Understanding the Causes of Design Errors in Construction Projects: A DEMATEL-Based Framework

Chia Kuang Lee[1]; Changsaar Chai[2]; Marián Bujna[3];
Muhammad Ashraf Fauzi[4]; and Ying Qi Boo[5]

Abstract: The design phase plays a crucial role in project development by providing a structured plan that transforms a vision into a tangible entity. Consequently, any errors detected during the design phase can have a profound impact on the overall project performance. Numerous researchers have identified design errors as one of the most critical factors contributing to disputes and project failure. However, they failed to investigate the direct factors, indirect factors, and interdependencies among the factors associated with construction design errors. Therefore, the objective of this study is to investigate the interrelationships among the causes of design errors. Nine causes of design errors were extracted and synthesized from the literature. Subsequently, 15 experts were interviewed, and the data collected was analyzed using the decision-making trial and evaluation laboratory (DEMATEL) algorithm. The critical factors and their relationships were then presented in an impact-relation map diagram. The findings confirm that the top three important causes of design errors are inadequate design experts (C1), lack of skills and experience (C2), and poor communication in a design team (C4). This study suggests that adoption of building information modeling (BIM), trainings, and design review may address these issues. The conclusions of this study can assist major players in the construction sector, as well as the government sector in establishing intervening strategies to mitigate errors and improve the quality of design. **DOI: 10.1061/JLADAH.LADR-1118.** © *2024 American Society of Civil Engineers.*

Practical Applications: The Malaysian construction industry can use BIM during the design phase as the studies identified insufficient design experts (C1), lack of skills and experience (C2), and poor communication in a design team (C4) as the top three causes of design errors due to their prominence value and influencing power on other factors. BIM improves communication within the design team as well as between the design team and clients. BIM enables a more integrated and collaborative approach to design, which lowers mistakes and misunderstandings. The Malaysian construction industry should invest in BIM training programs for design professionals as it continues to develop its training blueprints. This actionable initiative can improve the self-efficacies and proficiencies of design experts, ensuring that they are well-equipped to handle complex design challenges. Practically, the industry can significantly increase project performance, productivity, and overall success while minimizing design errors by concentrating on critical causal factors, implementing cutting-edge technologies like BIM, providing training and support to design professionals, and putting in place robust review processes. For those working in the engineering and construction fields, and professional practitioners who are involved in the settlement of construction disputes, this study's contribution is extremely important. It provides useful guidelines for enhancing project success while lowering the risks of legal and contractual issues caused by design errors.

Author keywords: Construction industry; Design errors; Decision-making trial and evaluation laboratory (DEMATEL).

Introduction

The design and construction phase in construction projects are interconnected as designs provide structural, architectural, and engineering plans that allow construction to turn the designs into entities (Ding et al. 2018). Numerous studies have revealed that design errors are commonly discovered during the construction phase. Even professionals, who are highly skilled and experienced, are susceptible to errors and mistakes during the execution of tasks, including the crucial aspect of designing (Choudhry et al. 2018). Designing requires a meticulous approach and attention to detail, as it involves complex decision-making processes that impact the overall success of a project. The design phase of a construction project presents greater difficulty and complexity compared to the construction phase. This is attributed to the specialized expertise, creative thinking, and profound knowledge required from design professionals to ensure that the proposed design not only meets the client's requirements but also effectively addresses the client's problems or challenges (Atsrim et al. 2015).

The effects of design errors could be detrimental. Errors in design have significant negative consequences that affect project

---

[1] Associate Professor, Faculty of Industrial Management, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, Kuantan, Pahang 26300, Malaysia (corresponding author). ORCID: https://orcid.org/0000-0001-6063-8071. Email: chia@umpsa.edu.my

[2] Associate Professor, School of Architecture, Building and Design, Faculty of Innovation and Technology, Taylor's Univ., Subang Jaya, Selangor 47500, Malaysia. Email: CS.Chai@taylors.edu.my

[3] Associate Professor, Faculty of Engineering, Slovak Univ. of Agricultural, Tr. A. Hlinku 2, Nitra 949 76, Slovakia. ORCID: https://orcid.org/0000-0003-4281-5649. Email: marian.bujna@uniag.sk

[4] Associate Professor, Faculty of Industrial Management, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, Kuantan, Pahang 26300, Malaysia. Email: ashrafauzi@umpsa.edu.my

[5] Project Student, Faculty of Industrial Management, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, Kuantan, Pahang 26300, Malaysia. Email: yqboo4297@gmail.com

Note. This manuscript was submitted on July 26, 2023; approved on November 17, 2023; published online on February 2, 2024. Discussion period open until July 2, 2024; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Legal Affairs and Dispute Resolution in Engineering and Construction***, © ASCE, ISSN 1943-4162.

quality and performance, including cost and schedule performance (Choudhry et al. 2018; Hasmori et al. 2018; Kazaz et al. 2017; Lopez et al. 2010). Peansupap and Ly (2015) further emphasized that design errors are unavoidable and they adversely impact project management efficiency and effectiveness. Moreover, design errors can trigger a cascade of additional problems, ultimately leading to project failure. This assertion is supported by Fuadie et al. (2017), who highlighted that errors in design, particularly rework, significantly diminish project performance.

Furthermore, design errors emerge as a primary source of variation in construction projects (Dosumu and Aigbavboa 2017; Osman et al. 2009; Zawawi et al. 2010). Variations, such as design errors and omissions, design changes, and other factors, contribute to slipped milestones, project delays, and cost overruns (Ubani et al. 2010; Zawawi et al. 2010). Notably, design errors can also lead to disputes and conflicts among project stakeholders (Choudhry et al. 2018).

The prevalence of design errors in construction projects encompasses misinterpretation and miscalculation (Lopez et al. 2010). Despite extensive discussions on design errors in prior studies, these errors persist in numerous projects, leading to ongoing project failures. Existing studies have predominantly focused on identifying the causes and consequences of design errors. However, there is a notable research gap regarding the interrelationship between the causes of errors in design and the strategies employed to enhance quality and minimize such errors. Consequently, this study assumes significance in examining the interrelationship among the causes of design errors and proposing suitable strategies for effectively managing diverse factors, ultimately facilitating optimal project success in the construction project. This study will help researchers and practitioners in deepening their understanding of the relationships between the causes and strategies of design errors, thereby supporting the advancement of related research endeavors.

Literature Review

The design phase is a crucial process in construction projects, where the initial project concept is transformed into functional and technical requirements based on the clients' needs. In the design-bid-build framework, the design phase involves several key stakeholders, including the project owner, design team (architects and engineers), and contractor. The primary objective of the design phase in construction projects is to ensure the design aligns with the functional, livable, sustainable, maintainable aspects of project delivery, and prevent potential safety concerns on construction sites (Fadeyi 2017).

Design errors continue to persist despite their critical impact on construction projects. Design errors refer to deviations from acceptable standards of practice during the design phase that are preventable (Dosumu and Aigbavboa 2017). Design errors overall can be classified into three categories: rule- or knowledge-based errors, skill- or performance-based errors, and violation or noncompliance errors (Lopez et al. 2010). Common design errors encountered during the design phase include inaccurate or insufficient specifications, design calculation errors, design clashes or conflicts, and violations of building codes. Design conflicts arise when two elements cannot be simultaneously constructed due to overlapping constraints (Peansupap and Ly 2015). Miscalculation involves inaccurately measuring the dimensions of engineering or system design, while building code violation occurs when the design of a building fails to comply with government regulations. Design errors stem from various causes and shall be highlighted in the following section.

Inadequate Design Experts (C1)

Achieving success in projects and business operations across various industries necessitates the involvement of specialized professionals with specific expertise and competence (Wu et al. 2017). For instance, a construction project involves a range of experts contributing at different stages of the project. Among these stages, the design phase in construction projects stands out as particularly complex. During this phase, the presence of adequate design experts with high levels of technical knowledge and experience becomes crucial for effective decision-making (Atsrim et al. 2015). The numbers of design professionals are of utmost importance to ensure that they possess the necessary skills, knowledge, and experience required to understand their job scope and successfully accomplish their tasks, ultimately contributing to project success.

Lack of Skills and Experience (C2)

According to Assaf et al. (2018), one of the most critical causes of design document errors is assigning the design task to inexperienced designers. Professionals with lower levels of experience have a higher potential to make mistakes and can be found negligent for a design error. Designers lacking work experience have a negative impact on project performance (Assaf et al. 2018). These findings align with Lopez et al. (2010), who asserted that individuals lacking work experience are more prone to errors due to their unfamiliarity with task processes. Furthermore, individuals with limited experience tend to generate more errors and require more time to complete tasks. Acharya et al. (2006) stated that designers lacking experience can cause an increase in project costs and tarnish a company's reputation due to design errors. In addition to experience, skill level also plays a significant role in design errors, as highlighted by Fuadie et al. (2017). Design professionals who lack skills and experience in preparing high quality designs may struggle to accurately determine client requirements, leading to design errors. High-quality designs are fundamental and necessary for project management, and detection of design errors can be made early via three-dimensional (3D) drawings (Kazaz et al. 2017). However, the quality of the design can be compromised when design professionals possess insufficient skills and competence (Love et al. 2012).

Poor Communication between Design Experts and Clients (C3)

Inadequate communication of design information can lead to design errors. Within the design phase of a construction project, poor communication can arise between the design experts and clients (Olanrewaju et al. 2017). The design cycle of a construction project typically commences with the clients expressing their requirements or stating their needs, and it progresses until the finalization of detailed drawings and specifications (Mujumdar and Maheswari 2018). The design team is responsible for designing the building in accordance with the client's ideas and requirements. However, when there is poor communication between the design experts and the clients, it often results in design errors due to the design experts' failure to fully comprehend the client's needs. The absence of effective communication between the design team and the client not only hampers the quality of design document preparation (Assaf et al. 2018), but it also undermines the accuracy of decision-making as the design team operates with incomplete knowledge regarding the project objectives and the precise requirements of the clients. Poor communication between the design team and the authority having jurisdiction (AHJ) may also lead to design errors. The design team may mistakenly develop designs that do not adhere to building codes and safety standards and other legal requirements. Conversely, the design team could unknowingly violate the law if the AHJ fails to clearly convey their unique expectations or interpretations of the building codes.

Poor Communication in a Design Team (C4)

Design errors can also arise from inadequate communication within the design team, including the architect and engineer (Wu et al. 2017). Effective communication is crucial among design teams throughout the project life cycle, encompassing information sharing, exchange, and transmission. During the design phase, particularly in the schematic design and design development stages, design iterations occur within the same design group or even across different design groups within the same organization, aiming to finalize the essential components or systems of the project (Mujumdar and Maheswari 2018). However, individuals within the design team may possess varying expertise and perspectives, leading to different understandings and ideas (Wu 2013). Conflicts can arise within the design team due to divergent interests and communication issues among team members. This may result in disagreements that take a long time to resolve if they are not appropriately managed. This, in turn, may have an adverse influence on the design team members' motivation and morale, which will ultimately have a negative impact on the final design (Atsrim et al. 2015). Differences in understanding among members of the design team, influenced by their individual perceptions and experiences, can exacerbate communication issues.

Lack of Organizational Support (C5)

Organizational-related practices can influence the nature and capability of individuals who perform tasks in design firm (Love et al. 2014). Organization support plays a significant role in shaping the behavior, decision-making processes, and overall approach within an organization. When it comes to design, the prevailing organizational support can have a substantial impact on the occurrence of design errors. Lopez et al. (2010) and Fuadie et al. (2017) argue that an unsupportive organization, characterized by a lack of emphasis on learning and knowledge sharing, contributes to design errors in construction projects. An organizational culture that does not promote learning, continuous improvement, and knowledge sharing is more likely to experience design errors (Fuadie et al. 2017). An unsupportive organization will apportion blame, and without a culture that encourages feedback, reflection, and learning from past projects, design mistakes and their underlying causes may be repeated. Failure to learn from mistakes and incorporate lessons into future designs can perpetuate a cycle of errors.

Excessive Workload (C6)

When design professionals experience excessive workload, they face several challenges that increase the likelihood of design errors (Cho and Ahn 2019). These challenges include time constraints, decreased attention to detail, mental fatigue, and compromised decision-making abilities. The cumulative effect of these factors can significantly hinder the quality of design. High workload often leads to cognitive overload, wherein individuals struggle to process information effectively, or struggle to execute increasingly complex (Chen et al. 2016) and difficult tasks (Wang et al. 2020). Critical thinking, problem-solving abilities, and the capacity to spot and fix design errors can all be hampered by cognitive overload. As a result, design errors increase as cognitive resources are stressed (Gregoriades and Sutcliffe 2008). The ability to collaborate and communicate effectively decreases in situations with a lot of work to be done. Professionals may find it difficult to solicit input from colleagues, convey important information, or participate in in-depth discussions. The lack of effective knowledge and expertise utilization increases the risk of design errors due to the breakdown in communication and collaboration. Design professionals eventually need to confront with myriads of difficulties such as time constraints, diminished attention to detail, mental exhaustion, and impaired decision-making skills, all of which together impact design quality and lead to design errors.

Clients' Change Requests (C7)

Change requests from clients have a big impact on how a project is designed. However, these requests may also bring about mistakes and difficulties that lower the overall design quality. Client demands for changes made throughout the design and construction phases can increase uncertainty and cause budget and schedule overruns (Okada et al. 2017). Client change requests frequently call for changes to the original design, which, if improperly integrated, might result in inconsistencies, conflicts, or omissions. These modifications may throw off the established design process and result in mistakes like misaligned specifications, incompatible parts, or adverse impacts to the structural integrity of the structures.

Schedule Constraints (C8)

The project's schedule limitations are critical, and straying from the project baselines might result in mistakes and difficulties that lower the design's overall quality. Design can be negatively impacted by time limitations in a variety of ways. First off, a lack of time can lead to insufficient design analysis and review, which can obscure design defects and produce less than ideal solutions. Second, rushed deadlines may make it more difficult for project stakeholders to collaborate and coordinate effectively, which raises the risk of misunderstandings and mistakes in design. Activities involving design demand close attention to detail, in-depth investigation, and rigorous analysis. However, schedule constraints may limit the time available for these critical tasks, forcing design teams to expedite the process. Individuals must efficiently manage requests in order to complete the assigned work in a short amount of time (Liu et al. 2020). This is worsened by the fact that insufficient time is allocated in the early stages of the design process to facilitate a proper engagement process between the client and the design team for studying and analyzing project requirement (Pikas et al. 2020). This time pressure can lead to oversights, incomplete assessments, and a higher likelihood of errors throughout the design phase. Effective design processes often involve multiple iterations and review cycles to refine and improve the design solution. However, when faced with schedule constraints, there may be limited time allocated for such iterations. As a result, design errors may persist, as there is insufficient opportunity for comprehensive feedback. Schedule constraints can induce time pressure on design teams, forcing them to make critical design decisions hastily. Under such circumstances, professionals may resort to shortcuts, rely on past experiences without adequate analysis, or make assumptions without thorough validation. These compromised decision-making practices increase the risk of design errors and may lead to poor design outcomes.

Budget Constraints (C9)

Budget constraints can adversely affect design in various ways (Fuadie et al. 2017; Love et al. 2013). Limited financial resources may lead to inadequate allocation for design activities such as research, analysis, and testing. This limitation can result in incomplete understanding of requirements and design errors that may be overlooked due to financial constraints. When faced with budget constraints, design teams may be forced to make trade-offs and compromises in various aspects of design, such as materials, technology, or scope. When fees do not adequately reflect the complexity and scope of the project, design firms may face resource constraints and cost-cutting measures, such as low and reduced design fees (Akampurira and Windapo 2018). These compromises, driven by financial limitations, can lead to poor design choices, functional mismatches, or compromised quality, potentially resulting in design errors. Effective design activities require adequate resources, including skilled personnel, tools, and technologies. The design team may be compelled to compromise on design quality in order to meet the allocated budget for design. This can entail eliminating certain aesthetic components, employing less expensive construction techniques, or reducing complex design features. However, meeting the standard of care is more important than remaining within budget. Regardless of budgetary limitations, design professionals have a duty of care to make sure that their designs comply with industry standards. Therefore, they may be held accountable for professional negligence if budgetary constraints result in design quality compromises that endanger safety, functioning, or regulatory compliance. In reality, design teams frequently exert great effort to balance budgetary constraints and the need to adhere to the standard of care. However, budget constraints can limit the availability of these resources, potentially hindering the design process. Insufficient resources may lead to rushed decision-making, reduced attention to detail, and inadequate analysis, increasing the likelihood of errors throughout the design phase.

Methodology

This study adopts the decision-making trial and evaluation laboratory (DEMATEL) method to understand the interrelationships between the causes. The DEMATEL method is a mathematical and multicriteria optimization technique utilized to assess both direct and indirect coupling relationships in order to determine the importance and causality of each criterion (Zhu et al. 2020). It models the relationships and elucidate the interactions among the criteria (Sin et al. 2020). In this context, the identification of relationships among factors is strongly based on expert opinions (Shahpari et al. 2020). The DEMATEL method is demonstrated through six steps as follows (Lee et al. 2023).

Step 1: Calculate Average Matrix Z Based on Experts' Opinion

A comprehensive analysis was conducted with the involvement of a group consisting of m experts and the consideration of n factors. The direct influence between two factors was determined through a rigorous pair-wise comparison process. The influence of factor i on factor j, as perceived by the experts, was represented by the numerical value x_{ij}. This value ranged between 0 and 4, denoting varying degrees of influence: 0 = no influence, 1 = low influence, 2 = medium influence, 3 = high influence, and 4 = very high influence. An nxn nonnegative matrix for each expert as $X^k = [X^k_{i_j}]$ was constructed, where k is the number of experts that involving in evaluation process with $1 \le k \le m$. Hence, the matrices of m experts are $X^1, X^2, X^3, \ldots, X^m$. To consolidate the assessments provided by m experts, the average matrix $Z = [zij]$ is employed as a means of aggregation

$$z_{ij} = \frac{1}{m} \Sigma_{i=1}^{m} x_{ij}^{k} \tag{1}$$

Step 2: Normalize Initial Direct-Relation Matrix D

The calculation of the normalized initial direct-relation matrix D, denoted as $[d_{ij}]$ involves assigning values to each element within the range of [0, 1]. The calculation is depicted as follows:

$$D = \lambda * Z \tag{2}$$

or

$$[d_{ij}]_{n\times n} = \lambda [z_{ij}]_{n\times n} \tag{3}$$

where

$$\lambda = \mathrm{Min}\left[\frac{1}{\max 1 \le i \le n \Sigma_{j=1}^{n} [z_{ij}]}, \frac{1}{\max 1 \le i \le n \Sigma_{i=1}^{n} [z_{ij}]}\right] \tag{4}$$

Based on the principles of Markov chain theory, the matrix D is raised to various powers denoted as D^m. These powers, such as $D^2, D^3, \ldots, D^\infty$ ensure the attainment of a convergent solution for matrix inversion

$$\lim_{m\to\infty} D^m = [0]_{n\times n} \tag{5}$$

Step 3: Derive Total Relation Matrix T

By employing Eq. (7), the total-influence matrix T can be derived, with the identity matrix I of size $n \times n$ being utilized. The indirect influence of factor i on factor j is represented by t_{ij}. Matrix T encompasses the comprehensive relationships between all pairs of system factors, effectively capturing the entirety of their interdependencies

$$T = \lim_{m\to\infty} (D + D^2 + \ldots + D^m) = \Sigma_{m=1}^{\infty} D^i \tag{6}$$

where

$$\begin{aligned} \Sigma_{m=1}^{\infty} D^i &= D^1 + D^2 + \ldots + D^m \\ &= D(I + D^1 + D^2 + \ldots + D^{m-1}) \\ &= D(I-D)^{-1}(I-D)(I + D^1 + D^2 + \ldots + D^{m-1}) \\ &= D(I-D)^{-1}(I-D^m) \\ T &= D(I-D)^{-1} \end{aligned} \tag{7}$$

Step 4: Calculate the Sums of Rows and Columns of Matrix T

Within the total-influence matrix T, the vector r denotes the summation of rows, while the vector c represents the summation of columns

$$r = [r_i]_{nxI} = \left(\sum_{j=1}^{n} t_{ij}\right)_{nxI} \tag{8}$$

$$c = [c_j]'_{I\times n} = \left(\sum_{j=1}^{n} t_{ij}\right)'_{Ixn} \tag{9}$$

where transposition matrix is represented as $[c_j]'$.

Within the matrix T, the sum of the ith row, denoted as r_i, signifies the cumulative impact that factor i has on the other factors, encompassing both direct and indirect effects. Similarly, in the matrix T, the sum of the jth column, represented as c_j, indicates the overall influence received by factor j from all other factors, encompassing both direct and indirect effects. The combined effects of both giving and receiving for factor i are reflected by the value of $(r_i + c_i)$, where $j = i$. Conversely, the net contribution of factor i to the system is indicated by the value of $(r_i - c_i)$ Notably, factor i is considered a net cause when the value of $(r_i - c_i)$ is positive, while it is regarded as a net receiver when the value of $(r_i + c_i)$ is negative.

Step 5: Set a Threshold Level (α)

Subsequently, the threshold value (α) was determined by computing the average of the elements within matrix T, while N represents the total number of elements encompassed by matrix T

$$\alpha = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}[t_{ij}]}{N} \tag{10}$$

Step 6: Construct a Cause-and-Effect Relationship Diagram

To construct the cause-and-effect diagram, all sets of coordinates ($r_i + c_i$, $r_i - c_i$) were mapped. This cause-and-effect relationship diagram serves as a visual representation, illuminating the intricate connections among factors and offering valuable insights into identifying the most influential factors and help to determine effective strategies to influence the affected factors.

Results and Discussions

Nine causes of design errors were extracted for examining their interrelationship. Based on the interrelationship evaluated from DEMATEL method, the strategies to mitigate and address the causes were discussed accordingly.

Demographic of Respondents

Table 1 shows the demographic profile of the respondents. Fifteen design experts were engaged via purposive snowball technique. The experts had a minimum of experience from at least 6 to more than 25 years in the construction industry. A total of 60% were male and 40% of the respondents were female. Note that 20% were in the range of 31–40 years old, and other 80% were in the range of 41–55 years old. The design experts claimed to hold positions as engineer (26.67%), quantity surveyor (26.67%), interior designer (20%), and director (26.67%). A total of 73% hold a bachelor degree, and 27% hold a diploma-level degree. Note that 26.6% of the respondents worked in the consultancy-based company, 60.0% in a contractor-based company, and other 13.33 % in both consultancy and contractor-based companies. A total of 13.33% of the experts had 6–10 years' experience, 6.67% had 11–15 years' experience, 13.33% had 16–20 years' experience, 60% had 21–25 years' experience, 6.67% had more than 25 years' experience. They were involved in residential (66.67%), commercial (13.33%), industrial projects (20.0%). A majority of the experts (46.67%) were involved

Table 1. Demographic profile of the respondents

Profile	Characteristic	Frequency	Percentage (%)
Gender	Male	9	60
	Female	6	40
Age	31–35	2	13.33
	36–40	1	6.67
	41–45	2	13.33
	46–50	9	60
	51–55	1	6.67
Job title	Engineer	4	26.67
	Quantity surveyor	4	26.67
	Interior designer	3	20.0
	Director	4	26.67
Education level	Bachelor degree	11	73.33
	Diploma	4	26.67
Organization's services	Consultancy-based	4	26.67
	Contractor-based	9	60.0
	Both consultancy and contractor	2	13.33
Year of experience in construction industry	6–10	2	13.33
	11–15	1	6.67
	16–20	2	13.33
	21–25	9	60.00
	>25	1	6.67
Type of project currently involved in	Residential	10	66.67
	Commercial	2	13.33
	Industrial	3	20.00
Project sum	MYR 0–MYR 10,000,000	2	13.33
	MYR 10,000,001–MYR 50,000,000	7	46.67
	MYR 50,000,001–MYR 100,000,000	3	20.00
	MYR 100,000,001–MYR 150,000,000	1	6.67
	MYR 150,000,001–MYR 200,000,000	0	0.0
	> MYR 200,000,000	2	13.33
Types of errors	Miscalculation	6	15.0
	Design conflict	14	35.0
	Building code violation	2	5
	Inaccurate description of specification	9	22.50

in projects with sum of MYR 10,000,001 to MYR 50,000,000, followed by 20% of them involved in projects with sum of MYR 50,000.001 to MYR 100,000,000. A total of 13.33% of them were involved in projects with sum of MYR 0 to MYR 10,000,000, and more than MYR 200,000,000. Only 6.67% of them involved in projects with sum of MYR 100,000,001 to MYR 150,000,000. All experts experienced design errors in their projects, and reflected that the types of design errors include miscalculation (15%), design conflict (35%), building code violation (5%), and inaccurate description of specification (22.5%).

Applying DEMATEL Method to the Nine Causes of Design Errors

The steps for applying the DEMATEL method to the nine causes of design errors are discussed as follows:

Step 1: The average matrix Z was calculated by using Eq. (1) and exhibited in Table 2.

Step 2: The normalized initial direct-relation matrix D was calculated using Eqs. (2)–(5) and is shown in Table 3.

Step 3: The total relation matrix T was calculated by using Eqs. (6) and (7) and is shown in Table 4.

Step 4: The sums of rows and columns of matrix T were calculated by using Eqs. (8) and (9) and are depicted in Table 5.

Step 5: Threshold value (α) was set up by using Eq. (10), and is shown in Eq. (11) as follows:

$$\alpha = \frac{52.477}{81} = 0.6479 \tag{11}$$

Step 6: The relationship diagram was constructed and is depicted in Fig. 1 (impact direction diagram) and Fig. 2 (relationship diagram).

Table 2 shows the average matrix Z, by averaging the inputs from 15 experts. Table 3 then exhibits the normalized initial direct-relation matrix D. Following that, Table 4 shows the total relation matrix T. Subsequently, Table 5 depicts the degree of prominence (importance) of each cause through the calculation of vector R and vector C (R + C). Table 6 further denotes the ranks for the prominence vector (R + C), while Table 7 shows the ranks for the relation vector (R-C). The descending order of prominence is as follows: inadequate design experts (C1) > lack of skills and experience (C2) > poor communication in a design team (C4) > poor communication between design experts and clients (C3) > schedule

Table 2. Average matrix Z (causes of design errors)

Factor	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	0	3.066667	3.400000	3.400000	1.933333	3.200000	3.266667	3.066667	3.066667
C2	3.133333	0	3.266667	3.466667	1.866667	3.066667	3.000000	3.466667	3.133333
C3	3.133333	2.933333	0	3.266667	2.066667	2.533333	3.266667	3.000000	2.866667
C4	3.066667	3.200000	2.933333	0	2.200000	2.533333	3.400000	3.000000	2.933333
C5	2.200000	2.200000	2.666667	2.800000	0	2.133333	2.066667	2.466667	2.533333
C6	2.866667	2.666667	2.266667	2.000000	1.933333	0	1.666667	2.800000	2.333333
C7	2.466667	2.200000	2.666667	2.600000	1.866667	1.733333	0	3.000000	3.000000
C8	2.266667	2.333333	2.133333	2.133333	0.800000	3.600000	2.866667	0	2.866667
C9	2.333333	2.266667	1.400000	1.666667	0.733333	2.800000	2.533333	3.000000	0

Table 3. Normalized direct-relation matrix D (causes of design errors)

Factor	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	0	0.125340	0.138964	0.138964	0.079019	0.130790	0.133515	0.125340	0.125340
C2	0.128065	0	0.133515	0.141689	0.076294	0.125340	0.122616	0.141689	0.128065
C3	0.128065	0.119891	0	0.133515	0.084469	0.103542	0.133515	0.122616	0.117166
C4	0.125340	0.130790	0.119891	0	0.089918	0.103542	0.138964	0.122616	0.119891
C5	0.089918	0.089918	0.108992	0.114441	0	0.087193	0.084469	0.100817	0.103542
C6	0.117166	0.108992	0.092643	0.081744	0.079019	0	0.068120	0.114441	0.095368
C7	0.100817	0.089918	0.108992	0.106267	0.076294	0.070845	0	0.122616	0.122616
C8	0.092643	0.095368	0.087193	0.087193	0.032698	0.147139	0.117166	0	0.117166
C9	0.095368	0.092643	0.057221	0.068120	0.029973	0.114441	0.103542	0.122616	0

Table 4. Total relation matrix T (causes of design errors)

Factor	A	B	C	D	E	F	G	H	I
C1	0.668037	0.762317	0.763054	0.778600	0.500565	0.791785	0.805945	0.845913	0.814724
C2	0.781211	0.650760	0.758254	0.780288	0.497543	0.788072	0.797274	0.858716	0.816757
C3	0.749258	0.726631	0.610545	0.743337	0.484486	0.737502	0.773599	0.808604	0.774884
C4	0.751100	0.739077	0.721552	0.629546	0.491490	0.741659	0.781934	0.813271	0.781488
C5	0.615309	0.601937	0.609457	0.626606	0.340968	0.619866	0.627073	0.677299	0.654949
C6	0.626279	0.606564	0.585596	0.588964	0.406174	0.529935	0.601682	0.676304	0.636379
C7	0.634410	0.611938	0.618894	0.629748	0.417201	0.618034	0.560716	0.707139	0.682259
C8	0.611634	0.599979	0.584159	0.595835	0.370113	0.663259	0.645797	0.579591	0.659213
C9	0.556287	0.541941	0.505318	0.524527	0.330289	0.580227	0.576691	0.626494	0.494870

Table 5. Sum of rows and column of matrix T (causes)

Causes	Sum R	Sum C	R + C	R-C
C1	6.730938	5.993524	12.724462	0.737415
C2	6.728875	5.841144	12.570019	0.887731
C3	6.408845	5.756829	12.165675	0.652016
C4	6.451116	5.897450	12.348566	0.553666
C5	5.373464	3.838829	9.212293	1.534635
C6	5.257877	6.070338	11.328215	−0.812462
C7	5.480338	6.170711	11.651049	−0.690373
C8	5.309580	6.593330	11.902910	−1.283750
C9	4.736645	6.315522	11.052168	−1.578877

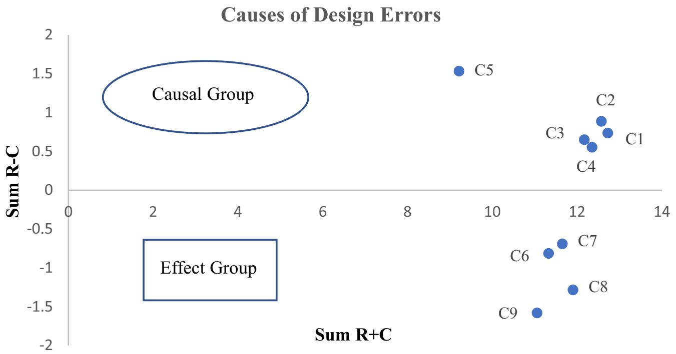

Fig. 1. Impact-direction diagram between nine cause factors of nonpayment.

constraints (C8) > client's change requests (C7) > excessive work load (C6) > budget constraints (C9) > lack of organizational support (C5). As shown in Fig. 1, inadequate design experts ($C1 = 0.7374$), lack of skills and experience ($C2 = 0.8877$), poor communication between design experts and clients ($C3 = 0.6520$), poor communication in a design team ($C4 = 0.5537$), lack of organizational support ($C5 = 1.5346$) show positive R-C value. Attention should be directed toward positive R-C values, indicating a smaller degree of influenced impact (C) compared to the degree of influential impact (R). Such values signify the presence of driver factors that exert significant influence on other factors, contrasting with factors that primarily influence themselves. On the contrary, four causes are identified with negative R-C value, including clients' change request ($C7 = -0.6904$), excessive work load ($C6 = -0.8125$), schedule constraints ($C8 = -1.2828$), budget constraints ($C9 = -1.5789$). Causes with a negative R-C relation vector indicate that the influence of other factors on themselves is more significant than the influence they exert on other factors. By averaging the total relation matrix T, the threshold value, $\alpha = 0.6479$ is the obtained. Table 8 exhibits the inner dependency matrix, which includes the entries that are higher than the threshold value of $\alpha = 0.6479$.

Depicted in the inner dependency matrix, budget constraints (C9) do not impact any other causes. However, all causes strongly impact on budget constraints (C9), and should be monitored carefully. With the highest R-C value, lack of organizational support (C5) is not impacted by any other causes; however, it has unidirectional impact on two other causes, such as the schedule constraints (C8) and the budget constraints (C9). Unsupportive organization eventually leads to time and cost issues and continue to perpetuate design errors in the projects. This results overall identifies inadequate design experts (C1), lack of skills and experience (C2), and poor communication in a design team (C4) as the three top causes of design errors due to their prominence value (high R + C), and their influencing power on the other factors (high R-C values). Fig. 2 overall shows the interrelationship between causes. The bidirectional relationship between the factors include C1-C1, C1-C2, C1-C3, C1-C4, C2-C2, C2-C4, C2-C3, C3-C4, C6-C8; while the unidirectional relationship between the factors include C1-C6, C1-C7, C1-C8, C1-C9, C2-6, C2-C7, C2-C8, C2-C9, C3-C6, C3-C7, C3-C8, C3-C9, C4-C6, C4-C7, C4-C8, C4-C9, C5-C8, C5-C9.

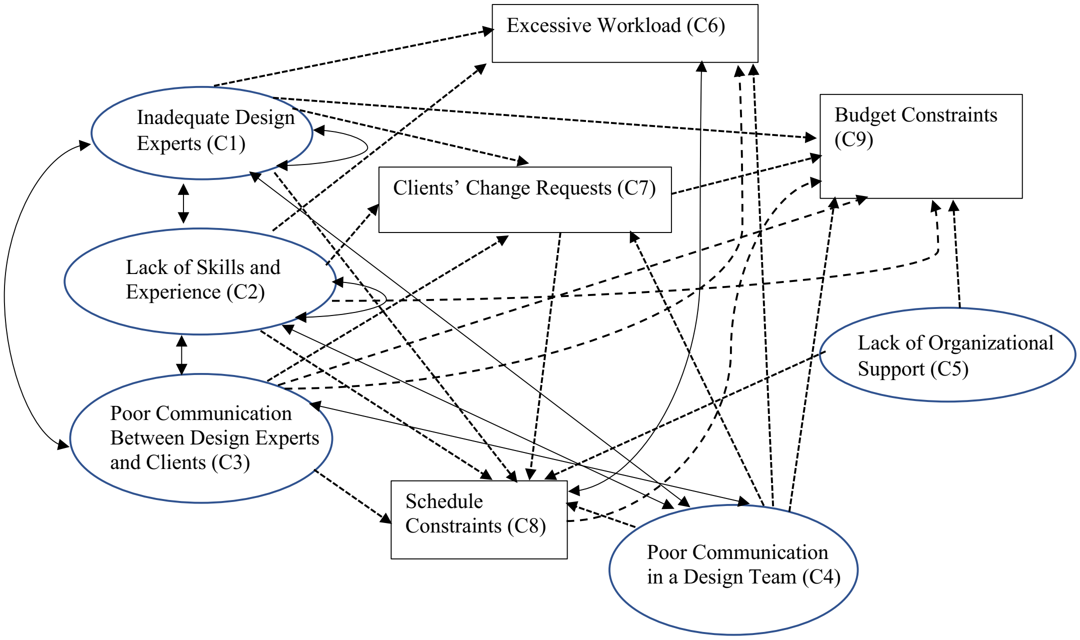

Fig. 2. Relationship diagram between nine causes of design errors. The circle shape is the causal group and the rectangle is the effect group. The dotted line is the unidirectional relationship, and the solid line is the bidirectional relationship.

Table 6. Prominence vector R+C (causes of design errors)

Rank	Factor	R + C
1	C1	12.7244
2	C2	12.5700
3	C4	12.348566
4	C3	12.165675
5	C8	11.902910
6	C7	11.651049
7	C6	11.328215
8	C9	11.052168
9	C5	9.212293

Table 7. Relation vector R-C (causes of design errors)

Rank	Factor	R-C
1	C5	1.534635
2	C2	0.887731
3	C1	0.737415
4	C3	0.652016
5	C4	0.553666
6	C7	−0.690373
7	C6	−0.812462
8	C8	−1.28375
9	C9	−1.578877

To address these tree important causes of design errors, organizations should focus on recruiting design experts (C1), improve professional skills among designers (C2), and improve communication effectiveness. The adoption of information technology is one of the key strategies for reducing design errors in construction projects (Al-Ashmori et al. 2020). It is pertinent to grow technological skills among design experts especially with the use of software technology. These tools if used properly, would help in reducing design errors, enhancing decision-making quality, optimizing resource allocation, and improving task completion efficiency. Building information modeling is an example of computer-aided design that can be used in design. BIM has been widely used during the design phase of construction projects (Sheikhkhoshkar et al. 2019) and widely used by professionals such as architects, engineers, and contractors in construction projects. BIM can be used to manage the planning, design, and construction processes more efficiently, ensuring project success (Haron et al. 2017). It can also facilitate clash detection during the design phase, identifying errors or defects early on and improving the quality of the final design before construction work begins (Wong et al. 2018), and foster effective communication through holistic visualization to the stakeholders (Cornish et al. 2015). According to Kazaz et al. (2017), designs generated in 3D with BIM rather than in two dimensions (2D), which also compiles all of the drawings into one, would allow for the early discovery of design errors throughout the design phase. The adoption of BIM in the construction sector has increased in Malaysia, and the Malaysian government has actively encouraged construction industries to adopt BIM as an innovation to improve productivity and efficiency in the industry (Afifuddin et al. 2019). Despite significant government encouragement, BIM adoption in Malaysia is still relatively slow due to certain barriers such as the high level of skill required and the associated costs (Haron et al. 2017). Rogers et al. (2015) highlighted the vital role that government, private agencies, and educational institutions in overcoming these obstacles by collaborating to implement proper BIM training structures and reduce BIM implementation costs. The use of AIA Document E203 can be included as an exhibit to an existing construction contract, where the parties' expectations are outlined in AIA Document E203 with regard to the creation and use of digital data, including BIM. Incorporating mandatory use of BIM into the contract can help streamline both design and construction processes effectively, and substantiate the need for efficient BIM training. Nur et al. (2018) supported this strategy, stating that training can improve user understanding and promote effective use of the system.

Trainings is seen as effective strategy to improve the quality of the design and reduce the design errors in construction especially for those designers who are lacking skill, knowledge, or inexperience. Love et al. (2013) believed training can reduce knowledge-based errors and foster knowledge transfer. Dimitrova et al. (2015) argued training not only contributes to performance improvement but also positively affects motivation, cognitive, and overall behavior. Building information modeling trainings would be beneficial for the design professionals. BIM courses and seminars are routinely held in Malaysia by a variety of professional building groups. Particularly recognized organizations that regularly hold and facilitate BIM-related training initiatives are the Institution of Engineers Malaysia (IEM) and the Royal Institution of Surveyors Malaysia (RISM). These training programs cover a wide range of BIM-related topics and skill sets, making them invaluable resources for design experts to advance their knowledge in BIM. To meet the different demands and experience levels of participants, these courses are often created to fit a range of skill levels, from basic BIM concepts to sophisticated applications.

On top of that, design review may help mitigate design errors. Design reviews is an effective mechanism to minimize design errors, minimize rework, improve design details and eliminate non-value-adding elements in construction projects (Palaneeswaran et al. 2014). It is an evaluation process of design solution for possible failures detection with respect to the project, overall performance, and function of spaces (Castronovo et al. 2013). Despite its importance, design firms failed or choose to neglect this crucial process due to time constraint (Assaf et al. 2018), significant workload, and cost issues (Choudhry et al. 2018).

Table 8. Inner dependency matrix (exceeding threshold value)

Factor	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	0.668037	0.762317	0.763054	0.778600	—	0.791785	0.805945	0.845913	0.814724
C2	0.781211	0.650760	0.758254	0.780288	—	0.788072	0.797274	0.858716	0.816757
C3	0.749258	0.726631	—	0.743337	—	0.737502	0.773599	0.808604	0.774884
C4	0.751100	0.739077	0.721552	—	—	0.741659	0.781934	0.813271	0.781488
C5	—	—	—	—	—	—	—	0.677299	0.654949
C6	—	—	—	—	—	—	—	0.676304	—
C7	—	—	—	—	—	—	—	0.707139	0.682259
C8	—	—	—	—	—	0.663259	—	—	0.659213
C9	—	—	—	—	—	—	—	—	—

Conclusion and Recommendations

The construction industry is one of the leading drivers of Malaysia's economic development. Design errors are one of the major issues in the Malaysian construction industry. However, many organizations have not yet been able to completely address this issue. Previous studies insufficiently examined the causal relationship between the influential factors of design errors in construction projects. This study aims to shed light on the direct factors, indirect factors, and interdependencies among the factors associated with construction design errors. By using decision-making and trial evaluation laboratory method, the results implied that inadequate design experts (C1), lack of skills and experience (C2), poor communication between design experts and clients (C3), poor communication in a design team (C4), and lack of organizational support (C5) are the critical causal factors. The study suggests that inadequate design experts (C1), lack of skills and experience (C2), and poor communication in a design team (C4) are the three top causes of design errors due to their prominence value (high $R + C$), and their influencing power on the other factors (high R-C values). The study suggests that the adoption of BIM, training, and design review can help minimize design errors. BIM in design phase enhances the communication between design team and client and within design team; trainings improve self-efficacies and proficiencies; and design reviews use experts' evaluation and allow early error detection. Through the creation of 3D model, BIM would help minimize errors in clashes, measurements and quantities, and reduce discrepancies between design intent and final construction. Professional institutes like the IEM and RISM play a crucial role in minimizing design errors through BIM education and training, and promoting best design practices. By enforcing detailed design requirements and criteria, design errors can be further reduced. The request for proposal and project specifications are among the procurement documents that provide detailed and precise design criteria. This can reduce misunderstandings and ambiguity, which may result in design errors. On top of that, inclusion of stringent quality assurance and quality control clauses into the contract can clearly minimize design errors. It would be easier to do the necessary quality control inspections at different design and construction phases if the procurement documents, regardless of the procurement methods, contained stringent quality assurance and quality control standards. By improving quality and minimizing design errors, project performance, productivity, and success can all be improved in the construction industry. By acknowledging the enduring nature of design errors and putting in place thorough and proactive strategies to prevent and limit their occurrence, construction projects can be completed with more efficiency, improved quality, and overall success.

Data Availability Statement

Some data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. The available data, models, or code include survey questionnaires, and analyzed data in Microsoft Excel format.

Acknowledgments

The authors would like to thank the Ministry of Higher Education (Malaysia) for providing financial support under Fundamental Research Grant Scheme (FRGS) No. FRGS/1/2021/SS02/UMP/02/3 (University Reference RDU210112) and Universiti Malaysia Pahang Al-Sultan Abdullah for computer laboratory facilities.

References

Works Cited

Acharya, N. K., Y.-D. Lee, and H.-M. Im. 2006. "Design errors: Tragic for the clients." *J. Constr. Res.* 7 (1–2): 177–190. https://doi.org/10.1142/S1609945106000505.

Afifuddin, H. H., K. A. H. Mohd, F. R. Ahmad, F. Farah, and I. C. A. Adi. 2019. "The fourth industrial revolution and organisations' propensity towards building information modelling (BIM) adoption." *Malays. Constr. Res. J.* 27 (1): 79–92.

Akampurira, E., and A. Windapo. 2018. "Factors influencing the quality of design documentation on South African civil engineering projects." *J. South African Inst. Civ. Eng.* 60 (3): 41–48. https://doi.org/10.17159/2309-8775/2018/v60n3a4.

Al-Ashmori, Y. Y., I. Othman, Y. Rahmawati, Y. H. M. Amran, S. H. A. Sabah, A. D. Rafindadi, and M. Mikić. 2020. "BIM benefits and its influence on the BIM implementation in Malaysia." *Ain Shams Eng. J.* 11 (4): 1013–1019. https://doi.org/10.1016/j.asej.2020.02.002.

Assaf, S., M. A. Hassanain, and A. Abdallah. 2018. "Review and assessment of the causes of deficiencies in design documents for large construction projects." *Int. J. Build. Pathol. Adapt.* 36 (3): 300–317. https://doi.org/10.1108/IJBPA-10-2017-0050.

Atsrim, F., J. I. T. Buertey, and K. Boateng. 2015. "Managing the design process in the construction industry: A literature review." *Archit. Res.* 5 (1): 16–30. https://doi.org/10.5923.j.arch.20150501.03.html.

Castronovo, F., D. Nikolic, Y. Liu, and J. I. Messner. 2013. "An evaluation of immersive virtual reality systems for design reviews." In *Proc., 13th Int. Conf. on Construction Applications of Virtual Reality*, edited by N. Dawood and M. Kassem. London: Teesside Univ.

Chen, J., X. Song, and Z. Lin. 2016. "Revealing the 'invisible gorilla' in construction: Estimating construction safety through mental workload assessment." *Autom. Constr.* 63 (Mar): 173–183. https://doi.org/10.1016/j.autcon.2015.12.018.

Cho, W. C., and T. H. Ahn. 2019. "A classification of electrical component failures and their human error types in South Korean NPPs during last 10 years." *Nucl. Eng. Technol.* 51 (3): 709–718. https://doi.org/10.1016/j.net.2018.12.011.

Choudhry, R. M., H. F. Gabriel, M. K. Khan, and S. Azhar. 2018. "Causes of discrepancies between design and construction in the Pakistan construction industry." *J. Constr. Dev. Countries* 22 (2): 1–18. https://doi.org/10.21315/jcdc2017.22.2.1.

Cornish, K., J. Goodman-Deane, K. Ruggeri, and P. J. Clarkson. 2015. "Visual accessibility in graphic design: A client–designer communication failure." *Des. Stud.* 40 (Mar): 176–195. https://doi.org/10.1016/j.destud.2015.07.003.

Dimitrova, N. G., C. Van Dyck, E. A. Van Hooft, and P. Groenewegen. 2015. "Don't fuss, focus: The mediating effect of on-task thoughts on the relationship between error approach instructions and task performance." *Appl. Psychol.* 64 (3): 599–624. https://doi.org/10.1111/apps.12029.

Ding, Z., M. Zhu, V. W. Y. Tam, G. Yi, and C. N. N. Tran. 2018. "A system dynamics-based environmental benefit assessment model of construction waste reduction management at the design and construction stages." *J. Cleaner Prod.* 176 (Apr): 676–692. https://doi.org/10.1016/j.jclepro.2017.12.101.

Dosumu, O. S., and C. O. Aigbavboa. 2017. "Impact of design errors on variation cost of selected building project in Nigeria." *Procedia Eng.* 196 (Jan): 847–856. https://doi.org/10.1016/j.proeng.2017.08.016.

Fadeyi, M. O. 2017. "The role of building information modeling (BIM) in delivering the sustainable building value." *Int. J. Sustainable Built Environ.* 6 (2): 711–722. https://doi.org/10.1016/j.ijsbe.2017.08.003.

Fuadie, D. F., Y. Rahmawati, and C. Utomo. 2017. "Factors of design errors in construction project (a review)." *IPTEK J. Proc. Ser.* 3 (6): 284–288. https://doi.org/10.12962/j23546026.y2017i6.3263.

Gregoriades, A., and A. Sutcliffe. 2008. "Workload prediction for improved design and reliability of complex systems." *Reliab. Eng. Syst. Saf.* 93 (4): 530–549. https://doi.org/10.1016/j.ress.2007.02.001.

Haron, N. A., R. Soh, R. P. Z. Ana, and A. N. Harun. 2017. "Implementation of building information modelling (BIM) in Malaysia: A review." *Pertanika J. Sci. Technol.* 25 (3): 661–673.

Hasmori, M. F., I. Said, R. Deraman, N. H. Abas, S. Nagapan, M. H. Ismail, F. S. Khalid, and A. F. Roslan. 2018. "Significant factors of construction delays among contractors in Klang Valley and its mitigation." *Int. J. Integr. Eng.* 10 (2): 32–36. https://doi.org/10.30880/ijie.2018.10.02.007.

Kazaz, A., T. Acikara, S. Ulubeyli, and H. Koyun. 2017. "Detection of architectural drawings errors in 3 dimension." *Proc. Eng.* 196 (2): 1018–1025.

Lee, C. K., M. Bujna, A. H. A. Jamil, and P. T. Ee. 2023. "A cause and effect of a nonpayment model based on the DEMATEL algorithm." *J. Leg. Aff. Dispute Resolut. Eng. Constr.* 15 (1): 04522050. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000592.

Liu, P., Y. Qiu, J. Hu, J. Tong, J. Zhao, and Z. Li. 2020. "Expert judgments for performance shaping factors' multiplier design in human reliability analysis." *Reliab. Eng. Syst. Saf.* 194 (Feb): 106343. https://doi.org/10.1016/j.ress.2018.12.022.

Lopez, R., P. E. D. Love, D. J. Edwards, and P. R. Davis. 2010. "Design error classification, causation, and prevention in construction engineering." *J. Perform. Constr. Facil.* 24 (4): 399–408. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000116.

Love, P. E. D., R. Lopez, D. J. Edwards, and Y. M. Goh. 2012. "Error begat error: Design error analysis and prevention in social infrastructure projects." *Accid. Anal. Prev.* 48 (Mar): 100–110. https://doi.org/10.1016/j.aap.2011.02.027.

Love, P. E. D., R. Lopez, and J. T. Kim. 2013. "Design error management: Interaction of people, organisation and the project environment in construction." *Struct. Infrastruct. Eng.* 10 (6): 811–820. https://doi.org/10.1080/15732479.2013.767843.

Love, P. E. D., R. Lopez, J. T. Kim, and M. J. Kim. 2014. "Influence of organizational and project practices on design error costs." *J. Perform. Constr. Facil.* 28 (2): 303–310. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000415.

Mujumdar, P., and J. U. Maheswari. 2018. "Design iteration in construction projects—Review and directions." *Alexandria Eng. J.* 57 (1): 321–329. https://doi.org/10.1016/j.aej.2016.12.004.

Nur, M. A., S. Hafez, and P. Deborah. 2018. "Human and information technology/information system (IT/IS) implementation success factors in construction industry." *Malays. Constr. Res. J.* 26 (3): 29–41.

Okada, R. C., A. E. Simons, and A. Sattineni. 2017. "Owner-requested changes in the design and construction of government healthcare facilities." *Procedia Eng.* 196 (Jan): 592–606. https://doi.org/10.1016/j.proeng.2017.08.047.

Olanrewaju, A., S. Y. Tan, and L. F. Kwan. 2017. "Roles of communication on performance of the construction sector." *Procedia Eng.* 196 (Jan): 763–770. https://doi.org/10.1016/j.proeng.2017.08.005.

Osman, Z., A. Omran, and C. K. Foo. 2009. "The potential effects of variation orders in construction projects." *J. Eng.* 7 (2): 141–152.

Palaneeswaran, E., P. E. D. Love, and J. T. Kim. 2014. "Role of design audits in reducing errors and rework: Lessons from Hong Kong." *J. Perform. Constr. Facil.* 28 (3): 511–517. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000450.

Peansupap, V., and R. Ly. 2015. "Evaluating the impact level of design errors in structural and other building components in building construction projects in Cambodia." *Procedia Eng.* 123 (Jan): 370–378. https://doi.org/10.1016/j.proeng.2015.10.049.

Pikas, E., L. Koskela, and O. Seppänen. 2020. "Improving building design processes and design management practices: A case study." *Sustainability* 12 (3): 911. https://doi.org/10.3390/su12030911.

Rogers, J., H. Y. Chong, and C. Preece. 2015. "Adoption of building information modelling technology (BIM)." *Eng. Constr. Archit. Manage.* 22 (4): 424–445. https://doi.org/10.1108/ECAM-05-2014-0067.

Shahpari, M., F. M. Saradj, M. S. Pishvaee, and S. Piri. 2020. "Assessing the productivity of prefabricated and in-situ construction systems using hybrid multi-criteria decision making method." *J. Build. Eng.* 27 (Jan): 100979. https://doi.org/10.1016/j.jobe.2019.100979.

Sheikhkhoshkar, M., F. Pour Rahimian, M. H. Kaveh, M. R. Hosseini, and D. J. Edwards. 2019. "Automated planning of concrete joint layouts with 4D-BIM." *Autom. Constr.* 107 (Nov): 102943. https://doi.org/10.1016/j.autcon.2019.102943.

Sin, K. Y., M. S. Jusoh, and A. Mardani. 2020. "Proposing an integrated multi-criteria decision making approach to evaluate total quality management best practices in Malaysia hotel industry." In *Proc., 1st Int. Conf. on Emerging Electrical Energy, Electronics and Computing Technologies 2019, ICE4CT 2019*. Bristol, UK: IOP Publishing.

Ubani, E. C., C. C. Nwachukwu, and O. C. Nwokonkwo. 2010. "Variation factors of project plans and their contributions to project failure in Nigeria." *Am. J. Social Manage. Sci.* 1 (2): 141–149. https://doi.org/10.5251/ajsms.2010.1.2.141.149.

Wang, P., W. Fang, and B. Guo. 2020. "A measure of mental workload during multitasking: Using performance-based timed petri nets." *Int. J. Ind. Ergon.* 75 (Jan): 102877. https://doi.org/10.1016/j.ergon.2019.102877.

Wong, J. K. W., J. X. Zhou, and A. P. C. Chan. 2018. "Exploring the linkages between the adoption of BIM and design error reduction." *Int. J. Sustainable Dev. Plann.* 13 (1): 108–120.

Wu, G., C. Liu, X. Zhao, and J. Zuo. 2017. "Investigating the relationship between communication-conflict interaction and project success among construction project teams." *Int. J. Project Manage.* 35 (8): 1466–1482. https://doi.org/10.1016/j.ijproman.2017.08.006.

Wu, G. D. 2013. "The relationship between project team dynamic feature, conflict dimension and project success—An empirical research from Shanghai, China." *Pak. J. Stat.* 29 (6): 935–952.

Zawawi, W. A., N. Amila, N. Azman, N. F. Izyan, S. Kamar, and M. Shamil. 2010. "Sustainable construction practice: A review of change orders (CO) in construction projects." In *Proc., Int. Conf. Environment 2010*. Gelugor, Malaysia: Universiti Sains Malaysia.

Zhu, Y., X. Niu, C. Gu, D. Yang, Q. Sun, and E. F. Rodriguez. 2020. "Using the DEMATEL-VIKOR method in dam failure path identification." *Int. J. Environ. Res. Public Health* 17 (5): 1480. https://doi.org/10.3390/ijerph17051480.