shape, size, orientation, and location; and information regarding detailing, fabrication, assembly, and installation. The model elements may also include non-graphic information.
- LOD 500 (as-built model): The model elements include field verified information in terms of quantity, shape, size, location, and orientation. The model elements may also include non-graphic information.

The LOD of a BIM model depends largely on the functions it is planned to be used for. To illustrate, accurate cost estimating requires sufficient details to obtain material quantities needed for cost evaluation. On the other hand, a less detailed model is adequate for scheduling, but the model should contain temporary works and present the phases of construction (Sacks *et al.*, 2018).

2.2.2. Parametric Modeling

The history of parametric modeling goes back to 1980s. Parametric modeling represents objects where the geometric and non-geometric properties are automatically determined by parameters and rules. In that regard, it differs from objects having fixed geometry and properties. As the rules and parameters might be related to other objects, the properties of objects are automatically updated according to the changing contexts. The followings are the properties of parametric BIM objects (Sacks *et al.*, 2018):

- Parametric objects consist of data and rules associated with their geometric definitions.
- The geometry of an object can never be represented internally redundantly. The plans and elevations are always consistent.
- An insertion of a new object results in automatic modification of associated geometries.

The parametric term refers to the ability to update object properties in accordance with the rule-based relationships between the objects. To illustrate, parametrically adjusting a door can save the time spent while modeling the door over and over again. In case a decision hasn't been made yet, an arbitrary value can be entered and the model can be updated when the information becomes available (Mordue *et al.*, 2016).

In the architecture industry, numerous base building object classes have been predefined by BIM software companies. These classes can be extended, modified, or added to create other object instances with varying forms. The object behavior indicates the way the object updates itself in conjunction with the contextual changes. The object classes clearly define the walls, slabs, and roofs with regard to their interaction with the other objects (Eastman *et al.*, 2011).

Parametric relationships between certain model components have been established in a set of current BIM packages. Nevertheless, they still cannot function bidirectional feedback loops. Parameters are passed along established routes in a linear way, which leads to hierarchical design process and does not provide the opportunity to make unexpected discoveries. A multidimensional dialog is not valid for most model components with inert geometries. These components are not capable of reversing the reasoning sequence (Kensek and Noble, 2014).

2.2.3. Building Information Exchange

Construction projects require collaboration between architecture, engineering, construction, and operation activities. In order to support these activities, various tools with overlapping data requirements are employed by various project participants. Project performance can be improved by enabling the project participants to smoothly share and exchange information. Interoperability can be defined as the ability to exchange data between different tools. Since late 1980s, data models have been developed to exchange product or object models (Sacks *et al.*, 2018).

Most of the high technologies are composed of sophisticated sequences of low-technology tools. The sophistication is a consequence of the capability to serve as a part of a system. In many industries, plenty of automated tools are designed to perform a simple, but specific task flawlessly. If these tools can serve as the components of an automated and integrated system with a predefined sequence, they can be regarded as interoperable (Smith and Tardif, 2009).

Majority of the software applications that are employed in the building industry are not fully interoperable. In other words, only few software applications can receive the information from another and transmit it to a third reliably. Most of them are designed to function in their own world. Even though interoperability has been seriously adopted in other industries, building industry has preferred to bundle greater number of tasks. The increasing complexity has resulted in slowly operating, difficult to learn, and less useful tools (Smith and Tardif, 2009).

Interoperability is one of the obstacles to building information exchange which can be overcome by the efforts made by software developers. The obstacle can be eliminated by the support in the software applications for open-standard data formats such as Industry foundation classes (IFCs) (Smith and Tardif, 2009). IFC is an ISO Standard (ISO 26739) building data model used for describing, exchanging, and sharing information. The alphanumeric information of objects can be linked by IFC without losing the semantic relationships. Nowadays, most BIM authoring tools can convert the model geometry to an IFC format. Even the non-compatible software applications can read the IFC format (Issa and Olbina, 2015).

Construction Operations Building Information Exchange (COBie) is an information exchange model which smoothly transfers the information throughout the phases of the facility lifespan, while preserving its context. The information (created by designers, contractors, or both) is captured and recorded at the point of origin (Issa and Olbina, 2015). COBie aims to (i) introduce a useful format to exchange real-time information for existing design, (ii) describe requirements for the business processes, (iii) generate a framework for information storage that can be exchanged in the subsequent stages, (iv) impose no additional on the operations and maintenance, and (v) permit direct import to the maintenance management system (East, 2007). Despite the publicized benefits, the construction industry has been slow to adopt COBie (Giel *et al.*, 2015).

2.2.4. BIM Platforms and Tools

A BIM software tool is a task-based application that generates a specific outcome. These tools can be used for generating models, producing drawings, writing specification, estimating the cost, detecting/eliminating the clashes, making energy analysis, scheduling, rendering, and visualizing. The outcome (drawings, reports, etc.) of one tool can be input of other tools. A BIM platform, on the other hand, is an application creating multiple-use data. A primary data model provided by the platform incorporates information regarding the BIM platform. Most of the BIM platforms can also function as a tool. To illustrate, they can produce drawings or detect clashes (Eastman *et al.*, 2011). Examples may include Revit, Tekla Structures, Bentley, ArchiCAD, AECOSim, Vectorworks, and Digital Project (Sacks *et al.*, 2018).

BIM tools aim to provide benefits to construction companies by solving the followings (Mordue *et al.*, 2016):

- Poor and slow systems (e.g., file storage or email document exchange),
- Lack of communication among the team members, multiple teams, or multiple companies,
- Need to obtain additional information (e.g., the time and provider of data entry),
- Lack of collaboration (e.g., combination of multiple information sets into one federal model),
- Updating the information (e.g., change of a door property across all documents),
- Visualization quality (e.g., production of high quality and realistic project renders)

The most critical decision for company owners and managers in BIM implementation strategy is the BIM tool to be utilized. The list of commercially available BIM tools is shown in Figure 2.1. BIM tools are categorized under six main headings as architecture, structures, construction, sustainability, mechanical, electrical, and plumbing (MEP), and facility management. The BIM tools are most of the time selected based on their popularities. The most commonly employed BIM tools are most likely to be preferred. The number of software licenses to purchase and the number of members to be trained are other two BIM implementation strategy decisions. An effective BIM implementation strategy requires software training to be accompanied by education. While training helps people learn how to do, education teaches them how to think. Employees provided with a BIM training can learn the way to perform certain tasks. However, only business leaders can improve or change the business processes (Smith and Tardif, 2009).

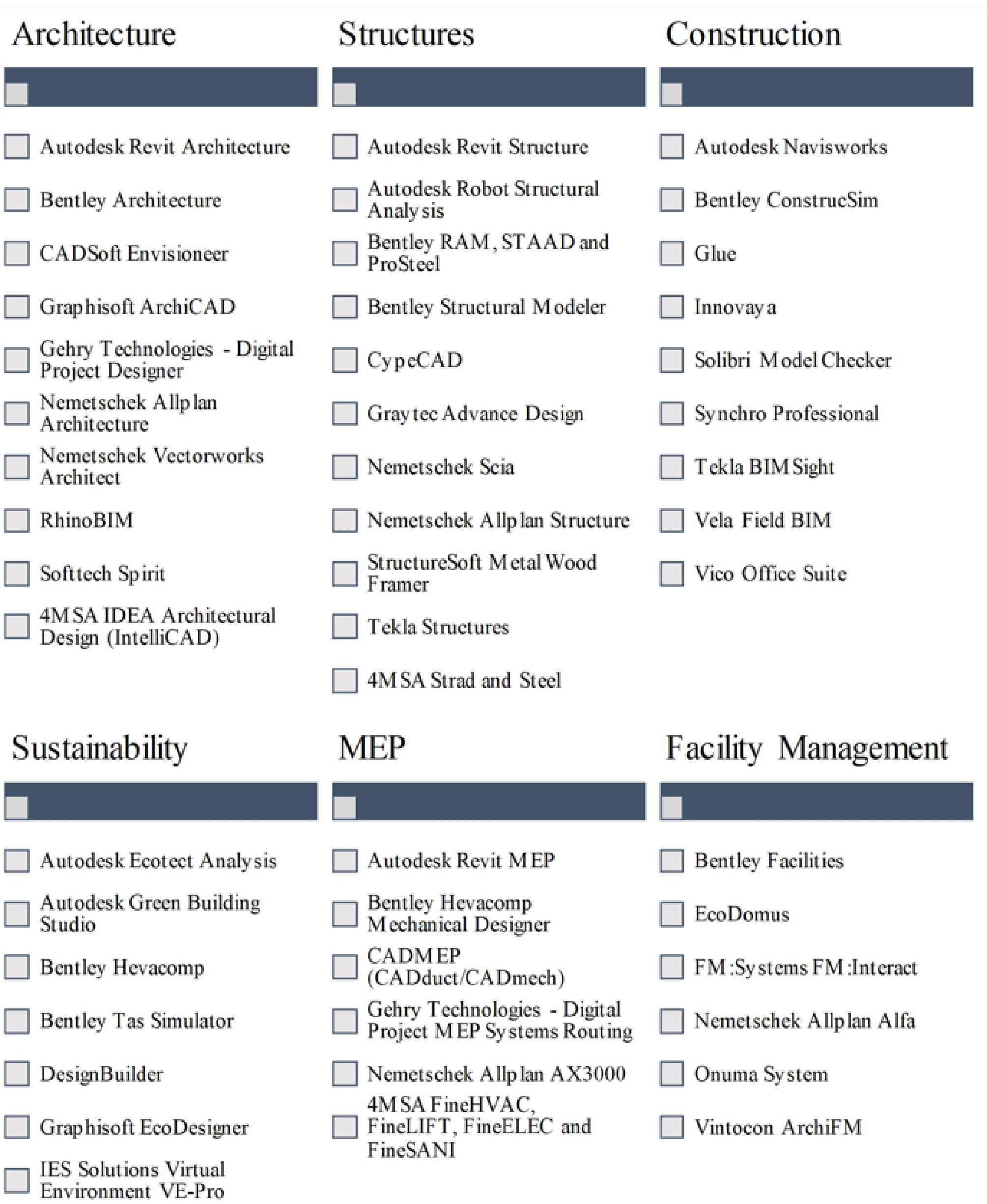

Figure 2.1. List of BIM Tools.

2.3. Worldwide BIM Efforts

BIM concept has gained popularity all over the world and its implementation is being accelerated by the attempts of the public sector. Cheng and Lu (2015) reviewed the efforts of the public sector (both the government bodies and non-profit organizations) for BIM adoption worldwide. Based on the review, the following actions were identified as efforts of the public sector to promote BIM implementation:

- Mandate BIM use: Implementation of BIM was mandated in a several countries by various organizations including the government bodies and non-profit organizations. Examples of government bodies in United States may include the Department of Veterans Affairs and the State of Wisconsin. Starting in 2009, Department of Veterans Affairs required BIM for construction and renovation projects worth over $10 million. In July 2009, state of Wisconsin required the design firms to use BIM on all projects that cost more than $5 million and new construction projects of more than $2.5 million. Indiana University can be given as an example of non-profit organization. The public university mandated BIM use for construction projects in the university with total funding of more than $5 million.
- State commitment to BIM adoption: Numerous government bodies stated their commitment to BIM adoption in different ways. In 2013, Swedish Transportation Administration stated their willingness to utilize BIM step by step in the following years and suggested BIM use to a certain degree in all investment projects after 2015. Chinese government included a BIM framework and BIM topics in the 12th National Five Year Plan and set the aim of spreading BIM use in the next five years. The BIM implementation roadmap released by the Korean Ministry of Land, Transport and Maritime Affairs stated that BIM would be implemented in three to four major construction projects in 2011 and all major construction projects would use 4D BIM in the period of 2012-2015.
- Develop BIM guidelines/standards: Government bodies including the institutions such as United States General Services Administration, state governments, and even city governments were actively involved in developing the BIM guidelines/standards. General Services Administration published BIM Guide Series 01 to 08. State of Ohio BIM Protocol was published in 2011 to serve as the foundation of BIM use in the state. In 2012, a city-wide BIM Guide was released by the New York City Department of Design + Construction. Non-profit organizations also published BIM guidelines/standards. British Standards Institution released several standards in United Kingdom and public universities in United States such as University of Connecticut, University of Florida, and University of Albany released several guidelines/standards.

- Establish BIM programs and committees: BIM programs and committees were established in various countries both by government bodies and non-profit organizations in an attempt to (i) develop BIM guidelines/standards and (ii) promote BIM use. The 2012-2014 BIM-program was set by a part of the Dutch Ministry of Infrastructure and the Environment, namely Rijkswaterstaat, to collaborate research institutes and stakeholders for the purpose of promoting BIM. A BIM steering committee was established by a Singaporean governmental agency, Building Construction Authority, to develop BIM requirement guidelines. The NBIMS-US project committee established by the National Institute of Building Sciences developed the national BIM standards and discussed whether BIM should be incorporated into college curricula or not.
- Execute pilot BIM projects: Pilot BIM projects were executed by government bodies to promote the technology. Following the government's commitment to BIM adoption, Norwegian Defense Estates Agency initiated three BIM pilot projects. In Denmark, BIM pilot projects were executed by the state clients such as the Defense Construction Service, the Danish University Property Agency, and the Palaces and Properties Agency. In Japan, the Ministry of Land, Infrastructure and Transport announced the execution of BIM pilot projects in 2010 for government buildings and repairs. The Architectural Services Department in Hong Kong conducted two BIM pilot projects and viewed them as an opportunity to share the experience with stakeholders.
- Reward successful BIM implementations: A number of government bodies rewarded the successful BIM implementations in their countries. A BIM fund was established by Building and Construction Authority in Singapore for the purpose of encouraging firms to practice the BIM technology in actual construction projects and many BIM competitions (both national and international) were held to encourage BIM innovation. Construction Industry Council in Hong Kong launched the BIM Excellence Awards in 2014 to recognize the parties that contributed to the local BIM adoption.
- Plan BIM training programs: BIM training programs were provided by some government bodies and non-profit organizations. In Australia, an 18 week BIM training plan was prepared by the Air Conditioning and Mechanical Contractors'

Association to train BIM beginners. In an attempt to support the central government's objectives, local government bodies in China conducted BIM projects and offered BIM training programs. The BIM Development Unit established by the Architectural Services Department in Hong Kong provided BIM-related training courses in 2013. An in-depth training framework was designed by the Building and Construction Authority in Singapore and a number of BIM training programs were offered.

- Organize BIM conferences and seminars: BIM conferences and seminars were organized by government bodies and non-profit organizations to increase the familiarity of the construction industry to the BIM concept. In November 2013, Japan Federation of Construction Contractors hosted an international one-day seminar on Integrated Design Delivery Solutions and BIM. The Research Center established by National Taiwan University organized several BIM activities including forums, conferences, workshops, publications, and consulting services. Building and Construction Authority hold BIM conferences in Singapore for public sector bodies. Hong Kong Institute of Building Information Modeling collaborated with buildingSMART Hong Kong to educate local industry through organizing BIM seminars.

2.4. Previous Studies

There is an increasing trend in the academia to conduct studies on BIM. Its implementation and adoption has been reported as the most trending topic (Yalcinkaya and Singh, 2015). Additionally, it has been analyzed from other perspectives including identification of BIM success determinants, evaluation of BIM performance, and realization of project benefits.

2.4.1. Determinants of BIM Success

Factors that influence the effectiveness of the BIM implementation process have been discussed by several researchers. These factors have frequently been called as the critical success/risk factors or key performance indicators. Researchers have created a list of factors based on literature review or interviews with experts, categorized the factors, evaluated their significance, determined the critical ones, and developed strategies to increase the possibility of project success.

Won *et al.* (2013) derived the critical success factors for (i) BIM adoption in the company, (ii) project selection to deploy BIM, (iii) BIM services selection, and (iv) BIM software selection. They analyzed 52 responses obtained from 206 surveys distributed to four different continents. They specified the most critical ones in each category as follows: willingness to share information (BIM adoption in the company), project manager's willingness to adopt BIM (project selection to deploy BIM), expected economic impact (BIM services selection), and supporting the services of interest (BIM software selection).

Chien *et al.* (2014) assessed the critical risk factors of BIM adoption in Taiwanese construction industry in terms of technical, management, financial, personnel, and legal aspects. They conducted a questionnaire survey to identify the relationships between the risk factors by using the decision-making trial and evaluation laboratory method. Critical risk factors were specified at various levels and proper response strategies were suggested for a case study project.

Tsai *et al.* (2014) assessed the BIM adoption in the construction industry by developing critical success factors. 123 influencing factors were identified specified as a consequence of a literature review. They derived a total of 58 critical success factors for BIM adoption with the execution and analysis of a questionnaire survey. Key factors were determined as top management support, functionality of BIM tools, and design validation.

Rogers *et al.* (2015) worked on BIM adoption among Malaysian engineering consulting firms. They collected primary data from questionnaire survey and focus group interview. They (i) explored the perceptions, main barriers, governmental support, and intentions; and (ii) identified the key drivers. Lack of qualified personnel and governmental support were reported as the main obstacles. Main drivers to adopt BIM within two years were stated as the market demands and competitive advantage.

Son *et al.* (2015) utilized an extension of technology acceptance model to analyze the factors facilitating BIM adoption by the architects and thus, to increase the chance of successful BIM adoption. Subjective norm, compatibility, top management support, and computer self-efficacy were labelled as the critical ones. Perceived usefulness and ease of use were found to mediate the relationships between the antecedent factors and behavioral intentions.

Ding *et al.* (2015) explored the key factors for BIM adoption by architects in China. A structural equation model was applied based on survey data obtained from design firms in Shenzehn, China. Motivation, BIM capability, and technical insufficiencies of BIM were the most significant factors. The least important ones were stated as the management support and knowledge structure.

Ozorhon and Karahan (2016) identified and analyzed the critical success factors of BIM implementations in Turkey as a representative of developing countries. They examined the relative importance of 16 critical success factors based on 96 data obtained from a questionnaire survey directed to public and private sector participants in Turkey. Staff quality, leadership, and technology were the most important factors.

Lee *et al.* (2018) demonstrated the positive influence of trust on the BIM performance of construction projects through proposing an integrative trust-based functional contracting model. They encouraged the construction industry to think beyond the conventional engineering, procurement, and construction contract setting for achieving a much more effective BIM use.

Liao and Ai Lin Teo (2018) proposed an organizational change framework to identify the hindrances and drivers of BIM implementation in people management. Investigation of previous studies revealed 24 hindrances and 13 drivers. Analysis of a questionnaire survey addressed to 84 experts in Singapore and post-survey interviews refined the factors in the list and resulted in 22 hindrances and 12 drivers.

Tan *et al.* (2019) conducted a study to identify the barriers specifically for the China's prefabricated construction and discover the interrelations between them by using interpretive structural modeling. Greatest obstacles were determined as lack of research in the country on BIM and absence of standards/domestic tools. A three-level strategy was proposed to facilitate implementation of BIM.

Chen *et al.* (2019) discussed BIM adoption in construction firms within the context of Chinese construction industry. They developed technology-organization-environment framework to create a research model and make evaluation. Two different data sets were collected from consulting and construction firms. Relative advantage of BIM was specified as the main enabler and complexity was regarded as an inhibiter. It was also noticed that younger firms had greater tendency to implement BIM.

2.4.2. Assessing the BIM Performance

Various studies have focused on BIM performance assessment and its reflections on the construction process. The BIM performance has usually been assessed based on previously defined BIM implementation levels or by implementing performing assessment models. Contributions of effective BIM implementation to the construction process have been investigated in great numbers of case studies and a positive influence has frequently been emphasized.

Bin Zakaria *et al.* (2013) examined the BIM process and level of implementation in the Malaysian construction industry. The level of BIM implementation was identified between Level 0 and 1, which corresponded to migrating from two dimensional working environment to three dimensional one. Construction companies had the intention to fully implement BIM at Level 2 in the following years.

Cao *et al.* (2015) examined the BIM practices in China and evaluated the impacts of certain practices on its effectiveness by investigating 106 projects. BIM utilization was observed to have positive influence on the construction process where task effectiveness improvements had been more substantial than efficiency improvements. BIM practices were indicated to involve both organizational and technological problems.

Nadeem *et al.* (2015) integrated a BIM tool into a suitably prepared electronic format with the intention of improving the bill of quantities used on construction projects. A questionnaire survey was directed to a number of experienced quantity surveyors and BIM experienced students to receive their comments. The results mostly showed a positive view towards the proposed format.

Poirier *et al.* (2015) assessed the BIM performance of a small mechanical contracting enterprise by conducting a cases study research over 2-year period. The BIM implementation performance was assessed using cost predictability, scope predictability, productivity indicator predictability, schedule predictability, and project quality.

Won and Lee (2016) studied the application of success level assessment model (SLAM) for BIM projects. They tested the validity of SLAM BIM by applying it to two construction projects. They collected and analyzed the data of design errors, response time, schedule, change orders, and return-on-investment. Importance of sharing SLAM key performance indicators and data collection methods in early project phases was highlighted.

Chang *et al.* (2017) investigated how implementation of BIM could influence the construction process through enhancing the acceptability of integrated project delivery. They used structural equation modeling to analyze data obtained from 145 BIM-enabled projects in China. It was reported that enhancing communication and encouraging supply change incentives could make the BIM implementation positively affect the construction process.

Ghaffarianhoseini *et al.* (2017) discussed the widespread benefits of BIM and current level of uptake. They handled the issue from technical, knowledge management, standardization, diversity, integration, economic, planning, building life cycle, and decision support perspectives. It was suggested that the level of BIM comprehension and adoption could be highly associated with the size of a construction firm.

Smits *et al.* (2017) conducted a survey of 890 Dutch construction professionals to explore their perceptions regarding the impact of BIM maturity on project performance. A limited influence of BIM maturity was observed on project performance. Maturity of BIM implementation strategy was noted to be the only determinant of time, cost, and quality performance.

Liu *et al.* (2017) studied how BIM might affect the design and construction process through enabling collaboration. BIM collaboration was reported to be influenced by following concepts: IT capacity, technology management, attitude and behavior, role-taking, trust, communication, leadership, and experience. Effects of BIM on the construction process were assessed under three categories, namely technology, people, and process.

2.4.3. Realization of BIM Benefits

A number of studies have targeted realization and quantification of the project benefits obtained. Project benefits have mostly been discussed in terms of monetary values. Value addition to the project and reduction in project costs have been highlighted. Monetary savings have been expressed as a percentage in total project cost. Several studies have also drawn attention to reduced project duration, quality improvements, and risk mitigation.

Barlish and Sullivan (2012) developed a holistic framework to analyze and quantify the benefits of BIM. Duration improvements, change orders, and requests for information were considered as the benefits metrics, while the design and construction costs were taken as the investment metrics. The developed model was applied to compare BIM implementing projects to traditional projects. The results demonstrated a high potential for BIM benefits to be realized.

Bryde *et al.* (2013) investigated the reported benefits of BIM utilization by conducting content analysis on secondary data obtained from 35 construction projects. Enhancements in cost control and cost reduction were indicated as the most frequently reported benefits. The reports also included great savings in project duration. Negative outcomes were mostly associated with the use of BIM software.

Lu *et al.* (2014) aimed to measure costs/benefits of BIM implementations through demystification of time-effort distribution curves of construction projects. Comparison of two housing projects (one with BIM) indicated more effort input at the design stage, but lower costs at the building stage. The ultimate contribution of BIM implementation to the project was 6.92% reduction in costs.

Zhou *et al.* (2017) formulated a framework to evaluate project-level BIM benefits from the viewpoint of various stakeholders and explained the methods for maximizing the benefits for each stakeholder. The benefits were prospected from the operational, organizational, managerial, and strategic perspectives. Methods of BIM implementation were expressed in order to maximize the benefits for each stakeholder.

Fadeyi (2017) demonstrated the value addition of BIM to the project through decreasing fragmentation among project members at each building delivery stage. It was emphasized that BIM could provide a virtual repository allowing easy access and information sharing. The integrated environment enabled by BIM for construction professionals was shown to add value to the project.

Olawumi and Chan (2018) used Delphi survey technique to identify and prioritize 36 perceived benefits of integrating BIM in construction projects. The derived data was analyzed by statistical tools and interrater agreement statics was used to validate the consensus reached by the expert panel. Enhancements in quality, building simulation, and product design were specified as the top benefits.

Ganbat *et al.* (2018) reviewed 526 peer-reviewed journal articles between years 2007 and 2017 to observe the effects of BIM applications on international construction risk management. According to the results, popularization of BIM could bring some risks to the construction projects. However, it was indicated that project risk might be reduced by effective use of the BIM functions.

Even though there have been great amount of studies investigating the determinants of BIM implementation, BIM and construction process performances, and the benefits obtained; few studies have considered them as a whole and investigated the interactions among them. The need for a comprehensive and systematic approach was also emphasized by Yalcinkaya and Singh (2015). This study develops an extensive and systematic framework that reveals the connections between the determinants, BIM effectiveness, its reflections on the construction process, and the outcomes.

3. RESEARCH METHODOLOGY

The flow of the research methodology is presented in Figure 3.1. The methodology is mainly composed of three phases: (i) preparation of the BIM framework, (ii) conducting a questionnaire survey, and (iii) structural equation modeling analysis. In the first phase, the BIM effectiveness framework was generated. Main components and their interactions were specified. A literature survey was conducted to identify the underlying factors of each component. The identified factors were either merged or removed in order to obtain a compact list. The second phase involved conducting a questionnaire survey. An online questionnaire survey was created by using google forms. The survey was directed to construction professionals with BIM experiences. Face-to-face interviews were performed to increase the response rate. SEM analysis was conducted in the third phase. The data was analyzed by using a commercially available software, namely IBM SPSS AMOS. The validity of the model was checked by the execution of content and construct validity tests. The results of the analysis were evaluated and suggestions were provided to construction practitioners.

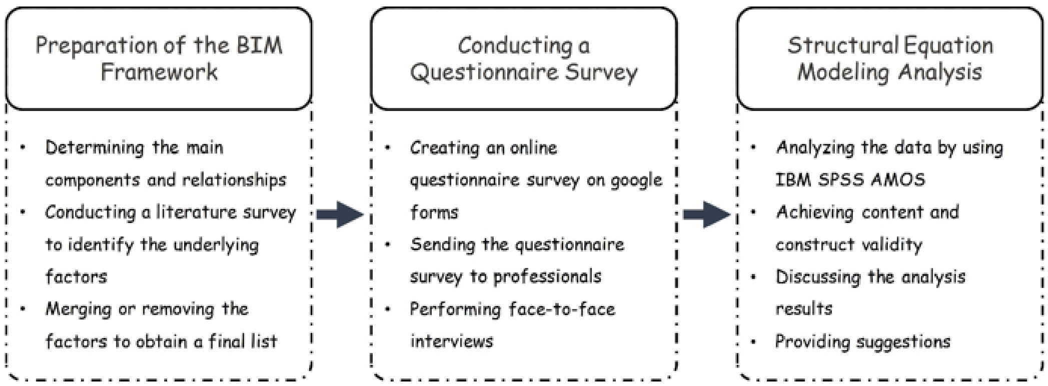

Figure 3.1. Flow of Research Methodology.

3.1. BIM Effectiveness Framework

Figure 3.1 shows the BIM effectiveness framework, its components, and their interactions. The framework comprises determinants, measurements, and outcomes.

The determinants are the components that determine how effectively BIM is implemented throughout the project. There are three determinants, namely project-based factors, company-based factors, and industry-based factors. Measurements are the criteria that evaluate the level of effectiveness of both BIM implementation and the construction process. The outcomes represent the benefits obtained owing to the BIM implementation throughout the project. The benefits are considered both project-wise and company-wise.

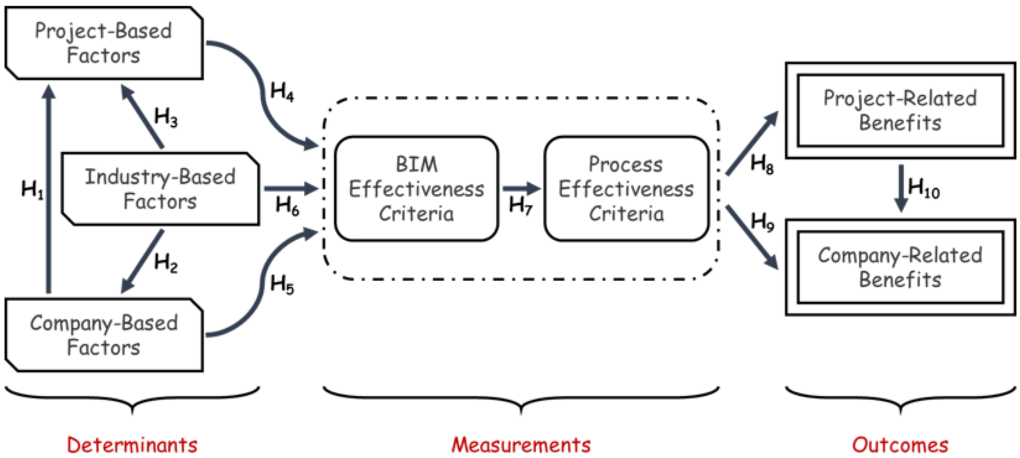

Figure 3.2. BIM Effectiveness Framework.

The determinants include project-based factors, company-based factors, and industry based factors. Project-based factors indicate the favorability of the project environment. For example, they involve training given to the project personnel, BIM capability of the staff, and motivation to implement BIM. Company-based factors reveal the competencies of the company. Availability of key personnel, company experience in software programming/BIM, and investments are some examples considered in this component. Industry-based factors demonstrate the maturity of the technology in the construction industry. Examples may involve availability of guidelines and protocols, interoperability level of software platform, and awareness within the industry.

Measurements incorporate criteria that measure the effectiveness of both BIM implementation and its reflections on the construction process. Effectiveness of BIM implementation is measured via assessing the extent to which the BIM model is generated successfully. A successfully generated BIM model is expected to result in proper construction documents, accurate quantity survey, and great visualization. Thus, such factors are embedded in the BIM effectiveness criteria. The reflections of a well-established BIM model on the construction process is measured by the process effectiveness criteria. These criteria contain indicators of an effective construction process such as increase in labor productivity, improved coordination of disciplines, and enhanced communications between the project participants.

The outcomes are the project-wise and company-wise benefits realized under favor of BIM implementation. While the project-related benefits represent the benefits obtained specifically for the project, company-related benefits stand for the contributions of BIM implementation to the company in the long run. Project-related benefits are evaluated in terms of the main features of projects such as time, cost, and quality. Company-related benefits, on the other hand, take into account the enhancements in company characteristics like technology adoption, long term profitability, and knowledge management.

3.1.1. Development of Hypotheses

Hypotheses were developed to examine the interactions among the model components. A total of ten hypotheses were constructed based on the relationships between the components and the evidences provided by the literature. The hypotheses are explained as follows:

H_1: Effectiveness of "company-based factors" has a direct and positive impact on "project-based factors".

Experienced and corporate companies are expected to create favorable project environment for implementing new technologies like BIM. These companies can accomplish a smooth project selection process by taking into account the strategic objectives and project environment (Costantino *et al.*, 2015). They attempt to change the project environment in a positive way by training the project staff, recruiting specialists, working with knowledgeable subcontractors.

H_2: Effectiveness of "industry-based factors" has a direct and positive impact on "company-based factors".

Companies are expected to make greater investment in new technologies with the increasing maturity of the technology within the industry. The increasing awareness, availability of much capable software, and nicely prepared guidelines and protocols may encourage companies to adopt themselves to the technology. Ahmed (2018) stated the suitability of the construction market as an important parameter for BIM implementation in construction companies.

H_3: Effectiveness of "industry-based factors" has a direct and positive impact on "project-based factors".

The favorability of project conditions should depend on the maturation of the technology within industry. To clarify, a positive correlation might be assumed between the existence of BIM protocols and clarification of rights and responsibilities in the project, awareness of the technology within the industry and commitment to updating the model throughout the project, and so on. It should be noted that the construction industry is still in the early phases of BIM adoption (Becerik-Gerber and Rice, 2010).

H_4: Effectiveness of "project-based factors" has a direct and positive impact on "BIM effectiveness criteria".

Effectiveness of BIM implementation might be influenced by the favorability of the project environment. A project with capable/committed participants and clarified responsibilities is expected to result in successful BIM implementation. Cao *et al.* (2015) reported that implementation of BIM should be directly associated with the project characteristics.

H_5: Effectiveness of "company-based factors" has a direct and positive impact on "BIM effectiveness criteria".

The context of a construction company shall contribute to the quality of the BIM process (Sackey *et al.*, 2015). Innovative companies with flexible organizational structure are more likely to fluently execute the BIM process. The innovation culture of companies comes partially from the internal capabilities (Kratzer *et al.*, 2017). An effective BIM adoption and implementation requires construction stakeholders to consider the organizational structure needed to support BIM (Ahn *et al.*, 2015).

H_6: Effectiveness of "industry-based factors" has a direct and positive impact on "BIM effectiveness criteria".

Industrial developments on BIM-related issues are expected to influence the success rate of BIM implementations. A BIM implementation is not likely to be successful at a time when guidelines and BIM protocols are missing (Porwal and Hewage, 2013), commercially available BIM tools are incapable (Korpela *et al.*, 2015), and software platform is not interoperable (Won *et al.*, 2013).

H_7: Effectiveness of "BIM effectiveness criteria" has a direct and positive impact on "process effectiveness criteria".

Contribution of BIM implementation to the efficiency of the construction process has been reported in previous studies. Majority of the projects surveyed by Cao *et al.* (2015) revealed the positive influence of BIM implementation on the construction process, where the benefits obtained from improved task effectiveness overwhelmed those related to efficiency improvements.

H_8: Effectiveness of "process effectiveness criteria" has a direct and positive impact on "project-related benefits".

A number of studies have emphasized the favorable project outcomes of BIM implementation obtained by improving the efficiency of the construction process (Stowe *et al.*, 2014; Ahn *et al.*, 2016). These studies have reported the positive influences of BIM implementation on the project time, cost, quality, and safety through improving communication, reducing rework, and increasing productivity.

H_9: Effectiveness of “process effectiveness criteria” has a direct and positive impact on “company-related benefits”.

An effective construction process is expected to bring not only project level benefits, but also benefits to the company that get beyond the limits of the project. The companies that execute the construction process efficiently with the BIM implementation should be more likely to adopt new technologies, improve knowledge management, and increase their reputation.

H_{10}: Effectiveness of “project-related benefits” has a direct and positive impact on “company-related benefits”.

A construction project that can achieve favorable project outcomes (being completed on time, within budget, and with high quality) can be considered as a successful project. Successfully completed projects are believed to result in company-wise benefits in the long run such as improved brand value and long term profitability.

3.1.2. List of Factors

An extensive literature review was conducted to derive the factors of the BIM effectiveness framework. A total of 42 factors were identified at the initial step as a result of reviewing 30 sources. After conducting a pilot study with two university professors and three industry practitioners, the list was refined by either combining or removing some of the factors. The resultant list including 36 factors under 7 components is presented in Table 4.7.

Table 3.1. List of Factors.

Component		Factor	Sources
Determinants	Project-based factors	Training the project staff	1, 3, 4, 5, 7, 9, 11, 14, 15, 17, 19, 21, 23, 25, 27, 29, 30
		BIM knowledge of the project participants	1, 7, 11, 12, 13, 15, 19, 24, 27, 30
		Clarification of rights and responsibilities	2, 5, 7, 9, 11, 15, 21, 22, 24, 30
		Commitment to updating the model	2, 9, 11, 13, 17, 20, 25, 30
		Existence of BIM specialists	1, 3, 9, 11, 17, 25, 27, 29, 30
	Company-based factors	BIM experience of the company	3, 9, 11, 13, 19, 20, 23, 24, 25
		Top management support	4, 9, 11, 15, 17, 19, 23, 25, 29
		Hardware and software investments	1, 3, 5, 7, 9, 11, 14, 17, 19, 23, 25, 27
		Employees' computer ability	5, 9, 13, 17, 19, 23, 25, 29
		Existence of company BIM procedures	1, 3, 7, 9, 24
	Industry-based factors	Availability of guidelines/standards	1, 2, 6, 11, 13, 15, 17, 19, 21, 23, 25, 28, 30
		Interoperability of software platform	1, 2, 4, 5, 6, 7, 11, 13, 14, 15, 18, 27, 29, 30
		BIM awareness within industry	5, 6, 7, 15, 17, 19, 21, 23, 25, 27, 29, 30
		Capacity and capability of current software	5, 6, 9, 11, 12, 19
		Availability of BIM protocols	2, 3, 7, 9, 11, 15, 17, 18, 23, 24, 25, 27, 30
Measurement	BIM effectiveness criteria	Proper construction documents	1, 5, 6, 7, 14, 21, 26
		Accurate quantity take-off	2, 3, 4, 6, 7, 8, 9, 16, 22, 23, 26, 28, 30
		Detection/elimination of clashes	2, 3, 4, 5, 7, 8, 9, 13, 15, 16, 20, 21, 22, 23, 24, 26, 30
		Improved cost control mechanism	2, 4, 5, 7, 16
		Better visualization of the project	1, 3, 4, 6, 7, 8, 9, 14, 16, 23, 24, 26, 28, 30
		Scope clarification	5, 14, 28
	Process effectiveness criteria	Improved communications and trust	1, 2, 5, 8, 13, 18, 19, 22, 26, 28, 30
		Reduced lead times and duplications	1, 2, 3, 7, 15, 18, 21, 26, 30
		Better coordination of disciplines	1, 2, 3, 5, 6, 7, 9, 10, 11, 14, 15, 16, 22, 23, 25, 26, 28
		Increased labor productivity	1, 3, 4, 7, 13, 14, 15, 21, 22, 23, 27
		Avoidance of unexpected costs	1, 8, 9, 18, 21
		Reduced change orders/claims/disputes	1, 3, 4, 5, 7, 9, 14, 26
Outcomes	Project-related benefits	Shortened project duration	1, 2, 5, 7, 8, 13, 14, 16, 18, 19, 20, 21, 22, 26, 27, 30
		Reduced project cost	1, 2, 5, 6, 7, 8, 14, 16, 18, 19, 20, 21, 22, 26, 27, 30
		Enhanced product quality	1, 2, 4, 5, 6, 10, 13, 14, 16, 18, 19, 21, 23, 26, 27, 28, 30
		Improved health and safety	4, 5, 7, 10, 14, 22, 26, 27, 28
		Client satisfaction	2, 7, 11, 14, 16, 19, 26
	Company-related benefits	Improved company image/brand value	1, 2, 3, 7, 9, 11, 20
		Enhanced knowledge management	7, 12, 13, 14, 18, 19, 21, 22, 26
		Long term profitability	1, 2, 3, 14, 20, 23
		Technology adoption	1, 7, 13, 15, 19, 20, 23, 26, 29

1. Ahn *et al.*, 2015; 2. Azhar, 2011; 3. Boktor *et al.*, 2013; 4. Cao *et al.*, 2015; 5. Bryde *et al.*, 2013; 6. Bynum *et al.*, 2013; 7. Ghaffarianhoseini *et al.*, 2017; 8. Kim *et al.*, 2017; 9. Hanna *et al.*, 2014; 10. Ding *et al.*, 2014; 11. Won *et al.*, 2013; 12. Korpela *et al.*, 2015; 13. Miettinen and Paavola, 2014; 14. Stowe *et al.*, 2014; 15. Porwal and Hewage, 2013; 16. Bhirud and Patil, 2016; 17. Ahmed, 2018; 18. Bhatija *et al.*, 2017; 19. Juan *et al.*, 2017; 20. Cao *et al.*, 2016; 21. Doumbouya *et al.*, 2016; 22. Fadeyi, 2017; 23. Harun *et al.*, 2016; 24. Monko *et al.*, 2017; 25. Ozorhon and Karahan, 2016; 26. Ghannadpour *et al.*, 2019; 27. Rogers *et al.*, 2015; 28. Shou *et al.*, 2015; 29. Son *et al.*, 2015; 30. Yaakob *et al.*, 2016

3.1.2.1. Project-Based Factors. Training the project staff (PBF1): Provision of BIM training programs is an important factor a contractor should consider for successful BIM implementation. It can be provided through a range of instruction strategies such as BIM courses, conferences and forums, training sessions, virtual BIM training programs, blogs, and group study sessions (Ahn *et al.*, 2015). Majority of organizations send their staff to seminars or training focusing on BIM implementation (Husain *et al.*, 2018).

BIM knowledge of the project participants (PBF2): Implementation of the BIM in construction projects highly depends on the familiarity of the project participants with the process. Low return on investment experienced by many BIM users around the world can be attributed to lack of BIM knowledge and experience of the users. Thus, smaller companies that do not frequently engage in BIM projects tend to suffer most (Ghaffarianhoseini *et al.*, 2017).

Clarification of rights and responsibilities (PBF3): An important issue that must be legally clarified is the rights and responsibilities of project participants. Potential disagreements on copyright issues could be prevented through explaining the ownership rights and responsibilities in the contract documents (Azhar, 2011). Standardized supplementary legal agreements, namely BIM protocols, should be incorporated into the construction contracts.

Commitment to updating the model (PBF4): Implementing the BIM approach throughout the project requires the company to commit itself truly to the practice and lead to process to take on the challenges. The BIM approach cannot be regarded as a test-drive (Hanna *et al.*, 2014). The participants should be willing to update the model and utilize it throughout the project phases from the design through construction to the facility management.

Existence of BIM specialists (PBF5): The BIM process should be guided by the specialists with great knowledge and experience in BIM implementations to overcome any unexpected situation that might pose an obstacle to the execution of the process.

Lack of BIM experts within the company was reported to obstruct implementation of the BIM technology to the construction industry in a couple of studies (Ozorhon and Karahan, 2016; Ahmed, 2018).

3.1.2.2. Company-Based Factors. BIM experience of the company (CBF1): Having implemented BIM in numerous construction projects increases the likelihood of companies to achieve success. Even though the technological advantages of BIM have been greatly recognized in the construction industry, it may not be properly implemented by construction companies that do not possess the required technical expertise of or process know-how (Cao *et al.*, 2016).

Top management support (CBF2): BIM is considered as a game-changing technology that influences the work processes, scope/project initiation, resourcing, and tool mapping (Gu and London, 2010). Therefore, it requires some organizational changes within the BIM adopting company (Juan *et al.*, 2017). The organizational readiness to employ the new technology depends highly on the top management support.

Hardware and software investments (CBF3): Employing the BIM technology requires both hardware and software investments. The former implies the expense of dedicated high-specification workstations. Unlike CAD software packages that can be operated on the majority of professional computers, BIM software necessitates these high priced workstations. The latter involves BIM software licenses for purchasing, maintaining, and upgrading the software. Compared to the cost of CAD software packages available on the market, BIM software licenses tend to be more expensive (Stowe *et al.*, 2014).

Employees' computer ability (CBF4): Implementation of BIM technology necessitates the project staff to be equipped with computer usage skills. Competency in computer usage helps the employees perform better throughout the BIM process because exploring the advantages of BIM technology requires intense interaction with computer. Moreover, being already exposed to various technologies creates an opportunity to faster adopt a new technology (Harun *et al.*, 2016).

Existence of company BIM procedures (CBF5): Development of BIM procedures shall promote BIM adaptation and implementation on construction projects and within companies. Creation of in-house BIM procedures helps the construction firms better allocate resources and budget (Boktor *et al.*, 2014). Especially, the companies that consider using the BIM technology in the coming years are suggested to create their internal BIM procedures (Hanna *et al.*, 2014).

3.1.2.3. Industry-Based Factors. Availability of guidelines/standards (IBF1): A limited number of countries have established their own legal regulations and presented guidelines regarding BIM (Kalfa, 2018). Guidelines are nonbinding statements issued by private or governmental organizations to streamline certain processes. BIM guidelines aims to help architects and designers to generate high performance structures. The need to standardize the process was highlighted by Azhar (2011).

Interoperability of software platform (IBF2): Interoperability feature of BIM software platforms is among the most fundamental benefits of BIM use. Digitally representing the characteristics of a BIM structure enables the users to transfer both design data and specifications between various BIM software applications (Ghaffarianhoseini *et al.*, 2017). Utilization of software platforms with interoperability problems might hinder data transfer and implementation of the BIM process.

BIM awareness within industry (IBF3): The growing awareness of BIM technology within construction industry can encourage more construction firms to make use of it and thereby increase the BIM adoption rate. The awareness could be raised through conference and seminars (Ismail, 2014). Another way to build awareness is to select the project leaders among the project managers trained in BIM as they are more likely to implement BIM in the project (Doumbouya *et al.*, 2016).

Capacity and capability of current software (IBF4): The level of current BIM technology should play an important role in determining the success of BIM-based services. Effectiveness of BIM depends largely on how efficiently available software applications can support the service of interest (Won *et al.*, 2013). The capabilities of BIM software are expected to accelerate in the following years along with the increases in BIM implementation rates.

Availability of BIM protocols (IBF5): A BIM protocol is a contractual guide to the BIM process such as model file formats, model ownership, sharing files, submitting models for review, and responsibility of model changes. It is based on direct contractual relationship between the parties (employer and supplier). It enables the production of BIM models at defined project phases. Use of common standards and protocols is an indicator of value generated by BIM usage (Boktor *et al.*, 2014).

3.1.2.4. BIM Effectiveness Criteria. Proper construction documents (BEC1): Document errors and omissions have been identified as one of the main sources of waste in the traditional construction workflow (Stowe *et al.*, 2014). Utilization of BIM software enables decreasing the waste through providing proper construction documents. BIM software tools support producing construction documents without the need for another tool (Bynum *et al.*, 2013).

Accurate quantity take-off (BEC2): BIM has the capacity to provide all the required information throughout the project including spatial relationships, quantity and specifications, list of materials, and cost estimations (Rezahoseini *et al.*, 2019). Material quantities are automatically given by the model; which improves budgeting, provides cost-loaded schedules, and enables interactive forecasts to make agile comparisons (Yaakob *et al.*, 2016). Quantity take-offs derived from the BIM model are more frequently used in the construction phase rather than the design phase, where utilization of BIM could provide greater benefits for the project cost control (Cao *et al.*, 2015).

Detection/elimination of clashes (BEC3): Construction models are composed of interdependent and historically changing elements. Changes in one of the elements result in clashes with other elements established in the previous development phase (Miettinen and Paavola, 2014). Utilization of BIM tools can provide great amount of savings in the contract value through detecting these clashes. BIM is used by most of the companies for the purpose of 3D and 4D clash detections (Azhar, 2011).

Improved cost control mechanism (BEC4): An effective cost control technique is essential for managing the risk of cost overrun in construction projects. Construction projects involve many stakeholders from various disciplines. The emergence of BIM technology is believed to improve the cost control mechanism by enhancing the collaboration between the stakeholders (Tahir *et al.*, 2018). BIM ensures better cost control mechanism through making improvements in planning, estimating, budgeting, and controlling the costs (Bryde *et al.*, 2013).

Better visualization of the project (BEC5): An accurate visualization of design is fundamental to figuring out the performance of building. Traditionally, visualization has relied on interpreting orthogonal drawings and envisioning the design based on two dimensional drawings. The advent of BIM enabled tools ensured better visualization of the project by providing high quality renderings, shaded 3D views, and animated walkthroughs.

Scope clarification (BEC6): Clarification of scope is one of the accredited benefits of BIM (Barlish and Sullivan, 2012). BIM allows the architects, engineers, and contractors to work together in a collaborative environment and leads to more efficient design and construction processes. Facilitated and encouraged data sharing among the team members is expected to result in several benefits such as increased reliability, greater transparency, and clarification of scope.

3.1.2.5. Process Effectiveness Criteria. Improved communications and trust (PEC1): Lack of trust among project stakeholders has been listed among the major factors affecting application of knowledge management in the construction industry (Bhatija *et al.*, 2017). Communication and trust among the project stakeholders have been noticeably improved thanks to the technological advances obtained by the increasing use of BIM. BIM improves communication and trust between the designers and site engineers through supporting a collaborative environment (Ahn *et al.*, 2016).

Reduced lead times and duplications (PEC2): Rework, being one of the chronical problems of the construction industry, has impacts on almost every criteria of the project success. A considerable loss of resources, materials, and workforce-time could be observed as the consequences of rework. A dramatic decrease has been noticed in the emergence of errors and inconsistencies with the widespread use of BIM (Rezahoseini *et al.*, 2019). Utilization of BIM in the design stage of construction process could result in reducing the lead times and duplications (Doumbouya *et al.*, 2016).

Better coordination of disciplines (PEC3): In addition to visualization, analysis, and supply chain integration, coordination is among the emerging applications of BIM in the current practices (Taylor and Bernstein, 2009). Complexity of building shapes and systems gives rise to spatial conflicts and clashes, where the advantages of the BIM-assisted space coordination can be realized most (Won *et al.*, 2013). BIM allows project participants from various disciplines to retrieve and generate information from the same model, fostering the collaboration and coordination among them (Ding *et al.*, 2014).

Increased labor productivity (PEC4): Productivity in construction can be defined as the amount of output generated from certain resources such as the materials, equipment, and labor. The need to achieve continuous improvement in the construction productivity points toward the use of BIM (Fadeyi, 2017). BIM is regarded as the technological innovation required to address falling level of construction productivity (Rogers *et al.*, 2015) and increase the labor productivity in the field by providing precise geometry and data needed to support construction activities (Ahn *et al.*, 2016).

Avoidance of unexpected costs (PEC5): Existence of uncertainty in construction projects brings about many unexpected costs that cannot easily be foreseen at the beginning of the construction process. Utilization of BIM helps avoiding the unexpected costs by decreasing the uncertainty (Ahn *et al.*, 2016) especially in the design phase, where BIM usage could lead to much efficient cost control management process (Cao *et al.*, 2015).

Reduced change orders/claims/disputes (PEC6): Change orders represent the work added to or deleted from the original scope of work, altering the original contract. Change orders are among the most critical reasons behind the cost growth and disruptions to field productivity. The change orders could be owner-generated or field-generated (Riley *et al.*, 2005). Adoption of BIM in construction projects can considerably decrease the number of change orders originating from field conflicts (Leicht and Messner, 2008).

3.1.2.6. Project-Related Benefits. Shortened project duration (PRB1): BIM is known to shorten project duration by accelerating the construction period (Giel and Issa, 2011). The additional work of 3D modeling might extend the design phase, however, this extension is expected to disappear in consequence of the increasing familiarity and capability with 3D (Rogers *et al.*, 2015). Accelerated schedule enables early occupancy of the building and realization of time-to-market opportunities (Stowe *et al.*, 2014).

Reduced project cost (PRB2): BIM has been indicated to provide significant reduction in the total cost of construction projects. Evidence for economic benefits has been a solid reason for adopting the technology (Lee *et al.*, 2012). Previously reported analyses have revealed high return on investment results for BIM implementations (Ghaffarianhoseini *et al.*, 2017), meaning that notable amount of cost savings could be obtained from BIM investments. Higher cost reduction can be achieved by higher utilization and contribution of BIM (Kim *et al.*, 2017).

Enhanced product quality (PRB3): BIM stands for utilization of a set of technologies and organizational solutions to improve quality of design, construction, and maintenance of construction projects (Miettinen and Paavola, 2014). BIM ensures higher production quality by enabling flexible documentation output and exploiting automation (Bhirud and Patil, 2016). Area of utilization of BIM in quality management may involve laser scanning for quality assessment and generation of BIM models from point cloud data for deviation analysis (Shou *et al.*, 2015).

Improved health and safety (PRB4): Project success has been evaluated in terms of time, cost, and quality. However, safety issues have also drawn great interest in recent years. Economic concerns are no longer the only focus point in project management as safety and security have gained much attention (Ding *et al.*, 2014). BIM usage in identifying and preventing safety issues can improve safety and availability of labor (Zhang *et al.*, 2015).

Client satisfaction (PRB5): The accelerating BIM usage leads to increasing profitability, reducing costs, enhancing time management, and improving customer-client relationships (Azhar, 2011). The clients' satisfaction levels are increased through visually verified design intent and knowledge sharing through virtual design and construction (Ghaffarianhoseini *et al.*, 2017). Owners can have greater awareness and more confidence on the design (Stowe *et al.*, 2014).

3.1.2.7. Company-Related Benefits. Improved company image/brand value (CRB1): Following the latest technological advancements is regarded as one way of demonstrating the competence of the company. BIM is regarded as a ground-breaking development that transforms the building design process. In this respect, construction companies can improve their company images through marketing their BIM capabilities to potential customers (Hanna *et al.*, 2014).

Enhanced knowledge management (CRB2): BIM provides knowledge management benefits to construction firms during both the construction and post-occupancy phases. BIM tools provide capability for integration by allowing inputs from various professionals to be collected under the model (Ghaffarianhoseini *et al.*, 2017). Any input entered to the model could be extracted at any time and used both during the current project and for the following projects.

Long term profitability (CRB3): BIM implementation in construction projects is known to provide economic contribution to the project (Bynum *et al.*, 2013). However, some implementations fail to be successful due to a couple of reasons such as lack of capable personnel, unfamiliarity with the process, insufficiency of the software, legal issues, etc. In the long run, these problems are expected to disappear thanks to the industrial developments and company investments in BIM. Thus, companies adopting the BIM approach should achieve long term profitability.

Technology adoption (CRB4): Technology acceptance assessment refers to the intention to accept a new technology. Organizational readiness, on the other hand, indicates the ability of an organization to adopt the new technology (Juan *et al.*, 2017). People tend to accept a new technology when they feel ready for the organizational change (Tsikriktsis, 2004). BIM implementation in a construction project encourages organizational change within an organization, which would trigger the technology acceptance or adoption.

3.2. Questionnaire Survey

A questionnaire survey is a widely-used data gathering method used for collection, analysis, and interpretation of the views of people from a particular population. It is regarded as a relatively cheap and quick way to obtain large amounts of data from a large population. Questionnaires could be carried out face-to-face, by telephone, or online. The design of the questionnaire survey depends largely on the type of information that is intended to be collected. Questions might be both qualitative and quantitative in nature. Qualitative questions are employed in the case of a need to collect exploratory information, whereas quantitative questions are used to test developed hypotheses.

A questionnaire survey was designed in accordance with the developed model to quantitatively analyze the interactions between the model components and determine the effectiveness of their factors (Appendix A). The questionnaire survey was composed of three main sections. The first section involved general questions regarding the respondent (experience, position, etc.) and the company (number of employees, annual return, etc.). The second section included project specific questions such as the duration, contract value, and BIM platforms utilized. The third section was the evaluation of the factors of each model component in a 1-5 Likert Scale (very low, low, medium, high, and very high).

The questionnaire was sent online to construction practitioners with BIM experiences. Face-to-face interviews were also conducted to increase the response rate. The respondents were requested to fill in the questionnaire according to their observations on the BIM implementation in a certain construction project. 172 questionnaires were returned out of 653 sent out, resulting in a response rate of 26%. The responses represented 107 different construction projects, where multiple data was obtained from different stakeholders (client, contractor, consultant, designer, subcontractor, etc.) of some projects. The respondents assessed the questions from their point of view and within the scope of their companies.

The collected 172 questionnaires were used for SEM analysis. SEM models were stated to perform quite well even with 50 to 100 samples. Nonetheless, the simplistic and conservative approach is to collect as much as 200 samples (Iacobucci, 2010). Xiong *et al.* (2015) reported that out of 84 SEM applications in construction, 26 models had less than 100 samples, 39 models had 100 to 200 samples, and 19 models had over 200 samples. Power analysis helps researchers to question the sufficiency of sample size (Kirby *et al.*, 2002). Statistical power analysis was conducted to check whether the SEM analysis with 172 samples would yield statistically significant results or not. The power was computed by using the software developed by Preacher and Coffman (2006) as 0.99, which is greater than the proposed value of 0.80 (Cohen, 2013).

3.3. Structural Equation Modeling Analysis

3.3.1. Definition and Basic Characteristics

SEM is a statistical methodology taking a confirmatory approach to analyze a structural theory related to a phenomenon. The term 'structural equation modeling' presents the basic features of the procedure: (i) causal processes are represented by a set of structural equations and (ii) structural relations can be visually modeled to provide a clear conceptualization of the theory (Byrne, 2016). SEM has also been referred in the literature as covariance structural modeling, covariance structural analysis, and analysis of covariance structures (Kline, 2015).

SEM models basically hypothesize the definition of constructs by a set of variables and the relations between the constructs. SEM enables development and testing of theoretical models. It depicts the interactions between observed and latent variables and tests the developed hypotheses (Schumacker and Lomax, 2016). A clear distinction exists between the observed and latent variables. While the former represent the data collected and entered in a data file, the latter correspond to hypothetical constructs that are not observable. Observed variables can be both categorical or continuous, whereas all the latent variables are continuous in SEM. The main difference that distinguishes SEM from standard statistical techniques is that SEM can analyze both the observed and latent variables as opposed to the others that can only analyze the observed variables (Kline, 2015).

Generating a structural equation model requires specification of causal effect directions among variables to reflect the hypothesis. In that sense, it can be regarded as a confirmatory process. However, inconsistency of the data with the theoretical model might result in modification of the hypotheses (Kline, 2015). In case the theoretical model is not supported by the sample data, either the model is alternated (modified) or the another theoretical model is hypothesized and tested (Schumacker and Lomax, 2016).

SEM analysis requires a number of statistical assumptions as follows (Kaplan, 2009):

- Data is normally distributed,
- There is no missing data in any variable,
- The structural equation model does not omit any relevant variable in any equation,
- Independent variables do not depend on the dependent variables.

Characteristics of available SEM computer tools are summarized in Table 3.2. There are eleven available computer tools listed based on whether the program operates as a stand-alone software package or is a package, procedure, or command in a larger environment. It is observed that only three of the SEM tools are offered for free. The packages belong to R (sem, lavaan, lava, systemfit, OpenMx), SAS/STAT (CALIS), Stata (Builder, sem, gsem), STATISTICA (SEPATH), and SYSTAT (RAMONA).

Table 3.2. Structural Equation Modeling Tools (Kline, 2015).

Computer tool		Free	Interaction modes		
			Batch (syntax)	Wizard (template)	Drawing editor
Stand-alone programs	AMOS		X	X	X
	EQS		X	X	X
	LISREL		X	X	X
	Mplus		X	X	X
	Ωnyx	X			X
Packages in larger environments	sem, lavaan, lava, systemfit	X	X		
	OpenMx	X	X		
	CALIS		X		
	Builder, sem, gsem		X	X	X
	SEPATH		X	X	
	RAMONA		X		

AMOS (analysis of moment structures) is used in this study to develop and analyze the theoretical model. AMOS is an add-on purchase in statistical package for the social sciences (SPSS). In AMOS, the SEM model is drawn with the help of diagramming tools and an SPSS data is linked to the model variables. The variable names can be dragged from the SPSS data set to the model, the SEM model diagram can be exported to Word via a clipboard tool, and multiple group models can be analyzed (Schumacker and Lomax, 2016).

3.3.2. Modeling Steps

Model development in SEM involves a series of steps, namely model specification, model estimation, model testing, and model modification.

3.3.2.1. Model Specification. Models imply a set of statistical statements about the relations on observed and latent variables. The relations are typically linear as in other linear models (Hoyle, 2012). Measurement and structural models are specified with reference to prior researches and theories. In a measurement model, observed variables are related to a latent variable. A structural model, on the other hand, represents the part where latent variables are related to each other. In an attempt to support the selection of observed and latent variables (measurement models) and relations among the latent variables (structural models), an extensive literature review is conducted (Schumacker and Lomax, 2016).

3.3.2.2. Model Estimation. Model estimation methods in SEM are listed mainly under two categories, namely single equation methods and simultaneous methods. Single equation methods analyze the equation for a single variable at a time. There is no assumption for multivariate normality. The disadvantage is that there is no test for checking the global model fit. The emphasis is given to local fit testing. Simultaneous methods, on the other hand, make an estimation for all free model parameters at once and usually emphasize the global fit testing (Kline, 2015). Maximum Likelihood (ML) estimation is a widely used simultaneous method that tends to produce unbiased estimates. Nevertheless, in the case of non-normality, the model X^2 is inflated and the standard error estimates are deflated (Finch *et al.*, 1997).

3.3.2.3. Model Testing. The model fit is analyzed by means of several fit indices as follows:

- Chi-square (X^2) is a statistical hypothesis test that is used to check whether a significant difference exists between the observed values and the expected values of the fitted model. A chi-square value of zero indicates a perfect fit between the model and data. It should be noted that the chi-square value tends to move upwards along with the increase in sample size (Kline, 2015).
- Comparative fit index (CFI) is an incremental fit index that assumes no correlation between the latent variables and compares the sample covariance matrix with the null model. The values range from 0 to 1 (Hooper *et al.*, 2008). A CFI value around 0.90 is acceptable and above 0.95 is considered as good fit (Bowen and Guo, 2011).
- Tucker-Lewis index (TLI) was initially developed by Tucker and Lewis (1973) for factor analysis and then extended to SEM. The index is used for making comparison between a proposed model and a null model. Similar to CFI, TLI values close to 0.90 or 0.95 imply a good model fit (Schumacker and Lomax, 2016).
- Root-mean-square error of approximation (RMSEA) is an index that measures the model lack of fit per degree of freedom. It enables quantifying the degree of model misspecification. SEM models having RMSEA values lower than 0.080 or 0.100 can be deemed acceptable (Hoyle, 2012).

3.3.2.4. Model Modification. The model might not fit the data and need modification. Researchers are not recommended to change the structural model by adding or deleting paths unless it is substantiated by additional theories. The practical way of providing a better model fit is to add an error covariance term between observed variables in the measurement model (Schumacker and Lomax, 2016).

3.3.3. Validity of Measures

The validity of measures is assessed through two widely used concepts, namely content validity and construct validity.

- Content validity is concerned with whether the test items represent the domain they are expected to measure. The basis for establishing content validity is the expert opinion, not any statistical analysis.
- Construct validity shows how accurately a hypothetical construct is measured by the test or experiment. As there is no single and definitive test for construct validity, it requires satisfaction of several sub-tests, namely scale reliability, discriminant validity, and convergent validity.
  - Scale reliability is a measure of the internal consistency. It represents the consistency of responses across the items of a measure. Cronbach's alpha is used to assess the scale reliability.
  - Discriminant validity checks whether the measures presumed to be unrelated are actually not related. It is supported when the level of inter-correlation among these measures is low.
  - Convergent validity, as opposed to discriminant validity, checks whether the measures presumed to be related are actually related. Overall goodness of fit and factor loadings are two ways of evaluating the convergent validity.

3.3.4. Model Development in AMOS

The SEM model is developed by using a commercially available software, namely IBM SPSS AMOS. The developed model is shown in Figure 3.3. The model comprises observed and latent variables. There are seven latent variables surrounded by circles. Each latent variable is composed of observed variables that are presented in rectangles. All the latent and observed variables include residual (error) variables shown in elliptical forms.

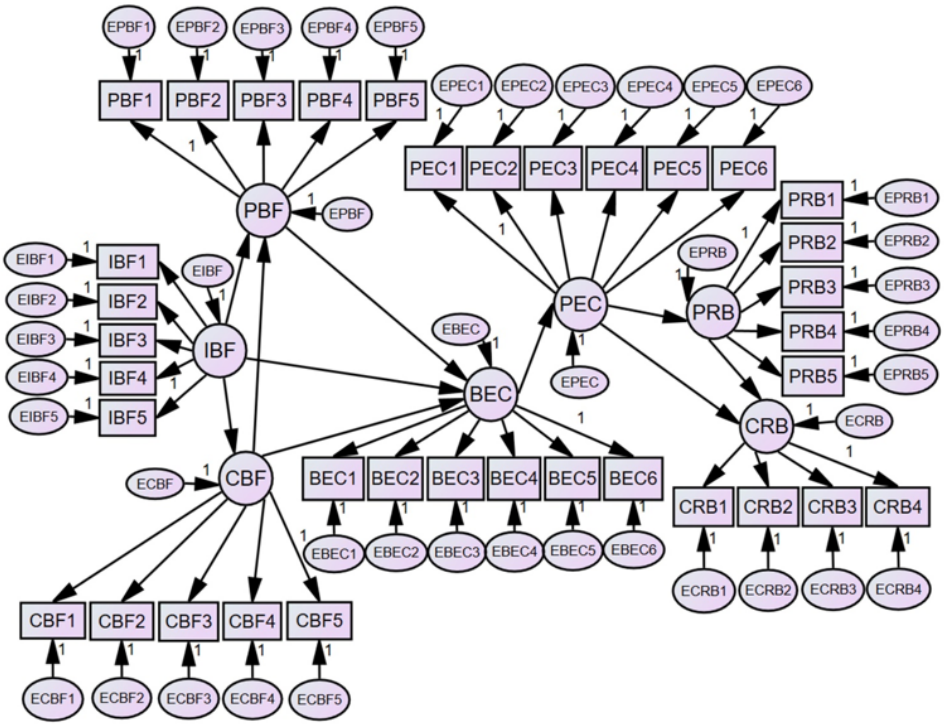

Figure 3.3. Model Developed in IBM SPSS AMOS.

3.4. Analysis of Variance (ANOVA)

A frequently used application in statistics is to compare a number of populations on some characteristics. The procedure of comparing more than two population means is termed as analysis of variance (ANOVA). In ANOVA, the variable that researchers intend to measure is called the dependent variable. It is measured to detect differences among groups. The type of ANOVA depends on the number of independent variables (factors). The procedure can be named as one-way ANOVA (for a single factor), two-way ANOVA (for two factors), three-way ANOVA (for three factors), and so on (Albright and Winston, 2013).

Power and effect size are two basic concepts to interpret the ANOVA results. Power can be defined as the probability of rejecting a false hypothesis. In other words, it is the probability of finding a statistically significant difference when it actually exists. If the probability of type-II error is called β, statistical power can be expressed as 1-β (Cohen, 2019). A power level of 0.80 or greater is generally regarded as satisfactory

(Ellis, 2010).

Effect size can be defined as the difference between the null and alternate hypotheses. It indicates the practical significance of the research. Achieving a statistically significant difference does not necessarily mean that it is meaningful. In order to decide whether it can be helpful in decision making, the effect size needs to be calculated. Guideline prepared by Cohen (2013) reported a small effect size for 0.010, medium effect size for 0.059, and large effect size for 0.138.

3.4.1. One-Way ANOVA

One-way ANOVA is a technique to compare the means of two or more samples. Random samples are obtained from each population classified on the basis of a single criterion and the dependent variable is measured at various levels of the criterion. The following hypothesis is tested (Walpole *et al.*, 2017):

- $H_0 : \mu_1, \mu_2 = ... = \mu_k$
- H_1: At least two of the means are not equal.

μ_1, μ_2 and μ_k represent the means of the first, second, and k^{th} populations, respectively.

3.4.2. Two-Way ANOVA

Two-way ANOVA is an extended form of one-way ANOVA. It examines the impacts of two independent categorical variables on the dependent variable. Two-way ANOVA enables detecting the difference caused by (i) variables acting independently and (ii) joint effect (MacFarland, 2011). The assumptions for the two-way ANOVA are as follows (Albright and Winston, 2013):

- Normality: Each sample is obtained from a normally distributed population.
- Homogeneity of variance: The variance of data in each category is equal.

4. RESEARCH RESULTS

4.1. Information about the Respondent, Company, and Project

4.1.1. Respondent Profiles

The respondents were the construction professionals who had experienced at least one project with BIM implementation. A total of 172 samples had been obtained from 107 different construction projects. Respondents had an average of 9.4 years of experience in the construction industry. Distribution of their experiences is presented in Figure 4.1. It is seen that almost two thirds of the respondents had experiences of 0-5 years (30%) and 6-10 years (35%). It can be stated that younger employees have more tendency to participate in such innovative projects. This can be explained by the fact that technical innovations require employees to invest in themselves. They need to spend time and effort to get accustomed to the changes the innovation brings about. The professionals are more likely to show internal resistance against innovations if it is uncertain that they can reap the benefits of these investments (Zwick, 2002).

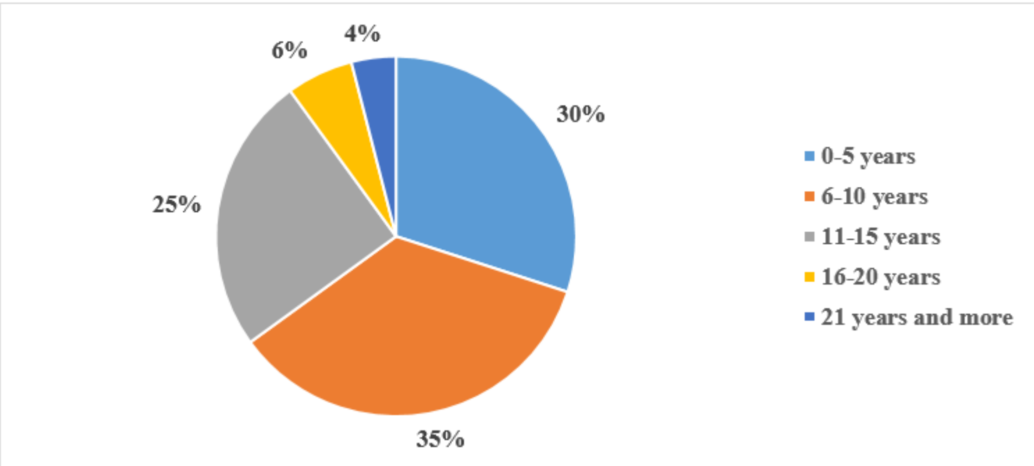

Figure 4.1. Respondents' Experiences in the Construction Industry.

Figure 4.2 shows how many BIM projects the respondents have been involved. Majority of the respondents (69%) had experienced less than 5 projects. Such a situation can be attributed to the fact that BIM approach is relatively new in Turkey. A great majority of the projects adopting the BIM approach have shown up in the last 5 years.

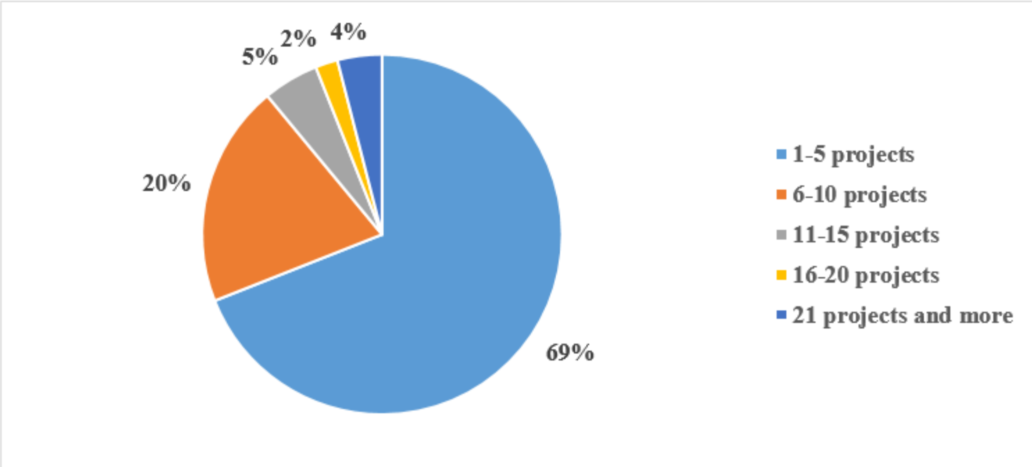

Figure 4.2. Number of BIM Projects Respondents have been Involved.

The positions of the respondents are summarized in Figure 4.3. Majority of the respondents were engineers/architects (53%) followed by department chiefs/managers (21%), coordinators/directors (12%), technicians (10%), and owners/board members (4%).

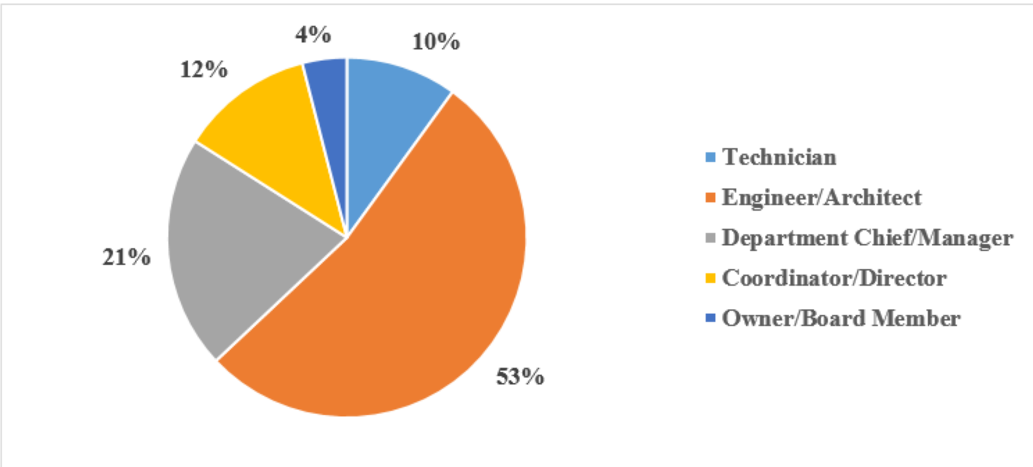

Figure 4.3. Respondents' Positions.

4.1.2. Company Information

The respondents provided information about the companies that they worked for during the BIM project for which they evaluated the SEM questions. The roles of the companies in the projects are demonstrated in Figure 4.4. The companies where the respondents worked were dominantly designers (37%) and main contractors (32%); which could be regarded as the main contributors of the BIM approach. The remaining one third of the companies were composed of subcontractors (11%), consultants (10%), and clients (10%).

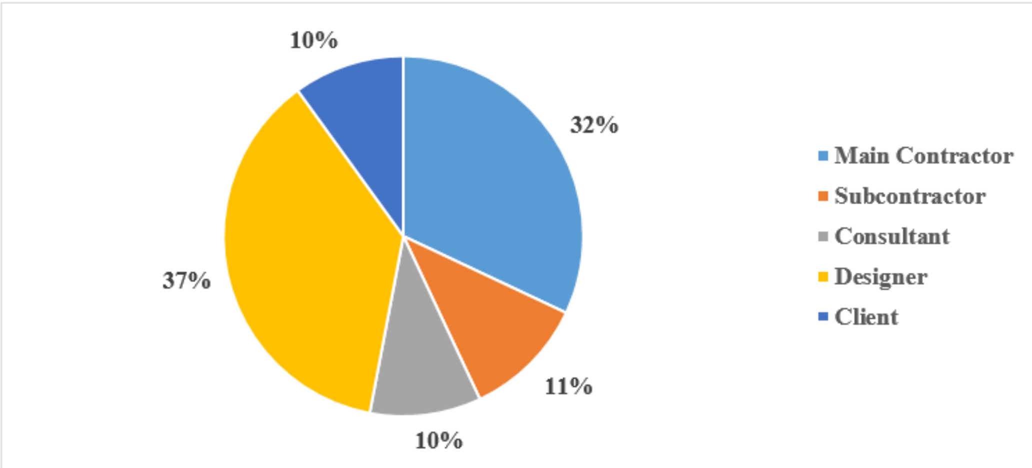

Figure 4.4. Company Role in the Project.

The number of employees working for the companies are summarized in Figure 4.5. Most of the companies had more than 100 employees (63%). One fourth of the respondents were working for small companies with less than 25 employees.

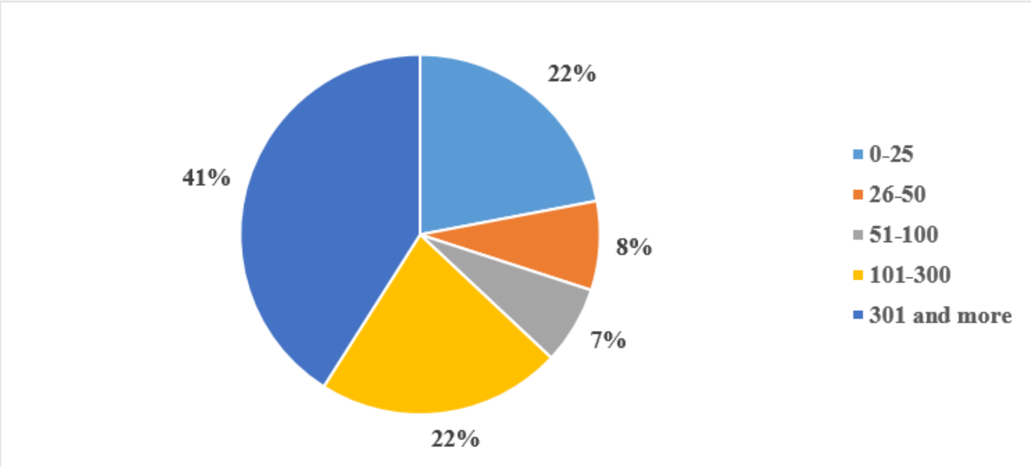

Figure 4.5. Number of Employees in the Company.

Figure 4.6 presents the annual return of the companies. It is seen according to the figure that more than one fourth of the companies had annual return more than $1 billion (26%). Among the rest, majority of the companies had annual return less than $10 million (32%) and between $10-100 million (24%).

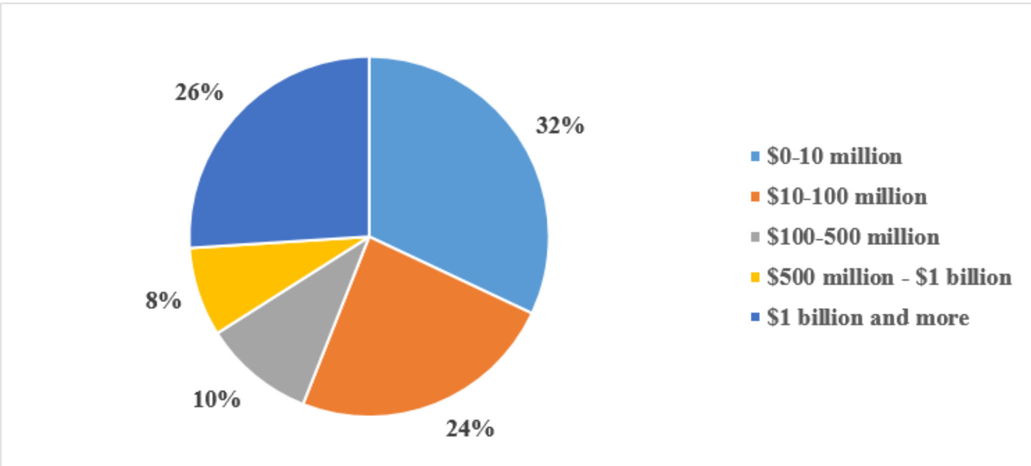

Figure 4.6. Annual Return of the Company.

The respondents were asked whether their companies had expertise in certain project types. The results are given in Figure 4.7. Almost all of the companies had experienced building projects (87%). More than one half of the companies had the expertise in industrial (54%) and infrastructure projects (53%). Highway projects

(25%) and water structures (17%) were the projects that less than one fourth of the companies had experienced.

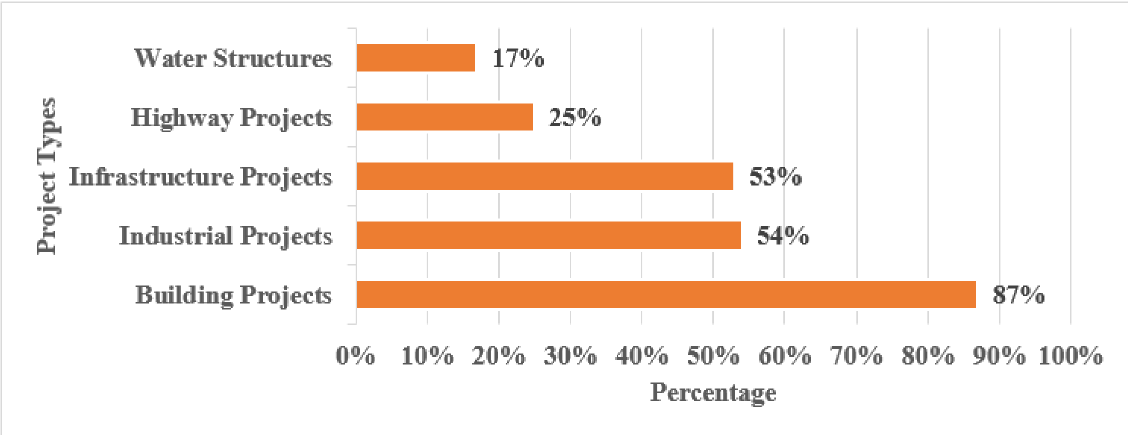

Figure 4.7. Area of Expertise of the Companies.

4.1.3. Project Information

The samples were obtained from a total of 107 different construction projects. The respondents were asked to indicate the type of client in the project. The result is shown in Figure 4.8. The client types were dominated by private sector clients (62%), while public sector clients corresponded to 38% of the projects.

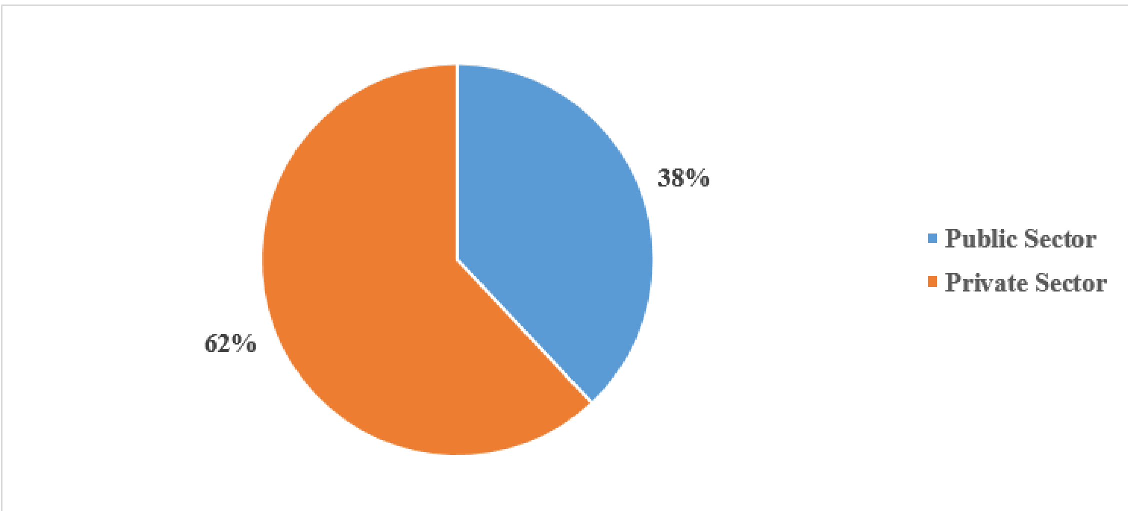

Figure 4.8. Client Type of the Projects.

The distribution of the project types can be seen in Figure 4.9. Most of the samples were collected from the building projects, which represent 64% of the data. It was followed by the infrastructure projects (16%), industrial projects (8%), and highway projects (6%). The remaining project types (airports, museum, and water structure) corresponded to only 6% of the data.

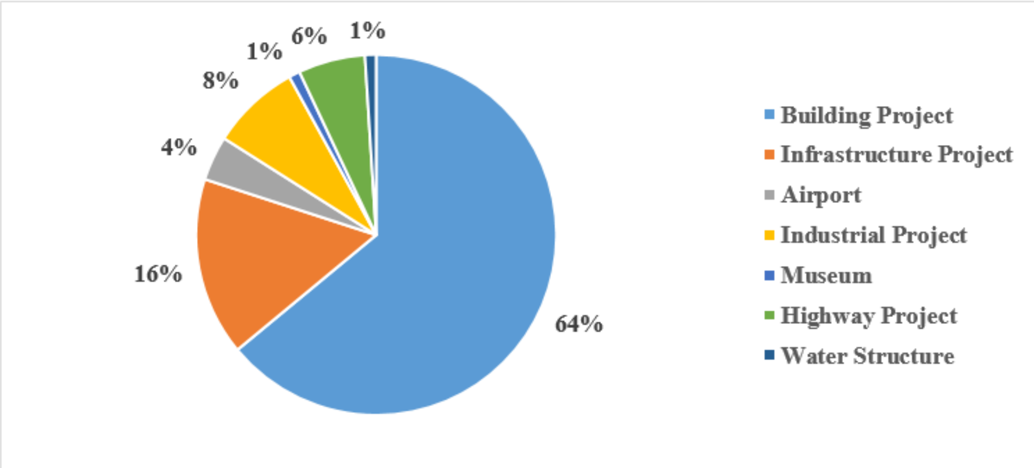

Figure 4.9. Project Types.

Durations of the projects are shown in Figure 4.10. It is realized that more than one half of the projects took between 1-3 years (51%) and majority of the projects were completed in less than 5 years. Projects with durations less than 1 year (15%) or more than 5 years (11%) corresponded to only one fourth of the data.

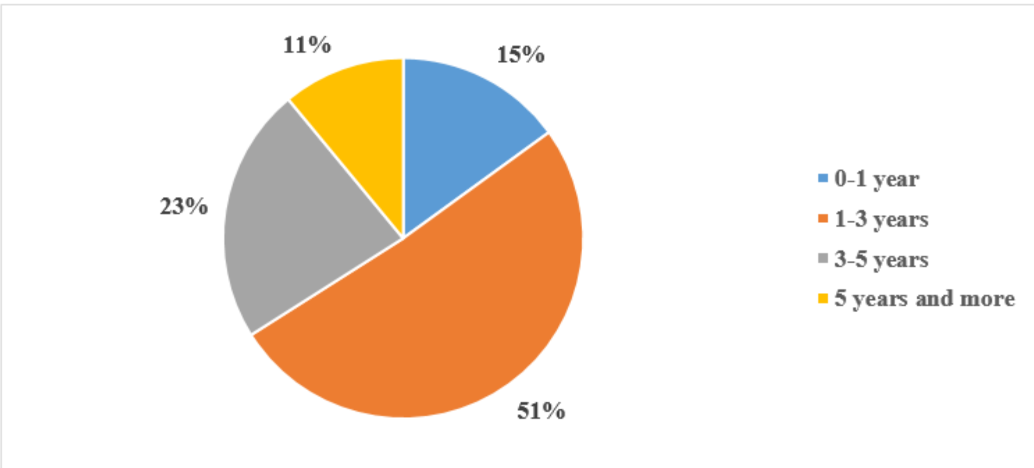

Figure 4.10. Project Durations.

Distribution of the contract values of the projects are demonstrated in Figure 4.11. It is observed that the contract values were homogenously distributed. Projects with contract values between \$0-10 million corresponded to greatest percentage (32%) followed by the contract values between \$100-500 million (23%).

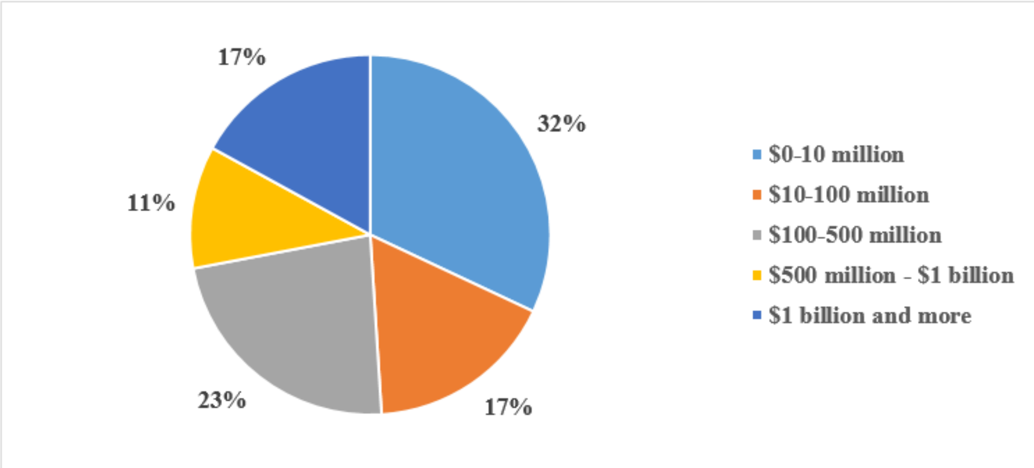

Figure 4.11. Contract Values of the Projects.

The respondents were requested to indicate the ratio of BIM investments to the project costs (Figure 4.12). In a great majority of the projects, BIM investment corresponded to 0-1% (44%) and 1-3% (34%) of the total project cost. Only 9% of the projects had invested in BIM more than 5% of the project cost.

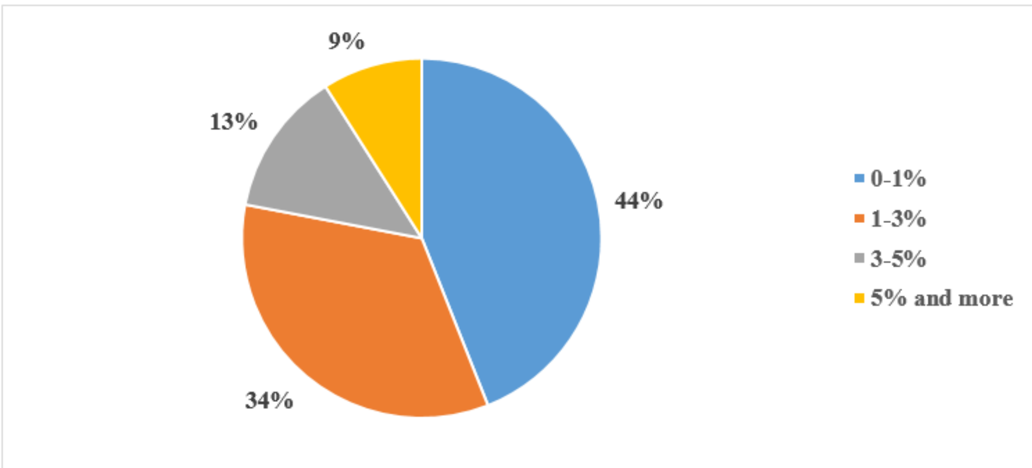

Figure 4.12. Ratio of BIM Investments to the Project Costs.

The respondents indicated the BIM implementations included in the project. The results are presented in Figure 4.13. Evaluation of design alternatives and constructability analysis, which are two crucial activities that take place in pre-design stage, were noticed to be the most frequently practiced BIM implementations with percentages of 83% and 69%, respectively. Pre-design is the key construction stage to create value addition to the project (Hareide *et al.*, 2016; Gade *et al.*, 2019) and these activities can play critical role in increasing the project value.

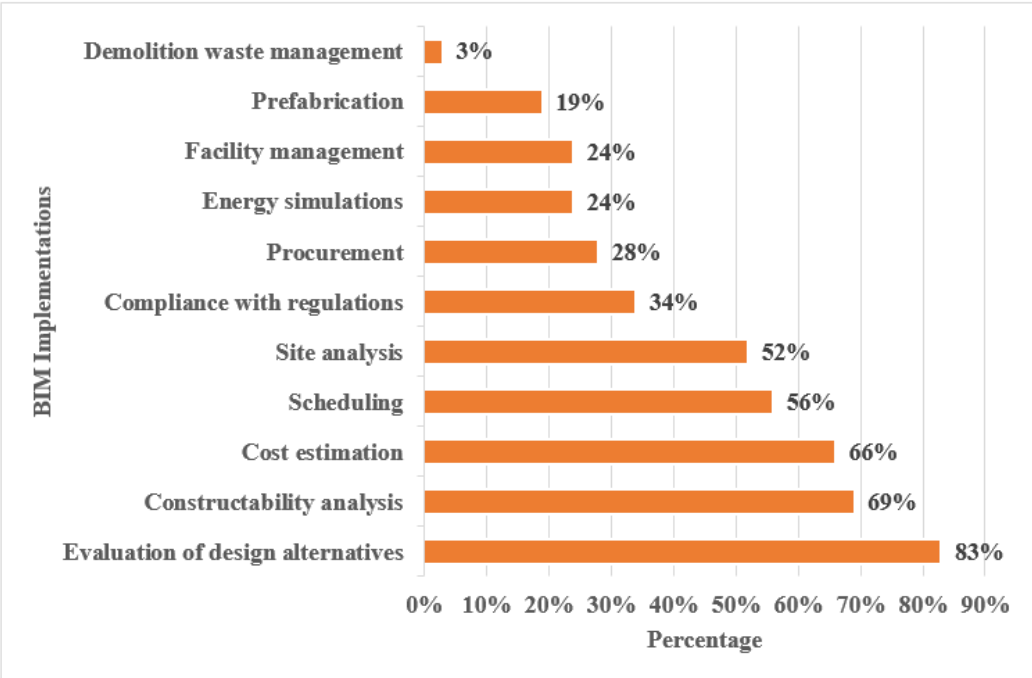

Figure 4.13. BIM Implementations in the Projects.

The respondents were requested to state which BIM platforms they had utilized in their projects. The results are given in Figure 4.14. It is realized that Autodesk Revit was dominantly the most preferred BIM platform, which was utilized in almost all of the projects (95%). Another noteworthy BIM platform that took place in more than one fourth of the projects is Tekla Structures (27%). The other BIM platforms were utilized in less than 10% of the projects.

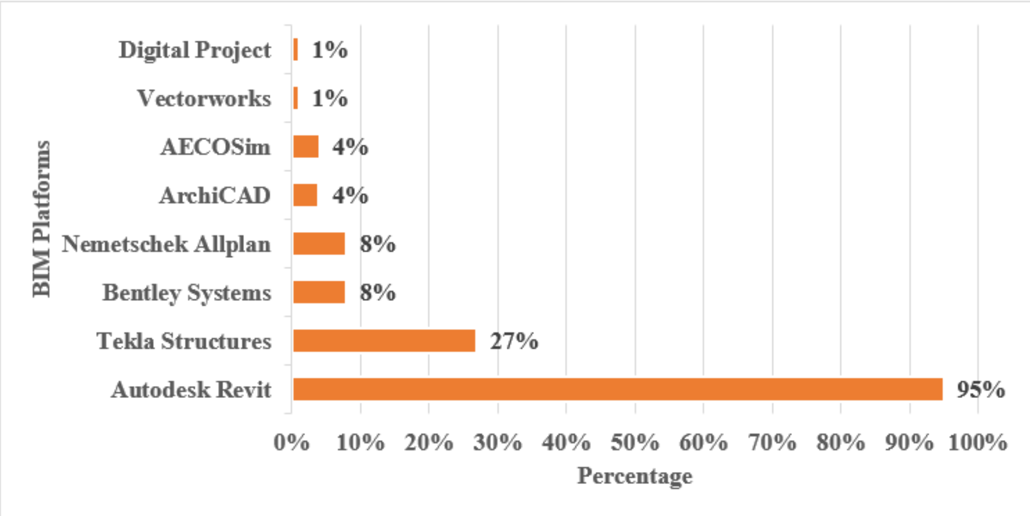

Figure 4.14. BIM Platforms Utilized in the Projects.

4.2. Descriptive Statistics

Descriptive statistic is a summary statistic that uses descriptive coefficients to describe certain features of a data set. These features may include central tendency, dispersion, and normality. The summary of the descriptive statics for each observed variable is presented in Appendix B. The descriptive statistics cover mean and median as the central tendency measures, standard deviation and variance as the dispersion measures, and skewness and kurtosis as the normality measures.

Central tendency is the description of a data set with a single value reflecting the center of data distribution. Mean and median are two measures that describe the central tendency of a data set. Mean is calculated by dividing the sum of all values in the data set by number of values. It is considered as the best estimate of central tendency (Tabachnick and Fidell, 2012). Median is the value that is located at the middle of a data set arranged in an ascending order.

Dispersion is a way of describing the degree to which a data set is spread out. Standard deviation and variance are two commonly used measures of dispersion. Standard deviation corresponds to the average distance between the data set values and the mean. Variance, on the other hand, is the square of average distance between each data set value and the mean. Standard deviation equals to the square root of variance.

Normality is the situation when the data fits a bell curved shape. Normality of a given data set can be measured by skewness and kurtosis. Skewness is a measure for lack of symmetry, whereas kurtosis is a degree of tailedness. Maximum likelihood estimation in SEM models include the assumption that data is normally distributed (Maydeu-Olivares, 2017). Significant problems can arise if the skewness and kurtosis values exceed the ± 2 and ± 7 limits, respectively (Curran *et al.*, 1996). Nevertheless, the values calculated in SPSS for each observed variable are well below these limits.

Figure 4.15 shows the mean values of project-based factors. Commitment to updating the model (PBF4) and existence of BIM specialists (PBF5) were highly rated factors above 3.50. Turkish construction companies taking part in BIM projects are aware of the effectiveness of the technology in determining the project success. Thus, they are committed to regularly updating the model. It is surprising to see existence of BIM specialists as another highly rated factor. Even though the BIM concept is relatively new to Turkey (implying lack of BIM experts), the respondents stated that the projects were guided by the BIM experts.

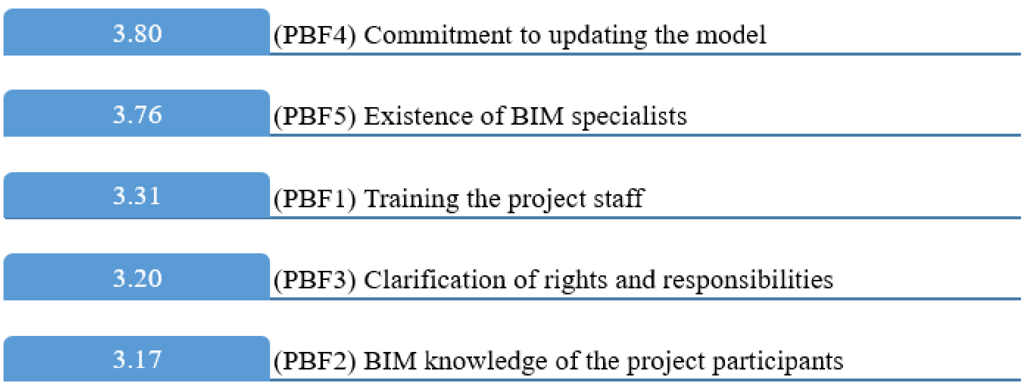

Figure 4.15. Mean Values of Project-Based Factors.

Figure 4.16 presents the mean values of company-based factors. Employees' computer ability (CBF4) and top management support (CBF2) were the highest rated factors. In an attempt to keep pace with the technology, Turkish construction companies have encouraged their employees to improve their computer abilities since the CAD software became first available in the market (Ozorhon *et al.*, 2018). Turkish practitioners, therefore, are talented in computer usage. Top management support was the other highly rated factor. Turkish construction companies that take part in BIM projects are mostly the corporate companies. Their executives have sufficient knowledge on the BIM concept/advantages and give full support for BIM implementation.

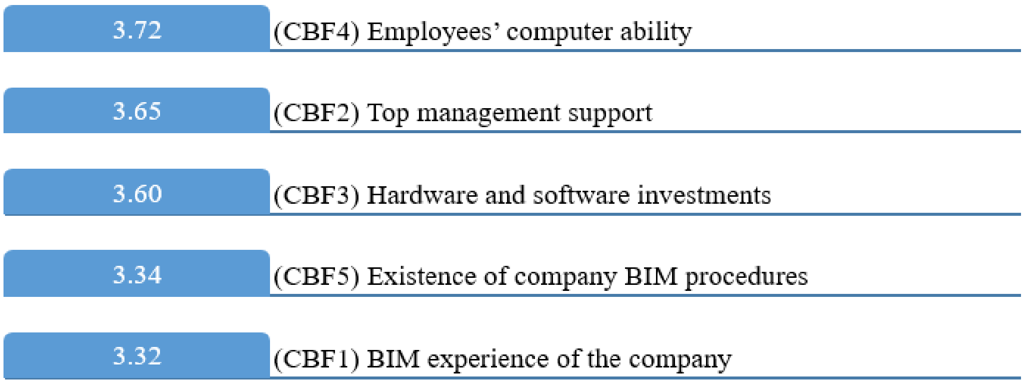

Figure 4.16. Mean Values of Company-Based Factors.

Mean values of industry-based factors are summarized in Figure 4.17. While capacity and capability of current software (IBF4) and interoperability of software platform (IBF2) were identified as the highest rated factors, BIM awareness within industry (IBF3) and availability of BIM protocols (IBF5) were lowest rated factors below 3.00. The respondents had no concern over the adequacy of the commercially available software. They appreciated the capability and interoperability of the commercially available software tools/platforms. Their concern was mainly about lack of BIM awareness and BIM protocols. Although corporate construction companies are familiar with the technological developments (such as the BIM concept), the case is different when the overall industry is concerned. Also, the respondents put emphasis on the need for a contractual guide, which is currently not available in Turkey (Atabay and Ozturk, 2019).

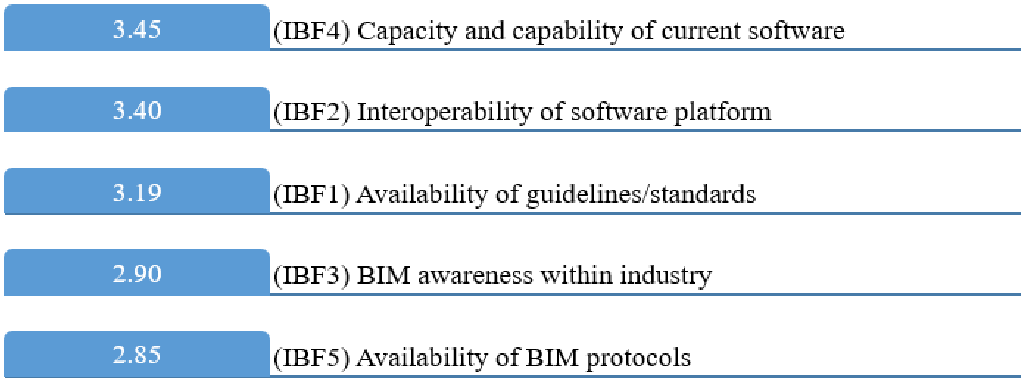

Figure 4.17. Mean Values of Industry-Based Factors.

Figure 4.18 shows the mean values of BIM effectiveness criteria. The top rated factors were detection/elimination of clashes (BEC3) and better visualization of the project (3.99). Detecting the clashes has been stated as the most frequently used application area of BIM in the construction stage (Azhar, 2011; Cao *et al.*, 2015). In that sense, the finding about Turkish construction industry confirms previous statements on global construction. Another confirmation is about the visualization of the project. Cao *et al.* (2015) reported 3D presentation as the most frequently used BIM application area in the design stage.

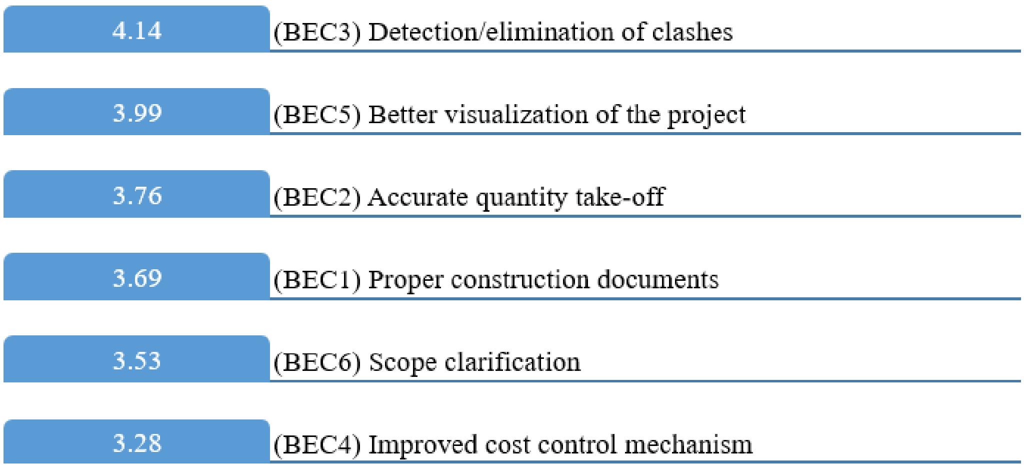

Figure 4.18. Mean Values of BIM Effectiveness Criteria.

Mean values of process effectiveness criteria are stated in Figure 4.19. Better coordination of disciplines (PEC3) and improved communications and trust (PEC1) were identified as the top rated criteria. Construction coordination is key to achieving continuity in construction phases and resolving issues. Improved communication, on the other hand, can support a collaborative environment. In that sense, high ratings observed for proper coordination of disciplines and improved communication could be regarded as the evidences for positive outcomes of BIM implementation in Turkish construction industry.

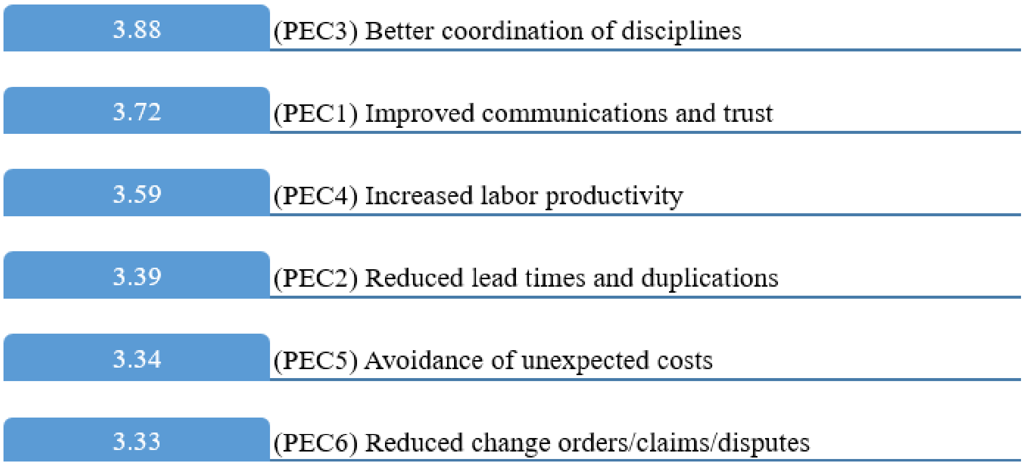

Figure 4.19. Mean Values of Process Effectiveness Criteria.

Figure 4.20 presents the mean values of project-related benefits. Greatest benefits were observed for client satisfaction (PRB5) and enhanced product quality (PRB3). BIM implementation is generally welcome by the clients in Turkish construction industry. In some cases, it is even requested by them (Atabay and Ozturk, 2019). Therefore, high client satisfaction obtained for BIM implemented projects is not surprising. Quality enhancements might be directly associated with certain process effectiveness criteria. To illustrate, improved coordination, which is also observed to be highly rated, should lead to high quality structures (Lee *et al.*, 2015). It should also be noted that BIM implemented Turkish construction projects show poor performance in improving health and safety (PRB4).

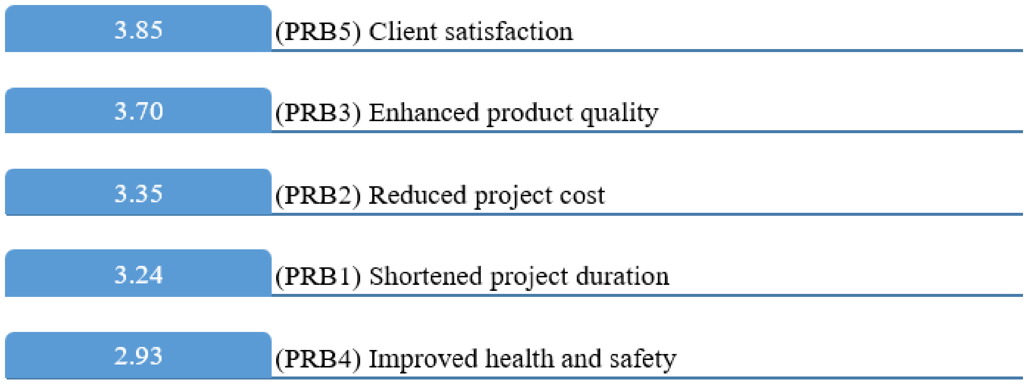

Figure 4.20. Mean Values of Project-Related Benefits.

Mean values of company-related benefits are shown in Figure 4.21. BIM implementation had the greatest influence on improving company image/brand value (CRB1) and technology adoption (CRB4). Turkish construction companies with BIM experiences frequently present their work in international events such as conferences, seminars, and symposiums. Such activities can improve their brand values to a great extent. Certain technological developments in the construction industry encourage the companies to make necessary changes within their organizations to adopt the new technologies. To illustrate, invention of 2D CAD software encouraged companies to stop manual drafting and embrace the new technology (Ozorhon *et al.*, 2018). In a similar way, emergence of BIM software tools should accelerate the technology adoption rate of Turkish construction companies.

Figure 4.21. Mean Values of Company-Related Benefits.

4.3. Model Results

4.3.1. Initial Model Results

A typical SEM model should satisfy the content and construct validities. No statistical analysis exists to test the content validity. The researcher's judgement was mainly applied for model generation. The model components and their interactions were finalized according to the suggestions of an expert group composed of two practitioners and two academicians. The indicators of each model component were determined in consequence of an in-depth literature review.

Construct validity is satisfied through scale reliability, discriminant validity, and convergent validity. Scale reliability is measured by Cronbach's alpha coefficient, which should be greater than 0.70 as suggested by Nunally (1978). Cronbach's alpha coefficients of each latent variable is shown in Table 4.1. The coefficients were well above 0.70, implying that the scale reliability was satisfied.

Table 4.1. Cronbach's Alpha Coefficient of Each Latent Variable.

Latent Variable	Cronbach's Alpha
Project-based factors	0.884
Company-based factors	0.886
Industry-based factors	0.837
BIM effectiveness criteria	0.830
Process effectiveness criteria	0.903
Project-related benefits	0.829
Company-related benefits	0.884

Discriminant validity was tested to make sure that variables did not measure the same thing. Inter-correlations between the measures of the constructs need to be checked to satisfy discriminant validity (Byrne, 2016). The inter-correlations should be less than 0.90 to ensure that there is no multicollinearity (Hair *et al.*, 2010). The correlation matrices are shown in Appendix C. The discriminant validity was satisfied as all the inter-correlations were below 0.90.

Convergent validity was checked to assure that the variables assumed to be related were actually related, in other words, the observed variables forming a latent variable would converge to a single latent variable. Convergent validity is assessed by overall goodness of fit indices and factor loadings. The goodness-of-fit is checked through X^2/dof, CFI, TLI, and RMSEA. The reliability value and fit indices of the model is presented in Table 4.2. The indices were noticed to satisfy the limits recommended by Kline (2015).

Table 4.2. Reliability Values and Fit Indices of the Initial Model.

Index	Recommended Value	Model Value
Cronbach's alpha	> 0.70	0.961
X^2/dof	< 3.00	1.997
CFI	0 (no fit) to 1 (perfect fit)	0.858
TLI	0 (no fit) to 1 (perfect fit)	0.847
RMSEA	< 0.10	0.076

Factor loadings of the observed variables are given in Table 4.3.1. The factor loading of each observed variable was significant at $\alpha = 0.05$.

Table 4.3. Factor Loadings of Observed Variables in the Initial Model.

Component	No	Variable Name	Factor Loading
Project-Based Factors	PBF1	Training the project staff	0.651
	PBF2	BIM knowledge of the project participants	0.756
	PBF3	Clarification of rights and responsibilities	0.796
	PBF4	Commitment to updating the model	0.826
	PBF5	Existence of BIM specialists	0.883
Company-Based Factors	CBF1	BIM experience of the company	0.691
	CBF2	Top management support	0.808
	CBF3	Hardware and software investments	0.819
	CBF4	Employees' computer ability	0.775
	CBF5	Existence of company BIM procedures	0.815

Table 4.3. Factor Loadings of Observed Variables in the Initial Model (cont.).

Component	No	Variable Name	Factor Loading
Industry-Based Factors	IBF1	Availability of guidelines/standards	0.713
	IBF2	Interoperability of software platform	0.796
	IBF3	BIM awareness within industry	0.612
	IBF4	Capacity and capability of current software	0.757
	IBF5	Availability of BIM protocols	0.703
BIM Effectiveness Criteria	BEC1	Proper construction documents	0.741
	BEC2	Accurate quantity take-off	0.652
	BEC3	Detection/elimination of clashes	0.679
	BEC4	Improved cost control mechanism	0.574
	BEC5	Better visualization of the project	0.572
	BEC6	Scope clarification	0.764
Process Effectiveness Criteria	PEC1	Improved communications and trust	0.749
	PEC2	Reduced lead times and duplications	0.782
	PEC3	Better coordination of disciplines	0.770
	PEC4	Increased labor productivity	0.819
	PEC5	Avoidance of unexpected costs	0.752
	PEC6	Reduced change orders/claims/disputes	0.804
Project-Related Benefits	PRB1	Shortened project duration	0.644
	PRB2	Reduced project cost	0.704
	PRB3	Enhanced product quality	0.784
	PRB4	Improved health and safety	0.569
	PRB5	Client satisfaction	0.793
Company-Related Benefits	CRB1	Improved company image/brand value	0.745
	CRB2	Enhanced knowledge management	0.881
	CRB3	Long term profitability	0.816
	CRB4	Technology adoption	0.810

The developed hypotheses were tested with the SEM approach. The structural equation model with path coefficients is shown in Figure 4.22. The arrows show the direction of influence among the model constructs and the grades (path coefficients) indicate the level of influence. The path coefficients can also be considered as the regression weights with no intercept term. The level of associations among the constructs was assessed based on a guideline recommended by Murari (2015). According to the guideline, path coefficients between 0.1-0.3 stand for week association, path coefficients between 0.3-0.5 imply moderate association, and a strong association is indicated by path coefficients over 0.5.

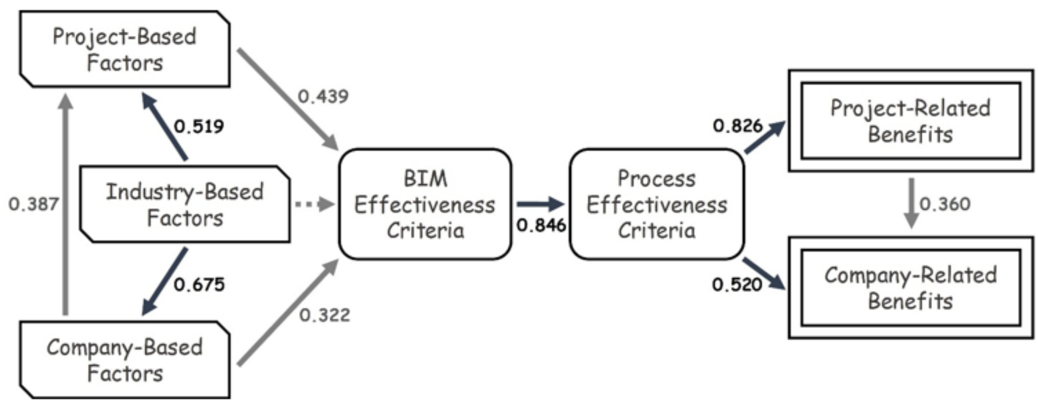

Figure 4.22. Path Coefficients of the Initial Model.

The developed model comprises a total of ten hypotheses. The results revealed 9 significant paths with moderate to strong associations. An insignificant path was identified between the industry-based factors and BIM effectiveness criteria. In an attempt to improve the fit indices, the model was modified. The insignificant hypothesis (H_6) was removed from the model.

4.3.2. Modified Model Results

Table 4.4 presents the reliability values and fit indices of the modified model. Great improvements were observed in the fit indices. The X^2/dof value, which was already below the recommended value of 3.00, decreased from 1.997 to 1.847. Similarly, CFI and TLI indices got more close to 0.90, implying a good model fit. Significant improvement was also noticed in the RMSEA value, which was already within the acceptable range.

Table 4.4. Reliability Values and Fit Indices of the Modified Model.

Index	Recommended Value	Initial	Modified
Cronbach's alpha	> 0.70	0.961	0.961
X^2/dof	< 3.00	1.997	1.847
CFI	0 (no fit) to 1 (perfect fit)	0.858	0.880
TLI	0 (no fit) to 1 (perfect fit)	0.847	0.870
RMSEA	< 0.10	0.076	0.070

Factor loadings of observed variables after modification are summarized in Table 4.5. Factor loadings of most of the observed variables remained unchanged, but some of them varied to a certain extent, which was mainly due to the removal of the insignificant path between the industry-based factors and BIM effectiveness criteria.

Table 4.5. Factor Loadings of Observed Variables in the Modified Model.

Component	No	Variable Name	Initial	Modified
Project-Based Factors	PBF1	Training the project staff	0.651	0.651
	PBF2	BIM knowledge of the project participants	0.756	0.756
	PBF3	Clarification of rights and responsibilities	0.796	0.795
	PBF4	Commitment to updating the model	0.826	0.826
	PBF5	Existence of BIM specialists	0.883	0.879
Company-Based Factors	CBF1	BIM experience of the company	0.691	0.740
	CBF2	Top management support	0.808	0.802
	CBF3	Hardware and software investments	0.819	0.848
	CBF4	Employees' computer ability	0.775	0.763
	CBF5	Existence of company BIM procedures	0.815	0.813
Industry-Based Factors	IBF1	Availability of guidelines/standards	0.713	0.714
	IBF2	Interoperability of software platform	0.796	0.797
	IBF3	BIM awareness within industry	0.612	0.611
	IBF4	Capacity and capability of current software	0.757	0.755
	IBF5	Availability of BIM protocols	0.703	0.702
BIM Effectiveness Criteria	BEC1	Proper construction documents	0.741	0.741
	BEC2	Accurate quantity take-off	0.652	0.658
	BEC3	Detection/elimination of clashes	0.679	0.675
	BEC4	Improved cost control mechanism	0.574	0.581
	BEC5	Better visualization of the project	0.572	0.571
	BEC6	Scope clarification	0.764	0.762
Process Effectiveness Criteria	PEC1	Improved communications and trust	0.749	0.752
	PEC2	Reduced lead times and duplications	0.782	0.780
	PEC3	Better coordination of disciplines	0.770	0.740
	PEC4	Increased labor productivity	0.819	0.793
	PEC5	Avoidance of unexpected costs	0.752	0.756
	PEC6	Reduced change orders/claims/disputes	0.804	0.812
Project-Related Benefits	PRB1	Shortened project duration	0.644	0.574
	PRB2	Reduced project cost	0.704	0.646
	PRB3	Enhanced product quality	0.784	0.800
	PRB4	Improved health and safety	0.569	0.573
	PRB5	Client satisfaction	0.793	0.811
Company-Related Benefits	CRB1	Improved company image/brand value	0.745	0.746
	CRB2	Enhanced knowledge management	0.881	0.885
	CRB3	Long term profitability	0.816	0.812
	CRB4	Technology adoption	0.810	0.809

The path coefficients of the modified model are demonstrated in Figure 4.23. The modified model included 6 strong (dark arrows) and 3 moderate (light arrows) associations among the latent variables. The most notable change was the increasing influence of the project-based factors on the BIM effectiveness criteria, which became a strong association after the modification.

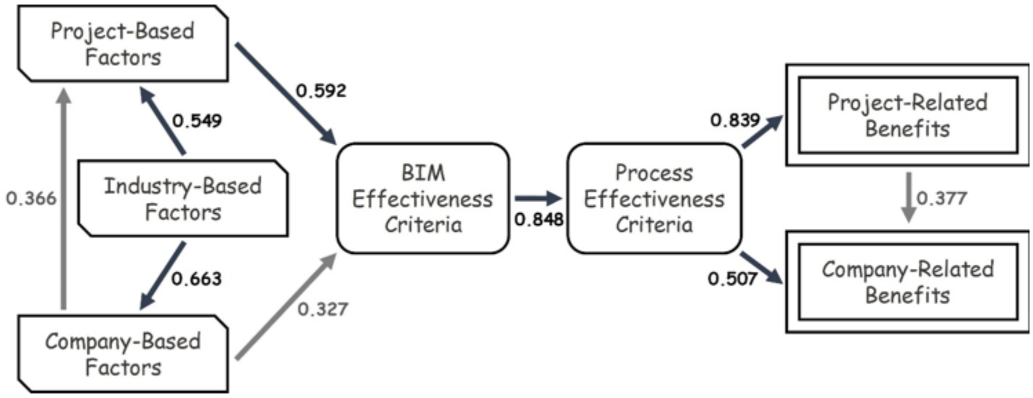

Figure 4.23. Path Coefficients of the Modified Model.

4.4. ANOVA Results

ANOVA was conducted to understand whether the factors vary by some categorical variables. The categorical variables were selected as the client type and project type. The client type included two categories, namely public sector and private sector. The categories of the project type were re-arranged such that the building projects and museum projects were renamed as residential constructions and infrastructure projects, airport projects, industrial projects, highway projects, and water structures were renamed as non-residential constructions.

The categorical variables of client type and project type were used to conduct two-way ANOVA. As already mentioned, the assumptions of two-way ANOVA involve normality and homogeneity of variance. The normality was satisfied for each dependent variable as shown in Appendix B. Failure to satisfy homogeneity of variance leads to utilization of non-parametric equivalents of the analysis. Therefore, the assumption stating the equality of population variances should be hold. Homogeneity of variance test has the following hypotheses:

- H_0: All the population variances are equal,
- H_1: Population variances are not equal.

Table 4.4 shows the homogeneity of variance of each dependent variable. The significance values were observed to be greater than 0.05, implying that the null hypothesis was not rejected and all the population variances were equal.

Table 4.6. Levene's Test of Equality of Error Variances Based on Mean.

Factor	Levene Statistic	df1	df2	Significance
PBF1	1.434	3	168	0.235
PBF2	0.434	3	168	0.729
PBF3	0.879	3	168	0.453
PBF4	2.218	3	168	0.088
PBF5	1.014	3	168	0.388
CBF1	0.384	3	168	0.765
CBF2	0.981	3	168	0.403
CBF3	1.876	3	168	0.136
CBF4	2.000	3	168	0.116
CBF5	2.470	3	168	0.064
IBF1	0.333	3	168	0.801
IBF2	2.628	3	168	0.052
IBF3	0.694	3	168	0.557
IBF4	0.323	3	168	0.809
IBF5	0.053	3	168	0.984
BEC1	1.360	3	168	0.257
BEC2	0.086	3	168	0.968
BEC3	0.746	3	168	0.526
BEC4	0.692	3	168	0.558
BEC5	2.607	3	168	0.053
BEC6	0.876	3	168	0.455

Table 4.6. Levene's Test of Equality of Error Variances Based on Mean (cont.).

Factor	Levene Statistic	df1	df2	Significance
PEC1	0.705	3	168	0.550
PEC2	1.023	3	168	0.384
PEC3	1.799	3	168	0.149
PEC4	2.540	3	168	0.056
PEC5	0.144	3	168	0.934
PEC6	1.381	3	168	0.250
PRB1	0.422	3	168	0.737
PRB2	0.326	3	168	0.807
PRB3	2.515	3	168	0.059
PRB4	1.528	3	168	0.209
PRB5	0.532	3	168	0.661
CRB1	1.631	3	168	0.184
CRB2	0.852	3	168	0.467
CRB3	1.710	3	168	0.167
CRB4	0.995	3	168	0.397

Two-way ANOVA was conducted for all the dependent variables. The results for the test of between-subjects effects are summarized in Table 4.4. The results were observed to be significant for IBF1 (availability of guidelines/standards), IBF3 (BIM awareness within industry), and CRB4 (technology adoption).

Table 4.7. Test of Between-Subjects Effects.

Factor	Significance			Partial Eta Squared			Observed Power		
	Client	Project	Client* Project	Client	Project	Client* Project	Client	Project	Client* Project
PBF1	0.147	0.193	0.748	0.012	0.010	0.001	0.305	0.255	0.062
PBF2	0.807	0.145	0.807	0.000	0.013	0.000	0.057	0.308	0.057
PBF3	0.609	0.846	0.684	0.002	0.000	0.001	0.080	0.054	0.069
PBF4	0.210	0.514	0.492	0.009	0.003	0.003	0.240	0.100	0.105
PBF5	0.369	0.609	0.848	0.005	0.002	0.000	0.146	0.080	0.054
CBF1	0.659	0.094	0.389	0.001	0.017	0.004	0.072	0.388	0.138
CBF2	0.255	0.070	0.212	0.008	0.019	0.009	0.206	0.442	0.238
CBF3	0.165	0.411	0.163	0.011	0.004	0.012	0.284	0.130	0.286
CBF4	0.662	0.151	0.352	0.001	0.012	0.005	0.072	0.300	0.153
CBF5	0.232	0.770	0.129	0.008	0.001	0.014	0.222	0.060	0.330

Table 4.7. Test of Between-Subjects Effects (cont.).

Factor	Significance			Partial Eta Squared			Observed Power		
	Client	Project	Client* Project	Client	Project	Client* Project	Client	Project	Client* Project
IBF1	0.022	0.540	0.020	0.031	0.002	0.032	0.633	0.094	0.644
IBF2	0.866	0.858	0.221	0.000	0.000	0.009	0.053	0.054	0.231
IBF3	0.057	0.854	0.036	0.021	0.000	0.026	0.477	0.054	0.558
IBF4	0.591	0.122	0.522	0.002	0.014	0.002	0.083	0.339	0.098
IBF5	0.800	0.569	0.611	0.000	0.002	0.002	0.057	0.088	0.080
BEC1	0.205	0.338	0.271	0.010	0.005	0.007	0.244	0.159	0.195
BEC2	0.790	0.806	0.598	0.000	0.000	0.002	0.058	0.057	0.082
BEC3	0.517	0.987	0.884	0.003	0.000	0.000	0.099	0.050	0.052
BEC4	0.375	0.175	0.547	0.005	0.011	0.002	0.143	0.273	0.092
BEC5	0.192	0.473	0.310	0.010	0.003	0.006	0.256	0.110	0.173
BEC6	0.545	0.604	0.750	0.002	0.002	0.001	0.093	0.081	0.062
PEC1	0.400	0.197	0.416	0.004	0.010	0.004	0.134	0.251	0.128
PEC2	0.220	0.198	0.737	0.009	0.010	0.001	0.232	0.250	0.063
PEC3	0.064	0.491	0.690	0.020	0.003	0.001	0.458	0.106	0.068
PEC4	0.344	0.113	0.767	0.005	0.015	0.001	0.157	0.353	0.060
PEC5	0.364	0.805	0.481	0.005	0.000	0.003	0.148	0.057	0.108
PEC6	0.768	0.338	0.851	0.001	0.005	0.000	0.060	0.159	0.054
PRB1	0.275	0.874	0.471	0.007	0.000	0.003	0.193	0.053	0.111
PRB2	0.326	0.735	0.572	0.006	0.001	0.002	0.165	0.063	0.087
PRB3	0.741	0.467	0.580	0.001	0.003	0.002	0.062	0.112	0.085
PRB4	0.898	0.651	0.637	0.000	0.001	0.001	0.052	0.074	0.076
PRB5	0.887	0.624	0.854	0.000	0.001	0.000	0.052	0.078	0.054
CRB1	0.286	0.903	0.136	0.007	0.000	0.013	0.186	0.052	0.319
CRB2	0.387	0.758	0.598	0.004	0.001	0.002	0.138	0.061	0.082
CRB3	0.182	0.654	0.632	0.011	0.001	0.001	0.266	0.073	0.076
CRB4	0.041	0.829	0.400	0.025	0.000	0.004	0.534	0.055	0.134

Table 4.8 shows the descriptive statics for availability of guidelines/standards (IBF1). The table presents the mean, standard deviation, and sample size for each combination of client and project types.

Table 4.8. Descriptive Statistics for IBF1.

Client	Project	Mean	Std. Deviation	N
Public	Residential	3.19	1.075	27
	Non-Residential	3.50	1.033	38
	Total	3.37	1.054	65
Private	Residential	3.19	1.081	84
	Non-Residential	2.65	0.982	23
	Total	3.07	1.079	107
Total	Residential	3.19	1.075	111
	Non-Residential	3.18	1.088	61
	Total	3.19	1.076	172

Pairwise comparison of client types for availability of guidelines/standards (IBF1) is presented in Table 4.9. A significant difference was observed between the means of public and private projects. It could be concluded that availability of guidelines/standards was rated significantly higher for public projects. However, the interaction between the client and project types should also be checked.

Table 4.9. Pairwise Comparison of Client Types for IBF1.

(I) Client	(J) Client	Mean Difference (I-J)	Std. Error	Sig.^{b}	95% Confidence Interval for Difference^b	
					Lower Bound	Upper Bound
Public	Private	0.421*	0.182	0.022	0.062	0.781

Based on estimated marginal means

* The mean difference is significant at the 0.05 level

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)

Pairwise comparisons of project and client types for availability of guidelines/standards (IBF1) are shown in Table 4.10. No significant difference was observed between the means of public and private projects within residential constructions, while a significant difference was observed within non-residential constructions. The level of significance was observed to improve (0.003 vs 0.022). It could be concluded that within non-residential constructions, availability of standards/guidelines was rated significantly higher in public projects. In Turkish construction industry, public clients request a more standardized BIM procedure that can easily be monitored. They direct the contractors to prepare a clear BIM execution plan and execute the BIM process in accordance with widely accepted standards. Thus, the respondents working at public projects might be more familiar with the international guidelines/standards and evaluate the factor with higher grades. Due to the complexity of and comparatively less BIM experience in non-residential constructions, guidance becomes more of an issue and the difference between the public and private projects becomes more obvious.

Table 4.10. Pairwise Comparisons of Project and Client Types for IBF1.

Project	(I) Client	(J) Client	Mean Difference (I-J)	Std. Error	Sig.b	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
Residential	Public	Private	-0.005	0.234	0.982	-0.467	0.456
	Private	Public	0.005	0.234	0.982	-0.456	0.467
Non-Residential	Public	Private	0.848*	0.279	0.003	0.296	1.399
	Private	Public	-0.848*	0.279	0.003	-1.399	-0.296

Based on estimated marginal means

* The mean difference is significant at the 0.05 level

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)

Table 4.11 shows the univariate tests for availability of guidelines/standards (IBF1). The univariate tests present the results for effect size (partial eta squared) and observed power. The interaction between the client and project types was noticed to have positive impact on both the effect size (0.052 vs 0.031) and observed power (0.855 vs 0.633).

Table 4.11. Univariate Tests for IBF1.

Project Type		Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent Parameter	Observed Power[a]
Residential	Contrast	0.001	1	0.001	0.001	0.982	0.000	0.001	0.050
	Error	187.744	168	1.118					
Non-Residential	Contrast	10.299	1	10.299	9.216	0.003	0.052	9.216	0.855
	Error	187.744	168	1.118					

a. Computed using alpha = 0.05

Each F tests the simple effects of Client Type within each level combination of the other effects shown.

These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

Table 4.12 shows the descriptive statics for BIM awareness within industry (IBF3).

Table 4.12. Descriptive Statistics for IBF3.

Client	Project	Mean	Std. Deviation	N
Public	Residential	2.85	1.064	27
	Non-Residential	3.24	1.051	38
	Total	3.08	1.065	65
Private	Residential	2.89	1.213	84
	Non-Residential	2.43	1.199	23
	Total	2.79	1.219	107
Total	Residential	2.88	1.173	111
	Non-Residential	2.93	1.167	61
	Total	2.90	1.168	172

Table 4.13 presents the pairwise comparison of client types for BIM awareness within industry (IBF3). A non-significant difference (not less than 0.05) was observed between the means of public and private projects.

Table 4.13. Pairwise Comparison of Client Types for IBF3.

(I) Client	(J) Client	Mean Difference (I-J)	Std. Error	Sig.a	%95 Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
Public	Private	0.381	0.199	0.057	-0.012	0.773
Based on estimated marginal means						
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)						

Table 4.14 shows the pairwise comparisons of project and client types for BIM awareness within industry (IBF3). The difference between the means of public and private projects within residential constructions was observed to be non-significant, while a significant difference was observed within non-residential constructions. An improvement was noticed in the level of significance (0.009 vs 0.057). It could be concluded that within non-residential constructions, BIM awareness within industry was rated significantly higher in public projects. The role of public clients to raise BIM awareness through influencing both their organizations and the industry as a whole has been acknowledged (Lindblad, 2019). Public clients create a BIM-conscious environment in their projects. In consequence, respondents working at public projects might assume the industry BIM awareness higher than it actually is. Interestingly, the

difference again became much obvious within non-residential constructions, where the technical complexity might enforce the public clients to give much emphasis on the BIM technique to manage the risks.

Table 4.14. Pairwise Comparisons of Project and Client Types for IBF3.

Project	(I) Client	(J) Client	Mean Difference (I-J)	Std. Error	Sig.b	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
Residential	Public	Private	-0.041	0.255	0.873	-0.545	0.463
	Private	Public	0.041	0.255	0.873	-0.463	0.545
Non-Residential	Public	Private	0.802*	0.305	0.009	0.200	1.404
	Private	Public	-0.802*	0.305	0.009	-1.404	-0.200

Based on estimated marginal means

* The mean difference is significant at the 0.05 level

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)

Table 4.15 shows the univariate tests for BIM awareness within industry (IBF3). It was noticed that the interaction between the client and project types increased both the effect size (0.040 vs 0.021) and observed power (0.744 vs 0.477).

Table 4.15. Univariate Tests for IBF3.

Project Type		Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent Parameter	Observed Power[a]
Residential	Contrast	0.034	1	0.034	0.026	0.873	0.000	0.026	0.053
	Error	223.964	168	1.333					
Non-Residential	Contrast	9.217	1	9.217	6.914	0.009	0.40	6.914	0.744
	Error	223.964	168	1.333					

a. Computed using alpha = 0.05

Each F tests the simple effects of Client Type within each level combination of the other effects shown.

These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

Table 4.16 shows the descriptive statics for technology adoption (CRB4).

Table 4.16. Descriptive Statistics for CRB4.

Client	Project	Mean	Std. Deviation	N
Public	Residential	4.15	0.818	27
	Non-Residential	4.24	0.634	38
	Total	4.20	0.712	65
Private	Residential	3.98	0.836	84
	Non-Residential	3.83	1.029	23
	Total	3.94	0.878	107
Total	Residential	4.02	0.831	111
	Non-Residential	4.08	0.822	61
	Total	4.04	0.826	172

Pairwise comparison of client types for technology adoption (CRB4) is presented in Table 4.17. A significant difference was observed between the means of public and private projects. It could be concluded that technology adoption was rated significantly higher in public projects. Public clients encourage the contractors to execute a systematic BIM process. The BIM execution plan, standards to follow, and deliverables are clarified beforehand. Once BIM is mandated by regulatory authorities, the discussion goes beyond whether to use the technology and focuses on promoting more advanced BIM use (Linderoth, 2010). Thus, respondents working at public projects might perceive greater technology adoption.

Table 4.17. Pairwise Comparison of Client Types for CRB4.

(I) Client	(J) Client	Mean Difference (I-J)	Std. Error	Sig.b	95% Confidence Interval for Difference^b	
					Lower Bound	Upper Bound
Public	Private	0.291*	0.142	0.041	0.012	0.571

Based on estimated marginal means

* The mean difference is significant at the 0.05 level

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)

Table 4.18 shows the descriptive statics for top management support (CBF2).

Table 4.18. Descriptive Statistics for CBF2.

Client	Project	Mean	Std. Deviation	N
Public	Residential	3.74	0.944	27
	Non-Residential	3.63	1.101	38
	Total	3.68	1.032	65
Private	Residential	3.76	1.137	84
	Non-Residential	3.17	1.193	23
	Total	3.64	1.169	107
Total	Residential	3.76	1.089	111
	Non-Residential	3.46	1.149	61
	Total	3.65	1.116	172

Pairwise comparison of project types for top management support (CBF2) is presented in Table 4.19. A non-significant difference (not less than 0.05) was observed between the means of residential and non-residential constructions.

Table 4.19. Pairwise Comparison of Project Types for CBF2.

(I) Project	(J) Project	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
Residential	Non-Residential	0.349	0.191	0.070	-0.029	0.726

Based on estimated marginal means

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)

Table 4.20 presents the pairwise comparisons of client and project types for top management support (CBF2). The difference between the means of residential and non-residential constructions within public projects was observed to be non-significant, while a significant difference was observed within private projects. An improvement was noticed in the level of significance (0.026 vs 0.070). It could be concluded that within private projects, top management support was rated significantly higher in residential constructions. In private projects, contractor selection is mainly based on the bid price. Such a situation increases the price-based competition in the industry (Olaniran, 2015). The competitive environment directs the construction companies to avoid risky attempts. BIM implementation is considered as an attempt that may involve various risks (Zou *et al.*, 2017). Thus, top management support for BIM implementation might be less in non-residential constructions, where BIM experience is relatively limited.

Table 4.20. Pairwise Comparisons of Client and Project Types for CBF2.

Client	(I) Project	(J) Project	Mean Difference (I-J)	Std. Error	Sig.b	%95 Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
Public	Residential	Non-Residential	0.109	0.279	0.696	-0.442	0.660
	Non-Residential	Residential	-0.109	0 .279	0.696	-0.660	0.442
Private	Residential	Non-Residential	0.588*	0.261	0.026	0.073	1.103
	Non-Residential	Residential	-0.588*	0.261	0.026	-1.103	-0.073

Based on estimated marginal means

* The mean difference is significant at the 0.05 level

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments)

Table 4.21 shows the univariate tests for top management support (CBF2). It was realized that the interaction between the project and client types had positive influence on both the effect size (0.029 vs 0.019) and observed power (0.610 vs 0.442).

Table 4.21. Univariate Tests for CBF2.

Client Type		Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent Parameter	Observed Power[a]
Public	Contrast	0.188	1	0.188	0.153	0.696	0.001	0.153	0.067
	Error	206.570	168	1.230					
Private	Contrast	6.243	1	6.243	5.077	0.026	0.029	5.077	0.610
	Error	206.570	168	1.230					

a. Computed using alpha = 0.05

Each F tests the simple effects of Project Type within each level combination of the other effects shown.

These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

5. DISCUSSION

5.1. Contribution to the Body of Knowledge

A BIM effectiveness framework was proposed to analyze the BIM implementation in Turkish construction industry. In previous studies, a number of BIM models/frameworks were developed for BIM competencies of facility owners (Giel and Issa, 2015), BIM based procurement in public construction projects (Porwal and Hewage, 2013), facility management process (Wetzel and Thabet, 2015), maintenance and refurbishment of housing stock (Alwan, 2016), life-cycle information management (Xu *et al.*, 2014), analysis of risks and rewards (Lam *et al.*, 2017), refurbishment of building projects (Okakpu *et al.*, 2018), and assessment of BIM implementation (Chen *et al.*, 2016; Zhou *et al.*, 2017; Abdirad, 2017; Abbasianjahromi *et al.*, 2019; Olawumi and Chan, 2019; Dowsett and Harty, 2019).

Models/frameworks proposed in previous studies for assessing the BIM implementations had different categorization schemes. To illustrate, the framework proposed by Chen *et al.* (2016) had the components of process management, technology management, information management, and BIM maturity. Zhou *et al.* (2017) formulated a project-level BIM evaluation framework consisting of the operational, managerial, organizational, and strategic indicators. Abdirad (2017) developed a thematic framework that was composed of the inputs, process, outputs, organizational management, and industry-level BIM factors. A BIM maturity assessment framework created by Abbasianjahromi *et al.* (2019) covered the economic and technical criteria. Olawumi and Chan (2019) proposed a BIM benchmarking model and included the BIM process, BIM product, and measures of practice as the components. An analytical framework adapted by Dowsett and Harty (2019) had the constructs as system quality, information quality, support quality, information use, user satisfaction, and net benefits.

The research contributes to the body of knowledge through proposing a novel conceptual framework to systematically assess the effectiveness of BIM implementations within the context of country characteristics. The comprehensive framework incorporated the project-based, company-based, and industry-based factors as the determinants; the BIM effectiveness and process effectiveness criteria as the measurements; and the project-related and company-related factors as the outcomes. Hypotheses were developed to discover the interrelations between the framework components. Data was collected from real construction projects to test the empirical validity and reliability of the framework, which was largely missing in the previous studies (Chen *et al.*, 2016). Recommendations were provided to promote effective BIM implementation in Turkish construction industry.

5.2. Interrelations between the Framework Components

Path coefficients of the modified model showed that project-based factors had the greatest influence on the effectiveness of BIM implementation followed by the company-based factors. This means that a corporate company with a solid BIM infrastructure (highly skilled employees, supporting top management, adequate hardware and software investments, etc.) may not implement BIM effectively unless the company reflects its capabilities on the project conditions. Impact of project characteristics on the BIM success has also been emphasized in a study investigating BIM implementation in Chinese construction industry (Cao *et al.*, 2015).

Company-based factors both directly and indirectly affected the BIM effectiveness. The direct effect was noticed to be at moderate level. Certain company characteristics can play an important role in achieving the BIM implementation success. To illustrate, Ghaffarianhoseini *et al.* (2017) stated that the degree of BIM comprehension and adoption could be related to the size of an AEC firm. In addition to the direct effect, company-based factors can indirectly affect the BIM implementation through influencing the project-based factors. A moderate level of association was observed among the company-based factors and project-based factors, which is an indication of favorable project environments enabled by capable companies.

The path between the industry-based factors and BIM effectiveness was specified as insignificant. It means that maturity of the BIM technology in the construction industry does not directly result in effective BIM implementations. Backing up this finding, the study conducted by Chen *et al.* (2019) revealed no significant impact of any environmental factor. Nonetheless, it should be noted that industry-based factors can indirectly promote BIM success through contributing to project- and company-based factors. Industry-based factors were detected to be strongly associated with both the project- and company-based factors. It is reasonable to infer that maturity of the BIM technology can be regarded as an incentive for the construction companies to (i) adapt themselves to the technology and (ii) build favorable project environment. Construction companies are disposed to making necessary infrastructural and software investments when the incentive is there (Ghaffarianhoseini *et al.*, 2017).

The interactions between the determinants and BIM effectiveness were illustrated in Figure 5.1 based on the results. The area of influence was observed to increase by moving outward, demonstrating the influence of the industry-based factors on the others. The darkness of the shaded areas represented the intensity of the influence on BIM effectiveness. It was noticed to increase by moving inward, explaining the strong influence of the project-based factors and the insignificant direct influence of the industry-based factors.

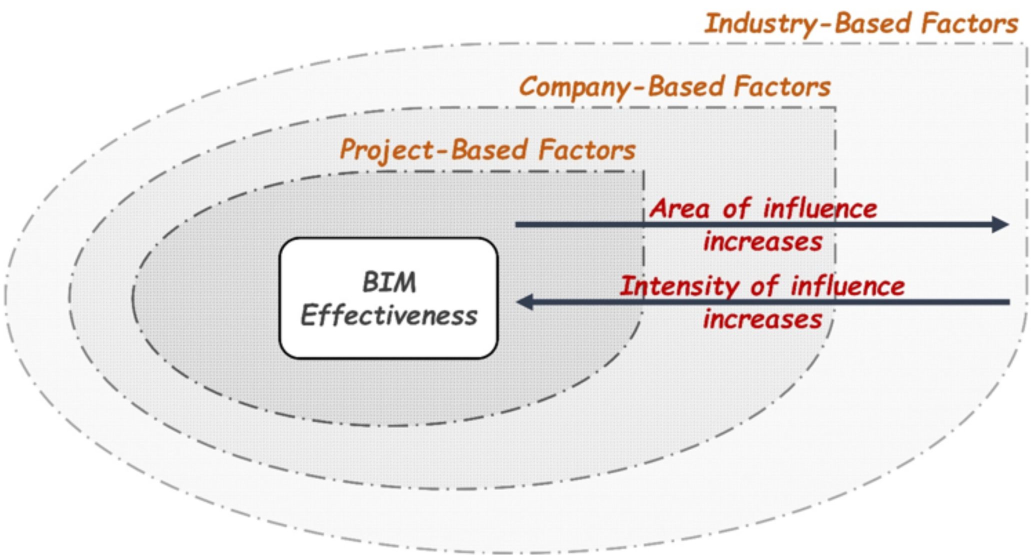

Figure 5.1. Influences of the BIM Effectiveness Determinants.

The results revealed a very strong association between the BIM effectiveness and process effectiveness. According to the results, a successfully built BIM model could give rise to smooth construction processes with coordinated project teams, less rework, and high labor productivity. Contribution of BIM effectiveness to process effectiveness has been highlighted in many studies investigating the effects of BIM implementation in construction projects (Azhar, 2011; Porwal and Hewage, 2013; Ahn *et al.*, 2015; Fadeyi, 2017). The results for the Turkish construction industry confirmed its contribution by demonstrating the strong association between them.

Effectiveness of the construction process was observed to directly influence both the project- and company-related benefits. The levels of associations were specified as strong for both paths, where process effectiveness was noticed to have slightly greater impact on the former one. It might be explained by the fact that project outcomes indicate the short term consequences of process effectiveness that are realized at the end of the project, while the benefits at the company level are shaped by all the projects carried out by the company as illustrated in Figure 5.2. The process effectiveness could also indirectly provide company-related benefits through promoting the project-related benefits. A moderate level of association was detected between the project- and company-related benefits.

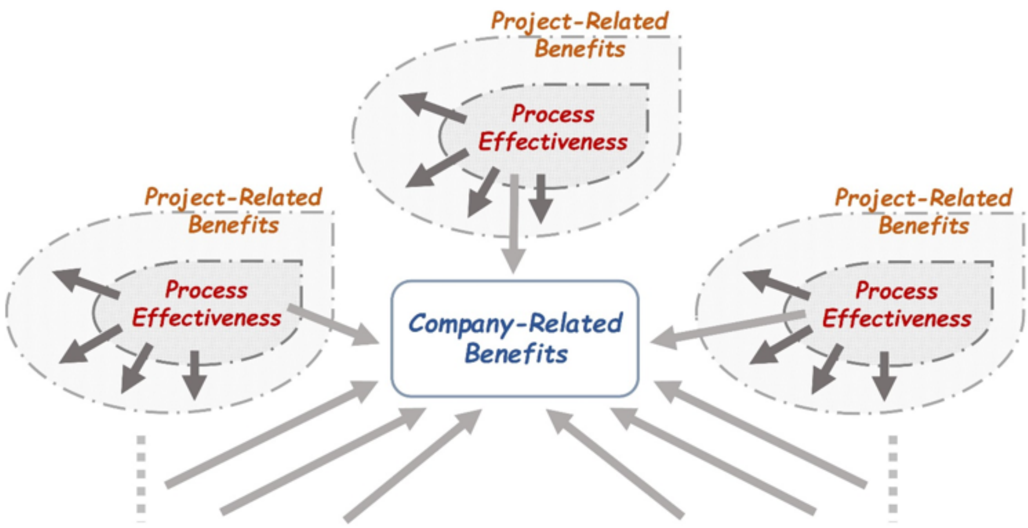

Figure 5.2. Impacts of the Process Effectiveness.

5.3. Evaluation of the Observed Variables

Factor loadings of the observed variables revealed that the most significant project-based factors were existence of BIM specialists (PBF5) and commitment to updating the model (PBF4). BIM concept is relatively new to Turkish construction industry. Its implementation has gained acceleration especially in the last five years. The respondents appreciated the ability of BIM specialists to increase the chance of successful BIM implementation through guiding their unexperienced companies and leading the team members. In order to implement BIM effectively, emphasis should also be given to updating the model. In many cases, Turkish construction companies start the project with a great motivation to flawlessly implement BIM. However, they lose their motivation and stop updating the BIM model as they encounter some challenges. In that sense, it is of prime importance for Turkish construction companies to be committed to the BIM process and updating the model. Backing up this finding, the willingness to adopt BIM was observed to be more significant than other technical and nontechnical factors in another study (Won *et al.*, 2013). Surprisingly, training the project staff (PBF1) was determined as the least significant project-based factor with a factor loading of 0.651, even though the factor was emphasized in many studies (Stowe *et al.*, 2014; Ahmed, 2018). The findings for project-based factors emphasized the significance of leadership for the Turkish construction industry. It was demonstrated that providing training for the entire project team could be far less influential than including few experts to lead to BIM process.

Hardware and software investments (CBF3) and existence of company BIM procedures (CBF5) were the most crucial company-based factors. Even though BIM technology contains financial risks associated with capital investments in hardware (dedicated high-specification workstations) and software (BIM software licenses), this study demonstrated the level of influence of these investments. Some Turkish construction companies refuse to modernize their technological infrastructures due to the additional costs it would bring. They consider it as an unnecessary investment as the existing infrastructure can already support the traditional project delivery methods. Lack of modernization unfortunately prevents the companies from effectively implementing the

BIM concept. To support this finding, Khosrowshahi and Arayici (2012) also concluded in their studies that the capital required to invest in hardware and software could be the least significant barrier. On the other hand, the factor was not regarded as critical in a previously conducted study by Won *et al.* (2013). Company BIM procedures were also stated to be essential for effective BIM implementation. Currently, majority of Turkish construction companies do not have sufficient know-how for BIM implementation. Hence, guidance becomes more of an issue for them to promote success in BIM projects. Such a guidance can be provided by creation of in-house BIM procedures. In a recent study, investing in the creation of in-house BIM procedures was determined as the investment planned by majority of the respondents in the following years (Hanna *et al.*, 2013). Companies willing to develop their own BIM procedures can look over the requirements of a widely accepted BIM execution plan (BEP) and complete the sections in line with their project/company characteristics. They can also obtain information from previously conducted studies focusing directly on the development/adoption of BEP (Wu and Issa, 2014; Lin *et al.*, 2016).

The most significant industry-based factors were interoperability of software platform (IBF2) and capacity and capability of current software (IBF4). Utilization of various BIM functionalities requires the designers to make use of a number of BIM software. How well the data is exchanged among them (by using open-standard Industry Foundation Classes) implies how efficiently the functionalities are utilized. Interoperability has frequently been perceived as a critical factor for successful BIM adoption (Young *et al.*, 2007; Lee *et al.*, 2012). Fortunately, Turkish construction companies have accelerated BIM implementation rate in their projects in the last five years, when the interoperability issues were resolved to a certain extent. Capability of software is of vital importance for reflecting the BIM theories on the project. If the software is incapable of performing the BIM functionalities smoothly, the objectives simply cannot be carried into execution. Software capability should not only be crucial for the Turkish construction industry, but also for global BIM implementations. The capability of a software to support services of interest was also emphasized in another study (Won *et al.*, 2013). The least significant industry-based factor was BIM awareness within industry (IBF3) with a factor loading of 0.611. Based on the finding, it could be stated that even if the industry is not sufficiently aware of the BIM concept, it can still be effectively implemented as long as the executives of the respective company are aware of its necessity and supports its implementation.

The most significant BIM effectiveness criteria were scope clarification (BEC6) and proper construction documents (BEC1). Turkish construction projects that involve many companies with different areas of expertise are frequently subjected to changes and it quite often becomes challenging to determine the scope of each company. At this point, BIM implementation can facilitate the clarification of scope as it provides clear 3D model of the project in early design phase. Clarification of scope enables project managers to make better resource allocation and cost control. It should be noted that scope clarification can be achieved not only by BIM based tools, but also by traditional 3D modelling tools (Bryde *et al.*, 2013). Interestingly, a previously conducted study reported a limited effect of BIM on the predictability of the project scope (Poirier *et al.*, 2015). Another challenge in Turkish construction industry was specified as the document errors and omissions. These errors and omissions can result in costly mistakes on site. As the rapidly changing nature of construction projects throughout the construction phases requires the construction documents to be revised frequently, such mistakes can pose considerable financial risks. The respondents appreciated the ability of BIM to put an end to these mistakes. BIM adoption was stated to enhance documentation quality by providing a flexible and automated documentation process (Azhar, 2011). The least significant BIM effectiveness criterion was better visualization of the project (BEC5) with a factor loading of 0.571. Better visualization might be useful for the project participants to see the whole project in details. However, it was shown to have limited contribution to the construction process.

The most significant process effectiveness criteria were reduced change orders/ claims/disputes (PEC6) and increased labor productivity (PEC4). Great numbers of conflicts take place in Turkish construction industry resulting in many claims and disputes. These conflicts are radically decreased with the help of BIM software that enable early detection and solution of the conflicts, which in turn results in significant amount of time and cost savings for the Turkish construction companies. Notable reduction in the number of change orders was also reported in another study investigating the benefits of BIM implementation (Barlish and Sullivan, 2012). Reduction in the number of change orders also gives rise to increased productivity. Low productivity usually stems from the discontinuity of work resulted by conflicts/change orders. Loss of productivity has been demonstrated to be directly associated with the change orders (Moselhi *et al.*, 1991). BIM implementation can increase productivity by providing the continuity of work on site and making the workers understand the project and their scope in detail. Olawumi and Chan (2018) reported improved productivity and efficiency as the most significant BIM implementation benefit among 36 factors.

The most significant project-related benefits were client satisfaction (PRB5) and enhanced product quality (PRB3). As already mentioned, clients are the promoters of BIM implementation in Turkish construction projects. In most instances, BIM implementation in the project is requested (made obligatory to take part in the tendering phase) by them. Especially, the public clients place emphasis on BIM implementation to build up reputation. BIM implementation enables the contractor to better communicate changes (which are frequently encountered in Turkish construction industry) with the client (Bryde *et al.*, 2013), resulting in higher client satisfaction. The positive influence of BIM on both the design and construction qualities has been a widely acknowledged phenomenon (Chen and Luo, 2014). Quality enhancements are noticed due to the early identification and resolution of conflicts before they are reflected on site. The less the number of conflicts are, the better the quality of the product becomes. The ability of BIM integration to enhance the overall project quality has also been reported by Olawumi and Chan (2018) among the most significant benefits. The least significant project-related benefit was improved health and safety (PRB4) with a factor loading of 0.573. Unfortunately, when it comes to health and safety, Turkish construction companies struggle with the resistance of the company culture to change the working habits. In line with this finding, Smart Market Report published by McGraw-Hill Construction revealed a negative value/difficulty ratio for BIM utilization for safety, meaning that the degree of difficulty is much higher than the end value (Jones and Bernstein, 2012).

The most significant company-related benefits were enhanced knowledge management (CRB2) and long term profitability (CRB3). Turkish construction companies don't seem to systematically keep the old project documents and effectively manage the data. In this respect, BIM implementation helps them create systematic construction documents and extract data whenever necessary. Data obtained from previous projects can also be used for the analysis/comparison of subsequent projects and increase the chance of obtaining desirable outcomes. Profitability of construction companies varies greatly by the type of the project and some project specific conditions. BIM implementation provides better understanding/analysis of the project and decreases the possibility of encountering unexpected situations, thereby mitigating the fluctuations in the project profits. Turkish construction companies frequently get involved in various types of projects taking place at different regions with distinctive characteristics. The unique nature of construction projects (size, type, location, complexity, socio-cultural and political environment, etc.) causes the construction companies to operate under a risky atmosphere. Turkish construction companies adopting the BIM approach can mitigate the risks by unveiling the unexpected situations in the design phase and monitoring them during construction (Zou *et al.*, 2017) and thus, can sustain long term profitability.

6. CONCLUSION

This study proposed a BIM effectiveness framework for construction companies. The framework was mainly composed of the determinants (project-based, company-based, and industry-based factors), the measurements (BIM effectiveness and process effectiveness criteria), and the outcomes (project-related and company related benefits). A total of 172 samples obtained from 107 different construction projects were analyzed to test the developed hypothesis and validate the framework by using SEM.

Major observations of the study are:

- Effectiveness of BIM implementation in construction projects is determined mostly by the project-based factors followed by the company-based factors.
- Industry-based factors do not have any direct impact on the effectiveness of BIM implementation, but they indirectly affect it through exerting influences on the project- and company-based factors.
- A very strong association exists between the effectiveness of BIM implementation and the effectiveness of the construction process.
- Effectiveness of the construction process directly influences both the project- and company-related benefits, where slightly greater impacts are observed on the project-related benefits.

Analysis of the determinants reveals the most significant

- Project-based factors as existence of BIM specialists (PBF5) and commitment to updating the model (PBF4);
- Company-based factors as hardware and software investments (CBF3) and existence of company BIM procedures (CBF5);
- Industry-based factors as interoperability of software platform (IBF2) and capacity and capability of current software (IBF4).

Analysis of the measurements reveals the most significant

- BIM effectiveness criteria as scope clarification (BEC6) and proper construction documents (BEC1);
- Process effectiveness criteria as reduced change order/claims/disputes (PEC6) and increased labor productivity (PEC4).

Analysis of the outcomes reveals the most significant

- Project-related benefits as client satisfaction (PRB5) and enhanced product quality (PRB3);
- Company-related benefits as enhanced knowledge management (CRB2) and long term profitability (CRB3).

Two-way ANOVA results are as follows:

- Within non-residential constructions, availability of standards/guidelines was rated significantly higher in public projects.
- Within non-residential constructions, BIM awareness within industry was rated significantly higher in public projects.
- Technology adoption was rated significantly higher in public projects.
- Within private projects, top management support was rated significantly higher in residential constructions.

A number of recommendations are provided to construction companies based on the observations as follows:

- Project conditions should be favorable for effective BIM implementation. Availability of BIM specialists is of prime importance to lead the BIM process and guide the team members. Companies should either recruit BIM experienced personnel specifically for the project or assign their key personnel to the project. The project team should be committed to updating the model. Even though generating the BIM model and updating it periodically can be demanding in terms of time and effort, the project team should be aware of the potential benefits and devote themselves to enhancing the accuracy of the model.

- The corporate culture should assist BIM implementation. Construction companies should take all the necessary steps to promote BIM effectiveness. They should not hesitate to invest in necessary hardware and software. They usually refrain from any attempt that may increase the costs. However, they should regard BIM implementation as an investment where the savings exceedingly overweigh the costs. Construction companies should also create in-house BIM procedures. Each construction company has its own organizational structure, participates in certain project types, and has different expectations from the BIM software. Therefore, in-house BIM procedures should be developed such that they perfectly fit the company needs. A company can align an existing BEP with its vision.
- The maturity of BIM technology in the construction industry should be taken into account. Companies should accelerate BIM investments (both company-wise and project-wise) in line with the technological advances in BIM. In this respect, attention should be given to the interoperability of the software platform and capabilities of commercially available software. The software platform should be fully interoperable, implying that no information loss should occur while exchanging data between various software. Occurrence of information loss results in unreliable deliverables. The commercially available software should be capable enough to enable utilization of BIM functionalities smoothly. Implementation of the BIM concept in a construction project makes sense only if the software can deliver what the construction company intends to receive.

Responsibility/strategy matrices were proposed for the Turkish construction industry to promote the determinants of BIM effectiveness. The matrices were developed by a team of four academicians and nine professionals (Table 6.1). The matrices were developed for project-based, company-based, and industry-based factors and presented in Table 6.2, Table 6.3 and Table 6.4. Each matrix was composed of five BIM effectiveness determinants. Under each determinant, the proposed actions to be taken by various parties were summarized. The party/parties that can put the action into practice were indicated at the end of each action. The party/parties could either be the construction companies, government bodies, or non-profit organizations.

Table 6.1. Features of the Team Members.

Team Member	Position	Experience
A	Professor	30
B	Professor	18
C	Associate Professor	22
D	Associate Professor	11
E	Company Owner	18
F	Digital Transformation Expert in Construction	21
G	Principal Structural Engineer	24
H	Architect	5
I	BIM and Technology Coordinator	7
J	Senior Information Management Lead	8
K	BIM Manager	16
L	BIM Responsible	10
M	Structural/Civil Design Group Lead	14

Table 6.2. Responsibility/Strategy Matrix for Project-Based Factors.

Factor	Mechanism/Strategy	Responsible Party		
		Construction Companies	Government Bodies	Non-Profit Organizations
PBF1	*- Training the project staff*			
	Prepare quick cards and informative material	X		
	Provide in-house training	X		
	Organize BIM conferences and seminars	X	X	X
	Plan BIM training programs	X	X	X
PBF2	*- BIM knowledge of the project participants*			
	Subcontract with BIM experienced firms	X		
	Adapt business process to BIM implementation	X		
	Quantify BIM influence on company success	X		
	State commitment to BIM adoption	X	X	
PBF3	*- Clarification of rights and responsibilities*			
	Use BIM protocols developed by the pioneers	X		
	Place clear contract clauses	X		
	Develop BIM protocols		X	X
	Establish BIM programs and committees		X	X
PBF4	*- Commitment to updating the model*			
	Report updated model periodically	X		
	Adapt business process to BIM implementation	X		
	State commitment to BIM adoption	X	X	
	Set reward mechanisms for BIM excellence		X	
PBF5	*- Existence of BIM specialists*			
	Recruit BIM experienced personnel	X		
	Incorporate key personnel into BIM process	X		
	Plan BIM training programs		X	X
	Organize BIM conferences and seminars	X	X	X

Table 6.3. Responsibility/Strategy Matrix for Company-Based Factors.

Factor	Mechanism/Strategy	Responsible Party		
		Construction Companies	Government Bodies	Non-Profit Organizations
CBF1	- *BIM experience of the company*			
	Use BIM in projects even if it is not mandatory	X		
	Familiarize experienced staff with BIM process	X		
	Execute pilot BIM projects	X	X	
	Mandate BIM use		X	X
CBF2	- *Top management support*			
	Bid for projects with BIM requirement	X		
	State commitment to BIM adoption	X	X	
	Set reward mechanisms for BIM excellence		X	
	Mandate BIM use		X	X
CBF3	- *Hardware and software investments*			
	Periodically renew workstations	X		
	Buy software programs as a package	X		
	Quantify BIM influence on company success	X		
	Set reward mechanisms for BIM excellence		X	
CBF4	- *Employees' computer ability*			
	Provide in-house training	X		
	Assign personnel with high computer skills	X		
	Plan training programs for computer usage		X	X
CBF5	- *Existence of company BIM procedures*			
	Align an existing BEP with the firm's vision	X		
	Develop BEP	X	X	X
	Establish BIM programs and committees		X	X

Table 6.4. Responsibility/Strategy Matrix for Industry-Based Factors.

Factor	Mechanism/Strategy	Responsible Party: Construction Companies	Responsible Party: Government Bodies	Responsible Party: Non-Profit Organizations
IBF1	*- Availability of guidelines/standards*			
	Use international BIM guidelines/standards	X		
	Develop BIM guidelines/standards		X	X
	Establish BIM programs and committees		X	X
IBF2	*- Interoperability of software platform*			
	Prefer BIM platforms with IFC support	X		
	Provide feedback to the BIM platform supplier	X		
	Prefer software from the same software company	X		
	Organize seminars on open-standard data formats	X	X	X
IBF3	*- BIM awareness within industry*			
	State commitment to BIM adoption	X	X	
	Set reward mechanisms for BIM excellence		X	
	Establish BIM programs and committees		X	X
	Organize BIM conferences and seminars	X	X	X
IBF4	*- Capacity and capability of current software*			
	Use BIM software with high-end capabilities	X		
	Inform the supplier about the incapabilities	X		X
	Organize workshops on software capabilities	X	X	X
IBF5	*- Availability of BIM protocols*			
	Use BIM protocols developed by the pioneers	X		
	Place clear contract clauses	X		
	Establish BIM programs and committees		X	X
	Develop BIM protocols		X	X

The main limitation of the study is that since the data was obtained from the BIM practitioners of Turkish construction companies, the results (descriptive statistics, model validity and reliability, factor loadings, and path coefficients) reflect their perceptions and experiences. Nevertheless, considering the appraised experience of the Turkish professionals especially in the international projects, the results and corresponding strategies can be generalized. Another limitation is regarding the development of hypotheses among the model components and identification of the underlying factors. The hypotheses were developed and underlying factors were identified based on literature review and expert suggestions, which might be subjected to personal judgement to a certain extent.

The proposed framework contributes to the body of knowledge by (i) determining the main components of BIM implementation, (ii) specifying the interrelations among them, and (iii) identifying the underlying factors. Similar studies might be conducted in other countries and results can be compared to observe BIM implementation differences across the world. Construction companies are suggested to make use of the proposed framework and recommendations provided to improve the effectiveness of BIM implementation in their projects. They can utilize the framework to learn the factors and their influences on BIM effectiveness, perceive how BIM effectiveness promotes construction process effectiveness, and realize the project- and company-wise benefits.

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APPENDIX A: QUESTIONNAIRE SURVEY

1) Respondent's experience in the construction industry ....

2) Number of BIM projects the respondent has been involved in ....

3) Company name ....

4) Respondent's position in the company

☐ Technician
☐ Engineer/Architect
☐ Department Chief/Manager
☐ Coordinator/Director
☐ General Manager/Vice General Manager
☐ Owner/Board Member
☐ Other ....

5) Company role in the project

☐ Main Contractor
☐ Subcontractor
☐ Consultant
☐ Designer
☐ Client
☐ Other ....

6) Number of employees in the company

☐ 0-25 personnel
☐ 26-50 personnel
☐ 51-100 personnel
☐ 101-300 personnel
☐ 301 personnel and more

7) Annual return of the company

☐ \$0-10 million
☐ \$10-100 million
☐ \$100-500 million
☐ \$500 million - \$1 billion
☐ \$1 billion and more

8) Area of expertise of the company

☐ Infrastructure projects
☐ Building projects
☐ Industrial projects
☐ Highway projects
☐ Water structures
☐ Other ....

Figure A.1. Section 1: Respondent Profiles.

This section involves questions about the project in which BIM approach was adopted.

9) Project name ....

10) Client type
☐ Public Sector
☐ Private Sector

11) Project type
☐ Infrastructure project
☐ Building project
☐ Industrial project
☐ Highway project
☐ Water structures
☐ Other ....

12) Project duration
☐ 0-1 year
☐ 1-3 years
☐ 3-5 years
☐ 5 years and more

13) Contract value of the project
☐ $0-10 million
☐ $10-100 million
☐ $100-500 million
☐ $500 million - $1 billion
☐ $1 billion and more

14) Ratio of BIM investments to the project cost
☐ 0-1\%
☐ 1-3\%
☐ 3-5\%
☐ 5\% and more

Figure A.2. Section 2: Project Information 1.

15) BIM implementations realized in the project

☐ Evaluation of design alternatives
☐ Constructability analysis
☐ Site analysis
☐ Cost estimation
☐ Scheduling
☐ Compliance with regulations
☐ Energy simulations
☐ Prefabrication
☐ Procurement
☐ Facility management
☐ Demolition waste management

16) BIM platforms utilized during the project

☐ Autodesk Revit
☐ Bentley Systems
☐ Nemetschek Allplan
☐ Tekla Structures
☐ ArchiCAD
☐ AECOSim
☐ Vectorworks
☐ Digital Project
☐ Other ....

Figure A.3. Section 2: Project Information 2.

In this section, the respondent is requested to indicate the extent the following factors were realized in the project. Please assess the factors in a 1-5 scale (very low, low, medium, high, and very high).

Please evaluate the following factors by considering the project conditions.

Project-Based Factors	**Very Low**	**Low**	**Medium**	**High**	**Very High**
Training the project staff	☐	☐	☐	☐	☐
BIM knowledge of the project participants	☐	☐	☐	☐	☐
Clarification of rights and responsibilities	☐	☐	☐	☐	☐
Commitment to updating the model	☐	☐	☐	☐	☐
Existence of BIM specialists	☐	☐	☐	☐	☐

Please evaluate the following factors by considering the company conditions.

Company-Based Factors	**Very Low**	**Low**	**Medium**	**High**	**Very High**
BIM experience of the company	☐	☐	☐	☐	☐
Top management support	☐	☐	☐	☐	☐
Hardware and software investments	☐	☐	☐	☐	☐
Employees' computer ability	☐	☐	☐	☐	☐
Existence of company BIM procedures	☐	☐	☐	☐	☐

Please evaluate the following factors by considering the industry conditions during the project.

Industry-Based Factors	**Very Low**	**Low**	**Medium**	**High**	**Very High**
Availability of guidelines/standards	☐	☐	☐	☐	☐
Interoperability of software platform	☐	☐	☐	☐	☐
BIM awareness within industry	☐	☐	☐	☐	☐
Capacity and capability of current software	☐	☐	☐	☐	☐
Availability of BIM protocols	☐	☐	☐	☐	☐

Please evaluate the following criteria by considering the BIM implementation.

BIM Effectiveness Criteria	**Very Low**	**Low**	**Medium**	**High**	**Very High**
Proper construction documents	☐	☐	☐	☐	☐
Accurate quantity take-off	☐	☐	☐	☐	☐
Detection/elimination of clashes	☐	☐	☐	☐	☐
Improved cost control mechanism	☐	☐	☐	☐	☐
Better visualization of the project	☐	☐	☐	☐	☐
Scope clarification	☐	☐	☐	☐	☐

Figure A.4. Section 3: BIM Effectiveness Framework 1.

Please evaluate the following criteria by considering the construction process.

Process Effectiveness Criteria	**Very Low**	**Low**	**Medium**	**High**	**Very High**
Improved communications and trust	☐	☐	☐	☐	☐
Reduced lead times and duplications	☐	☐	☐	☐	☐
Better coordination of disciplines	☐	☐	☐	☐	☐
Increased labor productivity	☐	☐	☐	☐	☐
Avoidance of unexpected costs	☐	☐	☐	☐	☐
Reduced change orders/claims/disputes	☐	☐	☐	☐	☐

Please evaluate the following benefits obtained project-wise.

Project-Related Benefits	**Very Low**	**Low**	**Medium**	**High**	**Very High**
Shortened project duration	☐	☐	☐	☐	☐
Reduced project cost	☐	☐	☐	☐	☐
Enhanced product quality	☐	☐	☐	☐	☐
Improved health and safety	☐	☐	☐	☐	☐
Client satisfaction	☐	☐	☐	☐	☐

Please evaluate the following benefits obtained company-wise.

Company-Related Benefits	**Very Low**	**Low**	**Medium**	**High**	**Very High**
Improved company image/brand value	☐	☐	☐	☐	☐
Enhanced knowledge management	☐	☐	☐	☐	☐
Long term profitability	☐	☐	☐	☐	☐
Technology adoption	☐	☐	☐	☐	☐

Figure A.5. Section 3: BIM Effectiveness Framework 2.

APPENDIX B: DESCRIPTIVE STATISTICS

Table B.1. Descriptive statistics of “Project-Based Factors”.

Statistics	**PBF1**	**PBF2**	**PBF3**	**PBF4**	**PBF5**
Mean	3.31	3.17	3.20	3.80	3.76
Median	3.00	3.00	3.00	4.00	4.00
Std. Deviation	1.258	1.129	1.103	1.143	1.118
Variance	1.583	1.275	1.216	1.306	1.250
Skewness	-0.298	-0.239	-0.200	-0.818	-0.622
Std. Error of Skewness	0.185	0.185	0.185	0.185	0.185
Kurtosis	-0.842	-0.697	-0.562	0.024	-0.342
Std. Error of Kurtosis	0.368	0.368	0.368	0.368	0.368
Range	4	4	4	4	4
Minimum	1	1	1	1	1
Maximum	5	5	5	5	5
Sum	569	545	551	654	646

Table B.2. Descriptive statistics of "Company-Based Factors".

Statistics	**CBF1**	**CBF2**	**CBF3**	**CBF4**	**CBF5**
Mean	3.32	3.65	3.60	3.72	3.34
Median	3.00	4.00	4.00	4.00	3.00
Std. Deviation	1.133	1.116	1.080	0.945	1.105
Variance	1.283	1.246	1.166	0.892	1.221
Skewness	-0.192	-0.577	-0.527	-0.467	-0.188
Std. Error of Skewness	0.185	0.185	0.185	0.185	0.185
Kurtosis	-0.828	-0.453	-0.243	-0.259	-0.737
Std. Error of Kurtosis	0.368	0.368	0.368	0.368	0.368
Range	4	4	4	4	4
Minimum	1	1	1	1	1
Maximum	5	5	5	5	5
Sum	571	628	619	640	575

Table B.3. Descriptive statistics of "Industry-Based Factors".

Statistics	**IBF1**	**IBF2**	**IBF3**	**IBF4**	**IBF5**
Mean	3.19	3.40	2.90	3.45	2.85
Median	3.00	3.00	3.00	3.50	3.00
Std. Deviation	1.076	0.989	1.168	0.957	1.160
Variance	1.158	0.978	1.364	0.915	1.345
Skewness	-0.150	-0.290	0.128	-0.518	0.140
Std. Error of Skewness	0.185	0.185	0.185	0.185	0.185
Kurtosis	-0.587	-0.263	-0.767	0.338	-0.736
Std. Error of Kurtosis	0.368	0.368	0.368	0.368	0.368
Range	4	4	4	4	4
Minimum	1	1	1	1	1
Maximum	5	5	5	5	5
Sum	548	585	499	593	490

Table B.4. Descriptive statistics of "BIM Effectiveness Criteria".

Statistics	BEC1	BEC2	BEC3	BEC4	BEC5	BEC6
Mean	3.69	3.76	4.14	3.28	3.99	3.53
Median	4.00	4.00	4.00	3.00	4.00	4.00
Std. Deviation	0.908	0.995	0.894	1.094	0.918	0.964
Variance	0.825	0.990	0.799	1.197	0.842	0.929
Skewness	-0.330	-0.515	-1.024	-0.086	- 0.896	-0.140
Std. Error of Skewness	0.185	0.185	0.185	0.185	0.185	0.185
Kurtosis	-0.415	-0.437	0.940	-0.622	0.795	-0.591
Std. Error of Kurtosis	0.368	0.368	0.368	0.368	0.368	0.368
Range	4	4	4	4	4	4
Minimum	1	1	1	1	1	1
Maximum	5	5	5	5	5	5
Sum	634	647	712	564	686	608

Table B.5. Descriptive statistics of "Process Effectiveness Criteria".

Statistics	PEC1	PEC2	PEC3	PEC4	PEC5	PEC6
Mean	3.72	3.39	3.88	3.59	3.34	3.33
Median	4.00	3.00	4.00	4.00	3.00	3.00
Std. Deviation	0.811	0.976	0.932	0.966	1.010	1.042
Variance	0.659	0.953	0.868	0.934	1.020	1.086
Skewness	-0.509	-0.239	-0.588	-0.506	-0.098	-0.216
Std. Error of Skewness	0.185	0.185	0.185	0.185	0.185	0.185
Kurtosis	0.257	-0.336	-0.236	0.040	-0.540	-0.560
Std. Error of Kurtosis	0.368	0.368	0.368	0.368	0.368	0.368
Range	4	4	4	4	4	4
Minimum	1	1	1	1	1	1
Maximum	5	5	5	5	5	5
Sum	640	583	667	617	574	572

Table B.6. Descriptive statistics of "Project-Related Benefits".

Statistics	**PRB1**	**PRB2**	**PRB3**	**PRB4**	**PRB5**
Mean	3.24	3.35	3.70	2.93	3.85
Median	3.00	3.00	4.00	3.00	4.00
Std. Deviation	1.063	1.018	0.955	1.085	0.905
Variance	1.130	1.035	0.912	1.176	0.819
Skewness	-0.017	-0.037	-0.597	0.196	-0.606
Std. Error of Skewness	0.185	0.185	0.185	0.185	0.185
Kurtosis	-0.568	-0.526	0.148	-0.463	0.150
Std. Error of Kurtosis	0.368	0.368	0.368	0.368	0.368
Range	4	4	4	4	4
Minimum	1	1	1	1	1
Maximum	5	5	5	5	5
Sum	557	576	637	504	662

Table B.7. Descriptive statistics of "Company-Related Benefits".

Statistics	**CRB1**	**CRB2**	**CRB3**	**CRB4**
Mean	4.16	4.03	3.77	4.04
Median	4.00	4.00	4.00	4.00
Std. Deviation	0.752	0.834	0.986	0.826
Variance	0.566	0.695	0.972	0.683
Skewness	-0.851	-0.851	-0.531	-0.832
Std. Error of Skewness	0.185	0.185	0.185	0.185
Kurtosis	1.355	0.809	-0.376	1.117
Std. Error of Kurtosis	0.368	0.368	0.368	0.368
Range	4	4	4	4
Minimum	1	1	1	1
Maximum	5	5	5	5
Sum	715	693	649	695

APPENDIX C: CORRELATION MATRICES

Table C.1. Intercorrelations for the variables of “Project-Based Factors”.

PBF	PBF1	PBF2	PBF3	PBF4	PBF5
PBF1	1.000	0.535	0.507	0.478	0.573
PBF2	0.535	1.000	0.653	0.592	0.653
PBF3	0.507	0.653	1.000	0.640	0.695
PBF4	0.478	0.592	0.640	1.000	0.763
PBF5	0.573	0.653	0.695	0.763	1.000

Table C.2. Intercorrelations for the variables of “Company-Based Factors”.

CBF	CBF1	CBF2	CBF3	CBF4	CBF5
CBF1	1.000	0.588	0.455	0.537	0.650
CBF2	0.588	1.000	0.694	0.645	0.605
CBF3	0.455	0.694	1.000	0.658	0.665
CBF4	0.537	0.645	0.658	1.000	0.619
CBF5	0.650	0.605	0.665	0.619	1.000

Table C.3. Intercorrelations for the variables of “Industry-Based Factors”.

IBF	IBF1	IBF2	IBF3	IBF4	IBF5
IBF1	1.000	0.556	0.429	0.470	0.557
IBF2	0.556	1.000	0.495	0.649	0.497
IBF3	0.429	0.495	1.000	0.422	0.490
IBF4	0.470	0.649	0.422	1.000	0.572
IBF5	0.557	0.497	0.490	0.572	1.000

Table C.4. Intercorrelations for the variables of "BIM Effectiveness Criteria".

BEC	**BEC1**	**BEC2**	**BEC3**	**BEC4**	**BEC5**	**BEC6**
BEC1	1.000	0.564	0.458	0.418	0.459	0.554
BEC2	0.564	1.000	0.505	0.572	0.324	0.390
BEC3	0.458	0.505	1.000	0.331	0.423	0.503
BEC4	0.418	0.572	0.331	1.000	0.260	0.523
BEC5	0.459	0.324	0.423	0.260	1.000	0.483
BEC6	0.554	0.390	0.503	0.523	0.483	1.000

Table C.5. Intercorrelations for the variables of "Process Effectiveness Criteria".

PEC	**PEC1**	**PEC2**	**PEC3**	**PEC4**	**PEC5**	**PEC6**
PEC1	1.000	0.611	0.597	0.583	0.536	0.592
PEC2	0.611	1.000	0.586	0.674	0.578	0.679
PEC3	0.597	0.586	1.000	0.736	0.547	0.535
PEC4	0.583	0.674	0.736	1.000	0.605	0.657
PEC5	0.536	0.578	0.547	0.605	1.000	0.662
PEC6	0.592	0.679	0.535	0.657	0.662	1.000

Table C.6. Intercorrelations for the variables of "Project-Related Benefits".

PRB	**PRB1**	**PRB2**	**PRB3**	**PRB4**	**PRB5**
PRB1	1.000	0.712	0.427	0.344	0.457
PRB2	0.712	1.000	0.498	0.388	0.496
PRB3	0.427	0.498	1.000	0.533	0.631
PRB4	0.344	0.388	0.533	1.000	0.496
PRB5	0.457	0.496	0.631	0.496	1.000

Table C.7. Intercorrelations for the variables of "Company-Related Benefits".

CRB	**CRB1**	**CRB2**	**CRB3**	**CRB4**
CRB1	1.000	0.692	0.640	0.535
CRB2	0.692	1.000	0.677	0.728
CRB3	0.640	0.677	1.000	0.694
CRB4	0.535	0.728	0.694	1.000