www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

ANALYZING THE ADDED VALUE OF COMMON DATA ENVIRONMENTS FOR ORGANIZATIONAL AND PROJECT PERFORMANCE OF BIM-BASED PROJECTS

SUBMITTED: November 2022
REVISED: October 2023
PUBLISHED: April 2024
EDITOR: Esther Obonyo
DOI: 10.36680/j.itcon.2024.012

Senem Seyis, Ph.D., Assistant Professor
Department of Civil Engineering, Faculty of Engineering, Özyeğin University
senem.seyis@ozyegin.edu.tr

Selen Özkan, M.Sc., Graduate Student
Department of Civil Engineering, Faculty of Engineering, Özyeğin University
selen.ozkan@ozu.edu.tr

SUMMARY: *Using common data environments (CDEs) adds value to BIM-based construction projects' organizational and project performance. However, CDEs are used very limitedly in the construction industry. One of the reasons for the limited implementation of CDEs can be associated with the need for construction companies' knowledge about the positive impacts of CDEs on performance management. A well-structured CDE can provide countless benefits and promote long-term improvements in construction projects and organizations, increasing their business success. Despite the acknowledged importance of CDEs, research needs to investigate the impacts of CDEs on project and organizational performance considering the construction KPIs. This study aims to reveal (1) how the CDEs facilitate performance measurement in the construction phase of BIM-based projects and (2) how the CDEs positively affect the project and organizational performance in the construction phase of BIM-based projects. This scope uses seven construction KPIs: time, cost, quality, safety, productivity, organizational sustainability, and client satisfaction. This study conducts a systematic literature review, semi-structured interviews with five subject-matter experts, and the two-rounded Delphi method to fulfill the research objective. The results show that implementing the CDEs in the construction phase of BIM-based projects positively affects productivity, quality, and time KPIs, followed by organizational sustainability, cost, client satisfaction, and safety, respectively. This research contributes to collating and uncovering the added value of CDEs for the organizational and performance management of BIM-based projects. Accordingly, this study would increase the awareness of construction companies about 'how they can benefit from the data located in the CDEs from project management through knowledge management in the best way.'*

KEYWORDS: *Performance Management, Project Management, Performance Measurement, CDE, Building Information Modeling, Information Management, Construction*

REFERENCE: *Senem Seyis, Selen Özkan (2024). Analyzing the added value of common data environments for organizational and project performance of BIM-based projects. Journal of Information Technology in Construction (ITcon), Vol. , pg. 247-263, DOI: 10.36680/j.itcon.2024.012*

1. INTRODUCTION

1.1 Research background

Numerous stakeholders from different disciplines are involved in construction projects requiring effective project management for successful execution. The practical and timely exchange of information and knowledge among multiple project participants is crucial for project success (Grau et al., 2012). Al Nahyan et al. (2019) emphasized the critical management processes such as communication, coordination, decision-making, and knowledge management that contribute to the performance of construction projects. In all these key management processes, information plays a vital role that shows the construction industry is information-intensive (Matthews et al., 2015) and information-dependent (Martínez-Rojas et al., 2016). However, the information required for executing works is kept in various formats (e.g., spreadsheets, drawings, documents, and photographs) and even in the verbal form in the construction industry (Martínez-Rojas et al., 2016). Accordingly, excessive, complex, discrete data saved in separate databases, software, and hardcopies may hinder data transformation into information and make data interpretation and benchmarking almost impracticable. Therefore, specific project information, such as who and when did the task, how long did it take to complete, or the measures, including the response durations in review/approval processes, root causes and statistics of the accidents as well as common causes of the defects and reworks, may not be obtainable. For this reason, performance measurement in the construction industry is a challenging task.

The UK best practice program launched the key performance indicators (KPIs) for construction projects to facilitate performance measurement. KPIs are the measurement tools that are used for evaluating the performance of a project (The KPI Working Group, 2000, Chan and Chan, 2004), organization (The KPI Working Group, 2000, Chan and Chan, 2004), and process (Haponava and Al-Jibouri, 2012). KPIs give information about the construction activities' performance (Autodesk, 2023). However, tracking these indicators could be time- and resource-consuming and require simple, standardized data collection (Chan and Chan, 2004), especially in projects executed in traditional ways. The challenges of successful performance measurement were explained by the previous researchers (Formoso and Lantelme, 2000, Lantelme and Formoso, 2000, Kagioglou et al., 2001, Costa and Formoso, 2003, Beatham et al., 2004) (Table 1). Some of these challenges are decentralized performance measurement systems (Costa and Formoso, 2003) as well as the availability and validity of data (Kagioglou et al., 2001). These challenges prove a strong relationship between performance measurement and information management which are the foundations of successful performance management at the project and organizational levels.

Table 1: Challenges related to performance measurement in construction projects.

References	Challenges related to the performance measurement in construction projects
Kagioglou et al. 2001	• Concerns related to the availability and validity of data
Beatham et al. 2004	• The use of KPIs for historical review at the end of the project rather than providing real-time control during project execution
Costa and Formoso 2003	• Decentralized performance measurement systems • Lack of automated data collection • Infrequent utilization of the information and measures to support decision-making • Ineffective communication and dissemination of the results
Formoso and Lantelme (2000), Lantelme and Formoso (2000)	• Selecting the measures that are easy to collect due to the insufficient resources for data collection and data processing • Unknowingness of construction managers about the benefits of a fully developed performance measurement system and generally focus on short-time results

1.2 Research gap

The construction industry's information technologies (ITs) use has increased exponentially in recent years. These technologies considerably aid in construction performance measurement and management. Building information modeling (BIM) supported by common data environments (CDEs), which can considerably improve project

performance by enabling efficient information management, becomes highly important in this scope. BIM is *"a digital representation of the building process to facilitate exchange and interoperability of information in digital format"* (Charles Eastman, 1999). Therefore, BIM helps architects, engineers, and constructors visualize what is to be built in a simulated environment to identify any potential design, construction, or operational issues (Seyis, 2019). On the other hand, ISO 19650-1 defines the common data environment as an *"agreed source of information for any given project or asset, for collecting, managing, and disseminating each information container through a managed process"* (International Organization for Standardization, 2019). The information (i.e., the 'I' in BIM) is valuable for all processes throughout the project life cycle (Dowd and Marsh, 2020) and the organization. Therefore, using CDEs in BIM-based construction projects ensures standardized and centralized data collection, on-time access to accurate data, data-driven decision-making, active project control, and practical knowledge management. For this reason, integrating BIM and CDEs is essential in minimizing the drawbacks related to information management, performance measurement, and management.

However, the positive impacts of CDEs in performance management are not extensively known and adopted by construction companies due to considering CDEs only as digital information repositories. Many researchers agree that CDEs are more than a digitalized information repository and exchange platform (Simeone et al., 2020; Stransky, 2020; Losev, 2020; Özkan and Seyis, 2021; Akob et al., 2019). In a well-structured CDE, based on international regulatory norms (e.g., BS PAS 1192; ISO 19650-1), information management can be standardized, and higher levels of project management performance can be achieved. Previous studies generally focus on the characteristics (Akob et al., 2019; Losev, 2020; Simeone et al., 2020), functions (Stransky, 2020; Özkan and Seyis, 2021), benefits (Özkan and Seyis, 2021), and challenges (Afolabi et al., 2018; Wong et al 2014) of CDE implementation. However, most of these studies are conference proceedings with little literature background and remain incapable of revealing the improvements and relation between CDEs and performance management. Moreover, no research investigates the impacts of CDEs on project and organizational performance considering the construction KPIs. These shortcomings in the current literature show the need for comprehensive research investigating the impacts of CDEs on the organizational and performance management of BIM-based projects.

1.3 Research objective

The objectives of this research are to (1) reveal how the CDEs facilitate performance measurement in the construction phase of BIM-based projects and (2) how CDEs positively affect the project and organizational performance in the construction phase of BIM-based projects by considering seven construction KPIs (i.e., time, cost, quality, safety, productivity, organizational sustainability, and client satisfaction). For this purpose, a mixed methodological approach, consisting of a systematic literature review, semi-structured interviews, and the Delphi Method, was conducted. This study contributes to the architecture, engineering, and construction (AEC) literature by uncovering the impacts of CDEs on performance management in the construction phase of BIM-based projects. Further, the research would increase the awareness of construction companies about 'how they can benefit from the data in the CDEs.

2. RESEARCH METHODOLOGY

This study performs a mixed-method approach which consists of a systematic literature review, semi-structured interviews, and the two-round Delphi Method. This approach allows the authors to analyze the added value of CDEs for the project and organizational performance of BIM-based projects qualitatively and quantitatively.

2.1 Literature review

The reason for using a systematic literature review as a research method is to collate and criticize former works addressing performance measurement and management in the construction industry and to identify significant construction KPIs. The Scopus and Web of Science databases were used to prevent missing publications on the subject domain. The keywords used in reviewing the literature are "performance measurement," "performance management," "performance indicator," "key performance indicators," "KPI," "construction performance," "project performance," "organizational performance," "construction sector," "building industry," "building sector," AND "construction industry" within the title, abstract, and keywords. The articles, conference proceedings, and book chapters, which were published between 2000 and May 2023, were considered in the review. One hundred twenty-three publications were found in total, considering these criteria. The articles were sorted based on their

citations from highest to lowest. In the review, the manual exclusion criteria are to eliminate (1) non-English documents and (2) documents that need to address construction KPIs as well as performance and organizational management in the construction industry. According to the manual exclusion criteria, 12 publications addressing the subject domain were selected. These twelve publications were utilized to prepare the questionnaire.

2.2 Interviews

The reason for performing semi-structured interviews is to obtain the professionals' opinions about the impacts of CDEs on project and organizational performance in the construction phase of BIM-based projects. The interviewees were selected based on their experience (i.e., at least ten years in the construction industry and at least five years in implementing ICT and/or IT and/or CDEs) and their profession. Five subject matter experts participated in the semi-structured interviews. Two of the interviewees work as Digital Transformation Expert in the construction industry. One is a Civil Engineer with a BSc degree, whereas the other is an Electric and Electronics Engineer with both BSc and MBA degrees. One of the interviewees works as a BIM Consultant, is a Mechanical Engineer, and has BSc and MBA degrees. Another interviewee works as a BIM Manager and has an MSc in Architecture. The other interviewee works as a BIM Consultant and has a BSc in Mechanical Engineering. Four of the interviewees' roles in using CDEs are Consultant and work at consultancy companies.

The other interviewee's role is the Leader at an engineering company. Four of the interviewees are from Turkey, and one of them is from Canada. Additionally, interviewees have experiences in several countries, such as Azerbaijan, England, France, United Arab Emirates (UAE), Kuwait, and Qatar. The interviewees' experiences in BIM-based projects are between six and nineteen years, while their experiences in construction are between eleven and twenty-six years. Additionally, their experience in using CDEs is between six and fifteen years. Four of the interviews were conducted using online platforms, from forty-five minutes to ninety minutes, and one of the interviewees delivered the answers in written form due to the Covid-19 pandemic. The interviews included open-ended questions divided into four topics: information management in the construction industry, common data environments, construction key performance indicators, and the relationship between CDEs and construction project and performance regarding construction KPIs, respectively.

2.3 The Delphi Method

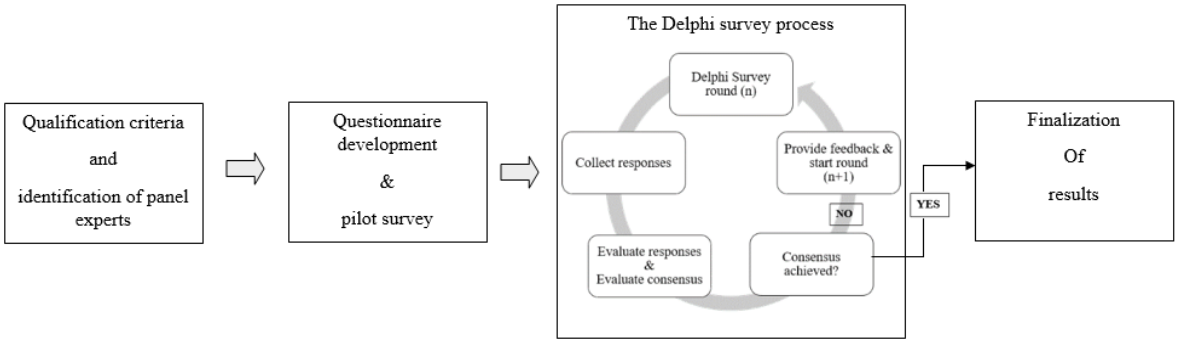

Figure 1: Procedure of the Delphi Method.

The Delphi method analyzes the impacts of CDE benefits on the construction project and organizational performance based on seven KPIs (i.e., time, cost, quality, safety, productivity, organizational sustainability, and client satisfaction). The Delphi method is a systematic research technique that ensures reaching a consensus on a subject domain among predetermined independent panel experts (Sourani and Sohail, 2015). This research technique is mainly utilized without empirical evidence or objective data (Hallowell and Gambatese, 2010). The Delphi method differs from the standard surveys by providing anonymous and controlled feedback from the panel experts conducted in multiple rounds (Hallowell and Gambatese, 2010). Figure 1 presents the procedure of the Delphi method.

2.3.1 Qualification criteria and identification of panel experts

The qualifications of panel experts play an essential role in acquiring valid and reliable findings on the topic. Hence, selecting panel experts should be done carefully to ensure sufficient experience and knowledge of the

subject domain (Hallowell and Gambatese, 2010). In this study, the panel experts were expected to (1) have experience and knowledge in BIM and CDEs, (2) have at least a Bachelor's degree in AEC industry-related fields, (3) hold an industry position as a BIM consultant, BIM coordinator, BIM manager, or BIM director, or a relevant position, and (4) have at least five years of experience in the construction industry, at least three years of experience in the BIM-based projects, and at least three years of experience in the CDEs. Based on these qualifications, an invitation was sent to 119 geographically dispersed experts through the LinkedIn platform. While between seven (Mullen, 2003) and fifty (Turaoff, 1970) participants can be involved in the Delphi survey, previous research highlighted that 8–12 qualified panel participants should involve in the Delphi process to achieve valid and reliable results (Hallowell and Gambatese, 2010). In the research, 17 experts participated in the first round, while twelve experts participated in the second round.

For this reason, the responses of twelve experts who contributed to both rounds of the Delphi method were analyzed. One of the experts is from Austria, one of them is from England, one expert is from Germany, one expert is from Italy, one is from Greece, one is from the Netherlands, three experts are from the United Arab Emirates, and two of them are from Turkey. Their experience in the construction industry and BIM-based projects is between eight and twenty-eight years. Additionally, their experience in the CDEs is between four and twenty-eight years. Two of the experts have Ph.D. degrees, eight of them have MSc degrees, and two of them have BS degrees. One expert who has a Ph.D. degree is Performance Assessor and works as a Director. Another expert with a Ph.D. in Architectural Engineering works as an Information Manager. Three experts have an MSc in Civil Engineering work as BIM Managers. The other expert having MSc in Civil Engineering, works as a BIM Coordinator. Another expert having MSc in Civil Engineering, works as a Construction Manager. One of the experts has an MSc in Architecture and works as a BIM MEP Coordinator. Another expert has an MSc in Architecture and works as a BIM and System Manager. The other expert has an MSc in Architecture and works as a Design Coordinator. One of the experts has a BSc degree in Civil Engineering and works as a BIM Manager, while the other works as a BIM Coordinator. It should be noted that the anonymity of the panel experts was ensured, as a requirement for the Delphi method, while providing feedback and sending the request for the survey.

CDEs & project and organizational performance matrix		Construction KPIs						
		Time	Cost	Quality	Safety	Productivity	Organizational Sustainability	Client Satisfaction
CDE benefits under Toyota's 4P Model	Problem Solving	Ranking based on five-point likert scale						
	People and Partners							
	Process							
	Philosophy							

Figure 2: CDEs & project and organizational performance matrix.

2.3.2 Questionnaire development & pilot survey

The Delphi questionnaire was prepared to analyze the positive impacts of CDEs on project and organizational performance in the construction phase of a BIM-based project. The CDE benefits (Seyis and Özkan, 2023) are included in the Delphi questionnaire, and leading construction KPIs (i.e., time, cost, quality, safety, productivity, organizational sustainability, and client satisfaction) were obtained from the literature review. In the previous study of the authors, 54 benefits of using CDEs in the construction phase of BIM-based projects were identified and categorized under Toyota's 4P Model (Liker, 2004) (process (PRs), problem-solving (PSs), people and partners (PPs), philosophy (PHs)) based on their prominent attributes (Seyis and Özkan, 2023). The reason for this categorization is that the impacts of CDE benefits on project and organizational performance may vary from one to another. The list of the benefits was shared with the panel experts. They were asked to evaluate the positive impacts of CDE benefits on the project and organizational performance under four categories of Toyota's 4P Model,

considering the following question: "To what extent do the benefits, under each subcategory (e.g., problem-solving), affect the presented KPIs?".

The pilot questionnaire was tested with the participation of two industry professionals, who have Ph.D. degrees and more than 15 years of experience in the construction industry, to validate the structure of the survey. The panel experts were asked to score the questionnaire, which consists of CDEs & project and organizational performance (CPOP) matrix (Figure 2). The participants scored the matrix using a five-point Likert scale. In this scale, five corresponds to 'high positive effect,' four corresponds to 'positive effect,' three corresponds to 'moderate positive effect,' two corresponds to 'a slight positive effect.' One corresponds to a 'without any positive effect. 'For example, survey participants think that the benefits listed under the 'process' category have a high positive effect on the 'cost' KPI of the project. In that case, they give 'five' points to this criterion. On the contrary, the participants give 'one' point if they think there is no positive effect on the 'cost' KPI.

2.3.3 The Delphi survey process

The Delphi survey was generated and distributed using an online questionnaire platform which is Jotform. The Delphi questionnaire was started on July 23, 2021, and completed on October 21, 2021. The mean, median, and standard deviations were calculated based on the scores collected in each round. Mean and median values were calculated to examine central tendency (Dalkey, 1969), while the standard deviation, expected to decrease in each round, was utilized to assess the consensus achieved among panel experts (Hallowell and Gambatese, 2010). Table 3 presents the results of the Delphi method (i.e., the mean, median, standard deviation, IRA, significance level, and agreement level).

The reliability of the responses and the consensus among panel experts were analyzed at the end of each round. Cronbach's alpha (α) and standard deviation were calculated to test the reliability and consensus levels of the results. Cronbach's alpha is a reliability test to evaluate the internal consistency of responses and the interrelatedness of the outputs. A Cronbach's alpha value of 0.7 or higher is considered an acceptable index for further analysis (Field, 2009, Olawumi and Chan, 2018). If consensus and reliability are not achieved based on the above criteria, another round should be performed until a consensus among panel experts is achieved. The internal consistency of the responses was examined using Cronbach's alpha reliability test. Table 4 presents Cronbach's alpha reliability test results.

Research suggested that the Delphi method should be performed in two or three rounds to achieve consensus among panel experts (Giel and Issa, 2016, Grisham, 2009). In this research, the Delphi method was carried out in two structured rounds, as the consensus was achieved in the second round. The mean values of the first round were shared with the SMEs for re-evaluation in the second round. Then, the panel experts compared and reevaluated their scores considering the outputs of the first round and re-rank them if they want to change. A decrease in the standard deviation values in the second round and Cronbach's alpha reliability test results, which are higher than 0.7 in the second round, prove the consensus achieved among the panel participants.

The interrater agreement statistics (IRA) were utilized to determine the consensus levels for each impact of CDEs on project and organizational performance. The IRA (r_{wg})values were calculated using the formula given in Eq. (1) (Brown and Haustein, 2005). In this equation, r_{wg} represents the interrater agreement statistic, M is the obtained mean value from the assessed output, A refers to the maximum scoring value (i.e., 5), B indicates the minimum scoring value (i.e., 1), n refers to the number of respondents (i.e., 12) and σ is the standard deviation.

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

The r_{wg} values' scale used in the research is 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" (Lebreton and Senter, 2008, Seyis, 2019, Seyis, 2020). The significance levels were determined based on the mean values (M) of the impacts of CDEs on project and organizational performance. The significance levels were interpreted based on the scale interval where "$M < 1.5$" 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" (Li et al., 2013, Seyis, 2019, Seyis, 2020).

3. LITERATURE REVIEW

Key performance indicators (KPIs) enable measuring organizational and project performance (Radujković et al., 2010; Swan & Kyng, 2004). In addition, KPIs are critical for efficient performance management and project success. Organizations can assess their performance using KPIs, foresee the causes of possible future problems, realize where improvements should be made, and improve the internal business processes (Waggoner et al., 1999, Mellado et al., 2019). Performance measurement generally focuses on the project level rather than the organizational level because of the project-based nature of the construction industry, (Love and Holt, 2000, Kagioglou et al., 2001, Mellado et al., 2019). The strategy development for an organization is a crucial management process that *"provides a vision of where the organization wants to be in the short- and long-term future."* (Kagioglou et al., 2001). Therefore, the measures regarding organizational levels are essential for business success.

Haponava and Al-Jibouri (2012) stated that most of the KPIs are product-oriented, which can be apparent at the end of the project and, thus, do not provide an opportunity to evaluate project performance at the process level. This issue means that lagging measures do not enable active performance control during the project development and execution, which hinders taking control actions if necessary (Haponava and Al-Jibouri, 2012). This situation causes non-assessment of whether a company is doing well on the project until it gets closer to completion. All these challenges address the need for a new approach that considers the products and processes while enabling active performance control (Haponava and Al-Jibouri, 2012). Time, cost, and quality measures called as *"three traditional indicators"* (Mohsini and Davidson, 1992) or *"the iron triangle"* (Atkinson, 1999; Leong et al., 2014; Mellado et al., 2019) are classified as lagging indicators and not sufficient to assess the actual performance. The lagging and leading indicators that provide insights about how to proceed with the processes should be considered and monitored to evaluate the 'true' performances of organizations and projects (Kagioglou et al., 2001).

Further, the soft performance measures that reflect the values of a company (e.g., safety and customer satisfaction) (Nassar and AbouRizk, 2014) should be considered because a project under budget and with many safety issues cannot be considered a well-performing project (Mellado et al., 2019). At this point, some questions may arise. For instance, does the lower construction cost mean the productivity is high, or are there fewer defects in the project? (Kagioglou et al., 2001). Yang et al. (2010) stated that the perspectives in performance measurement studies can be divided into three levels: project level, organizational level, and stakeholder level. The categorization conducted by Yang et al. (2010) is very well summarized and includes the whole performance measurement perspective. Thus, the seven KPIs used in this study comprise these three performance measurement levels, which are project level (i.e., time, cost, quality, productivity, and safety), organizational level (i.e., organizational sustainability), and stakeholder level (i.e., client satisfaction). The scopes of the KPIs and how they are handled and interpreted are provided in Table 2. It should be noted that the KPIs identified by reviewing the literature were corroborated by the findings from semi-structured interviews and strengthened with experts' comments.

Additionally, no study investigates the relationship between the CDEs and construction performance management in the literature. Interviews and the Delphi method identified the relationship between the CDEs and construction performance management. The selected KPIs (i.e., time, cost, quality, safety, productivity, organizational sustainability, and client satisfaction) were used in the Delphi Method to evaluate the magnitude of importance of each indicator to the project performance.

4. RESULTS

In the research, the CDE benefits were investigated to what extent they affect the presented KPIs (i.e., time, cost, quality, safety, productivity, organizational sustainability, and client satisfaction). Even though all identified benefits significantly impact these KPIs, their priorities may change one another. According to the outputs of the Delphi method (Table 3), the KPIs were identified as important and extremely important for performance management, with mean values ranging from 4.0 to 4.58. The most positively affected KPIs were productivity, quality, time, and organizational sustainability for the CDE benefits under problem-solving, people and partners, process, and philosophy subcategories, respectively. The authors also investigated the CDE benefits without any categorization to reveal the post-positively affected KPIs. According to the outputs gathered from the Delphi method, the CDEs significantly positively impact productivity, quality, and time KPIs, followed by the indicators, which are organizational sustainability, cost, client satisfaction, and safety, respectively.

Table 2: The construction KPIs.

KPIs	Scopes of the KPIs used in this research	Source of data
Time	• The schedule efficiency, effectiveness, and predictability of the project. • The measure of whether the project is progressing according to schedule. • The efficiency of the allocation of resources (e.g., labor, materials)	• Kagioglou et al., 2001, Chan and Chan, 2004, Bassioni et al., 2004, Yang 2010, Cha and Kim, 2011, Grau et al., 2012, Nassar and AbouRizk, 2014, Mellado et al., 2019, Mansour et al., 2020, Khanzadi et al., 2020
Cost	• The cost efficiency, effectiveness, and predictability of the project. • The measure of whether the project is progressing according to budget.	• Kagioglou et al., 2001, Chan and Chan, 2004, Bassioni et al., 2004, Yang, 2010, Cha and Kim, 2011, Grau et al., 2012, Nassar and AbouRizk, 2015, Mellado et al., 2019, Mansour et al., 2020, Khanzadi et al., 2020
Quality	• The level of meeting the technical standards and project requirements of products and processes. • The frequencies of defects and reworks.	• Chan and Chan, 2004, Bassioni et al., 2004, Cha and Kim, 2011, Grau et al., 2012, Nassar and AbouRizk, 2014, Mellado et al., 2019, Mansour et al., 2020, Khanzadi et al., 2020
Safety	• The efficiency and effectiveness of safety management and education. • Overall safety performance in compliance with the regulatory norms.	• Kagioglou et al., 2001, Chan and Chan, 2004, Yang, 2010, Cha and Kim, 2011, Grau et al., 2012, Nassar and AbouRizk, 2014, Mellado et al., 2019, Mansour et al., 2020
Productivity	• The efficiency and effectiveness of labor productivity and management productivity.	• Kagioglou et al., 2001, Bassioni et al., 2004, Yang, 2010, Cha and Kim, 2011, Mellado et al., 2019, Mansour et al., 2020
Organizational sustainability	• The level of internal business success and continuity of the business success. • The level of organizational ability to achieve short- and long-term goals & strategies • The effectiveness of continuous improvement, innovation, and learning. • The level of contribution to the organization's reputation and competitive advantage. • The level of ensuring collaboratively coordinated teams.	• Chan and Chan, 2004, Vargas-Hernández, 2021
Client Satisfaction	• End-users' level of satisfaction. • Success in meeting the client's needs and expectations. • Response level to the client in terms of flexibility and adjustments to changes.	• Kagioglou et al., 2001, Chan and Chan, 2004, Bassioni et al. 2004, Yang, 2010, Cha and Kim, 2011, Nassar and AbouRizk, 2014, Mellado et al., 2019, Mansour et al., 2020

The internal consistency of the findings (CDEs & project and organizational performance (CPOP) matrix) gathered from each round of the Delphi method was examined by Cronbach's alpha reliability test. Table 4 presents Cronbach's alpha values for the first and second rounds of the Delphi method based on each subcategory of Toyota's 4P Model. The obtained values in the first round are 0.679, 0.674, 0.681, and 0.689 for the subcategories

of Toyota's 4P Model, PSs, PPs, PRs, and PHs, respectively. However, the results of the first round did not meet the conditions of consensus achievement due to Cronbach's alpha values being lower than the required limit (i.e., 0.7 (Field, 2009)). Thus, the second round was performed to reach a consensus among panel experts.

Table 3: Results for the CDE benefits & project and organizational performance (CPOP) matrix.

Toyota's 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
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

	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
Philosophy	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

In the second round, the panel experts were asked to reconsider their rankings based on the given feedback. The feedback informed the panel experts about the general tendency and facilitated panel experts to achieve consensus. Based on the scores gathered in the second round, Cronbach's alpha values were greater than 0.7 (Table 4), which means a consensus was achieved. As seen in Table 4, Cronbach's alpha values increased in the second round of the Delphi survey. Additionally, the alterations in standard deviation values were investigated among the rounds of the Delphi survey. An 18.09% - 61.31% decrease was observed in the standard deviation values of the second round. Therefore, the decrease in standard deviation values and increase in Cronbach's alpha values prove that a consensus among panel experts in the second round is achieved.

Table 4: Alterations in Cronbach's alpha (α) values of the CPOP matrix.

Cronbach's alpha (α) Alterations			
	Toyota's 4P model subcategories	**Round 1**	**Round 2**
CDEs & project and organizational performance (CPOP) matrix	Problem-solving (PSs)	0.679	0.755
	People and partners (PPs)	0.674	0.712
	Process (PRs)	0.681	0.723
	Philosophy (PHs)	0.689	0.748

5. DISCUSSIONS

The relation between CDE benefits in the construction phase of BIM-based projects and construction project and performance (CPOP) is explained considering the question: "How and to what extent do the CDEs affect the KPIs?". Investigating the impacts of CDEs on the construction project and performance of the BIM-based projects was conducted according to the CDE benefits (Seyis and Özkan 2023), which were categorized under Toyota's 4P Model (Liker, 2004). The reason behind this categorization is that the authors aimed to reveal how the different benefits of CDEs affect each KPI. Implementing CDEs in the construction phase of BIM-based projects positively influences all the listed KPIs. However, their relative importance might change based on the attributes of the benefits. For example, which KPI is the most positively affected KPI from the contributions of the benefits listed under the problem-solving subcategory? In addition, the authors grouped the benefits based on their similarities under problem-solving, people and partners, process, and philosophy categories since the assessment of the impacts of each benefit on each KPI will be time-consuming and confusing as there are 54 benefits (Seyis and Özkan 2023). This categorization enables presenting a summarized, structured, and simplified questionnaire to the panel experts and articulable outputs for the readers.

5.1 The impacts of CDE benefits on the problem-solving subcategory (PSs) in the CPOP matrix.

In the 'problem-solving' subcategory (PSs), the impacts of the CDE benefits contributing to the minimization and prevention of possible problems and challenges (Table 1) on the CPOP were investigated. The results show that SMEs identified productivity and quality measures as the most positively affected and extremely important KPIs, with mean values of 4.58 and 4.50, respectively. This result means that the problem-preventative attributes of CDEs have direct positive impacts on productivity and quality. By having a single source of information and an opportunity to access accurate, reliable, and up-to-date information, and minimized double handling of documents, project teams can work with the correct information that may prevent possible defects and reworks. Consequently, the teams can work on optimal activities, which increases their productivity, rather than dealing with the issues on-site and misunderstandings caused by miscommunication. Simultaneously, the quality of the products and processes increases as they are executed based on accurate information.

The third most positively influenced KPI was identified as time, with a mean value of 4.33. Eliminating defects and reducing reworks provide an opportunity to improve schedule performance. As the CDEs enable efficient communication among project participants, the time losses caused by misunderstandings are considerably reduced. The opportunity of data-driven project monitoring allows accurate decision-making that helps stakeholders to achieve their schedule and financial objectives. Moreover, using CDEs can significantly reduce construction conflicts, yet it does not mean there will be no disputes. The construction processes involve many uncertainties which may not be controlled. In that case, with the preservation of audit trail records in the CDEs, dispute resolution processes can be significantly accelerated, which may prevent the waste of time while solving them. Accordingly, the additional cost of removing the defects on-site will be decreased due to the decreased ratio of reworks. The more the project follows the schedule, the more the risk of exposing prolongation costs decreases, positively impacting the cost KPI in the fourth place. All these KPIs are interrelated, and they influence each other. For example, if the time, cost, and quality KPIs are going well in the projects, it is not surprising that the clients will be more satisfied with the construction results.

The safety KPI is also positively influenced by the contributions of CDE benefits, such as the ability to foresee risks. From a safety perspective, the health and safety department can monitor the frequencies of near-misses and incidents by monitoring the data in the CDEs. When there is an increasing rate of near misses and incidents, an accident might happen (e.g., based on Heinrich Pyramid, Heinrich (1959)) if no precautions are taken. Similarly, improved and data-driven decision-making can improve the organizational sustainability KPI. The organizations can make better decisions based on the information and knowledge provided by the CDEs, before any corrective action is taken. Thus, the possibility of hindering business success decreases.

5.2 The impacts of CDE benefits on the people and partners subcategory (PPs) in the CPOP matrix.

In the 'people and partners' subcategory (PPs), the impacts of the CDEs, considering their benefits at the stakeholder level, on the CPOP were investigated. Among the investigated KPIs, quality was seen as the most positively affected indicator due to the CDE benefits at the stakeholder level, with a mean value of 4.5. Ensuring coordination in a construction project has always been challenging due to the complexity of relations and possible distances between construction sites and headquarters. Implementing CDEs provides many opportunities to enhance collaboration among project stakeholders, resulting in better construction performance. The CDEs do not only bring models, information, and documents into a single platform (Klemt-Albert, 2018) but also ensure a centralized working environment by connecting people across the project and organization. Hence, the quality performance of the products and services can be improved. Quality is a subjective measure and one of the challenging KPIs to measure. The owners' project requirements and whether the quality of the asset is ensured are interrelated measures; thus, client satisfaction KPI was identified as the second positively affected KPI with a mean value of 4.42. The more the client's needs are understood, the better design and project management can achieve. The client can better engage with the project and stakeholders by benefitting from the visualization and progress monitoring functions of CDEs, from the design phase to the handover phase. Moreover, problems related to the facility in the operation and management phase will be significantly reduced since the high-quality assets and asset information are being delivered to the client resulting in increased client satisfaction.

Effective communication is one of the essential factors that increase the productivity of project team members, accordingly, improve schedule performance because effective communication may streamline information flow. At this point, the CDEs facilitate communication and better coordination among project participants, increasing project productivity and accelerating project schedules. Therefore, SMEs' other most positively affected KPIs are productivity and time indicators.

The misunderstandings in communication may cause conflicts among team members, resulting in a loss of trust. Managers may look for who is to blame for the problems instead of what could have been done to resolve the problem (Formoso and Lantelme, 2000; Costa and Formoso, 2004). The CDEs can minimize these conflicts through efficient communication channels that ensure trust among participants and allow the continuity of organizational sustainability. Using the opportunity of evaluating the subcontractors' performances through the recordings in CDEs, the outcomes, such as which company causes the defects or safety issues most, can be obtainable. Based on the subcontractor qualification, the contractors can decide whether to continue the work with these companies. The early notice of the problematical companies can prevent possible future problems and accidents and add value to the organizational sustainability and safety KPIs.

5.3 The impacts of CDE benefits on the process subcategory (PRs) in the CPOP matrix.

Using BIM and CDEs together is drastically changing the working practices in construction projects by providing many opportunities. In the 'process' subcategory (PRs), the impacts of the CDEs considering their benefits related to the processual functions, on the CPOP were investigated. Among investigated KPIs, time and productivity KPIs were detected as the most positively affected indicators, with mean values of 4.58 and 4.50, respectively. The order of importance of these KPIs (i.e., time and productivity) is close because they can be considered interrelated measures. This outcome presents that the more project productivity increases, the more time performance can be achieved. CDEs ensure running to the planned schedule and decrease the possible delays caused by poor management. For example, digitally connected workflows (e.g., reviews, approvals, and requests for information (RFIs)) significantly reduce the duration spent completing these processes by eliminating manual data entrance. The Construction Disconnected Report (Schott, 2018) stated that the project participants spent approximately 5.5 hours a week only searching for the information they needed. The project participants can easily and quickly access information regardless of their location within the digitalized data storage in CDEs, which provides considerable time savings.

Additionally, optimizing construction operations and allocating resources contribute to the productivity of laborers and project teams. Using historical data saved in CDEs to identify root causes of defects, reworks, and RFIs, and measuring durations to receive a response can facilitate detecting where potential problems exist in communication among team members. Based on the detected communication bottlenecks, organizations can remove communication and coordination barriers that improve productivity and quality and streamline processes.

The third most positively affected KPI was detected as quality, with a mean value of 4.33. One of the most critical functions of CDEs that contribute to improving quality is standardized processes and workflows. In construction projects, there is an excessive number of various processes executed by different teams and disciplines. Standardization is essential to successfully carry out the required processes for delivering high-quality assets. Furthermore, the CDEs enable professionals to work with BIM systems and support interoperability among BIM tools that minimize the possible errors on models, schedules, and budgets during information exchanges.

Safety KPI arises at the forefront in the process subcategory compared to the other categories, with a mean value of 4.25. Health and safety (H&S) management requires many tasks, such as planning, inspection, monitoring, and execution on-site. The opportunity of real-time reported safety deficiencies and incidents can significantly minimize safety risks. The opportunity of using mobile devices for H&S tasks through CDEs accelerates the safety inspection processes and reduces the response time to remedying safety deficits on site. Moreover, with the capability of monitoring the safety KPIs, such as frequencies of near misses or incidents, forthcoming accidents can be prevented as these insights direct responsible parties to act. Optimized construction operations, carefully planned and managed logistics, and schedules can reduce on-site work hours, resulting in less exposure to safety hazards.

The following positively affected KPI was cost, with a mean value of 4.17. With the help of real-time insights and business intelligence reporting through CDEs, the accurate picture of the financial health of the project and

organizations can be monitored. BIM and CDEs enable efficient monitoring of change orders and cash flow management and facilitate value engineering that may result in cost savings. Moreover, as technology develops daily, organizations can have high-performance servers in the cloud at affordable prices rather than investing in the hardware. The expenses of hardcopies are also reduced significantly because the workflows are conducted in a digital environment.

The SMEs identified organizational sustainability and client satisfaction KPIs as very important and positively affected by the benefits of PRs. However, improvements in the benefits under PRs on organizational sustainability and client satisfaction remain relatively low compared to KPIs such as time, productivity, quality, safety, and cost. The opportunity for effective information management contributes to managing business performance which is crucial for the organization's sustainability. Besides, better H&S management through CDEs allows a safe working environment and increases company trust. Lastly, continuous data transfer across project phases and the easy use of the CDE platforms promote project transparency and contribute to the facility management processes that may escalate client satisfaction.

5.4 The impacts of CDE benefits on the philosophy subcategory (PHs) in the CPOP matrix.

Up to this point, the benefits under the 'problem-solving,' 'people and partners', and 'process' subcategories mainly comprised the improvements of CDEs at the project level. The most important contributions of CDEs to construction companies are more forceful and significant in supporting long-term goals. In the 'philosophy' subcategory (PHs), the impacts of the CDEs, considering their benefits at the strategic level, on the CPOP were investigated.

The benefits listed under the philosophy category mainly handle CDE's abilities from a strategic perspective that contributes to the organization's business success. Hence, organizational sustainability was the most prominent positively affected KPI, with a mean value of 4.33. One of the most important contributions of CDEs is organizational sustainability, as they enable and facilitate better knowledge management. One of the interviewees emphasized knowledge management, considering its importance in decision-making, and explained: *"The construction industry always requires adapting to changing situations such as working conditions of different countries, differentiating stakeholders. Construction companies should make continuous decisions to survive the business under these circumstances. Thus, the contractors must be able to analyze and compare their previous experiences and present conditions".* In this manner, the CDEs facilitate the transformation of data into knowledge (i.e., data to information, then information into knowledge) which is highly valuable for the successful business continuity of the organizations. The standardized data stored in CDEs, which allows a base for artificial intelligence, can be utilized to obtain beneficial lesson-learned outcomes. For example, the patterns of delays or reworks can direct contractors to find and remove their root causes in their future projects. Similarly, the contractors can assess their project portfolios and enter the bids with a better-estimated proposal based on their knowledge and experience in different locations.

The productivity KPI, the second most positively affected indicator with a mean value of 4.25, is also highly correlated with the benefits listed under the philosophy subcategory. Staff turnover is a phenomenon that can be seen in construction companies frequently. If the companies do not implement strategies, the knowledge might be centered around the project and temporary employees' minds. This issue may prolong the adaptation durations of new employees to the project and organization. To overcome this issue, CDEs help contractors to establish corporate memory for their organizations, ensuring preserving knowledge within the company boundaries and contributing to productivity.

The financial health of the organizations can be positively affected by the help of CDE benefits under PHs. This finding explains that the cost KPI was ranked as the third most positively affected indicator, with a mean value of 4.08. The digitalization processes are no longer optional; they have become business requirements in recent decades. The ability of contractors to successfully implement CDEs in BIM-based projects increases the companies' reputation and competitive advantage in the international market, which results in winning more business. The use of the CDEs contributes to return on investment (ROI) by reducing risks, maximizing efficiency, and increasing profits.

The construction companies can assess previous errors, constructability issues, reworks, reasons for RFIs, and change orders through CDEs. By benefiting from this outcome, the organizations can identify potential risks before starting new projects, reduce the number of RFIs and change orders, and increase the possibility of delivering high-quality assets to owners. Moreover, the contributions of continuous improvement help organizations improve their abilities in using technology, which is vital for increasing the quality of assets. Construction companies can contribute to their safety performance by not working with the subcontractors who prompt the most safety deficiencies in their previous projects. Additionally, construction companies can establish more improved health and safety policy statements with the help of the knowledge that they store in the CDE platforms.

Construction companies' increased reputation and competitive advantage can improve the customers' trust in contractors. Moreover, due to the successful handover of BIM models to the client and the opportunity to connect project phases, clients can benefit from the information in CDEs through building operations and management. The facilities team can be more knowledgeable and better manage their facilities, resulting in better client satisfaction. The last positively affected indicator was identified as time KPI in PHs with a mean value of 3.75. The contractors can investigate the team's capabilities and performance in tender preparation processes which can be beneficial before entering the new bids. For example, they can better schedule their preparation processes based on the average proposal completion times, which may increase bidding performance.

6. CONCLUSION

This study analyzes the added value of CDEs for project and organizational performance of BIM-based projects. For this purpose, the research utilizes a mixed methodological approach, including a systematic literature review, semi-structured interviews with five SMEs, and the Delphi method. Seven construction KPIs consisting of the project, organizational, and stakeholder perspectives (i.e., time, cost, quality, safety, productivity, organizational sustainability, and client satisfaction) were included in the Delphi survey to reveal the positive impacts of CDEs on performance management in the construction phase of BIM-based projects. The Delphi method was employed in two structured rounds with twelve SMEs for prioritizing the positive impacts of CDEs on seven KPIs. Cronbach's alpha, interrater agreement level, standard deviation, and significance level statistics were examined to assess and validate the outputs. Findings from the Delphi method show that the CDEs significantly positively impact productivity, quality, and time KPIs, followed by the indicators, which are organizational sustainability, cost, client satisfaction, and safety, respectively.

The research contributes to the construction industry by collating and uncovering the added value of CDEs at the project and organizational levels on performance management in the construction phase of BIM-based projects. The findings in this research could increase awareness in the construction industry about the value of processing the information in the CDEs for continuous improvement and knowledge management. The results are expected to encourage construction companies to utilize the data in the CDEs to the best advantage for both their project and organizational success, thereby enhancing their business performance.

The limitation of this study is that no actual clients participated in the interviews and the Delphi method. However, this limitation does not negatively affect the validity and reliability of outputs related to client satisfaction since four participants are consultants who work for clients. Moreover, consultants can evaluate the client's level of satisfaction, the success in meeting the client's needs and expectations, and the response level to the client regarding flexibility and adjustments to changes.

One of the future research directions could be measuring the positive impacts of using CDEs in asset management that would ensure realizing the added value of CDEs in terms of clients. Another future research could be implementing case studies to measure the positive impacts of CDEs on performance management. The other future work could be comparing traditional and CDE-implemented projects that would be beneficial to present the outputs quantitatively. Such studies could encourage construction stakeholders to implement CDEs in their projects.

ACKNOWLEDGEMENTS

The authors thank all experts who participated in the interviews and the Delphi survey for their valuable time and efforts.

REFERENCES

Al Nahyan, M. T., Sohal, A., Hawas, Y. and Fildes, B. (2019). Communication, coordination, decision-making, and knowledge-sharing: a case study in construction management. Journal of Knowledge Management, 23(9), 764-781.

Field, A. (2009). Discovering statistics using SPSS, 3rd ed., London, Sage Publications.

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.

Afolabi, A. O., Amusan, L. M., Owolabi, J. D., Ojelabi, R. A., Joshua, O. and Tunji-Olayeni, P. F. (2018). Assessment of the linkages and leakages in a cloud-based computing collaboration among construction stakeholder. American Society of Civil Engineers (ASCE) Construction Research Congress (CRC), 2018, 673-683, DOI: 10.1061/9780784481264.066, New Orleans, USA.

Akob, Z., Zaidee, M., Hipni, A. and Koka, R. (2019). Coordination and Collaboration of Information for Pan Borneo Highway (Sarawak) via Common Data Environment (CDE). In IOP Conference Series: Materials Science and Engineering, 512(1), 012001, IOP Publishing.

Atkinson, R. (1999). Project management: cost, time and quality, two best guesses and a phenomenon, its time to accept other success criteria. International Journal of Project Management, 17(6), 337–342.

Autodesk (2023). Autodesk Construction Cloud, https://constructionblog.autodesk.com/construction-kpis/ (Access date: November 15, 2022).

Bassioni, H. A., Price, A. D. and Hassan, T. M. (2004). Performance measurement in construction. Journal of Management in Engineering, 20(2), 42-50.

Beatham, S., Anumba, C., Thorpe, T. and Hedges, I. (2004). KPIs: a critical appraisal of their use in construction. Benchmarking: An International Journal, 11(1), 93-117.

Brown, R. D. and Hauenstein, N. M. (2005). Interrater agreement reconsidered: An alternative to the rwg indices. Organizational research methods, 8(2), 165-184, Available: http:// dx.doi.org/10.1177/1094428105275376.

Cha, H. S. and Kim, C. K. (2011). Quantitative approach for project performance measurement on building construction in South Korea. KSCE Journal of Civil Engineering, 15(8), 1319-1328.

Chan, A. P. and Chan, A. P. (2004). Key performance indicators for measuring construction success. Benchmarking: an international journal, 11(2), 203-221.

Costa, D.B and Formoso, C. T. (2003). Guidelines for conception, implementation and use of performance measurement system in construction companies. 11th International Conference of the International Group for Lean Construction, Virginia Tech, Blacksburg, Virginia, USA.

Dalkey, N. C. (1969). The Delphi method: an experimental study of group opinion. The Rand Corporation, Santa Monica, California, Tech. Report. 1-18.

Dowd T. and Marsh D. (2020). The future of BIM: digital transformation in the UK construction and infrastructure sector. Royal Institution of Chartered Surveyors (RICS), London, Insight paper, 2020.

Formoso, C. T. and Lantelme, E.M.V. (2000). A performance measurement system forconstruction companies in Brazil. International Project Management Journal, 6(3), 54-60.

Giel, B. and Issa, R. R. (2016). Framework for evaluating the BIM competencies of facility owners. Journal of Management in Engineering, 32(1), 04015024.

Grau, D., Back, W. E. and Prince, J. R. (2012). Benefits of on-site design to project performance measures. Journal of Management in Engineering, 28(3), 232-242.

Grisham, T. (2009). The Delphi technique: a method for testing complex and multifaceted topics. International Journal of Managing Projects in Business, 2(1), 112-130, Available: https://doi.org/10.1108/17538370910930545.

Hallowell, M. R. and Gambatese, J. A. (2010). Qualitative research: Application of the Delphi method to CEM research. Journal of Construction Engineering and Management, 136(1), 99.

Haponava, T. and Al-Jibouri, S. (2012). Proposed system for measuring project performance using process-based key performance indicators. Journal of Management in Engineering, 28(2), 140-149.

Heinrich, H.W. (1959). Industrial Accident Prevention: A Scientific Approach, McGraw-Hill, New York.

International Standards Organization. (2019). 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, Geneva.

Kagioglou, M., Cooper, R. and Aouad, G. (2001). Performance management in construction: a conceptual framework, Construction Management and Economics, 19(1), 85-95, https://doi.org/10.1080/01446190010003425

Khanzadi, M., Sheikhkhoshkar, M. and Banihashemi, S. (2020). BIM applications toward key performance indicators of construction projects in Iran. International Journal of Construction Management, 20(4), 305-320.

Klemt-Albert, K., Hagedorn, P. and Pullmann, T. (2018). Utilising the Potential of Standardised BIM Models by a Fundamental Transformation of Collaboration Processes. In Workshop of the European Group for Intelligent Computing in Engineering, 470-486, Springer, Cham.

Lantelme, E. M. V. and Formoso, C. T. (2000). Improving performance though measurement: the application of lean production and organisatonal learning 8th principles. International Conference of the International Group For Lean Construction, University of Sussex, Brighton.

LeBreton, J. M. and Senter, J. L. (2008). Answers to 20 questions about interrater reliability and interrater agreement. Organizational research methods, 11(4), 815-852, Available: https://doi.org/10.1177/1094428106296642.

Leong, T. K., Zakuan, N., Mat Saman, M. Z., Ariff, M., Md, S. and Tan, C. S. (2014). Using project performance to measure effectiveness of quality management system maintenance and practices in construction industry. The scientific world journal, 2014.

Li, T. H., Ng, S. T. and Skitmore, M. (2013). Evaluating stakeholder satisfaction during public participation in major infrastructure and construction projects: A fuzzy approach. Automation in construction, 29, 123-135, Available: https://doi.org/10.1016/j.autcon.2012.09.007.

Liker, J. (2004). The Toyota Way: 14 Management Principles from the World's Greatest Manufacture, New York, NY: McGraw-Hill.

Losev, K. Y. (2020). The common data environment features from the building life cycle perspective. In IOP Conference Series: Materials Science and Engineering 913(4), 042012, IOP Publishing.

Love, P.E.D. and Holt, G.D. (2000), "Construction business performance measurement: the SPM alternative", Business Process Management Journal, 6(5), 408-416. https://doi.org/10.1108/14637150010352417

Mansour, H., Aminudin, E., Omar, B. and Al-Sarayreh, A. (2020). Development of an impact-on-performance index (IPI) for construction projects in Malaysia: a Delphi study. International Journal of Construction Management, 2003-2012, DOI: 10.1080/15623599.2020.1762036.

Martínez-Rojas, M., Marín N. and Vila, M. (2016). The Role of Information Technologies to Address Data Handling in Construction Project Management, Journal of Computing in Civil Engineering, 30(4), Available: 10.1061/(asce)cp.1943-5487.0000538.

Matthews, J., Love, P., Heinemann, S., Chandler, R., Rumsey C. and Olatunj, O. (2015). Real time progress management: Re-engineering processes for cloud-based BIM in construction, Automation in Construction, 58, 38-47, Available: 10.1016/j.autcon.2015.07.004.

Mellado, F., Lou, E. C. and Becerra, C. L. C. (2019). Synthesising performance in the construction industry: An analysis of performance indicators to promote project improvement. Engineering. Construction and Architectural Management, 27(2), 579-608.

Mohsini, R.A. and Davidson, C.H.(1992). Determinants of performance in the traditional building process, Construction Management and Economics, 10(4), 343-359, https://doi.org/10.1080/01446199200000030

Mullen, P. M. (2003). Delphi: myths and reality. Journal of Health Organization and Management. 17(1), 37-52, Available: https://doi.org/10.1108/14777260310469319.

Nassar, N. and AbouRizk, S. (2014). Practical application for integrated performance measurement of construction projects. Journal of Management in Engineering, 30(6), 04014027.

Olawumi, T. O. and Chan, D. W. (2018). Identifying and prioritizing the benefits of integrating BIM and sustainability practices in construction projects: A Delphi survey of international experts. Sustainable Cities and Society, 40, 16-27.

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

Radujković, M., Vukomanović,M. and Dunović, I. (2010), Application of key performance indicators in South-Eastern European construction. Journal of Civil Engineering and Management, 16(4), 521-530.

Schott, P. (2018). Construction Disconnected: The High Cost of Poor Data and Miscommunication, Tech. Report., [Online] Available: https://blog.plangrid.com/2018/08/fmi-plangrid-construction-report/ [Accessed: March 29, 2021]

Seyis, S. (2019). Pros and cons of using building information modeling in the AEC industry. Journal of Construction Engineering and Management, 145(8), 04019046, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001681

Seyis, S. (2020). Mixed method review for integrating building information modeling and life-cycle assessments. Building and Environment, 173, 106703, https://doi.org/10.1016/j.buildenv.2020.106703

Seyis, S. and Özkan, S. (2023). Analyzing the Benefits and Challenges of Implementing Common Data Environments in the Construction Phase of BIM-based Projects. American Society of Civil Engineers, (under review)

Simeone, D., Cursi, S., Coraglia, U. M. and Fioravanti, A. (2020). Reasoning in Common Data Environments-Re-thinking CDEs to enhance collaboration in BIM processes. In Proceedings of 38th eCAADe Conference, 2, 499-506.

Stransky, M. (2020). Functions of common data environment supporting procurement of subcontractors. In Proceedings of 19th International Scientific Conference Engineering for Rural Development, 793-799.

Swan, D. and Kyng, E. (2004). An Introduction to Key Performance Indicators, Centre for Construction Innovation, 130, North West.

The KPI Working Group. (2000). KPI Report for the Minister for Construction, Department of the Environment, Transport and the Regions, Norwich, London, Tech. Report.

Vargas-Hernández, J. G. (2021). Strategic Organizational Sustainability. Handbook of Research on Novel Practices and Current Successes in Achieving the Sustainable Development Goal, 277-297, IGI Global.

Waggoner, D., Neely, A. and Kennerley, M. (1999), "The forces that shape organizational performance measurement systems: an interdisciplinary review", International Journal of Production Economics, Vol. 60-61, 53-60, https://doi.org/10.1016/S0925-5273(98)00201-1.

Wong, J., Wang, X., Li, H. and Chan, G. (2014). A review of cloud-based BIM technology in the construction sector. Journal of Information Technology in Construction, 19, 281-291.

Yang, H., Yeung, J. F., Chan, A. P., Chiang, Y. H. and Chan, D. W. (2010). A critical review of performance measurement in construction. Journal of Facilities Management, 8(4), 269-284.