



Development of a Prediction System for Design Defects of Buildings

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Abstract

The research aimed to establish a quantitative model to predict the occurrence of five types of design defects: unsafe design, incompatible design, inefficient design, design ambiguity, and design delays. It also examined the contractor's liability for design to determine who is ultimately responsible for design defects disputes between the employer and contractor. The study employed a descriptive methodology to identify fifteen potential influencing factors on design defects. Data were collected from 42 construction projects and tested using Design of Experiments (DOE). Out of these fifteen factors, only five—design schedule, design firm experience, stakeholders' involvement, project delivery system, and information accuracy—had a significant impact on design defects. These factors were used in the development of a new model to predict the occurrence of design defects. The model was validated using data that was held separate from the model development process for validation purposes. The calculated Mean Absolute Percentage of Error (MAPE) for the new model is 19%, which is considered a "good" prediction accuracy. The research achieved three significant milestones: 1) It identified the ultimate responsibility for the consequences of design defects in construction projects across different jurisdictions. This information can be used to resolve potential disputes between employers, designers, and contractors' organizations. 2) It provided guidelines on how to minimize design defects in construction projects, thereby mitigating the consequences of such defects. 3) It developed a new model to predict the occurrence of design defects in construction projects. This model aids decision-makers in responsible organizations during the process of predicting the appropriate reserve to be added to the project schedule and budget. Consequently, it helps mitigate the risk of design defect-related delays and cost overruns.

Keywords: Design Defects; Design Responsibility; Design of Experiment (DOE); Contractor Design Liability; Cost of Poor Quality.

1. Introduction

Design defects in buildings are one of the most significant factors affecting building projects, with direct impacts on project quality, schedule, and budget, in addition to their influence on end-user satisfaction if not discovered before the final handover of the building to the client [1–4]. Out of this massive importance, design defects represent a green field for researchers to dig down more for the reasons behind them, aiming to provide more insights into how to avoid these defects in future projects [5, 6]. Although many studies have delved into the reasons behind design defects, limited research has sought to predict their occurrence to keep enough buffer in schedule and budget to reach the desired results.

There were several previous studies investigating the reasons for design defects and their consequences. These studies were considered to provide a clear view of many reasons for design defects, in addition to their impact on buildings [7–10]. Hamzah et al. [11] described the importance of the design process and its impact on the overall building

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quality. In another study, Chong & Low [12] studied the reasons for design defects and the design strategies to prevent them.

Koo & O'Connor [13] examined the impact of using BIM on preventing design defects and highlighted its significant impact. Other researchers found that the application of BIM significantly reduced the occurrence of such defects, thereby enhancing the quality of the final design output. This finding underscores the importance of integrating BIM practices into the design process. Their research contributes to the growing body of evidence supporting the use of BIM in improving design efficiency and reducing errors. This aligns with the broader trend in the construction industry towards leveraging technology to enhance project delivery performance and safety [14, 15]. Ali et al. [16] discussed the impact of design defects on the maintenance process of school buildings in Malaysia. Zheng et al. [17] investigated the concept of concurrent design, considering all factors that affect design, such as budget, schedule, and customer requirements. Waziri [18] discussed the impact of design defects on residential buildings in Nigeria, while Minato [19] focused on the impact of human errors in design defects.

Tayeh et al. [20] studied factors affecting the occurrence of design defects in construction projects and recommended the usage of quality control and quality assurance techniques in the design process to reduce defect levels. They suggested that these methods could play a pivotal role in minimizing defect levels. Quality control, for instance, involves regular checks of materials to ensure their suitability for use, while quality assurance refers to the measures taken to ensure that the design process itself adheres to the required standards [21, 22]. Josephson [23] conducted a study on seven building projects in Sweden to identify the cost associated with design defects. Studies conducted by O'Connor & Koo [24], Lee [25], and Jiang et al. [26] suggested different tools to prevent the design defects in a proactive manner. Faqih & Zayed [27] and Lupășteanu et al. [28] explained the impact of design defects on the deterioration rate of buildings.

Gabaldón [29] discussed lessons learned from the collapse of the viaduct project in Venezuela. Madaj & Siekierski [30] determined defect factors affecting road bridge design. Abu-Reishah & Hiyassat [31] explored the influence of the design-construction interface in the Jordanian construction industry. Xu & Zou [32] developed a model to present the relationship between design defects and influencing factors in the concurrent design process. Hassanain et al. [33] assessed architectural defects related to the lack of feedback from the design team. Cruz et al. [34] tried to detect reasons for defects in concrete bridges. Vafeas & Hilton [35] discussed client defection in the design industry.

Although previous studies have tackled the design defects from several perspectives, three questions remain unanswered:

- Who is ultimately responsible for the consequences of design defects in construction projects in different jurisdictions? The designer or the contractor?
- How to achieve the minimum number of design defects in construction projects.
- How to predict the occurrence of design defects in construction projects?

This research aimed to answer these questions to fill the current scientific gaps.

2. Research Objectives & Methodology

This research applied a descriptive methodology to establish a new system for design defect prediction in building construction projects using design of experiments (DOE).

The following roadmap was adopted to conduct the study:

- Exploring the design process in construction projects and discussing the responsibility for design defects.
- Identifying factors that may affect the quality of buildings' design and result in design defects through two different techniques:
 - Performing a literature review to recognize factors described in previous research;
 - Conducting a brainstorming session with project management experts to identify further factors;
- Conducting interviews with project management experts to collect data related to their projects' performance;
- Using the design of experiments to identify the most critical factors that have a significant impact on design defects;
- Developing a model to predict design defects based on project circumstances; and
- Validating the new model using data that was not included in the new model development.

Figure 1 shows the research methodology steps.

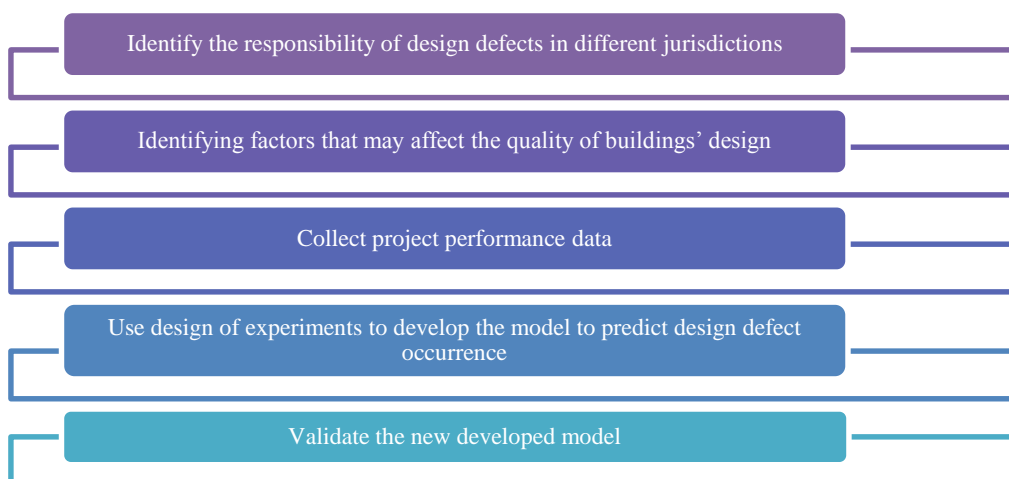


Figure 1. Research methodology flow chart

3. Design Responsibility

An important question should be asked before discussing the design defects and their reasons. *Who is responsible for the results of design defects?*

A simple answer may suggest that the design defect responsibility will be determined based on the contract type. As an example, the contractor should be liable for the design defects only if given the responsibility of design, such as in 'Design-Build' projects. On the contrary, the contractor should not be liable for design defects in 'Design-Bid-Build' projects [36].

Although it seems like a simple question, there is a lot of controversy about whether the contractor is responsible for the design defects in the 'Design-Bid-Build' projects or not. At first glance, anyone may think it is crystal clear and logical that the contractor should not be liable for the defects due to the design, as the contractor was not involved in developing it. Although the majority of countries' laws and international standard forms of contract insist on this conclusion, the situation doesn't look the same in the Middle East, as will be further discussed through the rigorous review of laws and standard forms of contract applied in several countries [37].

Several studies have investigated the design responsibility locally and globally in general or in specific types of projects. Qureshi [36] discussed the responsibility of designers towards their designs. Beade-Pereda [37] addressed the responsibility of designers in bridge projects specifically. Reich [38] explored the designer's responsibility towards the community and stakeholders in general. Eekels [39] argued for the engineer's moral responsibility as a designer. On the other hand, Davey et al. [40] discussed the responsibility of designers towards their designs during the defect liability phase, after the initial handover, and before the final handover.

All research concluded that designers have full responsibility for the consequences of their designs.

The Egyptian Civil Code, Article 651 stipulates that 'The architect and contractor jointly and severally warrant, for a period of ten years, against the total or partial collapse of buildings or other immovable structures erected by them, even if such collapse is because of a defect in the land itself, or if the employer authorized the erection of the defective structures, unless the parties, in this case, intended the structures to last for less than ten years'. The warranty provided for in the preceding paragraph extends to defects in buildings and structures threatening the solidity and security of the works. The ten-year period begins at the time of taking delivery of the works', and the design liability is solely the responsibility of the designer, emphasizing that the contractor should not be questioned nor legally claimed by any means because of any defects due to the design that was originally and basically developed by the designer [41].

Also, it is highlighted in 'Al Wassit' in an explanation of the civil code written by Dr. Abdelrazek El Sanhori, the famous law professor who wrote the Egyptian Civil Code in 1948 and held the position of Minister of Education twice in his life. He wrote in his book, which is the most reliable book referenced in such a debate, that if the error is due to the design, the warranty mentioned in the Egyptian Civil Code, Article 651, shall be applied to the person responsible for developing the design, which is the design consultant, whether the designer supervises the implementation of the work or not. Moreover, if the designer supervises the implementation of the works, the designer would be liable for the defects due to the implementation jointly and severally with the contractor, but when it comes to the defects due to the design, the designer will be completely liable, and the contractor will be subject to no obligations to bear with him the consequences of this error [42].

Other Arabic countries that are under the jurisdiction of civil law have clarified this matter in updated civil codes, like Qatar's civil code issued in 2004, Article 713 [43], and Kuwait's civil code issued in 1980, Article 694 [44], stating

that 'The contractor shall only be liable for defects that occur in the implementation, excluding the defects that come from error in developing the design, unless these defects are visible, according to the principles of workmanship. However, the contractor shall be responsible for defects due to the design if the engineer who developed the design is the contractor's subordinate.'

Many international institutes determined the design defect responsibility, such as:

- International Federation of Consulting Engineers (FIDIC),
- Institution of Civil Engineers (ICE),
- International Chamber of Commerce (ICC),
- American Institute of Architects (AIA), and
- Joint Contracts Tribunal (JCT).

These institutes tried to end this debate by drafting clauses in standard forms of contract between the contractor and the employer that transfer the risk of defects due to the design of the work to the employer. For example, the FIDIC institute in Red Book, sub-clause 8.2, stated that the contractor shall take full responsibility for the adequacy, stability, safety, and methods of all site operations and construction provided, but the contractor is not liable for the design or specification of any permanent works not provided by the contractor or for the design or specification of any temporary works not prepared by the contractor. Where the contract clearly states that the contractor is responsible for designing a section of the permanent works, the contractor is completely accountable for that portion of the works, regardless of the engineer's approval [45].

Furthermore, FIDIC Red Book 1999 Edition, sub-clauses 17.3 and 17.4, stated that one of the risks that the employer bears is the risk of any loss or error caused by the design of the works, except any part of the design already submitted by the contractor or for which the contractor is accountable. Not only that, but also, the employer is obligated to indemnify the contractor with an extension to the project completion date for any delays caused by the design defects and payment of any extra costs. These clauses provide the entitlement only for the contractor, but the contractor still has to send a notice of claim to the engineer under sub-clause 20.1 within the time range stated in the contract conditions. A fully detailed claim should follow, whereby the contractor can substantiate the delays and extra costs incurred by the contractor during the construction phase when dealing with the poor design developed by the designer [46].

In addition, ICE states in its Contracts Conditions [47], sub-clause 8.2, that the contractor shall take full responsibility for the adequacy, stability, and safety of all site operations and methods of construction, provided that the contractor shall not be accountable nor liable for the design or specification of the permanent works or any temporary works developed by the engineer (unless as specifically stated in the contract). Contract Conditions [48] state in sub-clause 8.2 that the contractor shall not be responsible for the design or specification of the permanent works or any part thereof (except as may be expressly provided in the contract) or of any temporary works designed by the engineer. The contractor shall exercise all reasonable skill, care, and diligence in designing any part of the permanent works for which he is responsible.

On the other hand, there is an opposite point of view in Egypt, the Middle East, and the North African region: the contractor shall review and revise all project drawings and specifications to be responsible for any design defects potentially affecting the structure's stability and safety. This extreme opinion derives its strength from the Egyptian administrative laws, which govern the administrative contracts in the construction industry between the contractor and the administrative authority that represents the state as a sovereign, which means that these projects are under state control. When it comes to administrative contracts, this opinion is true to some extent, as Article 80 of the implementing regulation of Egyptian Administrative Law No. 89 issued in 1998 [49] states that the contractor is obligated to investigate by himself the nature of the works and perform all necessary tests and others to ensure the validity of the approved specifications, drawings, and designs, shall notify the administrative authority in a timely manner of his observation on them, and shall be responsible accordingly for the correctness and safety of all what is stated in them, as if they were submitted by him.

Also, it's mentioned once more, with a few minor changes in Article 116 of the implementing regulation of Egyptian Administrative Law No. 182, issued in 2018 [50], that the contractor is legally responsible for investigating by himself the nature of the works and performing all necessary tests to ensure the validity of the approved technical specifications, engineering drawings, and designs, shall notify the administrative authority in a timely manner of his observation on them, and shall be responsible accordingly for the correctness and safety of all what is stated in them, as if they were submitted by him. It's now crystal clear that the Egyptian Administrative Laws load the contractor with a liability to make sure that all specifications, drawings, and designs are correct.

It may sound a little weird that the contractor is liable to the employer for any defects due to the design of the work already developed by the design consultant. However, this is written in the Egyptian administrative laws, giving the contractors only two options. On the one hand, they can hire a design consultant to review all the drawings, specifications, and designs made by the original designer before the tender to detect or discover any design defects

before the construction phase to notify the employer and mitigate the probability and impact of the defects, keeping in mind that this solution will cost them additional expenses that will result in a higher price bid than other contractors' bids. On the other hand, they may have to bear the risk of finding any defects due to the design during the construction phase not being considered when estimating the project schedule and budget during the tender phase.

Ironically, it may be discovered that many employers in civil contracts draft such clauses to transfer the risk of design defects to the contractor, which is totally against the civil law provisions.

To sum up, there is no better way to end this debate than viewing the ruling of the Egyptian Court of Cassation no. 1847 issued on November 18, 1993, which is considered the highest degree of litigation in Egypt. As stated, the text in Articles 651 and 652 of the civil code indicates that the scope of the warranty explicitly stated in Article 651 is not limited to the total or partial demolition of the building but also includes other defects that threaten the building's safety and durability, even if they are not in the event of its demolition. The original responsibility for this warranty is that the architect and the contractor are jointly responsible for these defects as long as they arise from the implementation of the construction, forming a responsibility based on an assumed error on their part. This responsibility arises from them by proving that they built according to the design developed by the designer and that the defect in the building is caused by the error of others. Therefore, if these defects arise from the design of the building without extending to its implementation, the warranty shall be applied to the engineer who developed the design separately, considering that the engineer is the only one from whom the error occurred.

4. Design Defects Reasons & Impact

Upon determination of the responsibility for design defects, it was time to search for factors affecting the occurrence of design defects and their consequences. Many factors, which may be the reason behind design defects, were identified throughout the literature review. Also, brainstorming sessions were held with project management experts to identify further factors [51]. Sixteen project management experts were selected with experience in the construction industry ranging from 11 to 35 years in local and global organizations, in addition to their academic and professional contribution to construction management research. They have positions in different disciplines, such as engineering and design, contract and claims, planning and scheduling, quality control and quality assurance, and cost control. Finally, fifteen factors were identified and categorized into two main groups of project- and design-related factors. Table 1 illustrates the source of each identified factor.

Table 1. Source of each identified factor

| Factors | | Literature Review | Brainstorming |
|------------------------|--|-------------------|---------------|
| <i>Project Factors</i> | | | |
| 1. | Type of project | √ | √ |
| 2. | Project delivery system | √ | √ |
| 3. | Original project value | √ | √ |
| 4. | Variation order value | | √ |
| 5. | Project duration | √ | √ |
| <i>Design Factors</i> | | | |
| 6. | Elicitation of requirements | | √ |
| 7. | Involvement of stakeholder | | √ |
| 8. | Information completeness & accuracy | √ | √ |
| 9. | Engineering system complexity | √ | √ |
| 10. | Design firm experience | √ | √ |
| 11. | Multiple designer involvement | | √ |
| 12. | Design schedule | √ | √ |
| 13. | Design changes | √ | √ |
| 14. | Contractor liability towards design review | | √ |
| 15. | Design software | | √ |

The detailed description of each factor, along with its measurement methodology, is illustrated as follows:

I. Project Factors

1. Type of project:

It is unclear how the project type may affect the design defect [52]; however, researchers didn't exclude any factor that may have contributed to the probability of defect occurrence. The project type will be identified in one of two categories:

- a) Residential
- b) Commercial

2. Project delivery system:

The project delivery system may affect the design defects due to the contractor's responsibility for the design in Design-Build projects.

Project delivery system will be identified as one of two categories:

- a) DBB (Design-Bid-Build), where the contractor is not liable for design.
- b) DB (Design-Build), where the contractor is liable for design.

3. Original project value:

An increase in the original project value indicates increased project scope and a higher probability of design defect occurrence.

The original project value will be measured in equivalent United States Dollars, using the exchange rates on the first of January 2022.

4. Variation order value

An increase in the variation order value indicates increased project scope changes, which may reflect a higher probability of design defect occurrence [53, 54].

Variation order value will be measured in equivalent United States Dollars, using the exchange rates on the first of January 2022.

5. Project duration

A shorter project duration may result in a compressed fast-track schedule, which rushes the design process and causes a higher probability of design defect occurrence [55]. The project duration will be measured in months.

II. Design Factors

1. Elicitation of requirements:

The first step in any design process is identifying the client requirements to be considered during the design process [56]. Design defects will be encountered in cases of unclear or inaccurate requirements [57].

Elicitation of client requirements will be measured on a scale from 1 to 10, with 1 and 10 representing improper and excellent elicitation of requirements during the design process, respectively.

2. Involvement of stakeholders:

The lack of involvement of key stakeholders, such as key vendors, will certainly affect the quality of design due to their role in the identification of design requirements [58, 59].

The involvement of key stakeholders will be measured on a scale from 1 to 10, with 1 representing that stakeholders were not involved during the design process and 10 indicating that stakeholders were involved appropriately.

3. Information completeness & accuracy:

Information provided to the designer during the design process plays a significant role in the design quality, and incomplete or incorrect information will lead to design defects [60].

The information completeness and accuracy will be measured on a scale from 1 to 10, with 1 representing that all information provided to designer was not accurate nor complete and 10 indicating that all information was accurate and complete.

4. Engineering system complexity:

The complexity of the engineering systems may affect the probability of design defect occurrence [61], increasing the probability of design defect occurrence.

The engineering system complexity will be measured on a scale from 1 to 10, with 1 representing the simplest engineering system and 10 indicating the most complex engineering system.

5. Design firm experience:

Design firm capabilities and experience in similar projects may help reduce the probability of design defect occurrence [62]. The design firm experience will be measured on a scale from 1 to 10, with 1 representing insufficient design firm experience and 10 indicating the highest design firm experience.

6. Multiple designer involvement:

Assigning design to multiple designers may generate a higher probability of design defects due to design inconsistency [63]. Designer involvement will be measured on a binary base, with 0 representing the involvement of one design firm and 1 indicating the involvement of multiple designers.

7. Design schedule:

Tight design schedule may generate a higher probability of design defects [64]. Design schedule will be measured on a scale from 1 to 10, with 1 indicating insufficient design schedule and 10 representing sufficient design schedule.

8. Design changes:

Frequent design changes requested by the owner may lead to a higher probability of design defects [65]. Design changes will be measured on a scale from 1 to 10, with 1 indicating minor few design changes and 10 representing frequent major design changes.

9. Contractor liability towards design review:

As discussed earlier in this research, contractors may be contractually liable for design review in a few cases, which will reduce the probability of design defects [66]. Contractor liability will be measured on a binary scale, with 0 representing no contractor liability and 1 indicating that the contractor is liable for design review.

10. Design software:

Availability of appropriate design software, such as Building Information Modelling (BIM), seems crucial in reducing the design defects, including contradictions in different design disciplines [67-69]. Design software availability will be measured on a binary scale, with 0 representing no design software and 1 indicating the availability of all design software.

III. Design Defects

Furthermore, five main design defects were identified through literature review and brainstorming sessions, as follows:

1. Unsafe design elements:

The output design may include unsafe elements, potentially jeopardizing people's lives, and properties [70]. This defect will be measured on a scale from 1 to 10, with 1 representing the unavailability of unsafe elements and 10 indicating many unsafe elements that threaten the overall building stability.

2. Incompatible disciplines:

Although incompatible disciplines, such as contradictions encountered between civil, mechanical, and electrical disciplines, did not have the highest impact on building design compared with unsafe design elements, its frequent occurrence entitled it for a decent ranking among design defects consequences [71]. Incompatible disciplines will be measured on a scale from 1 to 10, with 1 representing perfectly compatible disciplines and 10 indicating many incompatible disciplines.

3. Inefficient design:

Design should be efficient to allow for achieving stakeholders' requirements [72-75]. Symptoms of inefficient design include, but are not limited to, waste of material used in construction. Inefficient design will be measured on a scale from 1 to 10, with 1 representing perfectly efficient design and 10 indicating totally inefficient design.

4. Ambiguous design:

Design should provide all details to facilitate smooth construction process and avoid disruption of construction momentum by frequent requests for information [76]. Ambiguous design will be measured on a scale from 1 to 10, with 1 representing crystal clear design information and 10 indicating considerable ambiguous design information or missing design components.

5. Delays in Design Duration:

Design should be delivered according to its predefined schedule to avoid negative impact on construction schedule [77]. Design delays will be measured on a scale from 1 to 10, with 1 representing the delivery of design in predefined schedule or earlier and 10 indicating massive design delays.

5. Data Collection and Analysis

Data were collected from forty-seven projects through several interviews conducted with the project team responsible for design and construction activities. Collected data included the above-mentioned factors, in addition to the team evaluation for the design defects.

Five projects were selected out of the forty-seven projects using random number generated from Microsoft Excel. Those projects were kept away from the development of the new model to be used later in model validation. The remaining forty-two project data will be used in the development of the new model.

Table 2 includes all details of the selected forty-two projects to build the model.

Table 2. Characteristics of selected projects

| Project no. | Project Type | Project Delivery System | Project Value (K USD) | Variation Orders Value (K USD) | Project Duration |
|-------------|--------------|-------------------------|-----------------------|--------------------------------|------------------|
| 1 | Residential | DBB | 277,416 | 4,862 | 13 |
| 2 | Residential | DBB | 281,035 | 11,344 | 13 |
| 3 | Commercial | DBB | 140,345 | 10,556 | 20 |
| 4 | Commercial | DBB | 258,078 | 15,183 | 17 |
| 5 | Residential | DBB | 171,821 | 17,313 | 13 |
| 6 | Commercial | DB | 235,262 | 8,176 | 11 |
| 7 | Commercial | DBB | 203,843 | 15,811 | 21 |
| 8 | Residential | DBB | 291,495 | 18,102 | 20 |
| 9 | Residential | DBB | 189,932 | 5,047 | 18 |
| 10 | Residential | DB | 286,550 | 16,273 | 14 |
| 11 | Residential | DBB | 66,053 | 6,642 | 27 |
| 12 | Commercial | DB | 307,260 | 6,146 | 30 |
| 13 | Commercial | DBB | 74,191 | 14,127 | 22 |
| 14 | Residential | DBB | 111,233 | 8,430 | 18 |
| 15 | Residential | DB | 146,721 | 11,760 | 27 |
| 16 | Residential | DBB | 319,306 | 4,034 | 21 |
| 17 | Residential | DBB | 175,350 | 7,940 | 13 |
| 18 | Commercial | DBB | 230,943 | 4,218 | 11 |
| 19 | Residential | DB | 165,245 | 8,210 | 11 |
| 20 | Residential | DBB | 118,914 | 8,994 | 13 |
| 21 | Residential | DBB | 263,312 | 10,094 | 27 |
| 22 | Commercial | DB | 101,591 | 15,620 | 18 |
| 23 | Commercial | DBB | 256,723 | 10,101 | 18 |
| 24 | Commercial | DB | 145,573 | 10,318 | 21 |
| 25 | Residential | DBB | 312,355 | 8,126 | 27 |
| 26 | Residential | DB | 264,315 | 7,644 | 12 |
| 27 | Residential | DBB | 128,295 | 9,434 | 25 |
| 28 | Residential | DB | 114,835 | 15,570 | 19 |
| 29 | Residential | DBB | 305,459 | 10,143 | 15 |
| 30 | Residential | DB | 307,329 | 11,072 | 16 |
| 31 | Commercial | DB | 73,041 | 12,915 | 20 |
| 32 | Residential | DBB | 258,427 | 10,045 | 12 |
| 33 | Commercial | DB | 290,703 | 4,668 | 12 |
| 34 | Residential | DBB | 318,964 | 14,957 | 16 |
| 35 | Residential | DBB | 93,488 | 17,327 | 13 |
| 36 | Residential | DBB | 200,145 | 14,208 | 20 |
| 37 | Residential | DB | 145,686 | 4,982 | 27 |
| 38 | Residential | DBB | 302,996 | 5,520 | 18 |
| 39 | Residential | DBB | 225,174 | 8,560 | 27 |
| 40 | Residential | DB | 60,536 | 13,709 | 19 |
| 41 | Residential | DBB | 108,728 | 17,276 | 15 |
| 42 | Residential | DBB | 139,051 | 8,922 | 18 |

Data were tested using Design of Experiments (DOE), which can analyze the impact of multiple variables or attribute data on multiple output variables [78].

There are two main types of DOE: factorial experiments and custom factorial design, with the former providing specifications for each experimental run. It includes a blocking scheme, randomization, replication, and factor-level combinations. This information defines the experimental conditions for each test run. The response was measured at predetermined settings of the experimental conditions when performing the experiment. Each experimental condition employed to obtain a response measurement was a run [79].

In industry, the DOE can be used to identify input variables that influence process performance [80]. For example, DOE can be used to obtain the best combinations of coatings and temperatures to adjust the manufacturing conditions and investigate the influence of the coating type and furnace temperature on the corrosion resistance of steel bars. Custom factorial is more flexible for researchers as it allows for all design options while permitting the use of factors with continuous or attribute data with unlimited and uninformed numbers of levels. Therefore, a custom factorial can be used to analyze historical data. Custom factorial also allows for analyzing unchangeable factors, such as outdoor temperature, which cannot be controlled by researchers. One of the advantages of custom factorial is its ability to deal with inequality constraints on the factors. This means that there are no specific number of experimental runs to do.

In this study, a custom factorial design was used to create a design from historical data. The Minitab software was used to define the custom factorial design using the collected data. Each factor was granted two levels to define the limits of the experiment. The experiment was analyzed using Minitab to study the impact of each factor on each type of design defect. The analysis also examined the impact of interactions between factors, which may also affect each design defect type. The DOE analysis generated a Pareto graph that showed factors affecting each individual design defect in descending order. The critical value is shown in each Pareto chart in red font with a dotted line. Any factor that exceeds this critical value is considered to affect this type of design defect significantly.

Figure 2 shows that factors affecting design safety are as follows:

- Design firm experience shows a significant impact on design safety, highlighting that a lack of experience will lead to unsafe design elements.
- The design schedule shows a significant impact on design safety, highlighting that a tight design schedule will lead to unsafe design elements.

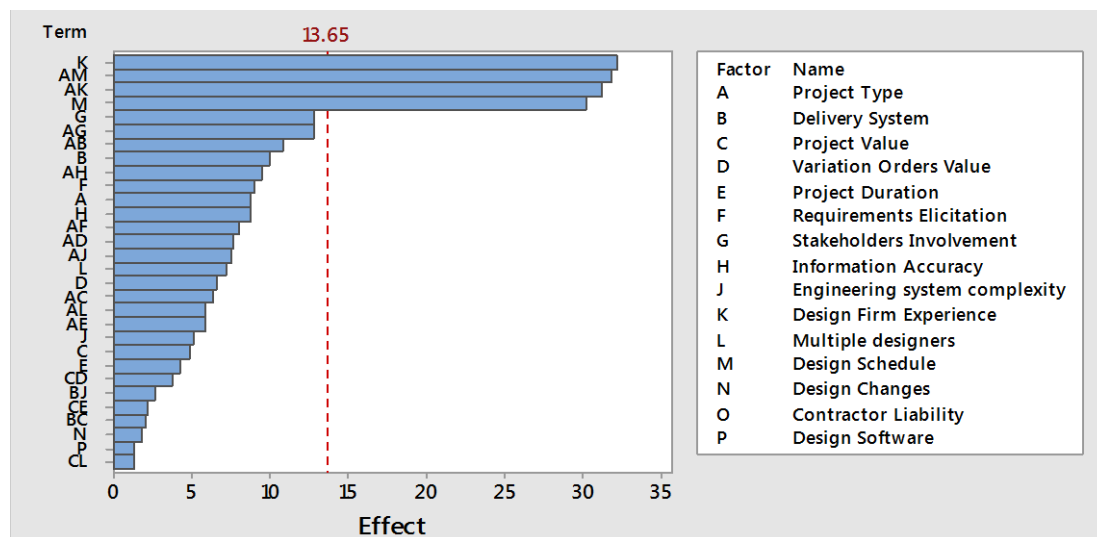


Figure 2. Factors affecting design safety sorted in a descending order

It was also noted from the graph that project type shows a significant impact when interacting with the design schedule or design firm experience.

Figure 3 shows that factors affecting incompatible design are as follows:

- Design schedule shows a significant impact on incompatible design, highlighting that a tight design schedule will lead to an incompatible design.
- Design firm experience shows a significant impact on incompatible design, highlighting that lack of experience will lead to an incompatible design.
- Stakeholders’ involvement shows a significant impact on incompatible design, highlighting that lack of stakeholders’ involvement will lead to an incompatible design.

- Project delivery system shows a significant impact on incompatible design, highlighting that lack of stakeholders’ involvement will lead to an incompatible design.
- Information accuracy shows a significant impact on incompatible design, highlighting the significant contribution of inaccurate information to an incompatible design.

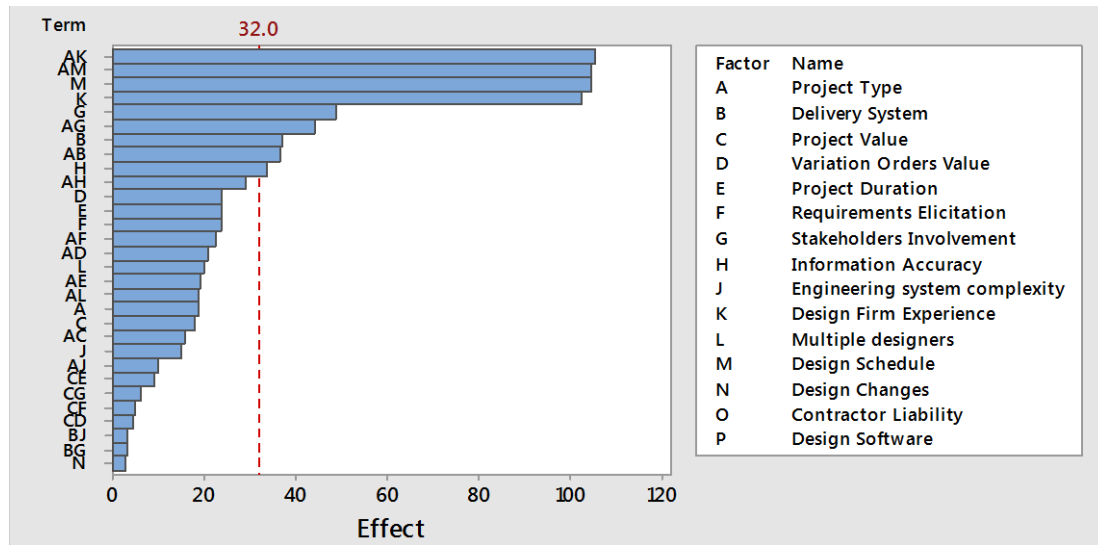


Figure 3. Factors affecting incompatible design sorted in descending order

It was also noted from the graph that many other factors have a significant impact on incompatible design when interacting with each other.

Figure 4 shows that factors affecting inefficient design are as follows:

- Design schedule shows a significant impact on inefficient design, highlighting that a tight design schedule will lead to an inefficient design.
- Design firm experience shows a significant impact on inefficient design, highlighting that lack of experience will lead to an inefficient design.
- Stakeholders’ involvement shows a significant impact on inefficient design, highlighting that lack of stakeholders’ involvement will lead to an inefficient design.
- Project delivery system shows a significant impact on inefficient design, highlighting that lack of stakeholders’ involvement will lead to an inefficient design.
- Information accuracy shows a significant impact on inefficient design, highlighting the significant contribution of inaccurate information to inefficient design.

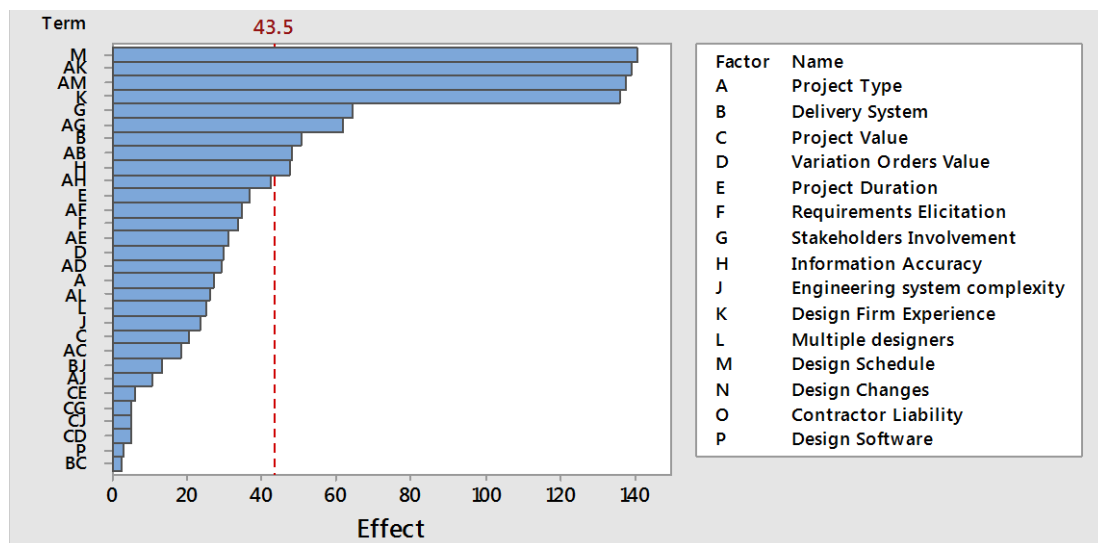


Figure 4. Factors affecting inefficient design sorted in descending order

It was also noted from the graph that many other factors have a significant impact on inefficient design when interacting with each other.

Figure 5 shows that factors affecting design ambiguity are as follows:

- Design firm experience shows a significant impact on design ambiguity, highlighting that lack of experience will lead to an ambiguous and unclear design.
- Design schedule shows a significant impact on design ambiguity, highlighting that a tight design schedule will lead to an ambiguous and unclear design.
- Stakeholders' involvement shows a significant impact on design ambiguity, highlighting that lack of stakeholders' involvement will lead to an ambiguous and unclear design.

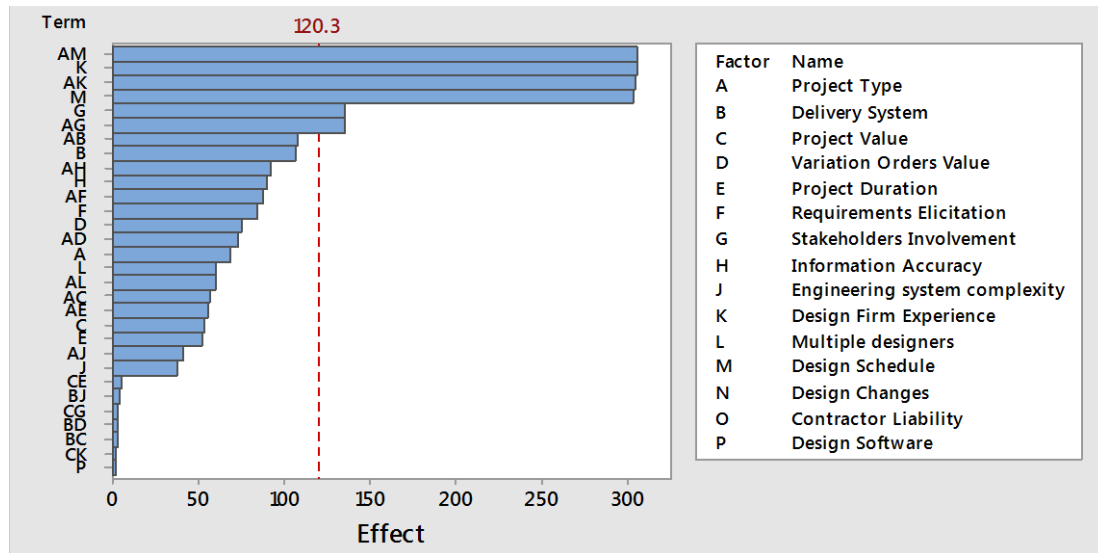


Figure 5. Factors affecting design ambiguity sorted in descending order

It was also noted from the graph that many other factors have a significant impact on design ambiguity when interacting with each other

Figure 6 shows that factors affecting design delays are as follows:

- Design schedule shows a significant impact on design delays highlighting that a tight design schedule will lead to design delays.
- Design firm experience shows a significant impact on design delays, highlighting that lack of experience will lead to design delays.
- Stakeholders' involvement shows a significant impact on design delays, highlighting that lack of stakeholders' involvement will lead to design delays.

It was also noted from the graph that many other factors have a significant impact on design delays when interacting with each other [81].

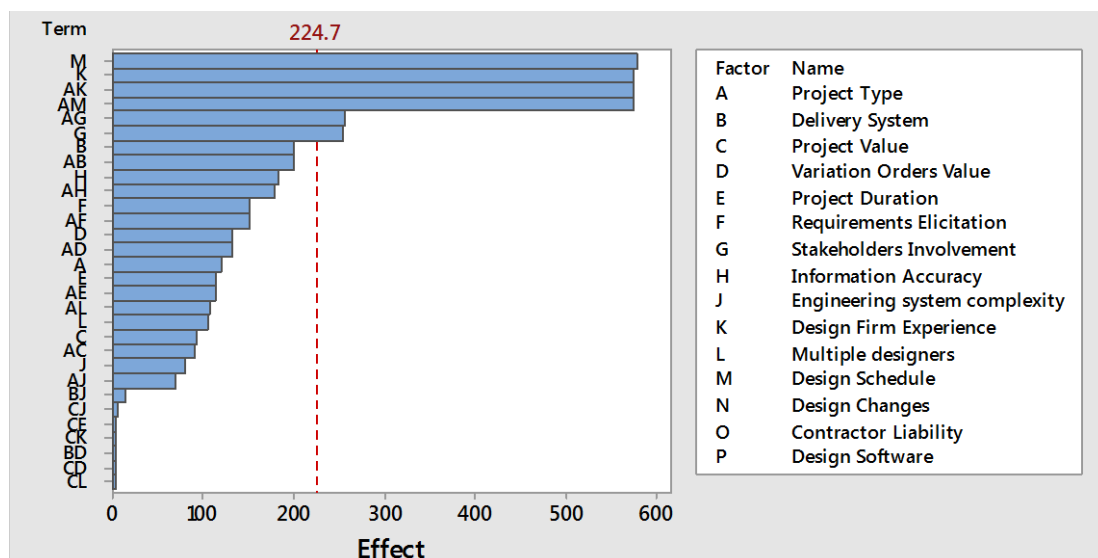


Figure 6. Factors affecting design delays sorted in descending order

Table 3 shows that only two factors, including Design Firm Experience and Design Schedule, had a significant impact on all types of design defects.

Table 3. Factors affecting each type of design defect

| Design Safety | Incompatible Design | Inefficient Design | Design Ambiguity | Design Delays |
|------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Design Firm Experience | Design Schedule | Design Schedule | Design Firm Experience | Design Schedule |
| Design Schedule | Design Firm Experience | Design Firm Experience | Design Schedule | Design Firm Experience |
| | Stakeholders Involvement | Stakeholders Involvement | Stakeholders Involvement | Stakeholders Involvement |
| | Project Delivery System | Project Delivery System | | |
| | Information Accuracy | Information Accuracy | | |

On the other hand, five common factors had a significant impact on one or more of the five types of design defects. Those factors included the following:

- Design Schedule;
- Design Firm Experience;
- Stakeholders Involvement;
- Project Delivery System; and
- Information Accuracy.

Those factors were chosen for development of the new model to predict the output design defects:

- Design Safety;
- Incompatible Design;
- Inefficient Design;
- Design Ambiguity; and
- Design Delays.

6. Establishment of Model

The above-mentioned five factors were used to build the prediction model utilizing the response optimizer in Minitab. Figure 7 presents the minimum design defects, which could be achieved throughout all experiments.

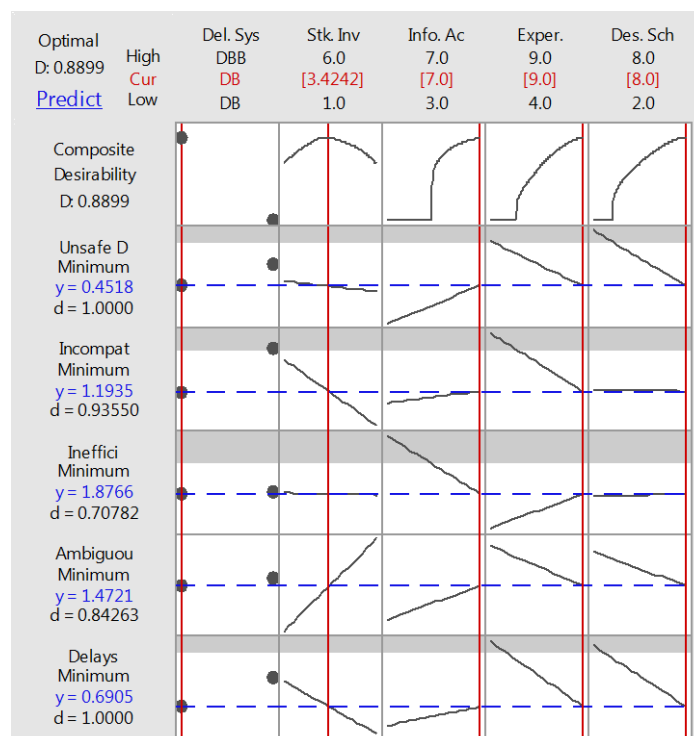


Figure 7. Minimum design defects

The values of factors associated with the minimum design defects were extracted from Figure 6 and presented in Table 4, alongside each factor's minimum and maximum value.

Table 4. Optimum factor level

| Factor | Optimum Level | Min. Level | Max. Level |
|-----------------------------|---------------|------------|------------|
| 1. Project Delivery System | Design-Build | - | - |
| 2. Stakeholders Involvement | 3.4 | 1 | 6 |
| 3. Information Accuracy | 7 | 3 | 7 |
| 4. Design Firm Experience | 9 | 4 | 9 |
| 5. Design Schedule | 8 | 2 | 8 |

It could be understood that Design-Build may be a better choice to ensure solid contractor liability for design, which will be reflected in the contractor's desire to minimize design defects to avoid the negative impact of design defects on construction activities.

Besides, having a design firm with excellent experience in similar projects and providing accurate information, in addition to allowing for a decent design period duration, will be reflected in a lower design defect. On the other side, the model predicted that having moderate stakeholders' involvement would be the best choice, perhaps because the excessive stakeholders' involvement would affect the design period duration negatively. One of the competitive edges of this model is its real-time prediction capability, which means that the graph can be changed dynamically in case any input value is changed. For example, changing the design firm experience from 9 to 7 would increase design defects dramatically. This modification takes place immediately on the graph upon the change of design firm experience value. Figure 8 shows the anticipated design defects.

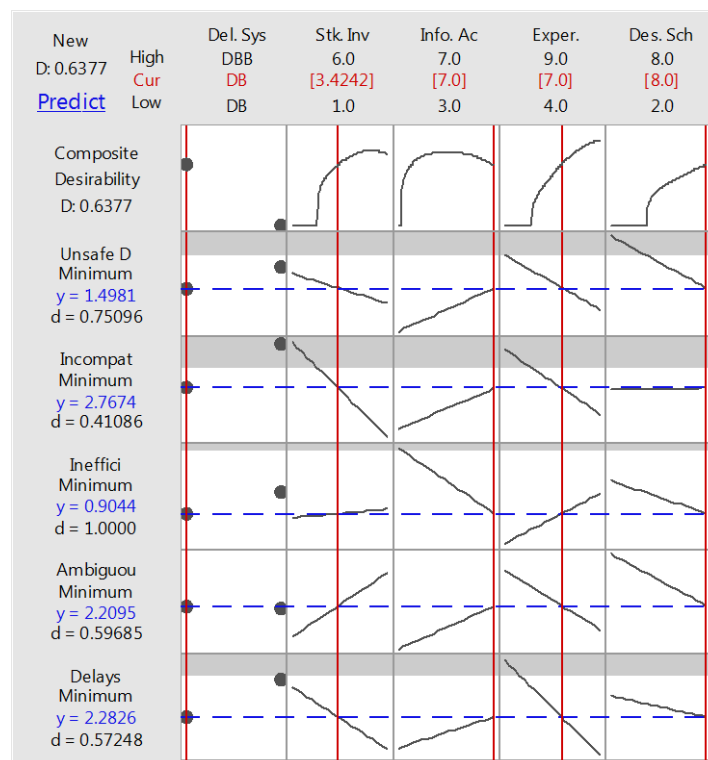


Figure 8. Updated graph

7. Model Validation

Data were collected from forty-seven projects through several interviews conducted with the project team responsible for design and construction activities. Five projects were selected out of the forty-seven projects using random number generated from Microsoft Excel. Those projects were kept away from the development of the new model to be used later in model validation. The remaining forty-two project data was used in the development of the new model.

Tables 5 and 6 summarize data related to all factors' values and the actual design defects encountered in each project.

Table 5. Actual values of factors

| Factor | A | B | C | D | E |
|-----------------------------|----|-----|-----|-----|----|
| 1. Project Delivery System | DB | DBB | DBB | DBB | DB |
| 2. Stakeholders Involvement | 3 | 6 | 4 | 5 | 5 |
| 3. Information Accuracy | 6 | 7 | 7 | 5 | 6 |
| 4. Design Firm Experience | 7 | 9 | 7 | 8 | 5 |
| 5. Design Schedule | 4 | 5 | 7 | 6 | 8 |

Table 6. Actual design defects values

| Design Defects | A | B | C | D | E |
|------------------------|---|---|---|---|---|
| 1. Design Safety | 3 | 2 | 3 | 2 | 2 |
| 2. Incompatible Design | 3 | 2 | 5 | 3 | 1 |
| 3. Inefficient Design | 2 | 2 | 2 | 3 | 1 |
| 4. Design Ambiguity | 4 | 5 | 3 | 3 | 4 |
| 5. Design Delays | 4 | 3 | 5 | 4 | 4 |

The new model was utilized to predict the design defects according to factor values. Table 7 presents the predicted value of design defects.

Table 7. Predicted design defects values

| Design Defects | A | B | C | D | E |
|------------------------|------|------|------|------|------|
| 1. Design Safety | 2.64 | 2.28 | 2.39 | 2.13 | 1.49 |
| 2. Incompatible Design | 2.76 | 2.43 | 4.5 | 2.29 | 1.09 |
| 3. Inefficient Design | 2.08 | 1.87 | 2.06 | 2.40 | 0.50 |
| 4. Design Ambiguity | 3.01 | 4.27 | 2.62 | 2.42 | 2.46 |
| 5. Design Delays | 2.66 | 2.21 | 3.49 | 2.69 | 3.19 |

The predicted results were compared with the actual values of design defects, and the error was presented in Table 8.

Table 8. Difference between actual & predicted design defects values

| Design Defects | A | B | C | D | E |
|------------------------|-------|-------|-------|-------|-------|
| 1. Design Safety | 0.36 | -0.28 | 0.61 | -0.13 | 0.51 |
| 2. Incompatible Design | 0.24 | -0.43 | 0.5 | 0.71 | -0.09 |
| 3. Inefficient Design | -0.08 | 0.13 | -0.06 | 0.60 | 0.50 |
| 4. Design Ambiguity | 0.99 | 0.73 | 0.38 | 0.58 | 1.54 |
| 5. Design Delays | 1.34 | 0.79 | 1.51 | 1.31 | 0.81 |

The Mean Absolute Percentage of Error (MAPE) was used to compare predicted and actual values and validate the prediction accuracy of the new established model [82].

The accuracy of the model was determined according to the following scale:

- MAPE from 0 to 10%: Excellent
- MAPE from 10 to 20%: Good
- MAPE from 20 to 50%: Reasonable
- MAPE from 50 to 100%: Not accurate

Table 9 shows the calculated error percentage, using the Equation 1:

$$Error = |(Actual - Forecast)| / |actual| \times 10 \tag{1}$$

Table 9. MAPE values

| Design Defects | A | B | C | D | E |
|-----------------------|-----|-----|-----|-----|-----|
| 1 Design Safety | 12% | 14% | 20% | 6% | 26% |
| 2 Incompatible Design | 8% | 22% | 10% | 24% | 9% |
| 3 Inefficient Design | 4% | 6% | 3% | 20% | 50% |
| 4 Design Ambiguity | 25% | 15% | 13% | 19% | 39% |
| 5 Design Delays | 34% | 26% | 30% | 33% | 20% |

MAPE for the new model was calculated to be 19%, using the Equation 2:

$$MAPE = (1/sample\ size) \times \sum[(|actual - forecast|)/|actual|] \times 100 \quad (2)$$

MAPE of 19% shows that the prediction accuracy of the new model is 'GOOD'.

8. Conclusions and Recommendations

This research aimed to establish a quantitative model to predict the occurrence of five types of design defects: Design Safety, Incompatible Design, Inefficient Design, Design Ambiguity, and Design Delays.

Fifteen factors were identified as potentially affecting the above-mentioned design defects through a literature review and brainstorming sessions held with experts. Factors were categorized into two main groups:

- I. **Project Factors:** Type of Project; Project Delivery System; Original Project Value; Variation Order Value; and Project Duration.
- II. **Design Factors:** Elicitation of requirements; Involvement of stakeholders; Information completeness & accuracy; Engineering system complexity; Design firm experience; Multiple designer involvement; Design schedule; Design changes; and Contractor liability towards design review; and Design software.

Data were collected from 42 projects and tested using Design of Experiments (DOE).

Analysis revealed that only five factors had a significant impact on different design defect types: Design Schedule; Design Firm Experience; Stakeholders Involvement; Project Delivery System; and Information Accuracy. Those factors were used in the development of the new model to predict the output design defects.

Data were obtained from five projects and were not included in the development of the model to be used for model validation. Actual values of design defects were compared with the predicted results, and the Mean Absolute Percentage of Error (MAPE) for the new model is 19%, which is rated as "Good" prediction accuracy. This margin of error is acceptable, considering the nature of subjective evaluation of design defects and the inherent complexity of translating subjective evaluation into quantitative values.

The novelty of this research originates from the achievement of three important objectives:

1. Identification of the ultimate responsibility for the consequences of design defects in construction projects at different jurisdictions, which can be used to settle potential disputes between employers, designers, and contractors' organizations.
2. Describing the method to minimize design defects in construction projects, which will mitigate design defect consequences.
3. Development of a new model to predict the occurrence of design defects in construction projects, which supports decision-makers in predicting the appropriate reserve to be added to the project schedule and budget, consequently mitigating the risk of design defect-related delays and cost overruns.

On the other hand, researchers can use the newly developed model in their future research in a dynamic mode, which means that they can modify any value of any of the five factors in the model inputs and monitor instantly the expected changes in design defects. This real-time analysis will allow a better understanding of the impact of each factor on design defects.

As a natural limitation of using DOE, the newly developed model can be applied to predict design defects based on data within the range of data used in the development of the model, which means that the model is confined within the specific measured values of factors.

Future research may explore this promising topic further in several dimensions, including the following areas:

1. Identify other factors influencing design defects.
2. Discover additional design defect types.
3. Use different project types.
4. Collect more project data and redevelop the model to reduce the Mean Absolute Percentage of Error (MAPE) and enhance prediction accuracy.

Development of new models to predict design defects using other techniques, such as artificial intelligence techniques, attempting to find a lower error range in predicting design defects.

9. Declarations

9.1. Author Contributions

Conceptualization, A.N. and K.A.; methodology, A.N. and K.A.; software, A.N. and K.A.; validation, A.N. and K.A.; formal analysis, A.N. and K.A.; investigation, A.N., E.E., and K.A.; resources, A.N., E.E., and K.A.; data curation, A.N. and K.A.; writing—original draft preparation, A.N. and K.A.; writing—review and editing, A.N., E.E., and K.A.; visualization, A.N. and K.A.; supervision, A.N. and E.E.; project administration, A.N., E.E., and K.A. All authors have read and agreed to the published version of the manuscript.

9.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

9.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

9.4. Conflicts of Interest

The authors declare no conflict of interest.

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