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Application of the DEMATEL approach to analyse the root causes of building defects

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Abstract
Building defects are a common phenomenon in the construction industry. The negative consequences of building defects are not limited to waste generation or low resource efficiency. This challenge can have several direct and indirect implications such as cost overruns, unforeseen delays in project completion time, building occupants' dissatisfaction and health and safety risks. Despite the increase in the number of studies investigating building defects in recent years, little is known about the prioritisation of their causes by considering the interaction among the causes of defects. Therefore, this study employed the decision-making trial and evaluation laboratory (DEMATEL) method to bridge this gap. Experts' opinion was sought using a questionnaire developed in the form of a matrix and semi-structured interview questions. Thereafter, the interactions among the causes of building defects were analysed and the most prominent causes are identified. The study showed that materials, workmanship and design are the major causes of building defects. Despite being specific context, the findings can be the basis for further research in this area with a focus on a range of different building typologies. Furthermore, the recommendations provided will act as a facilitator to minimise the occurrence of building defects. Lastly, the research findings can be considered in the planning stage of any construction project, to ensure the construction quality, reduce potential waste and enhance the circular economy and resource efficiency in the built environment sector.

Keywords Building defects · DEMATEL · Construction · Causes of defects · Construction and demolition waste

1 Introduction

It is documented that one of the main causes of material wastage in the building and construction sector is defects (Pereira et al. 2020a; Hauashdh et al. 2021). The occurrence of building defects is a prevalent phenomenon within the building and construction sector.

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Industry and public discourse have focused on building defects for over two decades (Johnston and Reid 2019; Gurmu et al. 2022). Industry reports from various countries have described building defect frequency as overwhelming (Waziri 2016; Hopkin et al. 2019; Johnston and Reid 2019; Strata Community Association NSW 2021). An example can be observed in the UK, as per a survey report, where 69% of newly-constructed residences were found to exhibit over five defects during the year 2018 (Hopkin et al. 2019). Additionally, research conducted in Russia indicated that about 80% of construction projects had critical defects (Baiburin 2017). A study conducted in Australia approximated that roughly 70% of buildings erected between the years 2000 and 2018 were found to possess at least one defect (Johnston and Reid 2019).

The negative consequences of building defects are not limited to waste generation or low resource efficiency. The literature indicates that this challenge can have several direct and indirect implications such as cost overruns (Yarnold et al. 2023), unforeseen delays in project completion time (Sharma and Laishram 2024), building occupants' dissatisfaction (Andrews et al. 2023) and health and safety risks (Azian et al. 2020; Coulburn and Miller 2022; Foster et al. 2022; Van Den Bossche et al. 2023). A recent study estimated that Australians have spent 10.5 billion dollars to manage building defects (Johnston and Reid 2019). Andrews et al. (2023) review of defects' impact on residents' health and well-being concludes living in poor-quality housing, especially with dampness/ mould and associated stigma, can lead to a poor sense of place. These issues have become increasingly pressing with more people working from home, a trend spurred by changes in working arrangements during and after the recent pandemic (Coulburn and Miller 2022). It is also shown that building defects can have far-reaching consequences, affecting the structural integrity, safety, and functionality of a structure (Crommelin et al. 2021).

Therefore, understanding the interconnected causes assists in addressing the root issues and preventing the recurrence of defects. By identifying interrelationships, a holistic understanding of how various factors interact to contribute to building defects can be understood. This comprehensive view is essential for developing effective strategies to address and prevent defects.

2 Research gap and objectives

Despite the growing number of studies on building defects in recent years, there remains a limited understanding of how to prioritise their causes by considering the interactions among these causes. While some research has explored the causes of building defects and their connections to the building life cycle (Kahn et al., 2021), proposed new methods for identifying recurring defects in residential construction (Lambers et al., 2023)

, and delved into the mechanics of latent conditions leading to impaired material usage (Aljassmi et al., 2014), there is still a gap in comprehensively analysing the interrelationships among these causes. Therefore, this study employed the decision-making trial and evaluation laboratory (DEMATEL) approach to bridge this gap within the context of Australian residential construction. The following objectives were articulated to provide a clear insight into building defect management in the construction industry:

1. To understand the interaction between various causes of building defects
2. To identify the most critical causes of building defects

2.1 Paper structure

The paper's organisation is as follows. In Sect. 2, pertinent literature was reviewed to identify the causes of building defects. The third section of this research paper delineates the methodology implemented in this investigation, which encompasses the utilisation of the DEMATEL approach. The advantages of this technique over other decision-making tools are also explicated. Section 4 presents the study results and Sect. 5 discusses the key findings. Lastly, Sects. 5 and 6 conclude the study by providing practical recommendations, indicating the study's contribution and suggestions for further research.

3 Literature review: the major causes of building defects

Recent studies have reported the major causes of building defects. In most studies, poor design and workmanship are the two factors giving rise to building defects. For instance, Sandanayake et al. (2021) showed that poor workmanship and design faults are the main causes of building defects worldwide. The authors maintained that 85% of total defects are caused by poor workmanship. Similarly, the content analysis of course cases by Shooshtarian et al. (2023) suggested similar results concerning the causes of building defects in various types of residential housing. Azian et al. (2020) investigation into the main reasons for defects in residential high-rise buildings revealed faulty design, poor workmanship and material quality are the main causes. The poor workmanship relates to the use of untrained labours (Mahamid 2022) on the construction sites, the mistakes that labours make during construction (Nagapan et al. 2012), poor material handling (Musarat et al. 2023) and labours lack of skills and experience (Fitchett and Rambuwani 2022).

These factors give rise to two categories of defects: patent defects that are readily discernible through visual inspection, and latent defects that remain concealed and evade detection until after the construction process (Saufi et al. 2023). A recent survey by Talib and Sulieman (2022b) concluded that appropriate architectural detailing in the design phase can reduce up to 90% of building defects. Each of these causes may involve many other underpinning factors that might go beyond the responsibility of one stakeholder while this is still their responsibility to ensure the risk of building failure is minimal.

In terms of design faults, for instance, the issues could be specifying a material that is not suitable for the project, the design being developer-led as opposed to owner or architect-led, the design not adhering to safety standards, or the design being misinterpreted by subcontractors (Delgado 2021). However, there are other causes of building defects that seem to play a crucial role in building defect occurrence. These include maintenance, materials, regulations, the scope of works, and weather (Fig. 1).

Poor material quality is one of the major reasons for building defects (Shooshtarian et al. 2023). According to Hashim et al. (2012) study, the quality of materials and construction, maintenance practices, and management are crucial factors in guaranteeing a minimal occurrence of building defects in public housing. Poor materials consist of 'poor material quality', 'poor material performance', and 'impaired material usage' (Yarnold et al. 2021). According to Othman et al. (2015), the most common causes of defects discovered during the period of liability for defects include poor manufacturing, low-quality construction materials, and inadequate design.

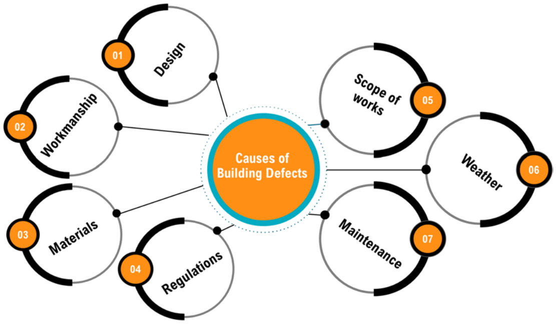

Fig. 1 The major causes of building defects. Source: Authors

Regulations can play a key role in the occurrence or prevention of building defects. Sandanayake et al. (2021) suggest that updating existing laws/regulations, improving trade qualification requirements, and enacting regulations to improve material and workmanship can be used as control and enforcement measures in the building defect management process. Hence, effective regulations are necessary to reduce the potential latent defects in buildings. For instance, compliant regulations demand the building surveyor and a certified engineer to conduct mandatory inspections at particular construction milestones and to produce engineering designs to ensure the quality of the build, accordingly (Aibinu and Paton-Cole 2023). Despite this, there is research highlighting that changes in legislation might not reduce the defects (Georgiou 2010), which implies that building defect control measures are not effective if considered individually.

Unfavourable weather conditions can cause moderate to significant defects in building materials. Given the current alarming changes in the climate at the global level, this factor can emerge as a serious issue in the building construction industry and is frequently cited in building defect reports. Chong and Low (2006) research ranked the effects of weather as the most important design-related causes of defects. Shooshtarian et al. (2023) research showed that for architects, the primary causes of defects were material performance and weather conditions. Particularly, weather agents have been reported to have noticeable negative impacts on building surfaces (Pereira et al. 2020b).

Incomprehensibility in the scope of workss may result in issues in managing defects in buildings. Any substantial work on a building necessitates the creation of a scope of workss which specify the works' specifications, quality and expected costs. There are circumstances under which that scope of workss is prepared for defects rectification.

The poor maintenance of a building refers to the occurrence of different flaws including poor service delivery, inadequate funds for repair, poor maintenance planning and maintenance backlogs (Wahab 2019). According to Yarnold et al. (2021), occupants' behaviour can be also categorised under this cause. Maintenance works are necessary for approximately 90% of building projects throughout their lifespan, as building performance may fail to meet the prescribed quality and standards, thereby necessitating remedial measures (Olanrewaju et al. 2022). Maintenance performed in a timely manner and following best practices will increase the service life of a building by preventing its degeneration.

The recurrence of various building defects suggests a pervasive deficiency in the understanding of fundamental principles of building physics (Lisø et al. 2020), which further highlights the key role of evidence-based education in the building and construction sector.

By analysing the cases reported from the observed defects, our knowledge of possible defects and their causes will improve. Hence, this research provides contemporary evidence of the major causes of building defects in Australia in the quest of informing decisions, behaviours and attitudes towards minimising building defects in the sector. This research focuses on low-rise buildings within the Australian context. Throughout the major cities in Australia, there has been a notable upswing in population, resulting in a substantial expansion of the residential building and construction sector (Kelly 2022). As indicated earlier, Australian studies show that there has been a corresponding surge in building defects in this sector (Paton-Cole and Aibinu 2021).

Industry and government reports from various Australian states and territories also highlight the same trend, particularly within the domain of low-rise buildings. For instance, in Victoria, the number of cases initiated in 2023, increased by 6% compared to the last year (VCAT 2023).

In NSW, a report by UNSW City Futures Research Centre (Crommelin et al. 2021) indicated that of schemes with more robust data, 51% have evidence of at least one defect, and 12% have evidence of at least ten types of defects. In response to increased concerns over building defects in the state's residential building and construction sector, the government introduced two laws in 2020, including Residential Apartment Buildings (Compliance and Enforcement Powers) Act 2020 (NSW Legislation 2022) aiming to grant sweeping powers for the authorised officers to take action against defective building work. Queensland, the third most populous state in Australia, has likewise taken proactive measures by implementing regulatory adjustments to enhance the oversight and management of building defects within the residential sector. As per the Queensland Civil and Administrative Tribunal, the number of complaints classified under the building list in 2022 was 27% greater than that in the preceding year (QCAT, 2022).

4 Methodology

4.1 Research design

This study used a concurrent mixed-method research design involving the collection of both quantitative and qualitative data at the same time. A major advantage of this design is that the researcher can return to the qualitative data and reread quotes in the context of the larger document (Leavy 2022). The research was conducted in five steps as shown in the following figure. These steps are explained in the subsequent sections.

4.2 Data collection

Two methods of data collection were employed in this study: a questionnaire survey and a semi-structured interview (Fig. 2). The questionnaire survey was intended to elicit

Fig. 2 The overview of the research process

information on the participants' experience in the industry and the influence of various causes of building defects on each other. Seven categories that were identified in the literature were added to a matrix table. These factors included design, maintenance, materials, regulations, the scope of works, weather and workmanship (Fig. 1). The perceptions of experts regarding the influence of one cause over the other are collected in the form of a matrix.

The participants were asked to rank the influence of each cause of building defects on a 5-point Likert scale (i.e., 0: no influence, 1 = very low influence, 2 = low influence, 3 = high influence and 4 = very high influence). The Likert scale is a method of assessing the perceptions of survey participants towards a set of statements (Jebb et al. 2021). The underlying principle of a Likert item is that an individual's opinion can be measured on a scale ranging from "negative". The 5-point Likert scale is widely used in construction management and building defect research (Zaneldin 2020; Talib and Sulieman 2022a).

The final version of the questionnaire underwent a thorough review by experts to ensure its content validity, as well as being assessed for online accessibility and comprehension by a cohort of construction professionals and seasoned researchers. The survey's content, clarity, and length were subsequently adjusted as necessary. The snowball sampling technique was employed to recruit research participants from Victoria, Australia's construction industry. This sampling method is useful for studying a population that is difficult to reach through conventional means. Central to snowballing sampling are the characteristics of networking and referral (Parker et al. 2019). Email communication with the extended networks of researchers was the main means to recruit the research participants.

Following the completion of the survey, a semi-structured interview was undertaken to gain a deeper understanding of how each of the seven cause clusters may contribute to building defects. The interviewees were recruited from the same sample size who participated in the survey study. The interviews were conducted online using the Microsoft Teams platform. The interviews were recorded following the participants' permission to do so.

4.3 Data processing and analysis

The interview responses that were in the form of audio data were transcribed using the word-for-word technique. To analyse the textual data the content analysis technique was applied using NVivo 13 software package. Subsequently, the textual quantitative data were analysed using the DEMATEL technique. DEMATEL was initially used by the Battelle Memorial Institute of Geneva to visualise the relationship of complex cause-and-effect models through matrices and graphs (Si et al. 2018). DEMATEL is seen as a central tool for the successful implementation of various applications that are guided by a process resulting in appropriate decisions. On the basis of cause-and-effect models, this instrument has been widely utilised to extract the interdependencies and interrelationships between different design criteria and characteristics (Ullah et al. 2021). DEMATEL ranks the criteria according to the nature and significance of their interrelationships. The criteria that have the most influence on others are classed as causes, while those that are influenced by others are labelled as effects (Koca et al. 2021).

The DEMATEL approach is deemed useful as it provides a bi-directional perspective on relationships, in contrast to the conventional one-way methodology. This technique can effectively model, map, and improve satisfaction levels, and enhance the comprehension of issues and interactions among factors and groups, criteria, and sub-criteria. Additionally, it is capable of proposing viable solutions by introducing and mapping a hierarchical network and relevant solutions (Koca and Yıldırım, 2021). To the best of the authors' knowledge, this approach has not been used before to prioritise the causes of building defects. Therefore, this is the first time that such an application is investigated.

Several other techniques were used by previous researchers to rank building defects. Zuraidi et al. (2018) used using Analytical Hierarchy Process (AHP) method to evaluate the criteria and attributes of defects in heritage buildings. Nonetheless, AHP is not an effective method to capture and visualize the causal relationships among the factors. Waziri (2016) deployed the Relative Importance Index (RII) technique to analyse factors associated with design and construction defects. Although RII is a convenient technique for ranking factors, it does not take into account the interdependencies among the factors. Likewise, Faqih et al. (2020) used the Analytic Network Process (ANP) to determine weighting coefficients for building defects. Although ANP is useful for the analysis of complex situations, DEMATEL is a more effective technique for a visual representation of interrelationships in the form of digraphs and identifying the causal relationships. Therefore, to achieve its objectives this study adopted the DEMATEL technique.

The application of DEMATEL involves five steps as follows:

Step 1- a scale for assessing the relationships between n factors F is defined. The influence of factor F_i on factor F_j was measured on a scale from 0 to 4.

Step 2- To determine the interdependence of the components, the group direct-influence matrix Z is formulated by contacting each specialist to generate an $n \times n$ matrix, wherein each value indicates the degree of influence between the components. The diagonal values of the matrix were subsequently set to zero when producing matrix Z ($Z = [z_{ij}]\ n \times n$) by averaging the impact allocated to the same components in the direct-influence matrices of these specialists, as per Eq. 1.

$$z_{ij} = \frac{1}{l} \sum_{k=1}^{l} z_{ij}^{k}, i, j = 1, 2, \ldots n \tag{1}$$

Step 3- Following the creation of matrix Z, the normalised direct-influence matrix X ($X = [xij]\ n \times n$) is computed. This matrix can be generated using Eqs. 2 and 3 when the influence of all elements fluctuates within the range of 0–1.

After the creation of the matrix Z, the normalised direct-influence matrix X ($X = [xij]\ n \times n$) is computed. When the influence of all elements ranges between 0 and 1, this matrix can be generated utilising Eqs. 2 and 3:

$$X = \frac{Z}{s} \tag{2}$$

$$s = \max \left(\max_{1 \le i \le n} \sum_{j=1}^{n} Z_{ij}, \max_{1 \le i \le n} \sum_{i=1}^{n} Z_{ij} \right) \tag{3}$$

Step 4- This step involves utilising matrix X to generate the total-influence matrix T ($T = [t_{ij}]\ n \times n$) by summing up the values of both direct and indirect effects, with I being the identity matrix, as shown in Eq. 4.

In this step, the matrix X is utilised to generate the total-influence matrix T (T = [t_{ij}] n n) by adding the values of the direct and indirect effects, where I is an identity matrix, as indicated in Eq. 4.

$$T = X + X^2 + X^3 + \ldots + X^h = X(I - X)^{-1}, whereh \rightarrow \infty \tag{4}$$

Subsequently, in this step, the sum of the matrix T's rows and columns that are represented by the vectors R and C, respectively, are calculated. Equations 5 and 6 define these vectors as follows:

$$R = [r_i]_{n\times1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times1} \tag{5}$$

$$C = [C_j]_{1\times n} = \left[\sum_{j=1}^{n} t_{ij}\right]^{T}_{1\times n} \tag{6}$$

In Eq. 6, *ri* denotes the summation of the *i*th row's total in matrix T, which reflects the cumulative direct and indirect effects of factor *Fi* on the other factors. Likewise, in Eq. 3, *cj* indicates the summation of the *j*th column's total in matrix T, illustrating the collective direct and indirect influence of the other factors on factor Fj.

Step 5- To remove any relatively unimportant elements from matrix T in the DEMATEL final phase before the diagram can be constructed, a threshold value (α) must be established (Yang et al. 2008). Equation 7 indicates how to determine the α by averaging the components of the matrix T, where N is the total number of elements in the matrix T.

$$a \sum\nolimits_{i=1}^{n} \sum\nolimits_{j=1}^{n} [t_{ij}] \tag{7}$$

An influential relation map (IRM) or cause-effect diagram is developed by plotting the data set (R + C; R–C) on a graph, where the horizontal axis R + C signifies "prominence" and the vertical axis R–C represents "relationship" (Zheng et al. 2021). Furthermore, Ri + Ci offers an index of impact intensity that clarifies the role *i* plays in the decision problem being studied. Four quadrants make up the IRM (Si et al. 2018). The most noticeable and intricately interconnected core elements are included in quadrant I. The less noticeable but strongly correlated autonomous driving parameters are seen in Quadrant II. The independent elements in Quadrant III are underappreciated and have shaky ties. Last but not least, quadrant IV includes the relatively significant influence factors that, while having weak links, are quite conspicuous.

5 Findings

5.1 Participants profile

The data was collected from 11 experts who have experience in the construction of both low-rise and high-rise buildings. At the time of the study, all participants were employed in the construction business in various roles such as project manager, contract administrator, and project coordinator (Table 1). The participants had an average of 8.3 years of experience in their field, which enabled them to comment on the major causes of building defects and their internal interaction.

Table 1 Demographics of the participants

Expert No	Role	Experience in the industry (years)
1	Project Manager	8
2	Contract Administrator	5
3	Contract Administrator	6
4	Project Engineer	15
5	Contract Administrator	4
6	Contract Administrator	3
7	Project Manager	15
8	Contract Administrator	10
9	Construction administrator	10
10	Project Coordinator	9
11	Project Coordinator	7

5.2 DEMATEL application

The DEMATEL technique's basic matrix was presented to each expert, and its format was explained. Using a scale that ranged from 0 to 4 (0 = 'no influence'; 1 = 'very low influence'; 2 = 'low influence'; 3 = 'high influence'; and 4 = 'very high influence'), the experts were asked to rate the influence of each cause of the defect. The respondents were informed that the matrix was non-symmetric, meaning that the score assigned to the impact of defect cause A on defect cause B could differ from the score assigned to the effect of defect cause B on defect cause A. The data collected from the experts (decision makers) were used to compute the average matrix (X) presented in Table 2.

The remaining equations provided in Sect. 3 were applied, using the average matrix as the initial input for the DEMATEL technique. Table 3 shows various stages of the application of the DEMATEL technique including the intermediary calculations needed to generate the total-influence matrix T, the Normalized direct influence matrix (D), the Identity matrix (I) and the difference between the identity matrix (I) and the normalised matrix (D) and the inverse of the (I-D) matrix.

Table 2 The average matrix (X)

	Design	Maintenance	Materials	Regulations	Scope of workss	Weather	Workmanship
Design	0.00	2.55	2.55	1.88	3.11	2.33	2.77
Maintenance	2.22	0.00	2.33	1.55	2.77	2.44	2.55
Materials	3.00	3.00	0.00	1.66	3.00	2.66	2.88
Regulations	2.66	1.66	2.00	0.00	1.88	1.55	2.11
Scope of workss	3.22	1.66	2.33	1.44	0.00	1.55	2.44
Weather	1.55	3.00	2.66	1.77	2.55	0.00	3.33
Workmanship	2.22	2.88	3.00	1.77	2.11	2.66	0.00

Table 3 DEMATEL application results

Step 1- Normalised direct influence matrix (D)							
	Design	Maintenance	Materials	Regulations	Scope of workss	Weather	Workmanship
Design	0.00	0.16	0.16	0.12	0.19	0.14	0.17
Maintenance	0.14	0.00	0.14	0.10	0.17	0.15	0.16
Materials	0.19	0.19	0.00	0.10	0.19	0.16	0.18
Regulations	0.16	0.10	0.12	0.00	0.12	0.10	0.13
Scope of workss	0.20	0.10	0.14	0.09	0.00	0.10	0.15
Weather	0.10	0.19	0.16	0.11	0.16	0.00	0.21
Workmanship	0.14	0.18	0.19	0.11	0.13	0.16	0.00
Step 2- Identity matrix (I)							
Design	1	0	0	0	0	0	0
Maintenance	0	1	0	0	0	0	0
Materials	0	0	1	0	0	0	0
Regulations	0	0	0	1	0	0	0
Scope of workss	0	0	0	0	1	0	0
Weather	0	0	0	0	0	1	0
Workmanship	0	0	0	0	0	0	1
Step 3- I-D Matrix							
Design	1.00	−0.16	−0.16	−0.12	−0.19	−0.14	−0.17
Maintenance	−0.14	1.00	−0.14	−0.10	−0.17	−0.15	−0.16
Materials	−0.19	−0.19	1.00	−0.10	−0.19	−0.16	−0.18
Regulations	−0.16	−0.10	−0.12	1.00	−0.12	−0.10	−0.13
Scope of workss	−0.20	−0.10	−0.14	−0.09	1.00	−0.10	−0.15
Weather	−0.10	−0.19	−0.16	−0.11	−0.16	1.00	−0.21
Workmanship	−0.14	−0.18	−0.19	−0.11	−0.13	−0.16	1.00
Step 4- Inverse (I-D) Matrix							
Design	2.04	1.18	1.18	0.84	1.24	1.07	1.26
Maintenance	1.08	1.96	1.09	0.77	1.15	1.01	1.17
Materials	1.26	1.26	2.11	0.87	1.30	1.15	1.34
Regulations	0.98	0.93	0.95	1.59	0.97	0.85	1.01
Scope of workss	1.06	0.99	1.03	0.71	1.93	0.90	1.09
Weather	1.11	1.18	1.17	0.82	1.20	1.93	1.27
Workmanship	1.13	1.17	1.18	0.82	1.17	1.07	2.09

5.3 The interaction among various causes of building defects

Table 4 presents the intermediate matrices generated during the application of the DEMATEL technique. The total-influence matrix T was obtained using these intermediate

Table 4 Total influence matrix (T)

	Design (A)	Maintenance (B)	Materials (C)	Regulations (D)	Scope of workss (E)	Weather (F)	Workmanship (G)	Ri
Design	1.04	**1.18**	**1.18**	0.84	**1.24**	**1.07**	**1.26**	7.81
Maintenance	**1.08**	0.96	**1.09**	0.77	**1.15**	1.01	**1.17**	7.23
Materials	**1.26**	**1.26**	**1.11**	0.87	**1.30**	**1.15**	**1.34**	8.29
Regulations	0.98	0.93	0.95	0.59	0.97	0.85	1.01	6.29
Scope of workss	**1.06**	0.99	1.03	0.71	0.93	0.90	**1.09**	6.71
Weather	**1.11**	**1.18**	**1.17**	0.82	**1.20**	0.93	**1.27**	7.68
Workmanship	**1.13**	**1.17**	**1.18**	0.82	**1.17**	**1.07**	**1.09**	7.62
Ci	7.66	7.67	7.71	5.42	7.96	6.98	8.23	

Ci sum of columns *Ri* sum of rows *Threshold* (α) 1.054

The values indicated in bold are greater than the Threshold (1.054) matrices. The results for the total influence matrix are also presented in Table 4. The sum of row (Ri) and the sum of column (Ci) for each cause of building defect has been computed as shown in Table 4. On the basis of the results shown in Table 4, the interactions among the causes of defect, cause, and effect identity were determined and discussed in subsequent subsections.

Once the total influence matrix T was constructed, a threshold value was defined to identify the relationships that had the most significant impact within the matrix. The threshold value (1.054) was determined by taking the average of the elements in matrix T. Values above the threshold value (α) are shown in bold in Table 4 to indicate that they are the most significant values in matrix T. Based on the values indicated in bold in Table 4, the relationship diagram (Fig. 3) is plotted. From the figure, design-related factors influence maintenance, materials, the scope of works, and workmanship. Whereas regulations do not have a significant influence on other factors when analysing building defects. Also, it was found that regulations are not influenced by other causes of defects.

5.4 Cause and effect relationships among causes of building defects

In addition to determining the threshold value α, it was also necessary to calculate the vectors R and C. These vectors were computed to indicate the influence of one factor on the others (R) and how much influence the other factors have on a specific factor (C). To create a cause-effect diagram using R + C and R–C, both vectors had to be calculated. The results of these calculations are presented in Table 5. The resulting DEMATEL cause-effect diagram (Fig. 3) displays the distribution of clusters based on their degree of prominence and relationship along the R–C and R + C axes.

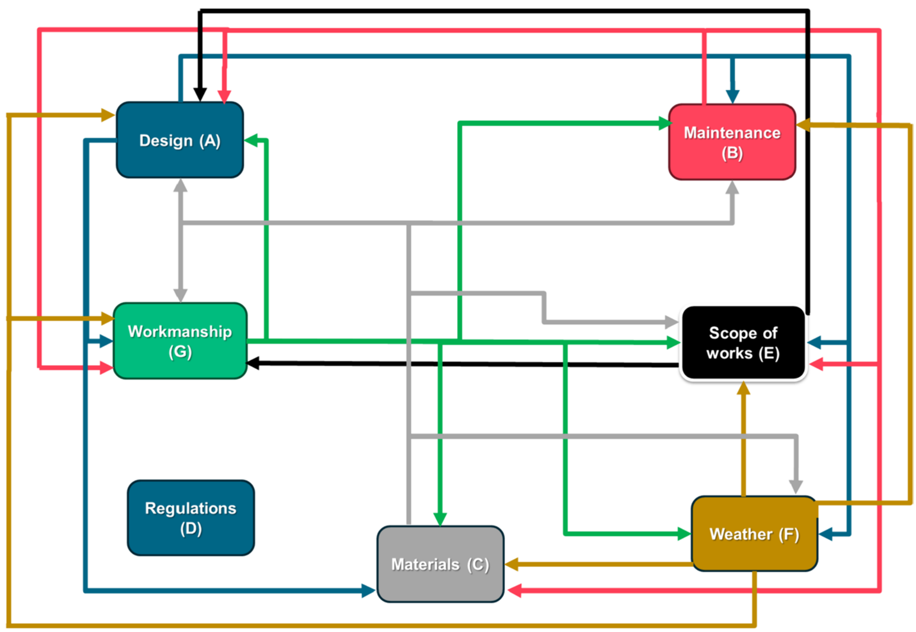

Fig. 3 Relationship among the causes of defect

Table 5 Prominence, the net effect, and criteria identity

	Ri	Ci	Prominence (Ri + Ci)	net effect (Ri-Ci)	identity
Design	7.81	7.66	15.48	0.15	cause
Maintenance	7.23	7.67	14.90	− 0.45	effect
Materials	8.29	7.71	16.00	0.58	cause
Regulations	6.29	5.42	11.71	0.87	cause
Scope of works	6.71	7.96	14.67	− 1.25	effect
Weather	7.68	6.98	14.66	0.70	cause
Workmanship	7.62	8.23	15.85	− 0.61	effect

Figure 3 indicates that clusters associated with design, materials, regulations, and weather have a greater impact on the other clusters, as evidenced by their R–C values being positive. In contrast, the clusters related to maintenance, the scope of works, and workmanship are more influenced by the other clusters, as demonstrated by their negative R–C values. The clusters that influence others are classified as "cause" clusters, while those affected are considered "effect" clusters. Furthermore, the causes of building defects associated with design, materials, regulations, and weather are categorised as "causes" since they have a direct impact on other clusters and have positive R–C values. On the other hand, maintenance, the scope of works, and workmanship are classified as "effects" since they are most affected by all clusters and have negative Ri-Ci values (Fig. 4).

5.5 Ranking the causes of defect

Based on the Ri + Ci values, the causes of building defects are ranked, and the results are presented in Table 6. Accordingly, the top three causes with the highest prominence are materials workmanship and design. According to the results of the DEMATEL technique, the cluster of materials has the highest R + C value of 16, indicating its significance as the most crucial factor in the model. Following this, workmanship has an R + C value of 15.85, and design has a value of 15.47, making them the second and third most important clusters,

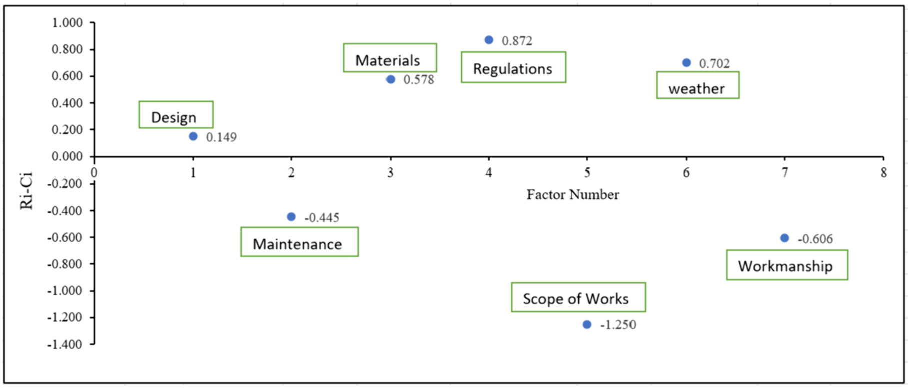

Fig. 4 Ri-Ci Graph

Table 6 Prioritised causes of building defects

Causes of building defects	Ri + Ci	Rank
Materials	16.00	1
Workmanship	15.85	2
Design	15.47	3
Maintenance	14.90	4
Scope of works	14.67	5
Weather	14.66	6
Regulations	11.71	7

respectively. As shown in Table 6, the values of the top three factors do not significantly differ. On the other hand, the clusters of 'regulations,' 'weather,' and 'scope of workss' have the lowest R + C values in the model, indicating that they are the least important factors in the occurrence of building defects.

5.6 Qualitative analysis of the prioritised causes of building defects

The results show that materials, workmanship and design faults are the major causes of building defects (Table 6). In terms of materials, two major issues were identified from the participant's responses to interview questions. First, it seems that some of the materials are damaged during transportation which are still somehow used in buildings. As one of the participants [P1] mentioned '*some materials come damaged some of them are very easy to be damaged, especially like Rimex metals which are used for finishing purposes.*' [P1]. Second, according to the fourth participant [P4] procuring low-quality materials will result in building defects. *'So if you try and save money on the use of cheaper material less adequate material the fact matter, because the material you bought is not as good as what is required, so the arrows again just go around at golden triangle cost money'* [P4].

In terms of poor workmanship, participants indicated that employing inexperienced trades may result in mistakes and defects if not resolved during the construction. P7 stated that *"in some trades, you really need to be a professional with experience and it is very easy to make mistakes. And most of the time, if you make a mistake, you are not going to admit it, you just gonna leave it someone gonna figure it out later yeah, but it will be late"*.

The other issue that was raised by P10 is the rush in completing a task due to the change in work sequence, other work commitments or simply time constraints. This will result in poor workmanship and building defects. "*maybe a rush from the builder to finish on time and to give the building, you know, to the client. Maybe sometimes the sequence of work will be changed, you know me because you want to issue, maybe one trade, one subcontractor will have He would be pushing and you are willing to work and he wants to finish, and he wants to get paid some other contracts, for example, will be like having problems getting a maturity or having problems sorted. Okay, so we have been talking about sequencing or rushing"* [P10].

In terms of design, one participant noted that sometimes designers want to use the same drawing for different projects. This will result in overlooking the specific details required for each unique project. "*When they do the shop drawings that just copy and paste design detail from one job to another, they would come to me asking how do I pull the slack like you don't want you to draw it when you when you"* [P2]. This is also highlighted in research conducted by Mahamid (2022) who argued that non-conformance with specification requirements is among the top three reasons for reworks in residential buildings.

The other issue is the unrealistic designs that will end up in problems during construction. P11 mentioned that "*if you build it based on drawings and you end up doing something smaller or bigger you'll have gaps or you will have gods and you're gonna have to hide this later on*".

6 Discussion

6.1 Validation of the model of interrelationships among causes of defects

To validate the findings of this research, interviews were conducted with architectural and structural designers who were not involved in the original model development. The profiles of the experts involved are presented in Table 7. The participants were provided with the model of interrelationships between the defect causes and a table providing these causes. In addition to demographic questions, they were asked to answer the following questions:

- To what extent do you think the following model can address appropriate influences among causes of building defects in low-rise residential building projects?
- Are there any influences/interrelationships that were overlooked by the model? If yes, which influence(s) do you think should be added or removed?
- The causes of building defects are ranked as shown in the Table below. Do you agree with the findings? Please provide your comments.

The findings of the validation interviews confirmed that all the identified factors are the main causes of defects in low-rise residential buildings. The experts agreed with the priority of the causes of defects. They suggested that the ranking could be changed for high-rise buildings. The following verbatim is taken from one of the respondents' interview transcripts "*For low-rise buildings I agree with the ranking. However, for the case of mid to high-rise buildings, I believe it is not applicable.*" This suggestion echoes the finding of a previous study (Hauashdh et al. 2022) that noted that nature of construction defects varies with building types and functions.

Regarding the model of interrelationships among the causes of defects. All the experts agreed that "regulations" affect the "design." One of the verbatims from the respondents includes *"Regulations and building design are closely linked, most of the time, if the design doesn't follow the regulations and is overlooked during construction, the defect occurs."*

Table 7 Profiles experts involved in validation

Background	Current position	Years of experience
Architect	Architect	10
Architect	Architect	6
Structural Engineer	Structural Engineer	18
Structural Engineer	Building Consultant	4

Based on the feedback from experts, the modified model is developed as shown in Fig. 5 below.

Furthermore, some of the experts mentioned that the lack of appropriate building regulations and material standard regulations can increase the likelihood of defects occurrence. Lastly, the lack of comprehensive contracts between clients and/or developers/builders and architects and engineers could be considered as the cause for defects.

6.2 Comparison with other studies

The findings of the research are in great harmony with those obtained in previous studies (Daud and Ishak 2018; Azian et al. 2020; Sandanayake et al. 2021). In many pieces of literature, the three top categories of design, material and workmanship were proposed as the major issues concerning building defects. For instance, Azian et al. (2020) observed that structural issues were the common subject of complaints among residents, and it was emphasised that design issues arose as a result of inadequate maintenance during the design and construction phase. Daud and Ishak (2018) observed that poor workmanship is the number one responsible for nine categories of defect causes.

Sandanayake et al. (2021) bibliometric analysis (1990–2020) showed the topic of "defects maintenance" has been recognised as a crucial area of research and has attained a high level of development, as many research studies have concentrated on defective materials (Dissegna et al. 2018; Di et al. 2023) and explored novel materials to ameliorate prevailing defects (Soliman et al. 2022). Another recent review study by Mésároš et al. (2024) showed that the key variables influencing the defects are poor maintenance, poor workmanship, and a faulty design. Similarly, a review of court cases in Norway between 1993

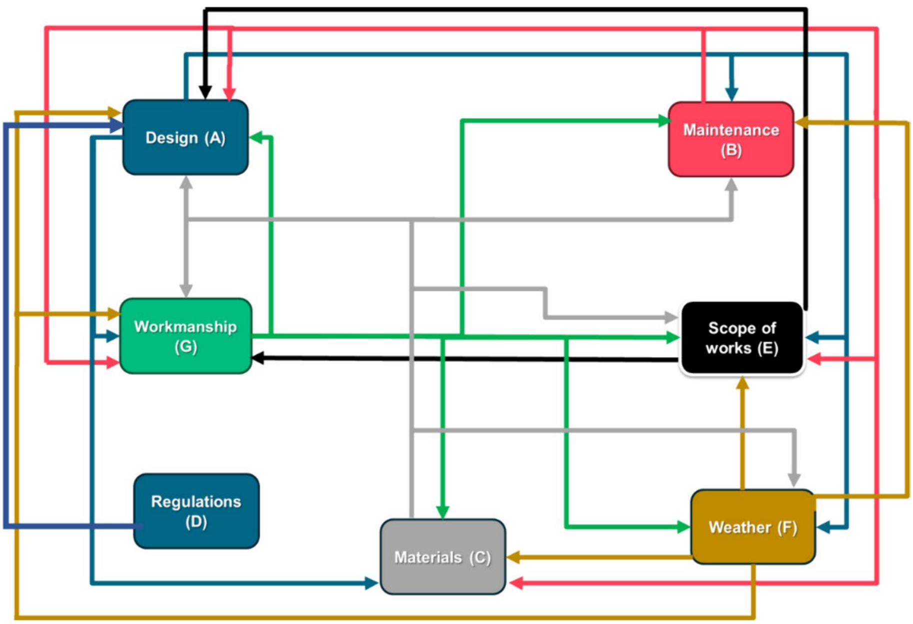

Fig. 5 Validated model of interrelationships among causes of defects

and 2003 (Lisø et al. 2020) showed that the three top reasons for building defects are inappropriate design and use of materials, and poor workmanship.

6.3 Recommendations

The findings highlight the role of three stakeholders in managing building defects: designers, sub-contractors and those who are involved in specifying and supplying construction materials. Therefore, it is advisable that these stakeholders and their areas of operations should be further investigated for possible solutions.

Drawing on the main quantitative and qualitative findings, the following is a set of recommendations that will result in the reduction of building defects. The recommendations target the three major causes of defects identified before.

- Appropriate time management to reduce the impact of changes in work sequence or time constraints on workmanship
- Effective communications between construction trades and the project managers to detect and address any material damage or poor workmanship during construction
- Procurement of materials with acceptable quality and durability
- Strict supervision of material transportation to minimise physical damage to materials brought to construction sites
- Custom the design of the construction projects according to the site specifications
- Engage experienced trades and workers to enhance workmanship
- Develop new building regulations that are satisfactorily flexible to accommodate new technologies and design approaches

7 Conclusions

Building defects are a big challenge to the construction industry and understanding their main causes can aid stakeholders in reducing their occurrence during the execution stage. Hence, this research aimed to prioritise the main causes of building defects captured in a survey study using the DEMATEL approach. To the best of the authors' knowledge, this approach has not been used before to prioritise the causes of building defects. The study showed that materials, workmanship and design are the major causes of building defects. This study contributes to the theory and practice of building defect management. While the results of this study are specific to the context of building defects in the construction industry, they can serve as a starting point for further research in this area. Future studies could explore building defects in different building typologies, such as residential buildings or commercial structures. This would allow for a more comprehensive understanding of the factors that contribute to building defects and the impact they have on different types of buildings. Furthermore, the recommendations provided will act as a facilitator to minimise the occurrence of building defects. Lastly, the research findings should be considered in the planning stage of any construction project, to ensure the construction of quality builds, reduce potential waste and enhance the circular economy and resource efficiency in the building and construction sector. Future research not only needs to investigate how the recommendations can be successfully implemented but also to what extent these recommendations can alleviate the issue of defects in buildings.

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Declarations

Conflict of interest The authors have not disclosed any competing interests.

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