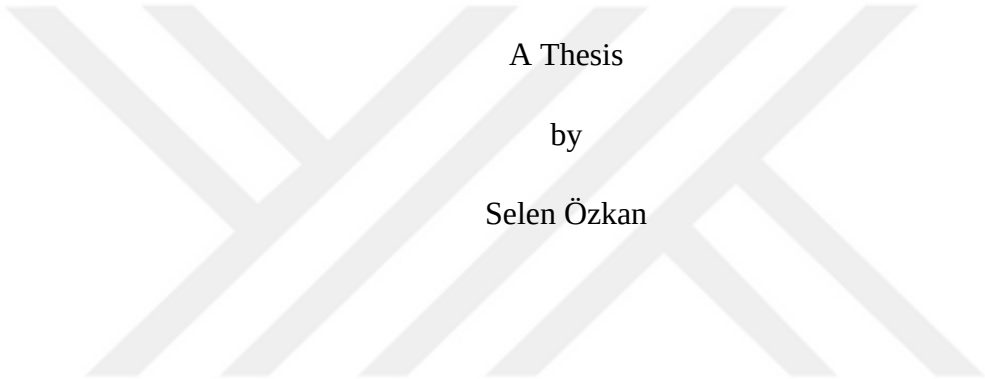


**ANALYZING THE BENEFITS AND CHALLENGES OF
COMMON DATA ENVIRONMENT IMPLEMENTATION IN
BIM-BASED PROJECTS: IMPACTS ON PROJECT
PERFORMANCE**



A Thesis

by

Selen Özkan

Submitted to the
Graduate School of Sciences and Engineering
In Partial Fulfillment of the Requirements for
the Degree of

Master of Science

in the
Department of Civil Engineering

Özyeğin University

December 2021

Copyright © 2021 by Selen Özkan

**ANALYZING THE BENEFITS AND CHALLENGES OF
COMMON DATA ENVIRONMENT IMPLEMENTATION IN
BIM-BASED PROJECTS: IMPACTS ON PROJECT
PERFORMANCE**

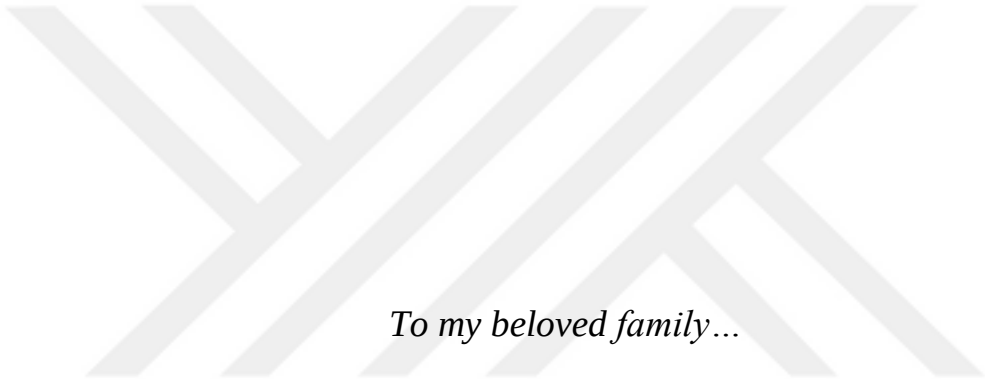
Approved by:

Assistant Professor Senem Seyis
Advisor,
Department of Civil Engineering
Özyeğin University

Assistant Professor Derya Deniz
Department of Civil Engineering
Özyeğin University

Professor Esin Ergen Pehlevan
Department of Civil Engineering
İstanbul Technical University

Date Approved: 27 December 2021



To my beloved family...

ABSTRACT

The construction industry is an information- and communication-dependent industry which requires a collaborative working environment among several stakeholders. The amount of produced data is being excessive considering the whole lifecycle of a building from design through demolition. Especially in the construction phase, which consists of many various operations, information management is crucial for project management and successful completion of the project. Traditional project management practices remain insufficient to manage excessive data and workflows, which may result in non-value-added activities such as delays, reworks, and loss of productivity. Building information modeling (BIM) is emerging as one of the significant milestones on the digitalization of the construction industry, which is fundamentally a digital representation of a building. However, the BIM is criticized for being insufficient to support communication, collaboration, and data exchange processes. At that point, common data environments (CDEs) are extensively changing the ways of working in built environment by combining BIM and cloud computing technology. Despite the general perception and current practices, CDEs should not be considered only as a digital information repository. CDEs are enablers of efficient project management by connecting all project data, processes, and teams in a single platform under BIM infrastructure. An accurately structured CDE for a project can provide numerous benefits, boosting both short- and long-term goals, to project stakeholders.

However, current practices and literature remain quite incapable to present whole aspects of CDEs as cloud computing in BIM is a relatively new technology in the industry. For this purpose, this study aims to reveal full potential of CDEs, focusing on

both short- and long-term benefits as well as challenges, through literature review, interviews, and the Delphi method. Benefits and challenges of CDEs were identified by literature review and semi-structured interviews with 5 subject matter experts (SMEs). Identified benefits and challenges were prioritized using the Delphi method in two rounds with twelve SMEs to reveal most significant factors of CDE implementation. Furthermore, the impacts of identified benefits on project performance were investigated based on the seven construction key performance indicators (KPIs) (i.e., time, cost, quality, safety, productivity, organizational sustainability, and client satisfaction). The results of this research were validated using Cronbach's alpha, interrater agreement (IRA), and standard deviation statistics.

This study presents a comprehensive overview on CDE implementation in BIM-based projects by considering the impacts on project performance. The results of this study can increase the awareness of CDE implementation in the construction industry and promote the use of CDEs in projects by clarifying their full potentials.

ÖZETÇE

İnşaat sektörü, çeşitli paydaşlar arasında işbirliğine dayalı bir çalışma ortamı gerektiren, bilgi ve iletişime bağımlı bir sektördür. Tasarımdan yıkıma kadar bir binanın tüm yaşam döngüsü düşünüldüğünde üretilen veri miktarı çok fazla olabilmektedir. Özellikle çok çeşitli operasyonlardan oluşan inşaat aşamasında bilgilerin yönetimi, projenin başarılı bir şekilde yönetilmesi ve tamamlanması için hayati önem taşır. Geleneksel proje yönetimi uygulamaları, gecikmeler, işlerin tekrar yapılması ve üretkenlik kaybı gibi katma değeri olmayan faaliyetlerle sonuçlanabilecek aşırı veri ve iş akışlarını yönetmek için yetersiz kalmaktadır. Temel olarak bir binanın dijital temsili olan yapı bilgi modellemesi (YBM), inşaat sektörünün dijitalleşmesinde önemli kilometre taşlarından biri olarak ortaya çıkmaktadır. Ancak, YBM iletişim, işbirliği ve veri alışverişi süreçlerini desteklemekte yetersiz olmakla eleştirilmektedir. Bu noktada, ortak veri ortamları (OVO'lar), yapı bilgi modellemesini bulut bilişim teknolojisiyle birleştirerek inşaat sektöründe çalışma yöntemlerini kapsamlı bir şekilde değiştirmektedir. Genel algı ve mevcut uygulamadaki anlayışın aksine ortak veri ortamları, sadece dijital bir bilgi deposu olarak görülmemelidir. Ortak veri ortamları tüm proje verilerini, süreçlerini ve ekiplerini YBM altyapısı altında tek bir platformda birbirine bağlayarak verimli proje yönetimine olanak sağlar. Bir proje için doğru yapılandırılmış bir ortak veri ortamı, tüm paydaşlara hem uzun hem de kısa vadeli hedefleri destekleyerek sayısız fayda sağlayabilir.

Buna rağmen, mevcut uygulamalar ve literatür, YBM ile bulut bilişim inşaat sektöründe nispeten yeni bir teknoloji olduğundan, OVO'ların tüm yönlerini sunmakta oldukça yetersiz kalmaktadır. Bu amaçla, bu çalışma, literatür taraması, görüşme ve

Delphi yöntemini birleştirme yolu ile, OVO'ların hem kısa hem de uzun vadeli faydalarına odaklanarak tüm potansiyelini ortaya çıkarmayı amaçlamaktadır. OVO'ların fayda ve uygulamadaki zorlukları literatür taraması ve konusunda uzman 5 kişi ile yapılmış yarı yapılandırılmış röportajlar ile belirlenmiştir. Bu kapsamda belirlenen faydalar ve zorluklar, OVO uygulamasındaki en önemli faktörleri ortaya çıkarmak için 12 katılımcı ile iki turdan oluşan Delphi yöntemi kullanılarak önceliklendirilmiştir. Ayrıca, belirlenen faydaların proje performansı üzerindeki etkileri, 7 inşaat anahtar performans göstergesine (zaman, maliyet, kalite, güvenlik, üretkenlik, organizasyonel sürdürülebilirlik ve müşteri memnuniyeti) dayalı olarak araştırılmıştır.

Bu çalışma, proje performansı üzerindeki etkileri göz önünde bulundurarak YBM tabanlı projelerde OVO uygulamasına kapsamlı bir genel bakış sunmaktadır. Bu çalışmanın sonuçları, inşaat endüstrisinde OVO uygulamalarının farkındalığını artırabilir ve OVO'ların tüm potansiyellerini açıklığa kavuşturarak projelerde kullanımını teşvik edebilir.

ACKNOWLEDGMENTS

First and foremost, I would like to give my sincere thanks to my supervisor Dr. Senem Seyis for her invaluable advice, continuous support, and patience during my MSc journey. Her knowledge, enlightening suggestions, and encouragements have inspired me to complete my research and build my academic career. I am grateful for her for always motivate me to think broader targets and achieve higher success. I would like to thank thesis committee members, Prof. Dr. Esin Ergen Pehlevan and Dr. Derya Deniz for their valuable consideration and suggestions.

I would also thank to all experts, who participated in my research interview and survey, for their valuable time and efforts. Although I cannot publish their names due to confidentiality, their opinions and suggestions are highly valuable for me.

I am thankful to Özyeğin University for providing great academic, physical, and financial conditions throughout my education. I would like to appreciate professors of the civil engineering department of Özyeğin University, especially Dr. Gürşans Güven Işın, for their contributions to my MSc study.

And my biggest gratitude would go to my parents Meral Özkan and Serat Özkan, who raised and supported me with patience and deepest love. I am grateful for their great support and patience during my study. I am also grateful to my grandparents, Ülfet Kayan and Ziya Kayan, for their unrequited love, who walked at home without slippers so as not to break my concentration. Furthermore, I am thankful to my lovely sister, Serap İzmirlioğlu for her guidance in my life, and her husband, Tolga İzmirlioğlu for cheering me up whenever I feel stressed. I would like to thank my friends Yasamin Moaiyedfar and Semih Gül for their friendship and support during my studies.

TABLE OF CONTENTS

ABSTRACT.....	iv
ÖZETÇE.....	vi
ACKNOWLEDGMENTS	viii
LIST OF TABLES	xii
LIST OF FIGURES	xiii
ABBREVIATIONS.....	xiv
I INTRODUCTION.....	1
1.1 An overview of digitalization in the construction industry.....	1
1.2 Research gap	3
1.3 Research objectives.....	4
II LITERATURE REVIEW.....	7
2.1 ICT and IT for digitalizing the construction information management	7
2.2 Cloud computing in BIM and cloud-BIM	10
2.3 Common data environments (CDEs)	11
2.4 Construction key performance indicators (KPIs)	20
III METHODOLOGY.....	22
3.1 Data Collection	22
3.1.1 Literature review	23
3.1.2 Semi-structured interviews.....	24
3.1.3 Online sources	26

3.2 Categorization of CDE benefits & creation of project performance matrix	26
3.3 The Delphi Method	28
3.3.1 Qualification criteria, identification, and participation status of panel experts	29
3.3.2 Questionnaire development & pilot survey.....	30
3.3.3 Delphi survey process	31
3.3.3.1 Collection of responses	31
3.3.3.2 Analysis of responses & evaluation of consensus.....	32
3.3.3.2.1 Survey round 1.....	33
3.3.3.2.2 Survey round 2.....	34
3.3.3.3 Finalization and prioritization of the results.....	36
IV RESULTS	37
4.1 Identification and prioritization of benefits on CDE implementation	37
4.1.1 Benefits under problem solving subcategory of Toyota's 4P model.....	46
4.1.2 Benefits under people and partners subcategory of Toyota's 4P model.....	48
4.1.3 Benefits under process subcategory of Toyota's 4P model.....	49
4.1.4 Benefits under philosophy subcategory of Toyota's 4P model.....	54

4.2 The impacts of CDE benefits on project performance.....	57
4.2.1 The impacts of CDE benefits, under problem solving subcategory (PSS), on project performance	61
4.2.2 The impacts of CDE benefits, under people and partners subcategory (PPS), on project performance	62
4.2.3 The impacts of CDE benefits, under process subcategory (PRS), on project performance.....	63
4.2.4 The impacts of CDE benefits, under philosophy subcategory (PHS), on project performance.....	65
4.3 Identification and prioritization of challenges on CDE implementation	67
4.3.1 Suggestions to mitigate current challenges of CDE implementation	77
V DISCUSSION	80
VI CONCLUSION.....	82
VII LIMITATIONS AND FUTURE WORKS.....	85
APPENDIX 1: Semi-structured interview questions	86
BIBLIOGRAPHY	89
VITA	105

LIST OF TABLES

Table 1: The benefits of CDE implementation in BIM-based projects.....	15
Table 2: The challenges of CDE implementation in BIM-based projects	19
Table 3: The list of construction KPIs.....	21
Table 4: Three pillars of literature review.....	24
Table 5: Profile of interview participants.....	25
Table 6: Profile of the Delphi panel experts.....	30
Table 7 : The gradation of the five-point Likert scale.....	31
Table 8: Alterations in Cronbach's alpha (α) values	35
Table 9: Results for the benefits of CDE implementation.....	39
Table 10: CDE benefits & project performance matrix.....	58
Table 11: Results of CDE benefits & project performance matrix.....	59
Table 12: Results for the challenges of CDE implementation.....	68

LIST OF FIGURES

Figure 1: Toyota's 4P Model. <i>Adopted from Liker (2004)</i>	27
Figure 2: The Delphi method procedure	28



ABBREVIATIONS

AEC	Architecture, engineering, and construction
AR/VR	Augmented reality/virtual reality
BIM	Building information modeling
C#	Challenge code
CCT	Construction collaboration technology
CDE	Common data environment
CDEs	Common data environments
CEM	Construction, engineering, and management
CIC	Construction Industry Council
DCIM	Digital construction-phase information management systems
E#	Expert code
EDI	Electronic data exchange system
EDMS	Electronic document management system
H&S	Health and safety environment
ICT	Information communication technology
IFC	Industry foundation classes
IRA	Interrater agreement
IT	Information technology
KPI	Key performance indicator
KPIs	Key performance indicators
M	Mean value

NEC	New Engineering Contract
OVO	Ortak veri ortamı
PH	Philosophy
PHS	Philosophy subcategory
PP	People and partners
PPS	People and partners subcategory
PR	Process
PRS	Process subcategory
PS	Problem solving
PSS	Problem solving subcategory
RFIs	Requests for information
YBM	Yapı bilgi modellemesi

CHAPTER I

INTRODUCTION

1.1 An overview of digitalization in the construction industry

Construction is an information-dependent [1] and information-intensive [2] industry where project success is highly dependent on timely access to accurate information via effective communication among multidisciplinary teams and applications. A massive amount of data is produced and exchanged over the project's lifecycle [3] even in a small-scale project. These data may consist of various formats (e.g., drawings, spreadsheets, and photographs) and are generally located in different software, databases, hard copies, or even verbal form [1]. The abundance of complex, discrete information in a project hinders the on-time access to reliable information, which may cause poor decision-making [2] and information management.

Similar to the challenges in information management, traditional communication techniques are one of the most dominant problems in the construction industry. Efficient communication is severely disrupted due to the lack of proper data exchange and transfer channels [4]. According to the Construction Disconnected Report, presented by PlanGrid and FMI in 2018 [5], 52% of reworks arise from miscommunication and poor data. Additionally, based on their report [5], construction professionals spent 5.5 hours weekly only for searching necessary project information. As a result of informal, non-standardized information exchanges and traditional unstructured communication techniques, ensuring a collaborative working environment may be disrupted. The distances

between construction sites and stakeholders, such as headquarters and material suppliers, make the collaboration practices more challenging.

Lack of collaboration, ineffective information management, and miscommunication on the project cause delays, reworks, cost overruns, that result in poor project performance, productivity, and profitability. For this reason, there is a strong need for a fundamental transformation in traditional information management and collaboration in the construction industry [6].

Construction firms and professionals have made great progress towards digitalizing the industry, for the purpose of ensuring effective project management, increased productivity, and project value in the last decades. Building information modeling (BIM) is one of the most recognized pioneers among information communication technology (ICT) developments. BIM is described by Charles Eastman (1999) as “*a digital representation of the building process to facilitate exchange and interoperability of information in digital format*” [7]. However, BIM has been criticized by many researchers due to its insufficient support for collaboration, communication, and information transfer [3, 6, 8, 9], and the standalone nature [10].

Cloud computing practices in construction became active as an innovation delivery enabler for ICT technologies [11], and an integration platform for BIM applications [30] to overcome their above-mentioned deficiencies. As a consequence of the combination of cloud computing practices and BIM, two new terms, cloud-BIM and cloud-based BIM, have entered to the literature in the early 2010s, and are considered as the second generation of BIM [10].

A diversified number of new opportunities and working practices have arisen in the industry since the applications and project management software have started to be run in the cloud servers [12]. Common data environments (CDEs) are considered as one of

the leading cloud-BIM platforms which are useful for delivering BIM-based projects [13]. Common data environments provide better-performing collaboration among stakeholders [14] and are seen as an enabler for the future development of BIM capabilities [15]. According to the ISO 19650-1, the definition of the CDE can be defined as an “*agreed source of information for any given project or asset, for collecting, managing and disseminating each information container through a managed process*” [16]. Despite the general perception, CDEs should not be regarded only as a digitalized information repository and exchange platform [17-21]. In a well-structured CDE, based on the international regulatory norms (e.g., BS PAS 1192; ISO 19650), information management can be standardized and higher levels of project management performance can be achieved. Construction industry has started to implement these platforms globally. For example, the UK government necessitates conducting information management through CDEs for achieving BIM Level 2 maturity [6, 22 23].

1.2 Research Gap

There is an excessive number of studies in the literature which focused on the impacts of ICT and information technology (IT) used in the construction industry [1, 24, 25]. However, the number of studies addressing CDEs [26-29] and cloud-BIM [3, 30,31] are very limited [10]. Only 116 cloud-BIM and cloud computing in BIM-related and 75 CDE-related papers, without any elimination or filtering, exist in the Scopus Database. This relatively low number of papers demonstrates the need for further research on these subjects.

There have been some works that describe the CDE characteristics before the CDE term emerged in the industry which are: centralized digital information management [32]. construction collaboration technologies (CCT) [33], collaborative coordinated

construction [34], common ICT platform [35], centralized data center [36], and BIM-based collaboration platform [37]. These works showed the need for central workspaces to ensure collaborative construction. However, among ICT papers, the CDE term was observed only in the studies of Parisi et al. (2021) and Wang and Meng (2021) as a supportive platform for cloud-BIM and as an IT tool, respectively [15, 38]. In the meantime, among cloud-BIM papers, the CDE term was observed in the works of Alreshidi et al. (2017) and Abanda et al. (2018) as an ICT factor and a leading cloud-BIM platform, respectively [13, 39].

Furthermore, current academic researches remain quite insufficient to reveal the whole aspects of CDEs in spite of the popularity of CDE platforms among cloud service providers in the construction industry. Simeone et al. (2020) highlighted that the full potential of the CDEs still remains unexplored [17]. There have been some studies to clarify the CDE functions and processes [6, 18, 20] and their benefits [21]. However, most of these researches on CDEs are the conference proceedings with a limited literature background. There is no extensive, peer-reviewed journal article that reveals the full potential of CDEs (e.g., benefits/barriers, advantages/challenges, and current status). Besides, there is no research investigating the effects of CDE usage on project performance.

1.3 Research Objectives

Common data environments are inevitable platforms for the future of the construction industry to achieve higher levels of information and project management performance. It is obvious that the CDEs provide many improvements in communication, collaboration, coordination, and control for information and project management. Beyond these most known and recognized technical advantages, the hidden advantages behind the

CDEs are more beneficial for achieving the long-term strategic goals of the companies. CDEs present a wide range of opportunities to both contractors and owners from project management (i.e., conceptual design, design, and construction phases) through portfolio management.

In spite of CDEs' importance, there are some deficiencies in the literature for revealing their full potential. The lack of clarity regarding the full potential of CDEs hinders the implementation of such platforms on construction projects. For this purpose, this study aims to investigate the common data environments from a wider perspective and expand the current body of knowledge on CDEs. The research objectives of this study are given below:

1. Investigate the current status of CDEs among ICT technologies.
2. Identify and prioritize benefits and challenges of CDE implementation in BIM-based projects.
3. Investigate the relation between CDE benefits and impacts on project performance based on main construction KPIs (i.e., time, cost, quality, safety, productivity, organizational sustainability, and client satisfaction).

In this scope, the benefits of implementing CDEs, the challenges while implementing CDEs, and the improvement effects on project performance were revealed within the scope of this study. Suggestions to mitigate current challenges of CDE implementation were also presented. This research provides a deeper understanding of CDE capabilities in construction project management from a contractor's point of view. This thesis carries an important role for being the first comprehensive and mixed-methodological research conducted on CDEs among the current literature. The findings may support industry professionals in promoting centralized working environments, by CDEs, in their business. Furthermore, this research provides insights to the cloud service

providers and researchers in terms of revealing CDE capabilities on construction project management.



CHAPTER II

LITERATURE REVIEW

The literature review was conducted under three research topics in this research. The keywords were extended, as CDEs are considered as a part of ICTs and cloud-based platforms in the literature. The first search was for selecting information and project management-related papers among the ICT domain in the light of digitalization. Secondly, cloud-BIM and cloud computing & BIM domains were investigated as they compound the basis for CDEs. Lastly, the articles related to CDEs, the main subject of this research, were investigated.

As a summary, this research collects CDE benefits and challenges by investigating both ICT, IT, and cloud-BIM literature. The detailed search terms and summary of the findings can be found in Chapter 3, Table 4.

2.1 ICT and IT for digitalizing the construction information management

The construction industry is adopting the ICT/IT tools as they improve project management [1] and improve data handling, storage, and exchange techniques in the last decades. There are plenty of papers investigating ICT/IT implementation and ICT/IT benefits/challenges/success factors in the industry. As the influencing factors for ICT/IT adoption may differentiate based on the location, some of the researches focused on a specific country/region [40-45]. Studies presenting the use of ICT/IT tools for project and

information management purposes [24, 25, 32, 46-49] from a general perspective were investigated to derive common benefits and challenges of the CDEs. Nitithamyong and Skibniewski (2004) clarified the benefits and challenges of web-based construction project management systems (WPMSs) [46]. Sulankivi (2004) identified the benefits of centralized digital information management systems [32]. Nitithamyong and Skibniewski (2006) investigated web-based construction project management systems (WPMSs) and determined 36 WPMS performance measures under 6 performance perspectives which are strategic, schedule/time, cost, quality, risk, and communication improvement [24]. Adriaanse et al. (2010) explained the reason behind the actors for avoiding using inter-organizational ICT in construction projects on a case study [47]. Vaughan et al. (2013) identified 21 qualitative benefits of construction information management systems under 4 categories which are communication, operation, clerical, and quality [48]. Hasan et al. (2019) investigated the implications of mobile ICT use for construction project management and presented the relationship between positive consequences of mobile ICT use and construction productivity [49]. A more recent study, Jahanger et al. (2021), listed the potential positive impacts of digital construction-phase information management systems (DCIM) for project owners and identified 18 positive impacts [25]. However, these articles did not directly focus on CDEs, even they mentioned very similar characteristics of the investigated systems.

Four review papers were found significant since they provided the current ICT/IT technologies in detail. Lu et al. (2015) reviewed the ICT applications in AEC organizations among literature between 2000 and 2015 and categorized the ICT technologies as web, wireless, virtual/augmented reality, BIM, and data exchange and management [50]. They [50] considered the electronic document management (EDMS) system and electronic data interchange system (EDI) under data exchange/management

as an enabler for collaboration without mentioning cloud platforms and CDEs. Following this, Rojas et al. (2016) listed the ICT pillars for construction management as web, semantic web, cloud; information systems (e.g., BIM, GIS, data warehousing, knowledge discovery, and intelligent information systems); tracking and location technologies [1]. The authors [1] also presented the way of data handling with these ICT pillars in terms of cost, project planning, risk management, safety, progress monitoring, quality management, and knowledge management perspectives. Even the authors [1] mentioned cloud technology, they did not mention the CDEs directly.

Based on the searched terms, the CDEs were mentioned in only two articles [15, 38]. Parisi et al. (2021) considered the CDEs as a supportive platform for cloud-BIM, while Wang and Meng (2021) considered the CDEs as an IT tool that enables BIM-based knowledge sharing [15, 38]. A few number of CDE-mentioned articles proves the need for further research on the subject matter. Even the ICT enhanced collaboration in BIM has transformed the process of information exchanges, current BIM practices needs protocols and tools for further collaboration, which orients the current systems to use cloud applications [22].

2.2 Cloud computing in BIM and cloud-BIM

The cloud computing technologies, combined with the ICT tools, are transforming the working practices for AEC professionals [23]. The developments in cloud computing are overcoming the industry's fragmentation issues and leading up a large spectrum of new possibilities in project management since the applications have been running in the cloud in the last decade [12]. The cloud-BIM is considered as the second generation of BIM. The cloud-BIM provides increased efficiency of collaboration as it enables streamlined communication platforms for the project team [10]. There are four cloud deployment models that are differentiated according to their accessibility. These models are as follows: (1) *public*, (2) *private*, (3) *community*, or (4) *hybrid services* [11, 51]. The NIST [52] identified the three service models for cloud computing which are (1) *software as a service (SaaS)*, (2) *platform as a service*, and (3) *infrastructure as a service (IaaS)*, from application domain-specific users to virtual hardware provisions [11]. In the AEC industry, Autodesk BIM 360, Oracle Aconex, Bentley ProjectWise, and Trimble Viewpoint can be exemplified as the most prevalent SaaS-based project management applications. Chong et al. (2014) reviewed and compared forty-two cloud computing applications (e.g., cloud project management applications and cloud-BIM applications) that are used in the built environment [12]. Although they [12] reviewed some of CDE platforms (e.g., BIM 360, Aconex, and Viewpoint), they mentioned these platforms as cloud project management applications instead of using CDE providers. Matthews et al. (2015) investigated the cloud-based BIM's effectiveness in terms of real-time information delivery [2].

The studies investigating the cloud-BIM or cloud computing in BIM & construction industry from the project and information management point of view [10, 11, 13, 30, 39, 53] were analyzed to derive common benefits and challenges of the CDEs.

Redmond et al. (2012) investigated the information exchanges through cloud-BIM and identified the capabilities, contractual issues, and barriers regarding cloud and BIM [30]. Wong et al. (2014) presented an overview of cloud-based BIM technology by mentioning cloud-based BIM's benefits and challenges based on the literature review findings [10]. Afsari et al. (2016) examined the way of building data transmission management and revealed the challenges in the current systems [53]. Bello et al. (2021) conducted a systematic review for cloud computing in the construction industry and identified the use cases, benefits, and challenges of the subject matter [11].

Alreshidi et al. (2017) listed the advantages and disadvantages of cloud in BIM and categorized the CDEs under ICT factors informing efficient BIM governance [39]. Abanda et al. (2018) identified the mobile/cloud BIM benefits and barriers and explained the common data environment for collaboration [13]. Alreshidi et al. (2017) and Abanda et al. (2018) are the only writers who mentioned the CDEs directly [13, 39], among the reviewed literature explained in this study.

2.3 Common data environments (CDEs)

As Redmond and West (2012) stated, *“The future of ICT is a service deployed from a centralised data centre across a network providing access to the applications from a central provider (cloud computing)”* [36], which lead the authors to the main subject, the CDEs, of this research.

Common data environments are the cloud-based shared workspaces [22] that contain models, information, and documents in a queryable, collaborative [6] and centralized environment. CDEs streamline and connect whole construction processes, with their corresponding building information, in a single model [54], throughout the building's lifecycle.

In literature review process, an uncertainty was noticed which is about the position of CDEs among ICT environment. Some researchers were made definitions which are very close to CDEs, yet they did not used exactly the “CDE” term. This can be explainable for the articles published before 2010, as the cloud computing has started to be used in the industry in 2010. However, it should be questioned why the articles published after 2010 do not include the “CDE” term. The presented notions which are similar to CDE functionalities were centralized digital information management [32], centralized data center [36], construction collaboration technology [33], collaborative coordinated construction [34], BIM-based collaboration platform [37], and common ICT platform [35] respectively. Moreover, different classifications were presented for CDEs by several researchers in the ICT domain. Furthermore, the researchers Alreshidi et al. (2017) and Wang and Meng (2021) were classified CDEs as IT tool and ICT factor respectively [38, 39]. Parisi et al. (2021) were interpreted the CDEs as the support for Cloud-BIM while Abanda et al. (2018) consider the CDEs as a leading cloud-BIM platform [13, 15]. According to the author, CDEs are leading project management systems based on BIM and cloud computing infrastructure among ICT domain and contains whole project data in a single platform corresponding to building lifecycle (i.e., documentation, the graphical model and non-graphical data [104] for the whole stakeholders).

After the introduction of cloud computing in the construction industry, the researches handling CDEs have started to increase significantly in design [55-58], quality [59]; sustainability [54, 60, 61], safety [62]. Some of the researchers presented the use of CDEs in case studies [21, 63-65], and Heritage BIM practices [66-70].

There are few researches that identified and classified the CDE functionalities [6, 18, 20]. Klemm-Albert et al. (2018) categorized the content and processes that are utilized within CDEs as models, documents, drawings, workflows, and comprehensive

information [6]. The authors [6] well summarized the possibilities in CDEs such as data querying, download and exporting, assigning, managing, conflict resolution, and issue management. However, they [6] did not clarify their method of sampling to uncover the presented CDE possibilities. Stransky (2020) compared four common data environment platforms which are Viewpoint, ProjectWise, Trimble Connect, and Dalux Tender, in terms of their support for procurement of subcontractors [18]. However, the findings [18] were not supported by the literature and directly derived from just online sources and interviews with the CDE representatives. Additionally, the numbers, qualifications of interview participants, interview questions, and durations were not clarified in their study [18], which are important requirements to prove the accuracy of the qualitative researches.

The current BIM processes in practice and the existing literature, generally consisting of conference papers, depicted the concept of CDE as just a documentation repository [17]. The common data environments should not be confused with the EDMS systems [6] as they are different concepts. A limited number of researchers expanded the CDE scope in their papers [17, 19, 20]. Simeone et al. (2020) proposed a system to achieve actual collaboration in CDEs which allows reasoning operations, coherence checking, and information comparison [17]. Losev (2020) discussed the CDEs from the building's lifecycle perspective and revealed the common knowledge environment (CKE) concept [19]. The CKE forms the smart experience of the building and provides the strategic targets of the building lifecycle [19] by benefiting from the CDEs. Ozkan and Seyis (2021) identified the fifty-three CDE functions which facilitate twelve management processes, from contract management to knowledge management, in a construction project [20]. Only Losev (2020) and Ozkan and Seyis (2021) mentioned the CDE capabilities from knowledge management perspectives [19, 20].

This study reveals the benefits and challenges of CDE implementation in the BIM-based projects in an elaborative manner based on the outputs from literature review and semi-structured interviews with 5 subject matter experts. Table 1 presents the benefits of CDEs whereas Table 2 shows the challenges of CDE implementation in BIM-based projects with the source of data.



Table 1: The benefits of CDE implementation in BIM-based projects

4P Category	ID	Benefits	References			
			ICT/IT	Cloud-BIM	CDE	Inter-view
Problem Solving	PS1	Access to accurate, reliable and up-to-date information	[25], [32]	[11], [13], [39]		X
	PS2	Facilitates foreseeing the risks	[24], [25]	[13], [39]		X
	PS3	Improved & data-driven decision-making	[24], [25], [32], [49]			X
	PS4	Minimizes double-handling of documents	[25]			X
	PS5	Possibility to make accurate forecasts & control	[24]			
	PS6	Preservation of audit trail records	[25], [32], [48]	[11]	[21]	X
	PS7	Prevents data loss	[25]	[11], [39]		X
	PS8	Prevents misunderstandings caused by miscommunication	[24], [25]			X
	PS9	Proactive problem solving		[11]		X
	PS10	Reduces construction conflicts & disputes	[24], [25]	[11], [13]	[71]	X
	PS11	Reduces defects	[24], [25], [49]			
	PS12	Reduces issues	[48], [49]			X
	PS13	Reduces reworks	[24], [25], [48]		[21]	X
	PS14	Supports dispute resolution processes	[46]	[11]	[71]	X
	PS15	Strengthens data security	[46]	[11]		X
	PS16	The single source of information & truth	[25], [32], [46], [48], [21]			X

Table 1: (Continued)

4P Category	ID	Benefits	References			
			ICT/IT	Cloud-BIM	CDE	Inter-view
People and Partners	PP1	Builds trust across teams & stakeholders	[24], [25], [49]			X
	PP2	Enhanced client satisfaction & relations	[24], [25]			X
	PP3	Enhances coordination and collaboration among teams & stakeholders	[24], [25], [32], [46]	[11], [13], [39]	[21]	X
	PP4	Ensures a centralized working environment for teams & stakeholders	[25], [46], [48]	[11]		X
	PP5	Facilitates communication between teams & stakeholders	[25], [46], [48], [49]	[13]		X
	PP6	Opportunity to evaluate the subcontractor's performance				X

Table 1: (Continued)

4P Category	ID	Benefits	References			
			ICT/IT	Cloud-BIM	CDE	Inter-view
Process	PR1	Connected & streamlined processes and workflows	[24], [25], [32]	[13]		X
	PR2	Contributes to measurement and tracking of key performance indicators	[24], [25]			X
	PR3	Customized & standardized data collection				X
	PR4	Digitalized data storage	[25], [32], [48], [49]	[11], [39]	[21]	X
	PR5	Easy use of systems for teams		[39]		X
	PR6	Enhanced health and safety management				X
	PR7	Easy & quick access to project information regardless of location	[24], [25], [32], [46], [49]	[11], [13], [39]		X
	PR8	Effective information management			[21]	X
	PR9	Eliminates manual data entrance				X
	PR10	Eliminates unnecessary expenses	[24], [46]	[11], [13], [39]	[21]	
	PR11	Enables interoperability between tools		[39]		X
	PR12	Enables to work integrated with BIM systems		[39]		X
	PR13	Enhances quality of the project	[24], [48]	[13]	[21]	X
	PR14	Enables real-time insights related to project performance	[25], [32]	[11], [13]	[21]	X
	PR15	Eliminates paper-based processes & paperwork	[25], [32], [48], [49]	[24]		X
	PR16	Increases the project productivity		[11]	[21]	X
	PR17	Less phone-/e-mail-based communication & face to face meetings		[24], [25]		X
	PR18	Opportunity to focus on optimal activities	[25], [32]	[13]	[21]	X
	PR19	Optimizes construction operations	[25]	[13]	[21]	
	PR20	Provides authorized data access	[25]			X
	PR21	Provides business intelligence reporting	[24], [25], [49]	[11]		X
	PR22	Seamless data transfer across project phases			[21]	X
	PR23	Successful project handover				X
	PR24	Standardized & improved data exchange	[24], [25], [32], [49]	[13]	[21]	X
	PR25	Standardized processes and workflows	[25], [46]			X

Table 1: (Continued)

4P Category	ID	Benefits	References			
			ICT/IT	Cloud- BIM	CDE	Inter- view
Philosophy	PH1	Contributes to gain competitive advantage in the international market	[24], [25]	[11]		X
	PH2	Contributes to provide requirements for facility management			[21]	X
	PH3	Enables a base for artificial intelligence in construction		[39]		X
	PH4	Enables continuous improvement for the company	[25]	[11]		X
	PH5	Helps to constitute corporate memory of the company				X
	PH6	Increases the return on investment (ROI)	[46]			X
	PH7	Provides a better knowledge management				X

Table 2: The challenges of CDE implementation in BIM-based projects

ID	Challenges	References			
		ICT/IT	Cloud-BIM	CDE	Inter-view
C1	Challenges in choosing the most suitable CDE platform for the project				X
C2	Closed-BIM approach (non-integrated software systems)	[46]	[13], [53]		X
C3	Deficiencies in cloud service provider's support & consultancy	[46]	[11], [30]		
C4	Deficiencies in obligating the use of CDEs within the contracts & inefficient contract suites	[46], [47]	[13], [30], [39]		X
C5	Deficiencies in the CDE platform functions				X
C6	Exclusion of the CDE planning at the project's feasibility stage		[13]		X
C7	Financial barriers to CDEs	[46]	[11], [13], [39]		X
C8	Inadequate, limited technological training in the industry		[10], [13], [30]		X
C9	Internet access & infrastructure on site	[46]	[11], [13], [30], [39]		X
C10	Lack of clarity on contractual relationships, ownership of the information and legal issues		[10], [13], [30], [39]		X
C11	Lack of contractors'/owners' motivation to use CDEs	[47]			X
C12	Low technological literacy level of people in the industry		[10]		X
C13	Security and privacy concerns about the CDE platforms	[46]	[11], [13], [30], [39], [53]	[72], [73]	X
C14	Tendency to use traditional information systems & resistance to change	[47]	[46]		X
C15	The fact that the construction industry has not fully embraced the digitalization culture	[47]	[30]		X

2.4 Construction key performance indicators (KPIs)

Key performance indicators (KPIs) are the measures for evaluating the project and organizational performance [74, 75] widely used in construction industry. In this study, the most prominent construction KPIs were identified from the literature in order to evaluate the impact of CDE benefits on project performance. The used keywords were “performance measurement” AND “construction industry”. Considering the most cited, peer-reviewed journal articles, seven main construction KPIs were selected to be included in CDE benefits & project performance matrix in the Delphi survey. The selected KPIs were time, cost, quality, safety, productivity, organizational sustainability, and client satisfaction. In the selection process, attention was paid to make a selection for including a wide range of perspectives (e.g., short-and long-term goals).

Mohsini and Davidson (1992) were interpreted the “*three traditional indicators of performance*” as time, cost, and quality [76]. However, Kagioglou et al. (2001) stated that even these three KPIs are suitable for assessing the success or failure of a project, they are not sufficient to assess project performance because they are considered as lagging measures rather than leading measures [77]. Thus, in this research, the selected KPIs do not only include lagging measures, but also leading measures such as productivity, safety, organizational sustainability, and client satisfaction, which are focusing on “how” rather than “what” question [77]. Furthermore, the selected KPIs comprise the three performance measurement categories which are project level (i.e., time, cost, quality, productivity, safety), organizational level (i.e., organizational sustainability), and stakeholder level (i.e., client satisfaction), presented by Yang (2010) [78].

The list of construction KPIs considered in the scope of this research is given in Table 3. The time and cost KPIs represent the schedule and cost efficiency. The quality

KPI represents the investigation of the whether the project was built in line with the contract and specifications. The safety KPI is for the assessment of whether the healthy environment for stakeholders is ensured during construction. The productivity KPI is for investigating the labor productivities during construction. The client satisfaction KPI investigates whether the owner's requirements are satisfied. Lastly, the organizational sustainability KPI comprises the contractor's long-term business goals, and internal factors such as employee satisfaction and turnover metrics, education and training.

Table 3: The list of construction KPIs

Construction KPIs	References
Time	[75], [77], [79], [80], [81]
Cost	[75], [77], [79], [80], [81]
Quality	[75], [79], [81]
Safety	[75], [77], [80], [81]
Productivity	[77], [80]
Organizational Sustainability	[75], [82]
Client Satisfaction	[75], [77], [80], [81]

CHAPTER III

METHODOLOGY

This study applies a combination of qualitative and quantitative research techniques. First, qualitative research techniques (i.e., reviewing literature, performing interviews, and investigating online sources) were utilized to identify the CDE benefits, challenges, and the main KPIs for construction projects in data collection process. As CDEs have numerous benefits, a categorization was made, based on Toyota's 4P method, with the aim of presenting a clear understanding to both readers and Delphi survey participants. Thereafter, the Delphi method, a qualitative and quantitative research technique, was utilized to rank and prioritize the CDE features (i.e., benefits, challenges, and improvement effects on project performance) among the preselected group of experts on the subject domain.

3.1 Data Collection

In the data collection process, literature review, semi-structured interviews, and online source investigation were performed to identify the CDE benefits, challenges, and the main KPIs for construction projects.

3.1.1 Literature review

A literature review was conducted to investigate previous studies, to explore the research gap, and collect data in the subject domain. Scopus database was used for searching the previous studies. While CDEs are the focus of this study, it is useful to look at also ICT/IT (Information and Communication Technology/Information Technology) and cloud computing literature as they are interrelated with the CDEs. For example, in the research of Jahanger et al. (2021), the benefits of digital construction-phase information management (DCIM) systems can be included in the CDE benefits as the CDEs provide digitalized information management for building lifecycle [25]. For this purpose, query keywords were extended and the concurrent research papers, which focus on ICT and cloud computing in information/project management, were included in the literature review. The details of query, filtering, selection processes and the numbers of obtained, investigated research papers can be seen in Table 4. The results of cloud computing & BIM and CDEs were not filtered and manually reviewed because there are relatively limited studies in the literature.

Table 4: Three pillars of literature review

Research Field	ICT & IT	Cloud Computing & BIM	CDE
Query	<i>Title, Abstract, Keywords</i>		
	"information technology", "IT", "information and communication technology*", "ICT", "electronic document management system*", "EDMS", AND ("construction industry OR "construction")	"cloud BIM", "cloud-BIM", "Cloud building information modeling", "cloud based BIM", "Cloud based building information modeling", "cloud computing based BIM", "cloud building information modeling", ("cloud computing" AND "BIM")	"common data environment", "common data environments"
	n 788	116	75
Filtering	2000-2022		
	Source selection		
	Subject area selection	none	none
	Exact keyword selection		
	n 183	116	75
Selection	<i>Elimination based on title, abstract, keywords</i>		
	n 153	45	49
	<i>Elimination based on full text read</i>		
	n 54	20	26
	<i>Articles identified benefits or challenges</i>		
	n 7	6	3

3.1.2 Semi-structured interviews

Semi-structured interviews were conducted with five subject matter experts (SMEs) to examine the CDE platforms from different perspectives (i.e., CDE platform users and providers, BIM consultants and managers) and capture additional benefits and challenges which may not mentioned in the literature. The interview participants were invited based on their years of experience and roles in a way to ensure a homogeneous profession distribution. Even the interviewees were from Turkey, they have experience

in several countries such as Azerbaijan, England, France, UAE, Kuwait, and Qatar that allows to achieve homogeneity in the outputs. The profile of the interviewees is given in Table 5. The interviews were conducted online due to the Covid-19 pandemic and one expert derived the answers in written form. The interview includes open-ended questions divided into four main topics: information management, key performance indicators, the common data environment, and the relationship between CDEs and project management based on KPIs respectively. The interview questions are provided in Appendix 1.

Table 5: Profile of interview participants

Expert code	Education	Profession	Title	Experience in construction industry	Experience in BIM-based projects	Interview durations
E1	BSc MBA	Electrical and electronics engineer	Digital Transformation Expert in Construction	10	10	55 min
E2	BSc MBA	Mechanical engineer	BIM Consultant	25	14	45 min
E3	MSc	Architect	BIM Manager	18	18	90 min
E4	BSc	Civil engineer	Digital Transformation Expert in Construction	10	5	90 min
E5	BSc	Mechanical engineer	BIM Manager	14	14	Written form

3.1.3 Online Sources

There are many CDE platform providers exist in the construction industry. As the capabilities of the CDE platforms can be informative, the websites of such providers were also investigated (i.e., Autodesk BIM360 [83], Tribble Viewpoint [84], Oracle Aconex [85], Asite [86], Bentley ProjectWise [87], and Isetia [88]). Each commercial cloud platform may have several functions; thus, the investigation of the online sources was found beneficial to collect all aspects of CDEs.

3.2 Categorization of CDE benefits & creation of project performance matrix

The benefits were categorized, based on Toyota's 4P Model [89], to present a clear understanding to panel experts, and readers. The Toyota's 4P Model can be seen in Figure 1. Toyota's 4P Model compose of four main pillars: *problem solving, people and partners, process, and philosophy* [89]. A top-down approach was used to categorize the identified benefits based on metadata from Liker (2004) [89]. The identified benefits were categorized under these four pillars based on their concurrent features as explained below;

- The benefits which contribute to eliminate problems were categorized under problem solving,
- The benefits which streamline the construction tasks were categorized under process,
- The benefits which improve inter/intra-organizational relations were categorized under people and partners,
- The benefits which represent the long-term strategies were categorized under

philosophy.

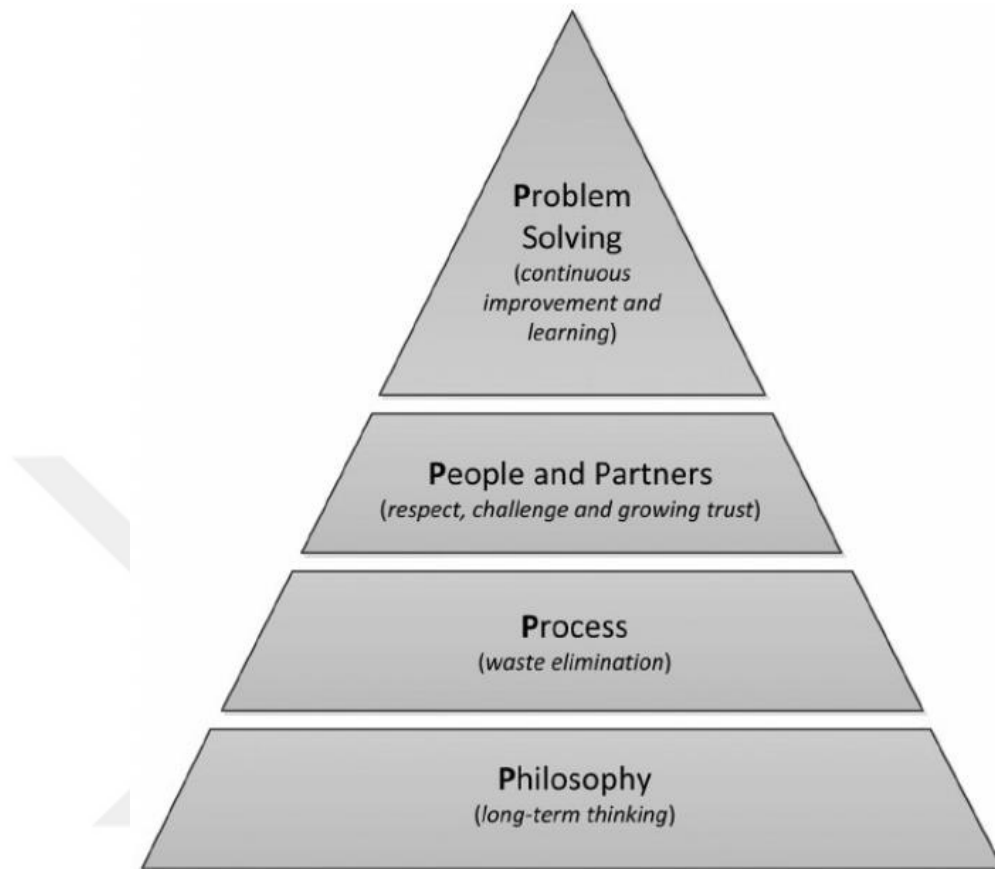


Figure 1: Toyota's 4P Model. *Adopted from Liker (2004) [89]*

Investigation of CDE benefits' impacts on project performance was made based on ranking the pillars of Toyota's 4P Model because, querying the impact of each benefit, on each KPI will be time-consuming. Therefore, the CDE benefits & construction KPIs matrix was created to be able to reveal the impacts of CDE benefits on project performance according to the reviewers' feedback. The created matrix is titled as CDE benefits & project performance matrix as presented in Table 10.

3.3 The Delphi Method

The Delphi method is a systematic technique that enables consensus among a predetermined panel of independent experts [90]. The Delphi method is a convenient way for construction engineering and management (CEM) research in the absence of empirical evidence or objective data. This research technique diverges from the standard surveys by providing anonymous, controlled feedbacks conducted in multiple rounds [91].

In this study, Delphi method was carried out in two structured rounds to prioritize the benefits and challenges of CDE implementation and reveal the importance levels of CDE's improvements in project performance based on 7 KPIs listed in Table 3. The Delphi method procedure in this study can be seen in Figure 2.

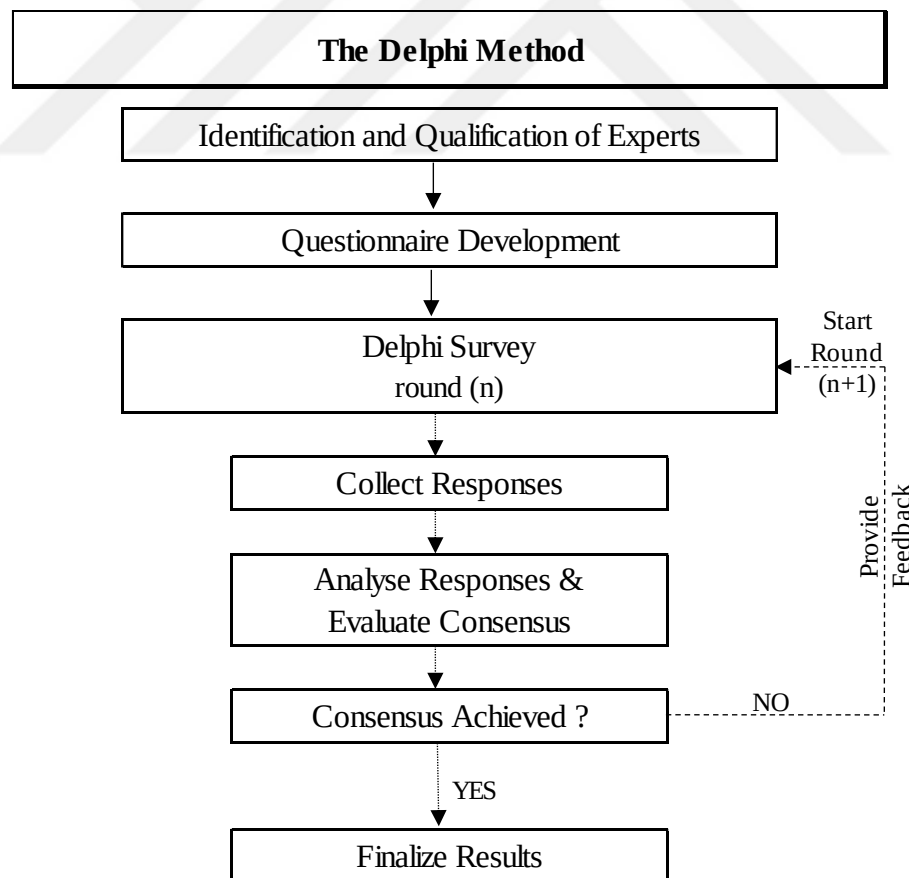


Figure 2: The Delphi method procedure

3.3.1 Qualification criteria, identification, and participation status of panel experts

The Delphi method relies on panel experts' opinions to reach a consensus about the CDE effects on information management and project performance. Thus, the qualifications of the panel experts carry an important role to obtain reliable and valid outputs on the subject. The selection criteria should be defined carefully to ensure they have experience and knowledge in the subject matter [91]. The required qualifications for this research are determined as follows:

1. Having experience and knowledge in CDE platforms,
2. Having at least a bachelor's degree in architecture, civil engineering, or other related engineering disciplines,
3. Holding an industry position in coordinator, BIM manager, or director,
4. Having at least 5 years of experience in the construction industry,
5. Having at least 3 years of experience in BIM-based projects.

Invitation for attending the Delphi survey was sent to 119 geographically dispersed experts, who have the above-listed qualifications, through LinkedIn. The qualifications of the experts were confirmed by them through personal questions appended at the beginning of the Delphi survey. The profile of the experts who participated in Delphi survey are shown in Table 6.

Table 6: Profile of the Delphi panel experts

Education level	Profession	Exp in construction industry	Exp in BIM-based projects	Firm role	Title	Country of employment
PhD	Performance Assessor	27	27	Performance Assessor	Director	Australia
PhD	Architectural Engineering	10	10	Consultant	Information Manager	England
MSc	Civil Engineer	17	7	Construction Management	BIM Manager	Germany
MSc	Civil Engineer	17	12	Design Firm	BIM Manager	United Arab Emirates
MSc	Architect	14	5	Consultant	Design Coordinator	Turkey
MSc	Civil Engineer	13	6	Engineering Firm	BIM Manager	Greece, Qatar
MSc	Civil Engineer	13	7	General Contractor	Construction Manager	United Arab Emirates
BSc	Civil Engineer	12	10	BIM Manager	BIM Manager	United Arab Emirates
MSc	Architect	11	3	Design and Construction Management	BIM and System Manager	Turkey
MSc	Civil Engineer	9	7	Engineering Firm	BIM Coordinator	Turkey
MSc	Architect	7	6	Construction Management	BIM MEP Coordinator	Italy
BSc	Civil Engineer	9	7	Construction Management	BIM Coordinator	United Arab Emirates

3.3.2 Questionnaire development & pilot survey

A mixed-method data collection procedure, explained in Section 3.1, was conducted to identify the CDE benefits, challenges, and construction KPIs. 54 benefits, 15 challenges, and 7 construction KPIs were identified and included in the Delphi method. A pilot survey was prepared and sent to two industry professionals, who have a PhD degree and more than fifteen years of experience in the construction industry, to test and validate the understandability of the structure. The questionnaire was updated based on

the reviewers' feedback. The final Delphi questionnaire was divided into five sections:

1. An introductory explanation about the research
2. Personal information section for the panel experts
3. CDE benefits ranking section
4. CDE challenges ranking section
5. CDE & project performance matrix ranking section

The gradings were carried out based on a five-point Likert scale. The gradation of the five-point Likert scale used in the questionnaire can be seen in Table 7.

Table 7 : The gradation of the five-point Likert scale

Likert scale	CDE Benefits	CDE Challenges	CDE benefits & project performance matrix
5	High positive effect	High negative effect	High positive effect
4	Positive effect	Negative effect	Positive effect
3	Moderate positive effect	Moderate negative effect	Moderate positive effect
2	Slight positive effect	Slight negative effect	Slight positive effect
1	Without any positive effect	Without any negative effect	Without any positive effect

3.3.3 Delphi survey process

3.3.3.1 Collection of responses

The Delphi questionnaire was generated and distributed via an online questionnaire platform named Jotform. The iteration process was executed based on the steps defined in Figure 2. The Delphi questionnaire was distributed to panel experts through LinkedIn. The panelists were briefed on the full participation requirement and were asked to complete each submitted round within three weeks. However, the Delphi

survey took approximately three months to complete. The survey rounds were started on 23 July 2021 and completed on 21 October 2021.

3.3.3.2 Analysis of responses & evaluation of consensus

The reliability of the responses and the consensus among panel experts were analyzed at the end of each round. The reliability and the consensus levels were examined through Cronbach's alpha (α) reliability test and the standard deviations. The internal consistency of the responses was controlled using Cronbach's alpha reliability test, which is useful in assessing the interrelatedness of the outputs. A Cronbach's alpha value of 0.7 or higher is considered an acceptable index for further analysis [92, 93]. Mean and median values were calculated to examine central tendency [94], and standard deviation was used to assess consensus between Delphi panel participants [91]. The standard deviations are anticipated to decrease at each round based on the reasoning mechanism of the Delphi method [94]. In this study, the survey rounds (i.e., two rounds) were re-performed until the consensus was achieved based on the Cronbach's alpha test and the alteration in the standard deviations. In Delphi surveys, 2-3 rounds are considered sufficient to reach consensus among the panel experts [95, 96], ranging from at least seven [97] to at most fifty participants [98].

Meanwhile, the interrater agreement statistics (IRA), developed by Brown and Hauenstein [99], was used to determine the consensus levels for each advantage, challenge, and improvement in project performance, among panel experts. The IRA (r_{wg}) values were calculated via the formula given in Eq. (1) [99].

$$r_{wg} = 1 - \frac{2 * \sigma^2}{\{(A + B)M - (M^2) - (A * B)\} * \frac{n}{n - 1}} \quad (1)$$

Here, r_{wg} represents the interrater agreement statistic, M is the obtained mean value

from the assessed output, A is the maximum scoring value (i.e., 5), B is the minimum scoring value (i.e., 1), n is the number of respondents (i.e., 12) and σ is the standard deviation. The gradation of the r_{wg} values are as follows: “ $0.0 \leq r_{wg} < 0.3$ corresponds to “lack of agreement”, “ $0.3 \leq r_{wg} < 0.5$ ” corresponds to “weak agreement”, “ $0.5 \leq r_{wg} < 0.7$ ” corresponds to “moderate agreement”, “ $0.7 \leq r_{wg} < 0.9$ ” corresponds to “strong agreement” and “ $0.9 \leq r_{wg} < 1.0$ ” corresponds to “very strong agreement” [100-102].

Additionally, the significance levels were determined based on the mean values (M) of each benefit, challenge, and improvement effect on KPIs. The significance levels were interpreted based on the scale interval as follows: “ $M < 1.5$ ” is “not important”, “ $1.5 \leq M < 2.5$ ” is “somewhat important”, “ $2.5 \leq M < 3.5$ ” is “important”, “ $3.5 \leq M < 4.5$ ” is “very important”, and “ $M \geq 4.5$ ” is “extremely important” [101-103].

The analysis results of the survey rounds are clarified in Section 3.3.3.2.1 and 3.3.3.2.2 in detail.

3.3.3.2.1 Survey Round 1

In the first round, 17 valid responses were received. The mean, median, and standard deviations were calculated based on the scores of 17 SMEs. The internal consistency of the responses was investigated using the Cronbach’s alpha reliability test. The Cronbach’s alpha values obtained in benefits, challenges, and CDE benefits & project performance matrix sections can be seen in Table 8. The obtained Cronbach’s alpha values were lower than the expected limit (i.e., 0.7 [92]) in some sections (i.e., benefits/people and partners section, challenges and matrix sections), which was not acceptable for further analysis. For this reason, the second round should be performed to reach consensus among panel experts. The calculated mean values were prepared for the feedback to be given in the second round.

3.3.3.2.2 Survey Round 2

In the second round, mean value gathered from the first round of Delphi were shared with the SMEs for reconsideration. The calculated mean values were appended next to each ranking item (i.e., benefits, challenges, CDE benefits & project performance matrix) for easier screening. The anonymity of the panel experts was ensured, as a requirement for Delphi method, while providing feedback and sending the request for the second round of the survey. Then, the questionnaire was sent back to panel experts. The panel experts were asked to reconsider their opinions in the second round, based on these given mean values. This facilitated panel experts to reach a consensus in the presence of differences between the scores given in the first round [102]. In the second round, 12 valid responses were received.

The Cronbach's alpha value was controlled in each section (i.e., benefits, challenges, and CDE benefits & project performance matrix). Internal consistency of the responses was achieved with the Cronbach's alpha values greater than 0.7. The internal consistency and interrelatedness of the given responses were increased significantly from first round to second round as can be seen in Table 8. In addition, even the Cronbach's alpha values obtained in the first round were lower than 0.7, mostly they were close to 0.7.

Table 8: Alterations in Cronbach's alpha (α) values

Cronbach's alpha (α) Alterations			
		Round 1	Round 2
Benefits	PS	0.762	0.787
	PP	0.503	0.815
	PC	0.918	0.923
	PH	0.789	0.803
	Combined	0.897	0.940
CDE benefits & project performance matrix	PS	0.679	0.755
	PP	0.674	0.712
	PC	0.681	0.723
	PH	0.689	0.748
Challenges		0.616	0.726

The mean, median, and standard deviations were calculated according to the scored collected from the second round of Delphi method. The alterations of standard deviations among two rounds were investigated. A decrease in standard deviations were observed, ranging from % 2.16 to % 59.01 in benefits, % 7.70 to % 54.48 in challenges, and % 18.09 to % 61.31 in CDE benefits & project performance matrix, respectively. The expert agreements on each ranking item (i.e., benefits, challenges, CDE benefits & project performance matrix) were analyzed using IRA statistics [formula 1]. The significance levels of the items were determined as specified in Section 3.3.3.2.

Increase in the Cronbach's alpha values and decrease in standard deviations among the Delphi rounds, shows the consensus was achieved among panel experts in the

second round. For this reason, the Delphi survey was stopped after the second round.

3.3.3.3 Finalization and prioritization of the results

The benefits and challenges of CDE implementation in the BIM-based projects were prioritized based on their mean values (Table 9, Table 12). In the case of where multiple factors had same mean values, the standard deviation values were taken into consideration for the prioritization.

The benefits were prioritized under their subcategories (i.e., problem solving, people and partners, process, philosophy) for a better understanding. Additionally, the benefits were combined, regardless their subcategories, to reveal the top 5 significant benefits. There were no subcategories for the challenges, thus, the challenges were prioritized individually. In the CDE benefits & project performance matrix, KPIs were prioritized under each subcategory of the benefits (i.e., problem solving, people and partners, process, and philosophy). The improvement effects of each subcategory of benefits (i.e., problem solving, people and partners, process, and philosophy), on each KPI (i.e., time, cost, quality, safety, productivity, organizational sustainability, and client satisfaction) were revealed with the prioritization in the project performance matrix.

CHAPTER IV

RESULTS

This chapter presents the research findings which are obtained from the Delphi method, as described in Section 3.3. This section includes the prioritization of CDE benefits, challenges, and the improvement effects of CDEs on project performance. Thereafter, the impacts of CDE benefits on project performance was revealed by the CDE benefits & project performance matrix.

4.1 Identification and prioritization of benefits on CDE implementation

In this study, 54 benefits of CDEs' were derived by triangulating the findings from the literature review, interviews, and online sources listed in Table 4. 16, 6, 25, and 7 number of benefits were categorized by top-down approach under problem solving, people and partners, process, and philosophy subcategories of Toyota's 4P model respectively.

The results and prioritization of the CDE benefits, obtained by the Delphi method, are given in Table 9, supported with the mean, median, standard deviation values (σ), significance levels, and agreement levels. The mean values of CDE benefits remained between 3.08 and 4.75 in which their significance levels vary from important to extremely important. Among these benefits, 5 of the benefits were identified as extremely important according to the scores given by the subject matter experts (SMEs) while 40 and 9 benefits

were detected as very important and important respectively. Based on the obtained significance levels, it can be concluded that the benefits associated with the use of CDEs have a high positive impact on the AEC industry.



Table 9: Results for the benefits of CDE implementation

4P model	Rank	ID	Benefits	Mean	Median	σ	r_{wg}	Significance level	Agreement level
Problem Solving	1	PS1	Access to accurate, reliable and up-to-date information	4.75	5.00	0.43	0.63	extremely important	moderate agreement
	2	PS16	The single source of information & truth	4.58	5.00	0.49	0.70	extremely important	strong agreement
	3	PS3	Improved & data-driven decision-making	4.33	4.00	0.62	0.68	very important	moderate agreement
	4	PS7	Prevents data loss	4.33	4.50	0.75	0.54	very important	moderate agreement
	5	PS6	Preservation of audit trail records	4.17	4.00	0.80	0.56	very important	moderate agreement
	6	PS8	Prevents misunderstandings caused by miscommunication	4.00	4.00	0.71	0.69	very important	moderate agreement
	7	PS13	Reduces reworks	3.92	4.00	0.64	0.76	very important	strong agreement
	8	PS10	Reduces construction conflicts & disputes	3.83	4.00	0.69	0.74	very important	strong agreement
	9	PS4	Minimizes double-handling of documents	3.75	4.00	0.72	0.72	very important	strong agreement

Table 9: (Continued)

4P model	Rank	ID	Benefits	Mean	Median	σ	r_{wg}	Significance level	Agreement level
Problem Solving	10	PS15	Strengthens data security	3.75	4.00	0.83	0.63	very important	moderate agreement
	11	PS14	Supports dispute resolution processes	3.58	3.50	0.64	0.79	very important	strong agreement
	12	PS2	Facilitates foreseeing the risks	3.50	3.00	0.65	0.80	very important	strong agreement
	13	PS11	Reduces defects	3.42	3.00	0.95	0.56	important	moderate agreement
	14	PS9	Proactive problem solving	3.25	3.00	0.43	0.91	important	very strong agreement
	15	PS5	Possibility to make accurate forecasts & control	3.25	3.00	0.60	0.84	important	strong agreement
	16	PS12	Reduces issues	3.08	3.00	0.86	0.66	important	moderate agreement

Table 9: (Continued)

4P model	Rank	ID	Benefits	Mean	Median	σ	r_{wg}	Significance level	Agreement level
People and Partners	1	PP3	Enhance coordination and collaboration among teams & stakeholders	4.67	5.00	0.47	0.67	extremely important	moderate agreement
	2	PP4	Ensures a centralized working environment for teams & stakeholders	4.42	4.50	0.64	0.62	very important	moderate agreement
	3	PP5	Facilitates communication between teams & stakeholders	4.33	4.00	0.62	0.68	very important	moderate agreement
	4	PP2	Enhanced client satisfaction & relations	4.25	4.00	0.60	0.73	very important	strong agreement
	5	PP1	Builds trust across teams & stakeholders	3.75	4.00	0.92	0.54	very important	moderate agreement
	6	PP6	Opportunity to evaluate the subcontractor's performance	3.08	3.00	0.76	0.74	important	strong agreement

Table 9: (Continued)

4P model	Rank	ID	Benefits	Mean	Median	σ	r_{wg}	Significance level	Agreement level
Process	1	PR7	Easy & quick access to project information regardless of location	4.58	5.00	0.49	0.70	extremely important	strong agreement
	2	PR4	Digitalized data storage	4.58	5.00	0.64	0.53	extremely important	moderate agreement
	3	PR8	Effective information management	4.42	4.00	0.49	0.78	very important	strong agreement
	4	PR24	Standardized & improved data exchange	4.33	4.00	0.47	0.82	very important	strong agreement
	5	PR1	Connected & streamlined processes and workflows	4.25	4.00	0.60	0.73	very important	strong agreement
	6	PR20	Provides authorized data access	4.25	4.00	0.72	0.61	very important	moderate agreement
	7	PR14	Enables real-time insights related to project performance	4.17	4.00	0.69	0.67	very important	moderate agreement
	8	PR25	Standardized processes and workflows	4.08	4.00	0.76	0.63	very important	moderate agreement
	9	PR21	Provides business intelligence reporting	4.08	4.00	0.86	0.52	very important	moderate agreement
	10	PR17	Less phone/e-mail based communication & face to face meetings	4.00	4.00	0.58	0.80	very important	strong agreement

Table 9: (Continued)

4P model	Rank	ID	Benefits	Mean	Median	σ	r_{wg}	Significance level	Agreement level
Process	11	PR5	Easy use of systems for teams	4.00	4.00	0.82	0.59	very important	moderate agreement
	12	PR2	Contributes to measurement and tracking of key performance indicators	3.92	4.00	0.64	0.76	very important	strong agreement
	13	PR13	Enhances quality of the project	3.92	4.00	0.64	0.76	very important	strong agreement
	14	PR15	Eliminates paper-based processes & paperwork	3.92	4.00	0.76	0.67	very important	moderate agreement
	15	PR3	Customized & standardized data collection	3.83	4.00	0.69	0.74	very important	strong agreement
	16	PR16	Increases the project productivity	3.75	3.50	0.83	0.63	very important	moderate agreement
	17	PR12	Enables to work integrated with BIM systems	3.75	4.00	0.92	0.54	very important	moderate agreement
	18	PR9	Eliminates manual data entrance	3.75	3.50	1.01	0.46	very important	weak agreement

Table 9: (Continued)

4P model	Rank	ID	Benefits	Mean	Median	σ	r_{wg}	Significance level	Agreement level
Process	19	PR18	Opportunity to focus on optimal activities	3.58	4.00	1.11	0.38	very important	weak agreement
	20	PR6	Enhanced health and safety management	3.50	3.50	0.76	0.71	very important	strong agreement
	21	PR22	Seamless data transfer across project phases	3.50	3.50	0.76	0.71	very important	strong agreement
	22	PR23	Successful project handover	3.50	4.00	0.87	0.63	very important	moderate agreement
	23	PR11	Enables interoperability between tools	3.42	3.00	0.49	0.88	important	strong agreement
	24	PR19	Optimizes construction operations	3.42	3.50	0.64	0.80	important	strong agreement
	25	PR10	Eliminates unnecessary expenses	3.17	3.00	0.90	0.63	important	moderate agreement

Table 9: (Continued)

4P model	Rank	ID	Benefits	Mean	Median	σ	r_{wg}	Significance level	Agreement level
Philosophy	1	PH7	Provides a better knowledge management	4.25	4.00	0.72	0.61	very important	moderate agreement
	2	PH2	Contributes to provide requirements for facility management	4.17	4.00	0.55	0.79	very important	strong agreement
	3	PH5	Helps to constitute corporate memory of the company	4.17	4.00	0.69	0.67	very important	moderate agreement
	4	PH4	Enables continuous improvement for the company	4.17	4.00	0.80	0.56	very important	moderate agreement
	5	PH1	Contributes to gain competitive advantage in the international market	4.08	4.00	0.86	0.52	very important	moderate agreement
	6	PH6	Increases the return on investment (ROI)	3.75	4.00	0.60	0.81	very important	strong agreement
	7	PH3	Enables a base for artificial intelligence in construction	3.42	3.00	0.95	0.56	important	moderate agreement

4.1.1 Benefits under problem-solving subcategory of Toyota's 4P Model

The benefits which contribute to minimization and prevention of possible problems and risks were categorized under the problem-solving subcategory (PSS) of Toyota's 4P model, as explained in Section 3.2. For example, as better decisions are made through data-driven decision-making, the more the problems can be solved accurately, and possible issues can be avoided. From this perspective, 16 benefits were found corresponding to the problem-solving sub-category, among the 54 benefits. The prioritization benefits, corresponding to PSS, are presented in Table 9.

“Access to accurate, reliable and up-to-date information (PS1)” and “the single source of information & truth (PS16)” were identified as the most prominent benefits of CDEs. The benefits, PS1, PS16, were determined as extremely important for SMEs with the mean values of 4.75 and 4.58, as they reflect the fundamental characteristics and the main purpose of CDEs. The CDEs bring all project information in a single platform, including documentation, graphical model, and non-graphical data [104], enabling all the stakeholders to work on accurate, reliable, agreed source of information. The barriers to accessing the most up-to-date and accurate information can be removed by having a single platform for collecting, sharing, and managing project information. Correspondingly, “improved & data-driven decision-making (PS3)” was ranked as the third greatest benefit, with the mean value of 4.33, as the better decisions can be made by the opportunity of accessing trustworthy information on time.

According to the Construction Disconnected Report, presented by PlanGrid and FMI in 2018 [5], %30 of the construction data is lost, starting from design to turnover. The preservation of the information in CDEs “prevents the data loss (PS7)”, by providing back-ups, which was ranked as the fourth benefit by the SMEs. Similarly, “the preservation of audit trail records (PS6)” was identified as very important, because it

provides a fully auditable record of events [2] and increases the accountability of the conducted tasks. Better control of confidential business data and information can be provided by the strengthened data security (PS15) in CDEs [105]. Furthermore, the CDE platforms “minimizes double handling of documents (PS4)”, which facilitates access to accurate information by removing duplicated documents.

Lee and Bernold (2008) stated that effective communication is seriously hindered in the absence of appropriate data channels. CDEs “prevent misunderstandings caused by miscommunication (PS8)” by providing an effective communication platform [106]. Furthermore, using CDEs, reworks (PS13), defects (PS11), and issues (PS12) can be reduced in the project, as the misunderstandings in communication and information are mitigated. Consequently, the use of CDEs “reduces construction conflict and disputes (PS10)” within the minimized issue and defects in the project. The preservation of the audit trails in CDEs, “supports dispute resolution processes (PS14)”, to be resolved timely and accurately, which is also an important benefit for the system users.

The benefits such as, “facilitates foreseeing the risks (PS2), “proactive problem solving (PS9), and “possibility to make accurate forecasts & control (PS5)”, are interrelated opportunities provided by CDEs. Hence, the benefits PS2, PS9, and PS5 were ranked close to each other (i.e., 3.5, 3.25, 3.25, respectively) by the SMEs. If it is necessary to explain through an example, it is possible that a setback in the arrival of an equipment to the construction site may hinder the project schedule. CDEs enable assessing the risks associated with the delay in equipment arrival, and correspondingly, support proactive problem-solving by enabling taking required precautions, rather than being defensive. The opportunity to monitor real-time setbacks and delays through CDEs enables making accurate forecasts about the progress of the project.

4.1.2 Benefits under people and partners subcategory of Toyota's 4P Model

The construction projects require multidisciplinary and multi-actor collaborations [3] and the project success is highly dependent on the relation, coordination, and communication of the teams. Ensuring the coordination among teams is generally being difficult having regard to complex relations in construction and possible distances between site and headquarters. CDEs provide many benefits which facilitate the relations and remove the barriers to efficient collaboration. In this study, 6 of these benefits were found corresponding to the people and partners subcategory (PPS) of Toyota's 4P model, among the 54 identified benefits. The prioritization benefits, corresponding to PPS, are presented in Table 9.

The most prominent benefit, under the people and partners subcategory, is “enhance coordination and collaboration among teams & stakeholders (PP3)” and considered as extremely important. The CDEs not only gather models, information, and documents in a single platform [6], but also bring people together and “ensures a centralized working environment for teams & stakeholders (PP4)”, which is the second prominent benefit under PPS.

The third very important benefit under PPS was detected as “facilitates communication between teams & stakeholders (PP5)” by the SMEs. In construction projects, generally, there is a disconnection between project parties such as contractors, architects, or personnel working in the headquarters [12], which increases the barriers on communication for ensuring on-time information transfer [107]. Disconnection and poor communication exist even within the contractor's teams, between site and office-based staff [13]. By enabling cloud-based communication and collaboration, CDEs bridge the communication gap among all stakeholders and teams as well as connect the office to the construction site. Furthermore, the client can also see how the contractor is carrying out

the project in terms of schedule, budget, and quality which enables an “enhanced client satisfaction (PP2)”. Working in the same platform, “builds trust across teams & stakeholders (PP1)” by providing transparent transactions which is one of the very important benefits of the CDEs under PPS. Additionally, as the main contractor can work with several subcontractors for a project, it is important to be able to monitor the subcontractors’ progress and performance. CDEs provide an “opportunity to evaluate the subcontractor’s performances (PP6)” easily, which is also important when there are many partial works conducted by the subcontractors. For example, the main contractor can analyze the subcontractors who have caused the most reworks or defects, and then, the main contractor can decide whether to work with this subcontractor again in further projects.

4.1.3 Benefits under process subcategory of Toyota’s 4P Model

In this study, the 25 benefits listed under the process subcategory (PRS) of Toyota's 4P model include the processual benefits arising from the adoption of CDEs, resulting in new working practices and possibilities. Two of the benefits were found as very important, twenty of them were identified as very important and three of them were determined as important by the SMEs. The prioritization benefits, corresponding to PRS, are presented in Table 9.

The “easy & quick access to project information regardless of location (PR7)” becomes possible, as CDEs remove the hard copy formed data silos and provide “digitalized data storage (PR4)” for the project. These two benefits, PR7 and PR4, were identified as extremely important by the SMEs, among the processual benefits with the mean values of 4.58. The project participants waste a significant amount of their time by searching for an information, approximately 5.5 hours a week, based on the Construction

Disconnected Report [5]. Vaughan et al. (2013) also stated that the construction managers spend a significant time for only gathering project information which may result in inefficient project management operations [48]. Furthermore, when the information is not being available on time for critical decision-making, this may cause a delay in the project schedule [11]. The CDE removes the barriers on accessing to project information and enables access from remote workstations, as it digitalizes all the documents and processes, and keeps project information in the cloud platform.

Considering the priority ranking results, another prominent benefit of CDEs under PRS, was “effective information management (PR8)” which was determined as very important with the mean value of 4.42. Despite the misconception that BIM is not for all professionals in built environment, Dowd and Marsh (2020) stated that the information (i.e., the “I” in BIM), is a valuable resource for all stakeholders throughout the building lifecycle [108]. Although 3D models are in the foreground of BIM, the most important issue in the BIM projects is the information, and the geometry (i.e., 3D model) forms a part of information. One of the interviewees (E4) very well explained the relation between BIM, CDE, and information as “*The BIM, without supported by the CDE, is being composed of just “M” (i.e., the model). There is a need for “I” (i.e., information), whose sources are CDEs, to conduct BIM*”. Correspondingly, CDEs are powerful enablers of information management as stated in benefit PR8.

Construction processes are complicated and measurement of the performance (e.g., quality, safety, and productivity) can be challenging. Thus, this might result in poor management and underperformance in construction projects. “*What gets measured gets improved*”, says Peter Drucker (1963) [109]. CDEs “contribute to measurement and tracking of key performance indicators (PR2)” and “enable real-time insights related to project performance (PR14)”. These two benefits under PRS are very important due to

the improvement in project performance becomes possible as long as the project teams can derive insights from this data. The benefit PR6, “enhanced health and safety management”, which can be achieved by deriving insights from KPIs, can be given as an example. The health and safety department can benefit from the measured KPIs on site. For example, they can monitor the near-miss frequencies and take precautions before an accident happened on-site, based on the predictions raised from the Heinrich Pyramid [110]. Furthermore, CDEs enable the analyses of data stored in the repository and “provide business intelligence reporting (PR21)” from static reports to interactive, real-time dashboards.

Most of these processes and workflows may include redundant activities due to the complex environment of construction projects. Efficient management of each process and workflow is critical due to a single setback may negatively affect the entire project. In disconnected construction projects, the process and workflows may differ by stakeholders. Furthermore, each process or workflow is different from each other and may require different standards. In this situation, an inconsistency in the standardization of the processes and workflows may occur in the project. At this point, CDEs allow stakeholders to adopt “standardized processes and workflows (PR25)” and enable them to incorporate with the international standards of information management such as ISO 19650 [16]. While CDEs ensure the standardization in the processes and workflows among stakeholders, they also allow “customized & standardized data collection (PR3)”. The customization helps to provide simplicity and useful structure for stakeholders while standardization helps to ensure uniformity of inputs measurement of data. In addition to providing a basis for more standard data collection, improved standardization for processes and workflows can result from precise data itself.

Construction processes and workflows cannot be attributed to a single party or

phase as they are conducted through teams and project phases together. When the processes and workflows are conducted in entirely different systems by the stakeholders, the successful collaboration in the project cannot be discussed. The CDEs provide “connected & streamlined processes and workflows (PR1)” across project teams and stakeholders as well as enable “seamless data transfer across project phases (PR22)” that facilitates “successful project handover (PR23)”. By the connected processes and workflows, the changes in the project become more visible to track by the project participants. Additionally, stakeholders can be notified on time and adjust their works based on the change/update event. In other words, CDEs enable everyone to work on the latest, correct versions of documents and models.

Construction projects may include plenty of request, review, and approval processes for each workflow (e.g., submittals and requests for information (RFIs)) during construction. On-time responses to these requests, reviews, and approvals are crucial to conducting works accurately and in line with the schedule. These processes become smoother by the CDEs and project participants do not waste their time and resources for waiting approvals. CDEs can “increase the project productivity (PR16)” by the streamlined processes. Otherwise, project participants may waste time and resources due to the approvals. Furthermore, the CDEs can “optimize the construction operations (PR19)” by better coordinating and allocating the materials, logistics, labors, schedules, and processes.

Similar to the processes and workflows, systems should also work together in a single platform to ensure information compatibility. CDEs connect software (e.g., for scheduling, cost estimating, energy analysis, document management etc.) to processes and workflows and “enable to work integrated with BIM systems (PR12)” which further streamlines the construction processes. For example, issue management and RFI

processes can be carried out through the BIM models, which can be reviewed from any device without requiring their native design software (e.g., Autodesk Revit).

Execution of construction projects requires many tasks which are performed by particular software. For instance, scheduling can be executed using Primavera or 3D modeling can be implemented using Graphisoft Archicad. Generally, data related to these tasks are not connected to each other as they are in separate locations or devices. When it comes to project management, project teams should obtain necessary information from multiple sources, such as deriving cost estimates for the use of productivity monitoring [111]. In that situation, project participants may run different software to review useful information and use their minds to gather fragmented information [1], which causes loss of time, missing and incorrect information. Thus, similar to the project participants, software should be also connected to each other and work together, to provide reliable and actionable information. To overcome these issues, the CDEs “enable interoperability between tools (PR11)” and provide an integrated platform of tools that allows “standardized & improved data exchange (PR24)”. For example, CDE platforms can obtain the schedule information from Primavera and provide the users with weekly progress reports by comparing the actual and planned progress. This opportunity (i.e., PR11) increases the project productivity (i.e., PR16) and “enhances quality of the project” by contributing the conduct task based on the accurate, reliable information. Additionally, the CDEs “eliminate manual data entrance (PR9)” which may cause mistakes and provide many opportunities, from automatic numbering of versions to standard templates, as they integrate processes, workflows, and software altogether.

In traditional construction projects, the project teams obtain the necessary information by communicating through phones, e-mails and conduct face-to-face meetings to solve issues or discuss the project progress. The traditional ways of

communication and coordination might be time-consuming and error prone. The project teams can conduct “less phone-/e-mail-based communication & face to face meetings (PR17)” as they can easily access to the information through CDEs, of course within their authorization permits (i.e., benefit, PR20). CDEs contributes to “eliminate unnecessary expenses (PR10)” because they “eliminate paper-based processes & paperwork (PR15)”. Additionally, CDE platforms have a user-friendly interface which is “easy to use for teams” and reduces the adaptation duration for the stakeholders. Consequently, CDEs provide an “opportunity to focus on optimal activities (PR18)”, instead of wasting time for searching an information among hardcopies or obtaining information from other stakeholders and ensure more efficient business meetings. Furthermore, instead of purchasing high-cost hardware, CDEs provide high-performance servers, within affordable prices through cloud computing and enable payments to be made based on the actual consumption in the project which further reduces unnecessary expenses.

4.1.4 Benefits under philosophy subcategory of Toyota’s 4P Model

In this study, 7 benefits listed under the philosophy subcategory (PHS) of Toyota’s 4P model, involve the benefits which promote mostly the long-term business goals of the contractors. 6 of the benefits (i.e., PH1, PH2, PH4, PH5, PH6, and PH7) were identified as very important and one benefit (i.e., PH3) was determined as important according to the scores given by the SMEs. The prioritization benefits, corresponding to PHS, are presented in Table 9.

The common data environments are the platforms that enable the transformation of data into information, afterward, into knowledge. CDE “provides a better knowledge management (PH7)”, as it enables the transformation of data into knowledge, which is one of the very important benefits of PHS. In the correct use of CDEs, learning from past

experiences becomes possible and these lessons-learned outcomes can be utilized for enlightening future projects. For example, the contractors can analyze the risks which they have faced in the previous projects, and they can place more accurate proposals in the similar regions or the project types, based on the foreseen risks, while entering the new tenders.

Most of the time, project information is not recorded and exchanged in verbal form among the project participants [1]. In that case, the gained knowledge and valuable experience last in only the project participants' minds [1]. The limited human memory and the circulation in the employees obstruct the knowledge transfer to the next generations and frustrate the business continuity. To overcome this issue, CDE “helps to constitute corporate memory of the company (PH5)” and correspondingly “enables continuous improvement for the company (PH4)”.

A CDE, set up in the earlier phases of a project, “contributes to providing requirements for facility management (PH2)”, by enabling successful delivery of BIM models [112] and COBie data [18] to the client. Hereby, the client (i.e., owner), can leverage project information to improve the operation and maintenance of their facilities which results in increased client satisfaction and long-lasting partnerships. Using CDE platforms, the contractors “increases the return on investment (PH6)” on both project and company basis. As the construction industry expeditiously started to adopt new technologies, the efficient use of CDEs by the contractors, “contributes to gain competitive advantage in the international market (PH1)” and provides earning more business.

Making sense of the data and extracting the knowledge from previous databases are challenging considering the vast amount of generated non-standardized data in the industry. The standardized data collection and processes in the CDEs, “enables a base for

artificial intelligence in construction (PH3)”, which contributes to many possibilities from quickly finding the documents to boosting knowledge management [113]. One of the interviewees (E4) very well described the significance of the CDEs for enabling AI and smart technologies in construction processes as “*The 3D model is the body and the CDE is the hearth and brain of this body. The body can fulfill its duties merely the correct functionalization of CDEs*”. Thus, the contractors and owners need a CDE to be able to benefit from the artificial intelligence practices efficiently, within the data stored in the CDEs, throughout the buildings’ lifecycle.



4.2 The impacts of CDE benefits on project performance

Al Nahyan et al. (2018) stated that the four key management processes are communication, coordination, decision-making, and knowledge management that affect the success of construction projects [114]. It is obvious that the traditional ways of project and information management practices are not sufficient to increase project performance in the construction industry. The abundance of disintegrated information [115], together with communication problems and data loss [116] may result in poor project performance. The use of CDE platforms eliminates the challenges in the industry and increases the project performance, in terms of the construction KPIs (Table 3) by providing several benefits (Table 9).

In this section, the improvement effects of CDEs on project performance will be revealed based on the seven construction KPIs (i.e., time, cost, quality, productivity, safety, client satisfaction, and organizational sustainability). The benefits, categorized under Toyota's 4P model, will be investigated to what extent they affect the presented KPIs. The reason for this subcategorization is that improvement effects may vary from one benefit to another. Therefore, the panel experts were asked to consider the CDE benefits under the four domains which are problem solving, people and partners, process, and philosophy. The panel experts were expected to give scores to the CDE benefits & project performance matrix (Table 10) by considering the following question: "To what extent do the benefits, under each subcategory (e.g., problem solving), affect the presented KPIs".

The outputs of CDE benefits & project performance matrix ranking can be seen in Table 11. Based on the obtained rankings from SMEs, the identified KPIs are very important and extremely important for the project performance improvement. Even though all identified benefits have certain improvement effects on the identified KPIs, the

priority improving each measure may differ. Thus, this section explains the relative importance priorities of the KPIs based on the categories of Toyota's 4P model.

Table 10: CDE benefits & project performance matrix

4P Model	KPIs					
	Time	Cost	Quality	Safety	Productivity	Organizational sustainability
Problem solving						Client satisfaction
People and partners						
Process						
Philosophy						

Ranked based on 5-point Likert scale

Table 11: Results of CDE benefits & project performance matrix

4P Model	KPIs	Mean	Median	σ	r_{wg}	significance level	agreement level
Problem Solving	Productivity	4.58	5.0	0.493	0.702	extremely important	strong agreement
	Quality	4.50	5.0	0.645	0.563	extremely important	moderate agreement
	Time	4.33	4.5	0.745	0.542	very important	moderate agreement
	Cost	4.25	4.0	0.595	0.734	very important	strong agreement
	Client Satisfaction	4.25	4.0	0.829	0.513	very important	moderate agreement
	Safety	4.08	4.0	0.493	0.842	very important	strong agreement
	Organizational Sustainability	4.08	4.0	0.640	0.734	very important	strong agreement
People and Partners	Quality	4.50	4.50	0.500	0.74	extremely important	strong agreement
	Client Satisfaction	4.42	4.00	0.493	0.78	very important	strong agreement
	Productivity	4.42	4.50	0.640	0.62	very important	moderate agreement
	Time	4.25	4.00	0.595	0.73	very important	strong agreement
	Organizational Sustainability	4.17	4.00	0.553	0.79	very important	strong agreement
	Cost	4.17	4.00	0.687	0.67	very important	moderate agreement
	Safety	4.00	4.00	0.577	0.80	very important	strong agreement

Table 11: (Continued)

4P Model	KPIs	Mean	Median	σ	r_{wg}	significance level	agreement level
Process	Time	4.58	5.00	0.493	0.70	extremely important	strong agreement
	Productivity	4.50	5.00	0.645	0.56	extremely important	moderate agreement
	Quality	4.33	4.00	0.624	0.68	very important	moderate agreement
	Safety	4.25	4.00	0.595	0.73	very important	strong agreement
	Cost	4.17	4.00	0.553	0.79	very important	strong agreement
	Organizational Sustainability	4.17	4.00	0.687	0.67	very important	moderate agreement
	Client Satisfaction	4.08	4.00	0.759	0.63	very important	moderate agreement
Philosophy	Organizational Sustainability	4.33	4.00	0.624	0.68	very important	moderate agreement
	Productivity	4.25	4.00	0.595	0.73	very important	strong agreement
	Cost	4.08	4.00	0.759	0.63	very important	moderate agreement
	Quality	4.00	4.00	0.577	0.80	very important	strong agreement
	Safety	4.00	4.00	0.816	0.59	very important	moderate agreement
	Client Satisfaction	3.83	4.00	0.799	0.65	very important	moderate agreement
	Time	3.75	4.00	0.722	0.72	very important	strong agreement

4.2.1 The impacts of CDE benefits, under problem-solving subcategory (PSS), on project performance

In PSS category, productivity and quality KPIs were detected as extremely important by SMEs with mean values of 4.58 and 4.50, respectively. That means, the benefits that contribute to reducing potential problems in collaborative construction projects through CDEs, have direct improvements on project productivity and quality. As the benefits under PSS remove the barriers to accessing accurate information and facilitate eliminating wastes (e.g., reworks and defects), the productivity of the project teams' gets increased and high-quality construction is achieved. The stakeholders can more work on optimal activities instead of dealing with the errors and conflicts. Furthermore, the project is being conducted based on accurate information, without any misunderstanding and data loss which results in better quality.

Following the productivity and quality improvement, the third most positively influenced KPI was identified as time, with the mean value of 4.33. This is because the elimination of reworks and conflicts prevents the time that will be wasted to correct the defect on-site or to solve the disputes. Correspondingly, next positively influenced KPI was determined as cost, as re-construction and prolongation costs are prevented. The following KPI was client satisfaction. The client can be more satisfied as the defects are minimized, better quality is ensured, and cost overruns are prevented.

The safety KPI can be positively affected as proactive problem solving becomes possible and accurate forecasts can be made related to safety hazards on site. Likewise, organizational sustainability KPI can be positively affected as better decisions are made for the subsequent projects. Although the safety and organizational sustainability KPIs were identified as very important and positively affected by the use of CDEs, they were seen as less affected KPIs from the benefits under PSS by the SMEs.

4.2.2 The impacts of CDE benefits, under people and partners subcategory (PPS), on project performance

In PPS category, the most prominent KPI was identified as quality, with a mean value of 4.50. The evaluation of the quality as very important explains that the benefits listed in PPS have a significant positive impact on delivering high-quality buildings. The improvement in quality results from the improved collaboration, better coordination and control, and streamlined communication flow among stakeholders through the use of CDE platforms. As better coordination is achieved, fewer defects occur.

Quality is one of the difficult KPIs to measure, due to its subjective nature. Owner's project requirements and whether the quality of the project is satisfied are interrelated measures. Thus, following the quality, client satisfaction was detected as the second most positively affected KPI, with a mean value of 4.42. This stems from the visualization opportunity for the client, which provides better engagement of the owner with project information and project stakeholders through all phases. As owner's project requirements become well understood, better design and construction solutions can be developed. Furthermore, as high-quality assets are delivered to the client in handover, the owner can benefit more in the asset's operation phase which ensures better client satisfaction.

Afterward, the next positively affected KPIs were observed as productivity and time, with mean values of 4.42 and 4.25, respectively. Productivity can be increased directly through better collaboration and communication, and this contributes to continuing to construct in line with the schedule. The following KPI is organizational sustainability by the SMEs. This is because the trust among project teams and stakeholders getting increased with the improved collaboration and transparent processes. The project teams can focus on their works instead of searching for the responsible party

when a mistake happens as each cause can be transparently identified through the audit trail records saved in the CDEs. The cost KPI was ranked lower than the time, as it is correlated with time KPI implicitly (e.g., as reworks and delays are avoided, cost overruns are eliminated) and safety was observed as the least positively affected KPI under the PPS.

4.2.3 The impacts of CDE benefits, under process subcategory (PRS), on project performance

In PRS category, the time and productivity KPIs were identified as extremely important with mean values of 4.58 and 4.50, respectively. That means the benefits of CDEs which contribute to facilitating construction processes have direct, and extremely important improvements on project time and team productivity. One of the main reasons for this improvement is that CDEs contribute to achieving promised project completion time by avoiding potential delays due to poor management, rework, and miscommunication. Additionally, CDEs reduce the time spent waiting for approvals by enabling notifications for deadlines. Thus, CDEs facilitate unnumbered review and approval processes of the construction tasks that save time to project teams. This prevents the delays of consecutive activities caused by late approvals and contributes to following the project schedule. Further, processes and workflows are being connected among all project phases and teams. Accordingly, processes and workflows can be monitored at any time effectively through CDEs. Thus, the schedule can be better optimized, controlled, and updated by benefitting from real-time project performance insights. The benefits such as enabling quick access to the project information regardless of location, decreasing the time spent on phone calls, e-mails, face-to-face meetings directly contribute to optimizing the working durations of project teams. Hence, the opportunity to focus on optimal

activities becomes possible, so the productivity of teams is getting increased.

Following the time and productivity KPIs, the third most positively influenced KPI was determined as quality, with a mean value of 4.33. Standardized processes and workflows, standardized data exchanges, elimination of the manual data entrances, and paperwork are the benefits under PRS that directly ensure minimizing the possibility of human-made mistakes. The minimized and prevented mistakes facilitate the project teams ensuring the quality of the building.

Safety KPI comes more forefront in this category, with a mean value of 4.25, compared to its place in other categories. The reason behind this is that CDEs provide many facilitator benefits on the health and safety environment (H&S) processes. For example, safety inspection processes can be conducted through CDEs, using mobile devices, which reduces the time for remedying the safety deficits on-site. Furthermore, project schedule and logistics can be better optimized so as to decrease the working hours on site which contributes to reducing exposure to safety hazards. The need for safety walks, in which many participants are involved, is getting decreased as the safety hazards can be identified by any project participant and quickly appointed to the responsible parties. This further decreases the unnecessary working hours on site. Real-time insights related to safety progress provide a better awareness about the possible risks on-site and facilitate adopting proactive prevention practices by the project teams.

Following the safety, the next positively affected KPI was identified as cost, with a mean value of 4.17. The preparation, control, and delivery of progress payments in accordance with contracts can be conducted through CDEs which contributes to providing better management of the cash flows. Consequently, better control and monitoring of cost and project profit margin can be ensured through business intelligence reports and real-time insights supported by CDEs. Furthermore, exposure to cost

overruns, including prolongation costs, site/head office overhead costs, can be avoided as the possible delays are minimized. Unnecessary expenses, such as expenses for document control experts, hardware costs, and even expenses of paper can be minimized as a result of using digitalized and cloud-based information repositories. Organizational sustainability and client satisfaction KPIs, which are found as very important by the SMEs, are also positively affected by the benefits under PRS. However, improvements of the benefits under PRS on these KPIs are relatively lower in comparison to KPIs such as time, productivity, quality, safety, and cost.

4.2.4 The impacts of CDE benefits, under philosophy subcategory (PHS), on project performance

In PHS, the most prominent positively affected KPI was detected as organizational sustainability with a mean value of 4.33. The fundamental reason for this is that the benefits under PHS mainly contribute to sustaining business success and represent the long-term goals for contractors. The most important benefit of CDEs to improve organizational sustainability is the opportunity for better knowledge management. The transformation of data into knowledge becomes possible and easier by the contributions of standardized data stored in the CDEs. Thus, the contractors can analyze their past experiences from several perspectives, so the continuous improvement for the company is sustained. One of the interviewees (E2) emphasized the importance of knowledge management in terms of decision making as these words: *“The construction industry always requires the adaptation to changing situations such as working conditions of different countries, differentiating stakeholders. Construction companies need to make continuous decisions for the purpose of surviving the business under these circumstances. Thus, it is crucial for the contractors to be able to analyze and compare their previous*

experiences and present conditions”. Furthermore, the contractors’ reputation can increase as they continue to improve their success by benefiting from knowledge management practices.

Following the organizational sustainability, the second most positively affected KPI was identified as productivity with a mean value of 4.25. Considering the long-term goals of a contractor, the productivity of the teams can be increased by stemming from the created corporate memory of the company. The employee circulation may hinder the project productivity due to the long duration of the adaptation phase and the differentiated working styles of each person. New employees can access and review the related information through CDEs and can be better adapted to the company's working style and culture.

The third most positively affected KPI was determined as cost with a mean value of 4.08. The contractors can increase their return on investment (ROI) in each project. When they utilize the benefits of technology (e.g., BIM and CDEs) comprehensively, they become able to compete globally; and correspondingly, win more business. Following the cost KPI, the next most positively affected KPIs were found out as quality and safety with mean values of 4.0. The contractors can analyze the root causes of the previous events, such as reworks, miscommunication, RFIs, change orders, incidents, and accidents. Accordingly, contractors can better identify their and/or the third parties’ deficient abilities, and better analyze the risks while entering the new projects. In addition, the client satisfaction KPI can be improved by the benefits under PHS. The increased reputation of contractors can reinforce customers' trust in the contractor. Lastly, the time was observed as the least positively affected KPI under the PHS. For example, the contractors can increase their bid efficiencies and decrease the completion durations of proposals by benefiting from the tools connected in CDEs which provide better

collaboration among project participants.

4.3 Identification and prioritization of challenges on CDE implementation

Identification of the current challenges carries an important role to mitigate the existing deficiencies in CDE implementation in the construction industry. For this purpose, 15 challenges about implementing CDE platforms in the construction industry were identified by triangulating the outputs from literature review, interviews, and online sources. Prioritization results of the challenges on CDE implementation, obtained from the Delphi method, are given in Table 12, supported with their mean, median, standard deviation values, significance levels, and agreement levels. Mean values of the identified challenges remained between 4.50 and 3.0 in which their significance levels vary from extremely important to important. Among these challenges, one of the challenges was identified as extremely important, while 8 and 6 of the challenges were determined as very important and important, respectively.

Table 12: Results for the challenges of CDE implementation

Rank	ID	Challenges	Mean	Median	σ	r_{wg}	Significance level	Agreement level
1	C6	Exclusion of CDE planning at the project's feasibility stage	4.50	4.50	0.50	0.74	extremely important	strong agreement
2	C2	Closed-BIM approach (non-integrated software systems)	4.42	4.50	0.64	0.62	very important	moderate agreement
3	C4	Deficiencies in obligating the use of CDEs within the contracts & inefficient contract suites	4.00	4	0.58	0.80	very important	strong agreement
4	C11	Lack of contractors' /owners' motivation to use CDEs	4.00	4	0.82	0.59	very important	moderate agreement
5	C10	Lack of clarity on contractual relationships, ownership of the information, and legal issues	3.83	4	0.80	0.65	very important	moderate agreement

Table 12: (Continued)

Rank	ID	Challenges	Mean	Median	σ	r_{wg}	Significance level	Agreement level
6	C14	Tendency to use traditional information systems & resistance to change	3.83	4	0.90	0.55	very important	moderate agreement
7	C8	Inadequate, limited technological training and education in the industry	3.75	4	0.60	0.81	very important	strong agreement
8	C13	Security and privacy concerns about the CDE platforms	3.50	3	0.65	0.80	very important	strong agreement
9	C9	Internet access & infrastructure on site	3.50	3	1.04	0.47	very important	weak agreement
10	C7	Financial barriers to implement CDEs	3.42	3	0.64	0.80	important	strong agreement

Table 12: (Continued)

Rank	ID	Challenges	Mean	Median	σ	r_{wg}	Significance level	Agreement level
11	C5	Deficiencies in CDE platform functions	3.42	3.5	0.86	0.64	important	moderate agreement
12	C15	The fact that the construction industry has not fully embraced the digitalization culture	3.42	3	0.95	0.56	important	moderate agreement
13	C3	Deficiencies in cloud service provider's support & consultancy	3.33	3	0.47	0.90	important	strong agreement
14	C12	Low technological literacy level of people in the industry	3.33	3	0.62	0.82	important	strong agreement
15	C1	Challenges in choosing the most suitable CDE platform for the project	3.00	3.00	0.58	0.85	important	strong agreement

The most prominent challenge of CDE implementation in the industry was detected as the “exclusion of CDE planning at the projects’ feasibility stage (C6)”, with a mean value of 4.50. Just to clarify the vital importance of constructing the CDE framework properly by quoting interviewees’ opinions, interviewee (E4) likened CDEs to a body's (i.e., construction project) heart and brain. Another interviewee (E3) promoted that description by likening CDEs to the brain of a company. These words prove that the CDEs have a vital role in successfully completing the construction projects and sustaining the success of the companies. Thus, starting from the early phases of a project, structuring CDE platforms, applying the standards, and defining the rules are crucial for utilizing the full potential of these platforms. When CDEs are not being constructed accurately based on the project needs, they cannot carry out their functions and the efforts cannot reach success. The failure in structuring CDEs in the early phases of a project causes loss of motivation for both contractors and owners (i.e., C11) as the expectations could not be met. Because, this failure, caused by poor planning of CDEs, led clients and contractors to think like “...okey we made investments for BIM and CDE, yet, we couldn’t use them efficiently in facility management...” according to one of the interviewees’ comments (E4).

Similar to exclusion of CDE planning at the project’s feasibility stage, the “deficiencies in obligating the use of CDEs within the contracts & inefficient contract suites (C4)” is one of the most faced challenges to implement CDEs, which prioritized as the third challenge among others. One of the facilitating factors for structuring the CDE platforms is the early involvement of all the stakeholders in planning phase. When facility managers are involved in earlier phases of a project, their needs can be clearly understood, and the necessities can be obligated through contracts. One of the interviewees (E4) clearly explained this challenge in these words, “*The client delivers their request to use*

BIM models in the facility management stage in the middle of the project, while the use of CDE is not obligated through the contract and there is no CDE for the project. Unfortunately, it is not possible to use BIM models for facility management without having a CDE platform for the project”. Furthermore, another interviewee (E3) supports this idea with the following statements “...working in CDEs is to be able to view the lifecycle of an asset. The COBie cycle of each object starts at the time that its necessities were revealed by the client, not at the time they are installed”. Thus, the lifecycle of the objects should be reflected in the models from the early phases of a project, which is possible by obligating the implementation of BIM and CDEs, starting from early phases, through contracts. Additionally, in the absence of proper contract suites, protocols comprising the use of BIM and CDEs are limited (e.g., NEC 4 suite of contracts and CIC BIM Protocol), which further constrains the use of CDEs in construction projects. When CDEs are not obligated through the contracts, the contractors might have to cover the expenses if they prefer to manage the project through CDEs, which also causes a decrease in contractors’ motivation (i.e., C11). Hence, obligation of using CDE platforms in the contracts is important for their successful implementation and contributes to fulfill the expectations of both clients and contractors.

The second most prominent challenge in CDE adoption was detected as the “closed-BIM approach (non-integrated software systems) (C2)” with a mean value of 4.42. As emphasized in the benefits section, not only the project teams but also software and systems must contact to each other and work together to utilize the full CDE potential. According to the Construction Technology Report 2021, conducted by JB Knowledge [117], %26.9 of the experts reported that they do not have any apps to integrate the project data, and %51.3 of them reported that they manually exchange data between apps in the absence of tools for integration. Correspondingly, mistakes and bottlenecks are inevitable

in data transfer when the systems are not fully integrated. Thus, systems integration occurs as an important enabler of effective collaboration [1, 118]. Additionally, limited number of standards for BIM interoperability specific to cloud computing further makes the interoperability practices more difficult and the development of these standards should be increased [53].

There are many reasons causing “lack of contractors/owners motivation to use CDEs (C11)” which was the fourth-ranked challenge to implement CDEs. One of these reasons is explained above, which is the decreased motivation caused by the failure of CDE due to poor planning. Therefore, the lack of clarity on the potentials and benefits of CDEs is to decrease the willingness to implement centralized and collaborative environments in construction projects. Additionally, Redmond et al. (2012) stated that the motivation of the industry to use new technologies is not being comprised, without being obligated through the contracts [30] (i.e., C4). The contractors may have issues covering the expenses, which further decreases the contractors’ motivation when the owner does not fully support the implementation of CDEs in the projects. Besides, as the successful implementation of CDEs requires the involvement of all stakeholders, the attempts which are done by the only contractor is being contrary to CDE nature.

Another challenge is “lack of clarity on contractual relationships, ownership of the information, and legal issues (C10)” in the fifth place which also cause resistance to change (i.e., C14). The issues in contractual relationships including debates on the ownership of shared data are one of the challenges to the implementation of cloud computing in BIM [30]. Thus, there are many arguments on the questions such as who is responsible for data, who owns the data after completion, and how the risks are distributed among stakeholders in the projects where BIM and CDE are implemented. These uncertainties may raise concerns for stakeholders about the legal issues which may hinder

the CDE implementation. This also emphasizes the deficiencies in current contracts (i.e., C4) in regard to support BIM and CDEs. There is no exact attribution for the ownership of the data and models as they can be changed based on the project needs. The important point is to properly clarify the liabilities, data exchange, and handover protocols, risk distributions in the contracts to avoid contractual and legal issues. In this way, Khawaja and Mustapha (2021) suggested that using the New Engineering Contract (NEC) 4 suite with the Construction Industry Council (CIC) BIM protocol can be a proper combination to mitigate legal issues [71].

The implementation of BIM through CDEs requires a fundamental change for all project stakeholders. Thus, the “tendency to use traditional information systems & resistance to change (C14)” arise as one of the common challenges in the implementation of CDEs in the industry. One of the root causes is that even with the rapid developments in technology, there is the “fact that the construction industry has not fully embraced the digitalization culture (C15)” as being the least second digitized sector in the world [119]. The second facilitator of this resistance can be considered as the “low technological literacy level of people in the industry (C12)”. Even the systems are fully connected, when the people, mostly the workers on site, do not have enough ability to use the tools which may prevent to streamline the processes. For example, if the workers, whose technological literacy is low, cannot open the documents or drawings from tablets, they will tend to traditional ways such as hard copies of 2D drawings and phone calls.

Another challenge is the “inadequate, limited technological training and education in the industry (C8)” which was identified as very important. One of the interviewees (E2) said that “*We are not an industry that is accustomed to recording the data or open to sharing the information with other people*” and emphasized the inadequacy of training in the industry. According to the Construction Technology Report 2021, conducted by JB

Knowledge [117], the lack of employees to support the technology was detected as one of the most limiting factors with a percentage of 35.2. This statistic proves the need for more profound training and education in the industry to break the resistance to CDE implementation.

There are some challenges that are more related to technological infrastructure. One of these challenges is the “security and privacy concerns about the CDE platforms (C13)” which was determined as very important. Security levels of CDEs are being determinant as they keep all confidential data and documents related to the project. Even project teams have access to the project data within their authorizations, main privacy concerns arise from the cloud service providers’ trustworthiness [13]. Additionally, stakeholders have concerns about the cybersecurity risks such as denial of service leading to delays and non-traceability of data [72] as well as cyberattacks by third parties. However, this is unlikely to happen based on the taken security measures on CDE platforms. Further, the concerns are more caused by psychological discomfort, and the security in cloud platforms is definitely higher than the security of in-house infrastructure [11].

Secondly, “internet access & infrastructure on site (C9)” was determined one of the challenges in CDE implementation. The availability of the connection and speed of the bandwidth are influencing factors for efficient CDE implementation, as the cloud applications are network-dependent [39]. Ensuring internet infrastructure and maintaining the connection speed for projects, especially in places where the infrastructure is not sufficient (e.g., the construction sites located far from the cities) said one of interviewees (E2). Poor connection in construction site may cause time losses when the connection is slowed down or lost. Despite the importance of internet infrastructure, this challenge was the only one that SMEs’ agreements were weak. This

can be explained by the different projects that the SMEs had experience on, in which some of them are located in the city, some of them are not.

The “financial barriers to implement CDEs (C7)” are also one of the challenges on CDE implementation. Even though CDE implementation brings many cost-saving during the project (e.g., elimination of unnecessary expenses and the non-value adding activities), the initial investment costs (e.g., payments for CDE platforms per consumption) hiring educated employees, or training expenditures might constitute some difficulties. This challenge might be more binding on small to medium-scale contractors as their financial resources could be limited in comparison to large-scale contractors. Additionally, the long period of using cloud infrastructure to implement CDEs may increase the accumulated costs of usage based on the model of deployment [11]. On the contrary, while some expenses are increasing, the need for high-performance hardware is decreasing by benefit from cloud computing [12]. Thus, conducting a proper feasibility study might be beneficial to decide on whether the implementation of CDEs is feasible for the project scope.

Lastly, there are some challenges that are related directly to CDE functions and the service providers, which have fewer negative effects on CDE implementation compared to previously mentioned challenges. The “deficiencies in CDE platform functions (C5)” can affect the CDE implementation. There are many cloud service providers and each of their functions are varying one platform to another. The stakeholders should evaluate the performances and expenses of different options and should decide on the most appropriate platform for the project. In fact, there might be some “challenges in choosing the most suitable CDE platform for the project (C1)” that fulfills all the needs of each stakeholder simultaneously. At this point, the support and consultancy services of the cloud service provider become forefront to develop

functionalities of CDE platforms based on client/contractor needs. When there exists “deficiencies in cloud service provider's support & consultancy (C3)”, the stakeholders can face some issues, such as they cannot fully integrate their workflows through CDEs.

4.3.1 Suggestions to mitigate current challenges of CDE implementation

Existing challenges regarding CDE implementation in construction projects were identified and explained in section 4.3 in detail. This section presents suggestions for mitigating current challenges of CDE implementation and promoting the use of such platforms in the industry.

For taking full advantage of CDEs, the first step should be defining the project needs, comprising the whole lifecycle of the building. In project feasibility phase, the stakeholders should express their requirements and expectations clearly to be able to construct CDEs based on the project needs. Early involvement of stakeholders and early feasibility studies are important, as working with BIM in a common data environment may not be efficient after the projects started. In that case, using the international standards for information management through CDEs (e.g., ISO 19360) can assist contractors in successfully implementing CDEs in their projects.

The usage of BIM and CDEs can be obligated by authorities or project owners. For example, the UK government necessitates conducting information management through CDEs for achieving BIM Level 2 maturity [6, 22 23]. The implementation of CDE platforms can become prevalent when they are obligated by authorities through contracts. Furthermore, the governments can offer incentives to the owner and contractors to direct them to use BIM and CDEs in their projects. The obligation of these systems and provision of government incentives can increase the motivation of the owners and contractors while helping them to remove financial barriers

to CDE implementation.

Inefficient contract suites, which may cause a lack of clarity on contractual relationships, ownership of the information, and legal issues, are one of the challenges identified in this study. Improvements of the current contract suites (e.g., NEC and FIDIC type of contracts) to support the implementation of BIM and CDEs in projects can facilitate defining the liabilities of the stakeholders. Risk of legal problems, such as disputes, can be mitigated with utilizing proper contract suites and protocols. In relation to this issue, Khawaja and Mustapha (2021) suggested that the use of NEC4 contract suite with CIC BIM protocol can be a proper combination to mitigate legal issues [71].

OpenBIM is one of the recent subjects in the construction industry which aims to remove barriers to actual interoperability and collaboration and break down the closedBIM approach. The openBIM is defined, by BuildingSMART International, as a collaborative process that supports seamless collaboration for project participants and facilitates interoperability to support projects and assets throughout their lifecycle by the creation of open and international standards [120]. Increase in openBIM practices and development of the industry standards (e.g., industry foundation classes (IFC)) can mitigate problems caused by the vendor-specific environment of the tools that are used for facilitating construction tasks.

Security and privacy concerns related to the CDEs can be mitigated with the implementation of decentralized or distributed common data environments, which is one of the recent studies in the industry, using blockchain technology [72]. In addition to the technical precautions against cyber threats, the firms should conduct training to raise information security awareness among project participants and strengthen the cyber resilience of their corporates.

Proper education and training should be organized regularly with the aim of

increasing employees' knowledge and abilities to work in CDEs. An acceleration in such trainings can facilitate finding solutions to current challenges of CDE implementation while creating awareness in the industry. Furthermore, trainings should be provided not only for head and site office staff but also for the workers on-site, to increase their technological literacy to be able to use current technologies such as smartphones, tablets, and AR/VR glasses.



CHAPTER V

DISCUSSION

There are many common data environments and cloud service providers exist in the construction market. Each of these tools has a different scope of functions and abilities based on their vendors. In this study, listed benefits are comprising whole beneficial aspects of the CDEs without being particular to only one provider. Thus, listed benefits cannot be attributed to a specific CDE, either provided by commercial tools or constituted by the internal organizations of contractors.

Classifying the benefits was conducted based on their dominant effects on the project (e.g., benefits related to problem solving). Even the 54 identified benefits were categorized under different subcategories, they can be interrelated to each other. For example, by conducting less phone/e-mail-based communication & face to face meetings (PR17), the probability of misunderstandings caused by miscommunication (PS8) is reduced. Additionally, it is possible to relocate the benefits under different subcategories. For example, it is possible to categorize PH3, “enables a base for artificial intelligence in construction”, both under process and philosophy subcategories. The author was categorized PH3 under philosophy subcategory by considering the long-term benefits artificial intelligence practices for the contractors.

In CDE benefits & project performance matrix, top third most positively influenced KPIs were observed as productivity, quality, and time with mean values of 4.44, 4.33, and 4.23 respectively. This can be explained by more controlled processes, easy access to accurate information, and connected workflows and processes among

stakeholders provided by CDE platforms. Thereby, with the elimination of non-value-added activities, productivity is increasing, the quality of the project is ensured, and delays are being prevented. The following KPIs were observed as organizational sustainability, cost, client satisfaction, and safety with mean values of 4.19, 4.17, 4.15, and 4.08 respectively. The cost KPI is relatively ranked behind the time and productivity KPIs because it affected implicitly by delays. For example, by the possibility of on-time access to the project information can directly affect the time and productivity, yet the cost is affected as the delays are prevented. The organizational sustainability and client satisfaction KPIs were in the middle while the safety KPI were observed as the at least positively affected KPI among others. Even the relative importance of the KPIs were different, the minimum average was 4.08 which is considered as very important, proves that CDEs has significant positive impact on these KPIs.

CHAPTER VI

CONCLUSION

This study explored and analyzed the benefits and challenges of CDE implementation in BIM-based projects and their impacts on project performance through a comprehensive literature review, semi-structured interviews, and the Delphi method. In total, 54 benefits and 15 challenges were identified by triangulating findings from literature review and interviews. The identified benefits were categorized into four domains (i.e., problem solving (PS), people and partners (PP), process (PR), and philosophy (PH)) based on Toyota's 4P model. The benefits under PS, PP, and PR subcategories include mostly the short-term, project-based benefits, while the benefits under the PH address the long-term, strategic benefits for the contractors. Furthermore, the impacts of these benefits on the project performance were investigated based on the seven construction KPIs (i.e., time, cost, quality, safety, productivity, organizational sustainability, and client satisfaction).

The Delphi method was performed in two rounds with twelve geographically dispersed and qualified experts for prioritizing the benefits, challenges, and impacts on project performance. Results were validated by evaluating Cronbach's alpha, interrater agreement, and standard deviation statistics. In addition, the significance level statistic was analyzed.

According to outputs of the Delphi method, five extremely important benefits are "access to accurate, reliable, and up-to-date information (PS1)", "enhances coordination and collaboration among teams & stakeholders (PP3)", "easy & quick access to project

information regardless of location (PR7)”, “the single source of information & truth (PS16)”, and “digitalized data storage (PR4)”, respectively. 40 of the benefits were detected as very important and remaining 9 benefits were determined as important considering the scores given by the SMEs in the second round of Delphi method. The results revealed that using CDEs in BIM-based construction projects has significant benefits for project and information management by removing the barriers to efficient collaboration, communication, and control among stakeholders.

Despite the proven benefits of CDEs, there are several challenges that exist in CDE implementation in BIM-based projects. 15 challenges of CDE implementation were identified to uncover the needs for successful CDE implementation. Based on the results, “exclusion of CDE planning at the project's feasibility stage (C6)”, “closed-BIM approach (non-integrated software systems) (C2)”, “deficiencies in obligating the use of CDEs within the contracts & inefficient contract suites (C4)”, “lack of contractors/owners motivation to use CDEs (C11)”, and “lack of clarity on contractual relationships, ownership of the information, and legal issues (C10)” were determined as the most influencing challenges of CDE implementation in BIM-based projects. Additionally, the suggestions for mitigating the current challenges of CDE implementation were also provided in this study.

The results also show that the implementation of CDEs in BIM-based projects has significant improvements in project performance. According to the Delphi survey results, the most positively influenced KPIs were observed as productivity, quality, and time, respectively. These KPIs are followed by organizational sustainability, cost, client satisfaction, and safety, respectively. The findings prove that a well-structured and implemented CDE for the projects contribute to long-term continuous improvement of contractors, by possibility of better knowledge management, while improving efficiency

of the projects.

This research contributes to the AEC literature and industry by providing a comprehensive, qualitative, and quantitative overview of the CDE implementation in BIM-based projects. Further, this study uncovers the importance of information and knowledge management for the contractors. Clarifying full potentials of CDEs can promote the use of CDEs in BIM-based projects.



CHAPTER VII

LIMITATIONS AND FUTURE WORKS

This research analyzes the benefits and challenges of CDE implementation in BIM-based projects from contractors' point of view. The benefits of CDE implementation can also be investigated for the different stakeholders as a future work. For example, the use of CDEs in facility management can be investigated from the owners' perspective or the supply chain can be investigated from the construction materials suppliers' perspective.

Challenges provided within the scope of this study reveal future research directions on this subject domain. As the panel experts have experience in different countries (i.e., Australia (1), England (1), Greece (1), Germany (1), Italy (1), Turkey (4), and UAE (3)), some fluctuations were observed in some of the challenges such as “the fact that the construction industry has not fully embraced the digitalization culture (C15)”. This is because the factors which are related to the countries' population, such as implementation of digitalization in the industry, the technological literacy level of the people in the industry, may change from one country to another. Thus, challenges can be investigated based on country-specific surveys.

APPENDIX 1

Semi-structured interview questions

1. Personal information

- 1.1 Name-surname
- 1.2 Profession
- 1.3 Accreditations (if available)
- 1.4 Title
- 1.5 Expert role
- 1.6 Firm role
- 1.7 Experience in construction industry
- 1.8 Experience in BIM-based projects

2. General questions

- 2.1 What is the importance of information management in construction industry?
- 2.2 What is the relation between digitalization and information management?
- 2.3 How the information can be effectively managed in the construction industry?

Which methods can be used for this purpose?

3. Common data environments (CDEs)

- 3.1 How do you identify CDEs?
- 3.2 For what purposes can we benefit from the CDE system? Can you give examples of usage areas under the categories given below? Is there any other category you would like to add to the following categories?

- Performance management

- Information management
- H&S management
- QA/QC management
- Design management
- Workflows and approval processes

3.3 What is the importance of CDE systems in the construction industry? What are the benefits of using CDEs? How do CDEs contribute to information management?

3.4 Can you talk about the benefits of CDE systems on the basis of project stakeholders? (Employer, project management firm, contractor, subcontractors, suppliers etc.)

3.5 Are there any difficulties in using CDEs in the construction industry? If exists, can you give some examples? What are your suggestions for solutions to overcome these difficulties?

3.6 What are the key factors for project stakeholders to take full advantage of the CDE system?

4. Key performance indicators

4.1 What is the importance of tracking key performance indicators (KPIs) in construction? What are the effects/contributions of KPI tracking on information management?

4.2 What are the KPIs followed in the construction industry? Can you give an example? What are the KPIs that are followed in the projects you are involved in?

5. The relation between CDEs and KPIs

5.1 It is possible to use the CDE for different purposes (question 2.2). How do you think that these functions are supporting the KPIs?

5.2 How does tracking and controlling key performance indicators with CDE systems affect project management?

5.3 How do you think CDE systems support the successful completion of BIM-based construction projects?



BIBLIOGRAPHY

- [1] M. Martínez-Rojas, N. Marín and M. Vila, "The Role of Information Technologies to Address Data Handling in Construction Project Management," *Journal of Computing in Civil Engineering*, vol. 30, no. 4, p. 04015064, 2016. Available: 10.1061/(asce)cp.1943-5487.0000538.
- [2] J. Matthews, P. Love, S. Heinemann, R. Chandler, C. Rumsey and O. Olatunj, "Real time progress management: Re-engineering processes for cloud-based BIM in construction," *Automation in Construction*, vol. 58, pp. 38-47, 2015. Available: 10.1016/j.autcon.2015.07.004.
- [3] Alreshidi, E., Mourshed, M., and Rezgui, Y. "Requirements for cloud-based BIM governance solutions to facilitate team collaboration in construction projects," *Requirements engineering*, vol. 23, no. 1, pp. 1-31, 2018.
- [4] J. Lee and L. Bernold, "Ubiquitous Agent-Based Communication in Construction," *Journal of Computing in Civil Engineering*, vol. 22, no. 1, pp. 31-39, 2008. Available: 10.1061/(asce)0887-3801(2008)22:1(31).
- [5] P. Schott, "Construction Disconnected: The High Cost of Poor Data and Miscommunication," Tech. Report., 2018. [Online] Available: <https://blog.plangrid.com/2018/08/fmi-plangrid-construction-report/> [Accessed: March 29, 2021].
- [6] K. Klemmt-Albert, P. Hagedorn, and T. Pullmann "Utilising the Potential of Standardised BIM Models by a Fundamental Transformation of Collaboration Processes," *Smith I., Domer B. (eds) Advanced Computing Strategies for Engineering. EG-ICE 2018. Lecture Notes in Computer Science*, vol 10864, 2018. Available: https://doi.org/10.1007/978-3-319-91638-5_26

- [7] C. Eastman, *Building Product Models*, 1st ed. Boca Raton: CRC Press, 1999.
- [8] T. H Chuang, B. C. Lee, and I. C. Wu, "Applying cloud computing technology to BIM visualization and manipulation," In Proc. 28th International Symposium on Automation and Robotics in Construction, 2011, vol. 201, no. 1, pp. 144-149.
- [9] K. Afsari, C. Eastman and D. Shelden, "Building Information Modeling data interoperability for Cloud-based collaboration: Limitations and opportunities," *International Journal of Architectural Computing*, vol. 15, no. 3, pp. 187-202, 2017. Available: 10.1177/1478077117731174.
- [10] J. Wong, X. Wang, H. Li, and G. Chan," A review of cloud-based BIM technology in the construction sector," *Journal of Information Technology in Construction*, vol. 19, pp. 281-291, 2014.
- [11] S. Bello et al., "Cloud computing in construction industry: Use cases, benefits and challenges," *Automation in Construction*, vol. 122: 103441, 2021. Available: 10.1016/j.autcon.2020.103441.
- [12] H. Chong, J. Wong and X. Wang, "An explanatory case study on cloud computing applications in the built environment," *Automation in Construction*, vol. 44, pp. 152-162, 2014. Available: 10.1016/j.autcon.2014.04.010.
- [13] F. Abanda, D. Mzyece, A. Oti and M. Manjia, "A Study of the Potential of Cloud/Mobile BIM for the Management of Construction Projects," *Applied System Innovation*, vol. 1, no. 2, 2018. Available: 10.3390/asi1020009.
- [14] C. M. Eastman, C. Eastman, P. Teicholz, R. Sacks, and K. Liston, *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*. John Wiley & Sons, 2011.

- [15] F. Parisi, M. Fanti and A. Mangini, "Information and Communication Technologies applied to intelligent buildings: a review," *Journal of Information Technology in Construction*, vol. 26, pp. 458-488, 2021. Available: 10.36680/j.itcon.2021.025.
- [16] "Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) – Information management using building information modeling – Part 1: Concepts and principles," ISO 19650-1, International Standards Organization, Geneva, 2019.
- [17] D. Simeone, S. Cursi, U. M. Coraglia, and A. Fioravanti, "Reasoning in Common Data Environments-Re-thinking CDEs to enhance collaboration in BIM processes," In Proc. 38th eCAADe Conference, 2020, vol. 2, pp. 499-506.
- [18] M. Stransky, "Functions of common data environment supporting procurement of subcontractors," In Proc. 19th International Scientific Conference Engineering for Rural Development, 2020, pp. 793-799.
- [19] K. Y. Losev, "The common data environment features from the building life cycle perspective," In Proc. IOP Conference Series: Materials Science and Engineering, 2020, vol. 913, no. 4, pp.042012.
- [20] S. Ozkan and S. Seyis, "Identification of common data environment functions during construction phase of BIM-based projects," In Proc. 38th International Conference of CIB W78, 13-15 October 2021, Luxembourg, pp. 253-262 (ISSN: 2706-6568). Available: <http://itc.scix.net/paper/w78-2021-paper-026>. [Accessed: 19 Nov. 2021].
- [21] Z. Akob, M. Zaidee, A. Hipni and R. Koka, "Coordination and Collaboration of Information for Pan Borneo Highway (Sarawak) via Common Data Environment (CDE)," In Proc. IOP Conference Series: Materials Science and Engineering, 2019, vol. 512: 012001. Available: 10.1088/1757-899x/512/1/012001.

- [22] A. Akponeware and Z. Adamu, "Clash Detection or Clash Avoidance? An Investigation into Coordination Problems in 3D BIM," *Buildings*, vol. 7, no. 3, 2017. Available: 10.3390/buildings7030075.
- [23] M. Leon and R. Laing, "Cloud and computer mediated collaboration in the early architectural design stages: A study of early design stage collaboration related to BIM and the cloud," In Proc. 5th International Conference on Cloud Computing Technology and Science, 2013, vol. 2, pp. 94-99.
- [24] P. Nitithamyong and M. J. Skibniewski, "Success/failure factors and performance measures of web-based construction project management systems: professionals' viewpoint," *Journal of construction engineering and management*, vol. 132, no.1, pp. 80-87, 2006.
- [25] Q. K. Jahanger, J. Louis, C. Pestana, and D. Trejo, "Potential positive impacts of digitalization of construction-phase information management for project owners," *Journal of Information Technology in Construction (ITcon)*, vol. 26, no. 1, pp. 1-22, 2021.
- [26] J. Radl, and J. Kaiser, "Benefits of implementation of common data environment (CDE) into construction projects," In Proc. *IOP Conference Series: Materials Science and Engineering*, Feb 2019, vol. 471, no. 2, p. 022021.
- [27] C. Preidel, A. Borrmann, C. H. Oberender, and M. Tretheway, (2016). "Seamless integration of common data environment access into BIM authoring applications: The BIM integration framework," *E-work and Ebusiness in architecture, engineering and construction*, 2016.
- [28] C. Preidel, A. Borrmann, H. Mattern, M. König, and S.E. Schapke, "Common data environment," *Building Information Modeling* Springer, 2018, pp. 279-291.

- [29] D. Bucher and D. M. Hall, "Common Data Environment within the AEC Ecosystem: moving collaborative platforms beyond the open versus closed dichotomy," In Proc. EG-ICE 2020: Workshop on Intelligent Computing in Engineering, Universitätsverlag der TU Berlin, Germany, 1-4 July 2020, pp. 491-500.
- [30] A. Redmond, A. Hore, M. Alshaw, and R. West, "Exploring how information exchanges can be enhanced through Cloud BIM," *Automation in construction*, vol. 24, pp. 175-183, 2012.
- [31] J. Du, R. Liu, and R. R. Issa, "BIM cloud score: benchmarking BIM performance," *Journal of Construction Engineering and Management*, vol. 140, no.11, 04014054, 2014.
- [32] K. Sulankivi, "Benefits of centralized digital information management in multipartner projects," *Journal of Information Technology in Construction (ITcon)*, vol. 9, no.3, pp. 35-63, 2004.
- [33] K. Duffy, B. Graham, and K. Thomas, "Assessing the potential for construction collaboration technologies (CCT) in small to medium enterprises in the Irish construction industry," In: Boyd, D (Ed) Proc. 23rd Annual ARCOM Conference, 3-5 Sept. 2007, Belfast, UK, Association of Researchers in Construction Management, pp. 461-468.
- [34] N. M. El-Gohary and T. E. El-Diraby, "Dynamic knowledge-based process integration portal for collaborative construction," *Journal of Construction Engineering and Management*, vol. 136, no. 3, pp. 316-328, 2010.
- [35] N. Berente, R. Baxter, and K. Lyytinen, "Dynamics of inter-organizational knowledge creation and information technology use across object worlds: the case of an innovative construction project," *Construction Management and Economics*, vol. 28, no.6, pp. 569-588, 2010.

- [36] A. Redmond and R. West, "The use of cloud enabled building information models-an expert analysis," *The Australasian Journal of Construction Economics and Building*, vol. 12, no. 4, pp. 53-67, 2012.
- [37] S. Zhang, F. Pan, C. Wang, Y. Sun, and H. Wang, "BIM-based collaboration platform for the management of EPC projects in hydropower engineering," *Journal of Construction Engineering and Management*, vol. 143, no. 12, 04017087, 2017.
- [38] H. Wang and X. Meng, "BIM-Supported Knowledge Management: Potentials and Expectations," *Journal of Management in Engineering*, vol. 37, no. 4, p.04021032, 2021.
- [39] E. Alreshidi, M. Mourshed, and Y. Rezgui, "Factors for effective BIM governance," *Journal of Building Engineering*, vol. 10, pp. 89-101, 2017.
- [40] R. A. Stewart, S. Mohamed, and M. Marosszeky, "An empirical investigation into the link between information technology implementation barriers and coping strategies in the Australian construction industry," *Construction Innovation*, vol. 4, no. 3, pp. 155-171, 2004.
- [41] V. Peansupap and D. Walker "Factors affecting ICT diffusion: a case study of three large Australian construction contractors," *Engineering, construction and architectural management*, vol. 12, no. 1, pp. 21-37, 2005.
- [42] V. Ahuja, J. Yang, and R. Shankar "Perceptions affecting ict adoption for building project management in the Indian construction industry," *International Journal of Construction Management*, vol. 10, no.2, pp.1-18, 2010.
- [43] A. Alaghbandrad, E. Asnaashari, C. Preece, "Problems and barriers of ICT utilization on Iranian construction sites: Case study on the successful use of ICT in remote construction sites," *Journal of Information Technology in Construction (ITcon)*, vol. 17, no. 6, pp. 93-102, 2012.

- [44] A. O. U. Ozumba and Q. Shakantu, "Exploring challenges to ICT utilisation in construction site management," *Construction Innovation*, vol. 18, no. 3, pp. 321-349, 2018.
- [45] Ž Turk, "Structured analysis of ICT adoption in the European construction industry," *International Journal of Construction Management*, pp. 1-7, 2021. Available: <https://doi.org/10.1080/15623599.2021.1925396>.
- [46] P. Nitithamyong and M. J. Skibniewski, "Web-based construction project management systems: how to make them successful?, " *Automation in construction*, vol. 13, no. 4, pp. 491-506, 2004.
- [47] A. Adriaanse, H. Voordijk, and G. Dewulf, "Adoption and use of interorganizational ICT in a construction project," *Journal of construction engineering and management*, vol. 136, no. 9, pp. 1003-1014, 2010.
- [48] J. L. Vaughan, M. L. Leming, M. Liu, and E. Jaselskis, "Cost-benefit analysis of construction information management system implementation: Case study," *Journal of Construction Engineering and Management*, vol. 139, no. 4, pp. 445-455, 2013.
- [49] A. Hasan, S. Ahn, R. Rameezdeen, and B. Baroudi, "Empirical study on implications of mobile ICT use for construction project management.," *Journal of Management in Engineering*, vol. 35, no. 6, p.04019029, 2019.
- [50] Y. Lu, Y. Li, M. Skibniewski, Z. Wu, R. Wang, and Y. Le, "Information and communication technology applications in architecture, engineering, and construction organizations: A 15-year review," *Journal of Management in Engineering*, vol. 31, no. 1, p.A4014010, 2015.
- [51] S. Subashini, and V. Kavitha, "A survey on security issues in service delivery models of cloud computing," *Journal of network and computer applications*, vol. 34, no. 1, pp. 1-11, 2011.

- [52] P. Mell, and T. Grance, *The NIST definition of cloud computing*, 2011, NIST Spec. Publ. 800, 7.
- [53] K. Afsari, C.M. Eastman, and D.R. Shelden, “Cloud-based BIM data transmission: current status and challenges,” In Proc. of the International Symposium on Automation and Robotics in Construction, 2016, vol. 33, p. 1.
- [54] K. L. Mugumya, J. Y. Wong, A. Chan, and C. C. Yip "The Role of Linked Building Data (LBD) in Aligning Augmented Reality (AR) with Sustainable Construction,” *International Journal of Innovative Technology and Exploring Engineering*, vol. 8, no. 64, pp. 366-372, 2019. Available: 10.35940/ijitee.f1074.0486s419 [Accessed: 20 Dec. 2021].
- [55] D. Reed, “Eight-stage guide to implementing BIM on a project,” *The Structural Engineer: Journal of the Institution of Structural Engineer*, vol. 95, no. 7, pp. 28-30, 2017.
- [56] B. Duguid, J. Hyde, and H. Pullan, “The Ordsall Chord, Manchester, UK–digital delivery of design,” In *IABSE Symposium Report*, 2017, vol. 109, no. 41, pp. 1566-1573.
- [57] M. Mohsen, S. Albitar, M. Essam, and A. Radwan, “Necessity of monitoring vital BIM information for optimized design process management,” *WIT Transactions on The Built Environment*, vol. 192, pp. 81-91, 2019.
- [58] M. T. Shafiq, “A case study of client driven early BIM collaboration,” In Annual Conference Canadian Society for Civil Engineering, 2019, Laval, Canada.
- [59] C. Staples, and J. Spillane, “Exploring the potential improvement of quality control in the construction industry with the use of digital technology,” In Proc. 35th Annual ARCOM Conference, 2-4 Sept. 2019, Leeds, UK, Association of Researchers in Construction Management, pp. 406-415.

- [60] M. Zanni, K. Ruikar, and R. Soetanto, "Systematising multidisciplinary sustainable building design processes utilising BIM," *Built Environment Project and Asset Management*, vol. 10, no. 5, pp. 637-655, 2020.
- [61] C. Vite, A. S. Horvath, G. Neff, and N. L. H. Møller, "Bringing human-centredness to technologies for buildings: An agenda for linking new types of data to the challenge of sustainability," In *CHIItaly 2021: 14th Biannual Conference of the Italian SIGCHI*, 2021, pp. 1-8.
- [62] P. Mayer, T. Funtík, J. Gašparík, and P. Makýš, "Analysis of the Current State of Automation of Hazard Detection Processes in BIM in Slovakia," *Applied Sciences*, vol. 11, no. 17, p.8130, 2021.
- [63] M. Taylor, "Crossrail project: building a virtual version of London's Elizabeth line," In *Proc. of the Institution of Civil Engineers-Civil Engineering*, 2017, vol. 170, no. 6, pp. 56-63.
- [64] J. Sherry, "Digital engineering enables multinational input on Bergen's light rail extension, Norway," In *Proc. Institution of Civil Engineers-Civil Engineering*, 2018, vol. 171, no. 5, pp. 49-56.
- [65] R. Dickenson and B. Harland, Digital engineering on the Sydney Metro, In *Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art*, pp. 2043-2050, CRC Press, 2019. [E-book] ISBN: 9780429424441
- [66] A. Pili, "BIM process, ontologies and interchange platform for cultural architectural heritage management: State of art and development perspectives," In *2nd International Conference of Geomatics and Restoration*, Milan, Italy, pp. 969-973, 8-10 May 2019. Available: <https://doi.org/10.5194/isprs-archives-XLII-2-W11-969-2019>

- [67] R. Pontrandolfi, "Multiscale GIS-BIM methodological approaches and digital systems for the knowledge of the modern architectural heritage in Italy. the rural village "la Martella" in matera," In the International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. 44, pp. 279-286, 9-12 Sept. 2020. Available: <https://doi.org/10.5194/isprs-archives-XLIV-M-1-2020-279-2020>
- [68] J. E. Nieto-Julián, L. Lara, and J. Moyano, "Implementation of a TeamWork-HBIM for the Management and Sustainability of Architectural Heritage," *Sustainability*, vol. 13, no. 4, p. 2161, 2021.
- [69] R. Brumana, R. C. Stanga, F. Banfi, "Models and scales for quality control: toward the definition of specifications (GOA-LOG) for the generation and re-use of HBIM object libraries in a Common Data Environment," *Applied Geomatics*, pp.1-29, 2021. Available: <https://doi.org/10.1007/s12518-020-00351-2>
- [70] M. L. A. Trani, and M. Ruschi, "Cross Information Improvement for an H-BIM Common Data Environment," 2021, In Ioannides M., Fink E., Cantoni L., Champion E. (eds) Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection, EuroMed 2020, *Lecture Notes in Computer Science*, vol. 12642. Springer, Cham. https://doi.org/10.1007/978-3-030-73043-7_55
- [71] E. U. R. Khawaja and A. Mustapha, "Mitigating Disputes and Managing Legal Issues in the Era of Building Information Modelling," *Journal of Construction in Developing Countries*, vol. 26, no. 1, pp. 111-130, 2021.
- [72] A. Tao, X. M. Das, Y. Liu, and J. C. Cheng, "Distributed common data environment using blockchain and Interplanetary File System for secure BIM-based collaborative design," *Automation in Construction*, vol. 130, p.103851, 2021. Available: <https://doi.org/10.1016/j.autcon.2021.103851>

- [73] E. A. Parn and D. Edwards, "Cyber threats confronting the digital built environment: Common data environment vulnerabilities and block chain deterrence," *Engineering, Construction and Architectural Management*, vol. 26, no. 2, pp. 245-266, 2019.
- [74] The KPI Working Group, "KPI Report for the Minister for Construction", Department of the Environment, Transport and the Regions, Norwich, London, Tech. Report., Jan. 2000.
- [75] A. P. C. Chan and A. P. L. Chan, "Key performance indicators for measuring construction success," *Benchmarking: an international journal*, vol. 11, no. 2, pp. 203-221, 2004. Available: <https://doi.org/10.1108/14635770410532624>.
- [76] R. A. Mohsini and C. H. Davidson "Determinants of performance in the traditional building process," *Construction Management and Economics*, vol. 10, no. 4, pp. 343-359, 1992.
- [77] M. Kagioglou, R. Cooper and G. Aouad, "Performance management in construction: a conceptual framework," *Construction management and economics*, vol. 19, no. 1, pp. 85-95, 2001.
- [78] H. Yang, J. F. Yeung, A. P. Chan, Y. H. Chiang and D. W. Chan, "A critical review of performance measurement in construction," *Journal of Facilities Management*, vol. 8, no. 4, pp. 269-284, 2010. Available: <https://doi.org/10.1108/14725961011078981>
- [79] M. Khanzadi, M. Sheikhhoshkar and S. Banihashemi, "BIM applications toward key performance indicators of construction projects in Iran," *International Journal of Construction Management*, vol. 20, no. 4, pp. 305-320, 2020.
- [80] H. S. Cha and C.K. Kim, "Quantitative approach for project performance measurement on building construction in South Korea. KSCE," *Journal of Civil Engineering*, vol. 15, no. 8, pp. 1319-1328, 2011.

- [81] N. Nassar and S. AbouRizk, "Practical application for integrated performance measurement of construction projects," *Journal of Management in Engineering*, vol. 30, no. 6, p.04014027, 2014.
- [82] J. G. Vargas-Hernández, "Strategic Organizational Sustainability," *Circular Economy and Sustainability*, pp. 1-19, 2021. Available: <https://doi.org/10.1007/s43615-020-00003-y>
- [83] "Construction Management Software | Autodesk BIM 360", *BIM 360*, 2021. [Online]. Available: <https://www.autodesk.com/bim-360/>. [Accessed: 08 Jan.2021].
- [84] "About Viewpoint United Kingdom", *Trimble Viewpoint*, 2021. [Online]. Available: <https://www.viewpoint.com/en-gb/company/about?redirected=y>. [Accessed: 09 Jan. 2021].
- [85] "Aconex - Construction Project Controls Software | Oracle Türkiye", *Oracle.com*, 2021. [Online]. Available: <https://www.oracle.com/tr/industries/construction-engineering/aconex-project-controls/>. [Accessed: 10 Jan. 2021].
- [86] "Asite, cloud collaboration system for seamless collaboration across disciplines.", *Asite.com*, 2021. [Online]. Available: <https://www.asite.com/>. [Accessed: 04 Jan. 2021].
- [87] "Document Management Software | ProjectWise | Bentley Systems", *Bentley.com*, 2021. [Online]. Available: <https://www.bentley.com/en/products/brands/projectwise>. [Accessed: 5 Jan. 2021].
- [88] "ISETIA", *ISETIA*, 2021. [Online]. Available: <https://isetia.com/>. [Accessed: 23 Jan. 2021].
- [89] J. Liker, *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*, McGraw-Hill, New York, NY, 2004.

- [90] A. Sourani and M. Sohail, "The Delphi Method: Review and use in construction management research," *International Journal of Construction Education and Research*, vol. 11, no. 1, pp. 54–76, Jan. 2015.
- [91] M.R. Hallowell, J.A. Gambatese, "Qualitative research: application of the Delphi method to CEM research," *J. Construct. Eng. Manag.* Vol. 136, no. 1, pp. 99–107, 2010. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000137](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000137).
- [92] A. Field, *Discovering statistics using SPSS*, 3rd ed., London, Sage Publications, 2009.
- [93] T.O. Olawumi, D.W.M. Chan, "Identifying and prioritizing the benefits of integrating BIM and sustainability practices in construction projects: a Delphi survey of international experts," *Sustain. Cities Soc.*, vol. 40, pp. 16–27, 2018. <https://doi.org/10.1016/j.scs.2018.03.033>.
- [94] N. C. Dalkey, "The Delphi method: an experimental study of group opinion", The Rand Corporation, Santa Monica, California, Tech. Report. 1-18, 1969.
- [95] B. Giel and R. R. Issa, "Framework for evaluating the BIM competencies of facility owners," *Journal of management in engineering*, vol. 32, no.1, p.04015024, 2016.
- [96] T. Grisham, "The Delphi technique: a method for testing complex and multifaceted topics," *International Journal of Managing Projects in Business*, vol. 2, no. 1, pp. 112-130, 2009. Available: <https://doi.org/10.1108/17538370910930545>.
- [97] P. M. Mullen, "Delphi: myths and reality," *Journal of health organization and management*, vol. 17, no. 1, pp. 37-52, 2003. Available: <https://doi.org/10.1108/14777260310469319>
- [98] M. Turoff, "The design of a policy Delphi. *Technological forecasting and social change*," vol. 2, no. 2 pp. 149-171, 1970.

- [99] R. D. Brown and N. M. A. Hauenstein, "Interrater agreement reconsidered: An alternative to the rwg Indices. *Organizational Research Methods*," vol. 8, no. 2, pp. 165–184, 2005. Available: [http:// dx.doi.org/10.1177/1094428105275376](http://dx.doi.org/10.1177/1094428105275376).
- [100] J.M. Lebreton, J.L. Senter, "Answers to 20 questions about interrater reliability and interrater agreement," *Organ. Res. Methods*, vol. 11, no. 4, pp. 815–852, 2008. Available: <https://doi.org/10.1177/1094428106296642>.
- [101] S. Seyis, "Pros and cons of using building information modeling in the AEC industry," *Journal of Construction Engineering and Management*, vol. 145, no. 8, p.04019046, 2019.
- [102] S. Seyis, "Mixed method review for integrating building information modeling and life-cycle assessments," *Building and Environment*, vol. 173, p.106703, 2020. Available: <https://doi.org/10.1016/j.buildenv.2020.106703>.
- [103] H. Li, S.T. Ng and M. Skitmore, "Evaluating stakeholder satisfaction during public participation in major infrastructure and construction projects: a fuzzy approach," *Automation in Construction*, vol. 29, pp. 123–135, 2013. Available: <https://doi.org/10.1016/j.autcon.2012.09.007>.
- [104] M. Richards, "Building information management: a standard framework and guide to BS 1192," BSI Standards, London, 2010. <http://app.knovel.com/hotlink/toc/id:kpBIMASFG1/building-information-management>.
- [105] "Digital Builder - Autodesk's Construction Blog", Digital Builder, 2021. [Online]. Available: <https://constructionblog.autodesk.com/>. [Accessed: 23 Feb. 2021].
- [106] J. Lee and L. E. Bernold, "Ubiquitous agent-based communication in construction," *Journal of Computing in Civil Engineering*, vol. 22, no. 1, pp. 31-39, 2008.

- [107] Z. M. Deng, H. Li, C. M. Tam, Q. P. Shen and P. E. D. Love, "An application of the Internet-based project management system," *Automation in construction*, vol. 10, no. 2, pp. 239-246, 2001.
- [108] T. Dowd and D. Marsh, "The future of BIM: digital transformation in the UK construction and infrastructure sector," Royal Institution of Chartered Surveyors (RICS), London, Insight paper, 2020.
- [109] P. F. Drucker, "Managing for business effectiveness," *Harvard Business Review*, vol. 41, no. 3, pp. 53–60, 1963.
- [110] H. W. Heinrich, *Industrial accident prevention: A scientific approach*, 2nd ed., McGraw-Hill, New York, 1941.
- [111] A. Pradhan and B. Akinci, "Planning-based approach for fusing data from multiple sources for construction productivity monitoring," *Journal of computing in civil engineering*, vol. 26, no. 4, pp. 530-540, 2012.
- [112] J. Patacas, N. Dawood and M. Kassem, "BIM for facilities management: A framework and a common data environment using open standards," *Automation in Construction*, vol. 120, p.103366, 2020.
- [113] H. Jallow, S. Renukappa and S. Suresh, "Knowledge Management and Artificial Intelligence (AI)," In Proc. ECKM 2020 21st European Conference on Knowledge Management, 2-4 Dec. 2020, pp. 363-374.
- [114] M. T. Al Nahyan, A. Sohal, Y. Hawas and B. Fildes, "Communication, coordination, decision-making and knowledge-sharing: a case study in construction management," *Journal of Knowledge Management*, vol. 23, no. 9, pp. 764-1781, 2019.
- [115] M. J. Skibniewski and S. Ghosh, "Determination of key performance indicators with enterprise resource planning systems in engineering construction firms," *Journal of construction engineering and management*, vol. 135, no. 10, pp. 965-978, 2009.

- [116] G. B. Ozturk, “Interoperability in building information modeling for AECO/FM industry,” *Automation in Construction*, vol. 113: 103122, 2020.
- [117] JB Knowledge, “The annual Construction Technology Report”, 10th ed., 2021.
[Online] Available: <https://contechreport.com/> [Accessed: 6 Nov. 2021]
- [118] W. Shen et al., “Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review,” *Advanced Engineering Informatics*, vol. 24, no. 2, pp. 196–207, 2010.
- [119] A. Rajat, C. Shankar, and S. Mukund, “Imagining construction’s digital future,” McKinsey Productivity Sciences Center, Singapore, Jun. 2016.
- [120] openBIM - buildingSMART International", buildingSMART International, 2022.
[Online]. Available: <https://www.buildingsmart.org/about/openbim/>. [Accessed: 15 Nov. 2021].

VITA

Selen Ozkan received her Bachelor of Science degree in Civil Engineering at Dokuz Eylül University, in 2018. Following her graduation, she started pursuing a Master of Science degree in Civil Engineering at Özyeğin University under the supervision of Dr. Senem Seyis. She is currently working as a research assistant at Özyeğin University. Her research interests include building information modeling (BIM), common data environments (CDEs), and construction project management.

Education

Master of Science in Civil Engineering at Özyeğin University, December, 2021.

Bachelor of Science in Civil Engineering at Dokuz Eylül University, July, 2018.

Publications

S. Ozkan and S. Seyis, “Identification of common data environment functions during construction phase of BIM-based projects,” In *Proceedings of the 38th International Conference of CIB W78*, 13-15 October 2021, Luxembourg, pp. 253-262 (ISSN: 2706-6568). Available: <http://itc.scix.net/paper/w78-2021-paper-026>. [Accessed: 19 Nov. 2021].

Certificates

Certificate of Expertise – International Construction Contracts and Claims Management Certificate Program, İstanbul Technical University, November 2021.

Awards

Design together with BIM Competition at ITU– First place award, February, 2020.