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C-DREEM: A framework for estimating the cost of earthquake-damaged buildings – A New Zealand study

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ABSTRACT

Natural hazards created by earthquakes require an accurate post-earthquake cost estimation mechanism on the road to recovery. However, there are no identifiable accurate post-earthquake cost estimation mechanisms. This has led to major deviations between the initial and final construction costs. For example, the estimated cost of repair of the 2010–2011 Canterbury earthquake sequence changed from 41 billion NZD to $53 billion NZD (adjusted for inflation). Previous research identified eleven factors that specifically impact post-earthquake cost estimation. The recognisable literature was unable to identify a post-earthquake cost estimation model that considers these factors. Therefore, this research aims to fill this gap by developing and validating the cost of damage repair (including refurbishment) and the Earthquake Estimation Model (C-DREEM) framework. The C-DREEM framework was developed based on previous literature and inputs from a development team that included eleven industry professionals. The developed framework was then verified through a focus group interview consisting of nine professionals. The research developed and verified a framework for cost estimation for earthquake damage repair work, C-DREEM, that impacts earthquake damage repair work. C-DREEM incorporates the factors affecting post-earthquake cost estimation and improves the speed and accuracy of post-earthquake cost estimations for damage repair work.

1. Introduction

Cost estimation is one of the three pillars of delivery objectives in a construction project, alongside time and quality (or scope) [1,2]. For a project to succeed, it must achieve its estimated cost goals and remain within reasonable expenditure. Accurate cost estimations at the project's outset are crucial to achieving this. Based on a precise cost estimate, cost management plans can be developed, and project spending can be effectively monitored and controlled to meet the required cost outcomes [3–5]. However, the cost estimation process is complex and requires extensive information, knowledge, and procedures to ensure accuracy [6].

The challenge of creating accurate cost estimates for a construction project is directly linked to the characteristics of the construction process. Construction projects are unique, complex, and require multidisciplinary inputs, with costs influenced by factors such as location, weather, and time [5,7,8]. Consequently, cost elements vary from project to project. As a project becomes more ad

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hoc and its details more uncertain, additional cost factors emerge, further complicating the estimation process [8,9]. Therefore, the type and characteristics of a project significantly impact cost estimation.

Cost estimation for repairing earthquake-damaged buildings presents similar challenges, as these projects are influenced by additional variables that affect estimate accuracy. Earthquake-induced damage is particularly difficult to assess due to the complex nature of seismic forces and secondary hazards. The difficulty in achieving accurate estimates is evident in the fluctuations of cost projections for various earthquakes. For instance, the estimated repair costs for the 2011 Tōhoku earthquake increased from $210 billion USD [10] to $360 billion USD [11]; for the 2008 Wenchuan earthquake, from $100 billion USD [12] to $124 billion USD [13]; and for the 2010–2011 Canterbury earthquake, from NZ$41 billion (adjusted for inflation) [14,15] to NZ$53 billion (adjusted for inflation) [15–17].

Previous studies identified eleven factors influencing the cost estimation process for earthquake damage repair work and proposed methods for incorporating each factor into cost estimates [18,19]. However, past research has not established how the overall cost estimation process should function based on available information. This research bridges that gap by developing a comprehensive cost estimation model for earthquake damage repair work.

This paper begins with a review of the literature on earthquake characteristics and cost estimation practices. It then outlines the research methodology used and explains the developed model. Next, the results from the focus groups will be discussed, followed by the conclusion.

2. Literature review

Earthquakes cause various types of damage to buildings, primarily due to the shaking generated by seismic waves. In addition to this direct impact, further damage can result from secondary effects such as soil liquefaction, landslides, tsunamis, fires, seiches, and surface faulting, all of which can be triggered by the main earthquake [20–23]. These secondary effects, known as 'earthquake-induced hazards,' can significantly amplify the overall damage to buildings when combined with the primary seismic forces.

Major earthquakes in Japan (2011), Haiti (2010), and Indonesia (2004), along with their secondary effects, resulted in over 500,000 fatalities and caused economic losses exceeding USD 200 billion [24]. Consequently, earthquakes and their cascading effects have catastrophic economic consequences, and the resulting damage requires a thorough evaluation before repairs can be undertaken. For example, following the Canterbury earthquake in New Zealand, more than 168,000 building insurance claims were processed, with payouts exceeding 22 billion dollars. Each claim requires a comprehensive damage evaluation before compensation can be determined, thus highlighting the extensive assessment needed and its significant impact [25].

For an earthquake-damaged building, the impact of the damage needs to be identified before any repair work can be carried out. A post-earthquake damage evaluation facilitates this process. In the United States, the 'ATC-20-1 Field Manual: Post-earthquake Safety Evaluation of Buildings' [26] and, in New Zealand, the Level 2 Rapid Assessment Method are used for the rapid assessment of buildings following an earthquake [27]. However, these processes only provide an initial screening of the building and cannot serve as a comprehensive source of information for damage repair work [19,26].

Therefore, more detailed evaluations are conducted to determine the extent of the damage. In New Zealand, Targeted Damage Evaluation (TDE) and Detailed Damage Evaluation (DDE) have been used as assessment methods [28]. TDE identifies and assesses hotspots in buildings where damage is most likely to occur and is only conducted on buildings that meet specific criteria. In contrast, DDE specifies the damage both qualitatively and quantitatively [29].

However, DDE has certain drawbacks, such as the absence of a standardised reporting method, which leads to inconsistencies and a lack of comprehensive information required to estimate the total cost of earthquake damage repair, including site constraints [19,29]. Consequently, in New Zealand, an engineer's evaluation is required alongside the DDE report. Based on this information, along with a joint site visit by the contractor and engineer, a cost estimation is developed for earthquake damage. However, this estimation process cannot rely solely on the provided data, as its accuracy is influenced by various factors affecting any construction project. Therefore, a closer examination of cost elements and estimation methods is essential to understanding the costs related to earthquake damage repair work.

2.1. *Cost of construction*

The term 'cost' in the construction industry is unique, with its meaning varying depending on the party to which it refers. For contractors, 'cost' refers to the total expenditure associated with the project, including overheads. For the client, 'project cost' is the total price that must be paid to develop the project [30]. The project cost referenced in this study is the construction project cost to the client. The cost of construction can be further divided into three main sections: direct costs, indirect costs, and mark-ups.

Costs that cannot be linked to specific construction work activities are classified as indirect costs [31,32]. An example of such indirect costs includes supervision and the cost of hiring a tower crane. Indirect costs are generally calculated using preliminaries and profit percentages. Preliminaries consist of the indirect, fixed, or time-related costs of the project and can be incorporated into the estimate using unit rates [33]. The markup typically includes profit, contractor's overhead (not covered by the preliminaries section), project overhead, and contingencies [34].

With correct initial details, direct costs, indirect costs and mark-ups can be used to provide an initial estimate of the total cost of a project. However, some cost items cannot be predicted accurately in the initial stages. According to the literature, provisional sums, prime costs and daywork sections are typically used to cover expected uncertainties in a cost estimate. Costs that cannot be defined directly, such as contingencies and undefined work items, are included under provisional sums [35]. Prime costs of items are used to specify the estimated cost of the work of nominated subcontract work, suppliers and materials [36]. Incidental work in a project is calculated as daywork, which includes all labour, material, and plant rates and is measured using different methods [30]. Other than the above, the cost of professional services, inflation, government taxes and levies are also typically considered when estimating costs.

2.2. Earthquake damage prediction tools

Several cost estimation tools have been developed to predict the financial loss of earthquake damage repair work. These include examples of loss estimation tools that are applicable in New Zealand and the USA, such as HAZUS-MH, PACT, SP3, and SLAT [37]. HAZUS was developed by Whitman et al. and the Federal Emergency Management Agency (FEMA) [38]. The HAZUS method was created to estimate regional damage by using historical data, Geographic Information System (GIS) information and expert judgments. It relies on general parameters, such as building category-based floor area, inclusion of garages, building usage, type of structure, damage level, building category, and potential earthquake forces for these estimates [39]. Department of Homeland Security and FEMA [39] FEMA has acknowledged that there might be a large variation between the HAZUS estimate and the actual loss. Variation may have resulted from using building category, floor area, probability-based loss estimation, and rates from standard cost databases as parameters.

Alternatively, PACT, SP3 and SLAT are P-58 methodology-based tools developed by the Applied Technology Council to produce building-specific estimates to predict probable damage. P-58 methodology uses parameters such as residual building drift, peak floor velocity, storey drift ratio, and peak floor acceleration to identify the probable occurrence of different defined damage severity levels (called damage states) due to the impact of an earthquake and uses fragility curves and consequences functions for cost estimation [21, 40]. Fragility curves were developed using earthquake simulations that indicate damage to elements based on changes in element type and earthquake characteristics, such as the size of an earthquake. Damages to elements are then categorised into damage states focusing on factors like repair work required, cost of repair, duration, and impact on human life. Based on this data, fragility curves link the 'damage states' of building elements to the earthquake force [41,42]. Each damage state for a building element will have certain consequences such as repair cost, downtime, casualties, and environmental impact. Consequence functions or seismic loss curves express this information while considering the quantity of material used and the economies of scale [21,41]. The FEMA P-58 methodology further includes Building Information Modelling (BIM) concepts, which incorporate element visualization, damage visualization, repair activity sequencing, and productivity sequencing [43,44].

The HAZUS method was developed for regional damage estimation using historical data and judgments for estimations. It uses generic parameters like building category-based floor area for estimations. Alternatively, the P-58 methodology focuses on each specific building element and creates an element-wise detailed estimate using past data, experimental data and Monte Carlo simulations [21,39]. Cook et al. [45] compared HAZUS and P-58 methodology which indicated that both methods produce similar results.

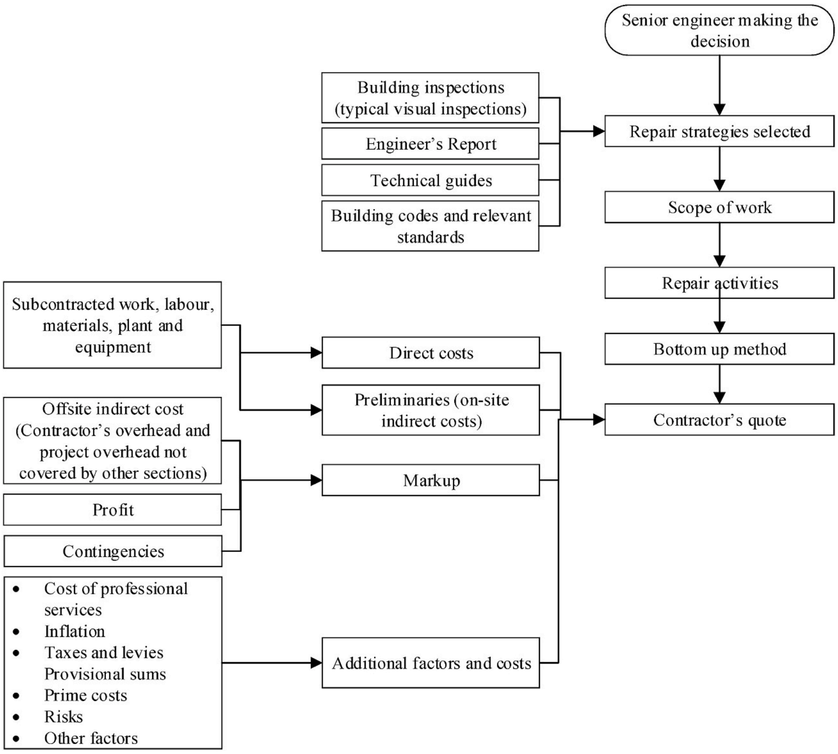


Fig. 1. Traditional cost estimation process.

However, when considering the base concept, HAZUS mainly uses typical parameters like gross floor area, building type and damage state and the P-58 methodology produces building-specific and element-based cost estimates, which are more useful in a post-earthquake CEEDRW process. In the context of using the results of these tools for post-earthquake cost estimation, further analysis reveals several drawbacks of P-58 methodology-based tools. These include the generation of one-off results, not providing detailed estimates that are required for post-earthquake damage repair work, and inaccurate estimation of project cost because the preliminary costs are included in the direct cost rate [19,46,47]. Therefore, there is a need for a cost estimation tool for earthquake damage repair work. For this, we should first investigate the current cost estimation processes used by the construction industry.

2.3. Traditional cost estimation

Currently, no standardised model has been developed and used for post-earthquake cost estimation for earthquake damage repair work. According to previous research [28,48], the cost estimation for earthquake damage repair work (CEEDRW) process conducted after the Canterbury earthquake sequence involved identifying damage using an engineer's report and building inspections (typically without destructive testing). Repair strategies were then determined by a senior engineer using technical guides and standards. Once the repair method was identified, the traditional bottom-up method was used as the post-earthquake cost estimation method (PEQ-CEEDRW) [18,28,48]. Contractors employed the bottom-up method to calculate costs by accumulating the resource costs for each construction activity required for the total repair process [49]. The bottom-up methods estimate the cost using the resource requirements (labour, material, and plant) for direct and indirect costs, to which overhead, profit and contingencies are added (Refer to Fig. 1 for the traditional costing process).

Direct costs are those that can be directly and physically attributed to a defined economic activity. For example, all permanent construction work [31,50]. Direct costs include the resource costs for labour, materials, plant, and subcontracted work. These costs are typically calculated using unit rates that take into consideration all the resource requirements for a work activity [36,50].

Costs that cannot be linked to specific construction work activities are classified as indirect costs [31,32]. An example of such indirect costs includes supervision and the cost of hiring a tower crane. Indirect costs are generally calculated using preliminaries and profit percentages. Preliminaries consist of the indirect, fixed, or time-related costs of the project and can be incorporated into the estimate using unit rates [33]. The markup typically includes profit, contractor's overhead, project overhead (not covered by other sections) and contingencies [34].

With correct initial details, direct costs, indirect costs and mark-ups can be used to provide an initial estimate of the total cost of a project. However, some cost items cannot be predicted accurately in the initial stages. According to the literature, provisional sums,

Table 1
Factors affecting CEEDRW and their explanation adopted from [19,48].

No	Factor	Explanation
1	F 01 - Consequential damage repair	The interrelated building components can cause damage to other elements. This can occur during an earthquake or during repair work, where undamaged building elements can be damaged.
2	F 02 – Professional services – structural, engineering, geotechnical, land surveying, architectural, quantity surveying, legal and dispute resolution	Costs associated with acquiring different professional expertise during a repair project to identify the damage, develop repair strategies, prepare cost estimates, manage legal problems and resolve disputes.
3	F 03 - Varying profit margins depending on the type of building contract	Based on the contract type, project profit and overhead margins can impact the project's overall cost.
4	F 04 - Restrictions to repair work	Repairing a building can create constraints compared to new construction, which includes repairing occupied buildings. These constraints can involve time, access, sound, and construction method restrictions, as well as additional costs, such as daily start-up and clean-up work.
5	F 05 - Damage from aftershocks, earthquake-induced hazards and weather conditions	Other than the main earthquake, damage to the building can result from secondary aftershocks, earthquake-induced hazards (e.g., liquefaction, seiches, tsunamis, landslides, and inundation), and weather damage to integrity-compromised buildings.
6	F 06 - Price fluctuations due to changes in demand for resources caused by an earthquake	Earthquake damage-induced demand for construction resources causes price fluctuations.
7	F 07 - Duration of repairs	Time has a direct relationship with the cost of a project, and there are duration-based costs for repair work.
8	F 08 - Initially unforeseen damage	Initially unidentified damage, which was not identified during the detailed damage inspection stage and later identified during damage repair work.
9	F 09 - Changes required to final repair state - to meet statutory compliance/stakeholder requirements	The cost of construction work also depends on the required final quality expected and the specifications set to achieve the final product. This includes variation between as-built conditions vs the needs of the stakeholders and the current prescribed building code.
10	F 10 - Pre-earthquake state of the building	Insurance-funded repair work only covers earthquake damage. However, a building may contain pre-earthquake damage caused during its use, as well as errors during construction, which should be repaired during the repair process.
11	F 11 - Substandard initial repair work	In some instances, initial repair work conducted might not meet the required quality due to the people involved and the volume of work, which can lead to secondary repair work.

prime costs and Daywork sections are typically used to cover expected uncertainties in a cost estimate. Costs that cannot be defined directly, such as contingencies and undefined work items, are included under provisional sums [35]. Prime costs of items are used to specify the estimated cost of the work of nominated subcontract work, suppliers and materials [36]. Incidental work in a project is calculated as Daywork rates, which include all cost-inclusive labour, material, and plant rates and are measured using the usage of resources [30]. Other than the above, the cost of professional services, inflation, government taxes and levies and risks are also typically considered when estimating costs.

The cost developed based on the bottom-up method has been inaccurate in some instances. For example, the initial estimate for repair and rehabilitation costs after the Canterbury earthquake sequence were estimated to be **NZ$41 billion (in 2012)** (adjusted for inflation) [14,15], which was later increased to **NZ$53 billion** (adjusted for inflation) [15–17]. Given that New Zealand is often impacted by significant earthquakes, there is a pressing need to identify the reasons for this variation in cost estimations and final costs.

2.4. Factors affecting the cost of earthquake damage repair work

Kahandawa et al. [19,47,48] identified eleven factors that specifically impacted the earthquake damage repair context in New Zealand. These factors have been identified as reasons for variations between the initial cost estimation and the final cost of the Canterbury earthquake sequence [18,19,48]. These factors are summarised in Table 1. It was identified that these factors had a substantial impact on earthquake damage repair work, and it is vital to include these factors in the cost estimation process. The study identified that factors such as consequential damage, initially unforeseen damage, and changes in final repair state, along with the cost of professional services, had a significant impact on cost estimation for earthquake damage repair work (CEEDRW). However, factors such as the cost of professional services for dispute resolution, damage from earthquake-induced hazards, changes to meet stakeholder needs, and varying profit margins were found to have relatively low significance. Nonetheless, it was concluded that all these factors significantly impacted earthquake damage repair work, and previous research did not identify how to incorporate the impact of these factors in the cost estimation process.

At present, the impact of these factors is not fully realised in estimations conducted using P-58-based models and traditional cost evaluation processes. For example, P-58 models account only for earthquake-induced hazards, as they can incorporate such data and predict probable damage based on past information [18,19,46,51,52]. In contrast, PEQ-CEEDRW considers additional factors such as contract type, repair time, and changes to the repair state [19,48]. However, factors like initially unforeseen damage, restrictions during repair work, consequential damage repairs, and earthquake-induced high rates and price fluctuations are incorporated only when relevant data becomes available. Furthermore, aspects such as substandard repairs, pre-earthquake building conditions, and certain professional costs (e.g., legal services) are often excluded or treated as variations in cost estimations. This study, therefore, focuses on developing a framework that integrates these factors into the post-earthquake costing process to enhance current cost estimation methods. The term “repair work’ in this context also encompasses rehabilitation and refurbishment, depending on the building’s condition and Building Code requirements.

3. Methodology

This research used interviews and a focus group to develop and validate the Cost of Damage Repair and Earthquake Estimation Model (C-DREEM) framework. The framework incorporates the 11 key factors affecting earthquake damage repair work. According to the framework development support team, integrating these factors into the costing process does not merely enhance cost estimation methods. Therefore, the TRIZ methodology (the ‘Theory of Inventive Problem Solving’), was adopted, as it provides a systematic and rigorous approach to problem-solving through innovation [53].

Based on the TRIZ process and input from the framework development team, the study identifies two key improvements to the cost estimation system. First, the integration of probability-based costing methods with traditional costing processes enhances estimation accuracy. Currently, traditional and probability-based data are used separately, and the traditional approach often lacks sufficient information at the outset, as it requires building damage evaluations. Incorporating probability-based data helps bridge this gap until actual site investigations are conducted, after which the estimates can be refined and updated at the end of each project.

Second, improvement involves segmenting the costing process into distinct divisions, each performing a specific function and interacting only through defined inputs and outputs. This segmentation allows for individual optimisation and improvement of each section. Based on these principles, the C-DREEM framework was developed.

The framework development process included 11 participants (two quantity surveyors experienced in CEEDRW, three quantity surveyors involved in building repair work, three quantity surveyors involved in new construction, a builder with experience in repairing earthquake-damaged partitions, and two academics) who were selected through the convenience sampling method. After multiple iterations, the development team finalizes the framework.

Finally, a focus group interview was conducted to validate the framework. According to Caillaud and Flick [54], focus group interviews can serve as a validation method. The focus group is a type of interview suitable for discussing specific issues within a small group led by a moderator [55]. The focus group interview lasted 133 min and included nine expert participants with experience in loss estimation frameworks, consisting of eight quantity surveyors and one engineer. These participants had not been involved in the framework development process, eliminating any bias in validating C-DREEM.

The focus group interview session contained two main sessions, each focusing on validating specific aspects of the C-DREEM: (1) the framework’s clarity and (2) the overall system. Each session includes four parts: a PowerPoint-assisted explanation, participant discussions, a question-and-answer session, and a survey questionnaire. At the end of the focus group session, participants provided final comments regarding the barriers to C-DREEM implementation, potential future improvements, and its usability as a practical solution for CEEDRW.

The Likert scale is a verified, balanced scale with high internal consistency and reliability [56]. Therefore, the focus group questionnaire utilised a five-point Likert scale for ordinal data. The data sources for this study originated from New Zealand's earthquake damage repair context. Consequently, the output framework is most applicable to the New Zealand setting. Members of the validation team had an average of 26.1 years of experience in the construction industry and 6.9 years of experience with CEEDRW.

Previous research recommends a sample size of 9–17 participants for interviews and 4–8 participants for focus group interviews to achieve data saturation [57,58]. This research included 11 interview participants and 9 focus group participants, aligning with findings from past research. Furthermore, the study concluded that saturation was achieved when no new information was generated [59]. The methodology followed in this research is included in Fig. 2.

4. Results

At the time this study commenced, there were no known post-earthquake cost estimation frameworks. Therefore, the main purpose of C-DREEM is to provide a standardised process that produces rapid and accurate cost estimates for a large number of buildings. Previous data collections were used to formulate post-earthquake cost estimation examples, identify methods that could improve

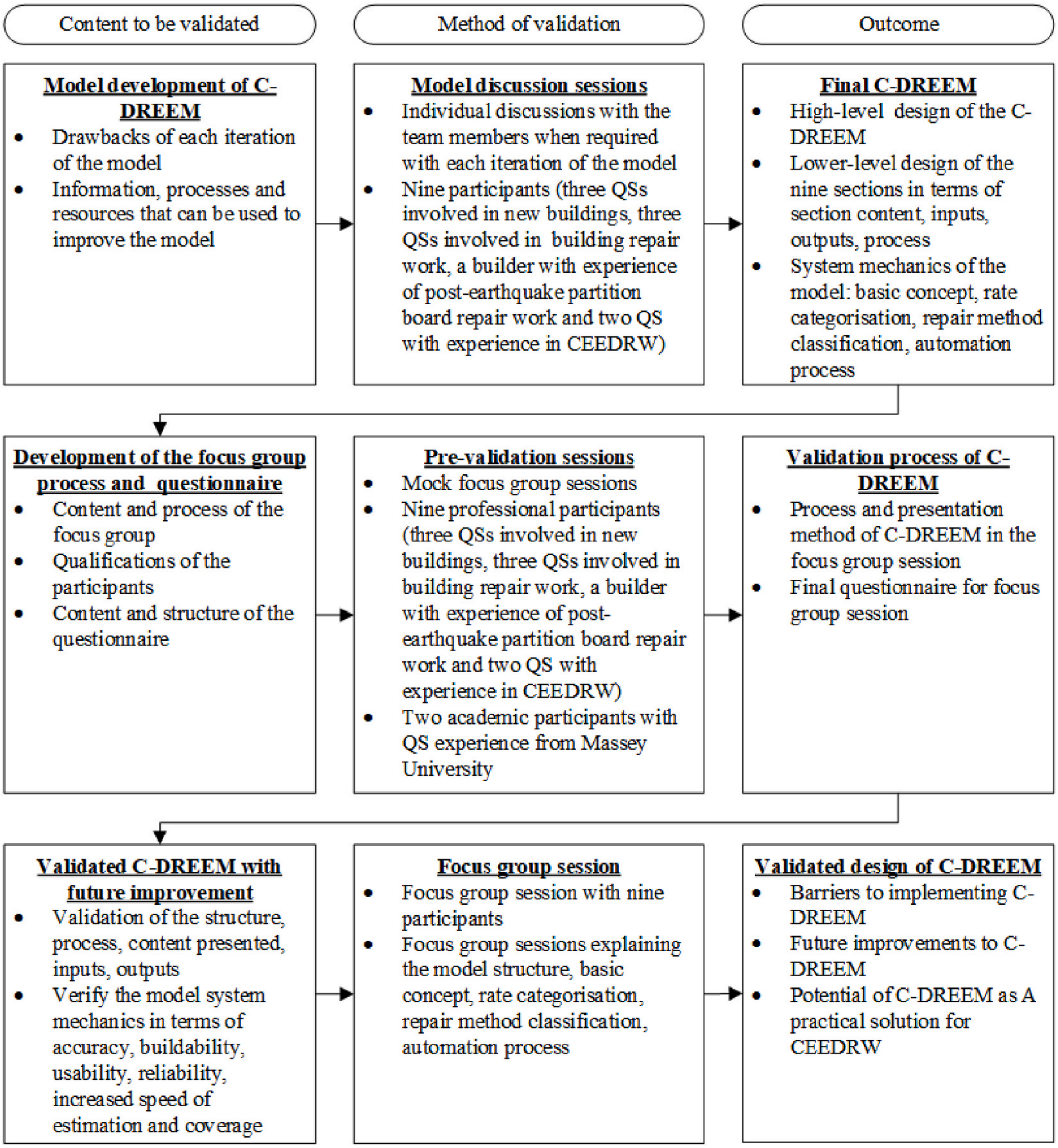


Fig. 2. – C-DREEM development and validation map.

estimation speed using Bills of Quantities (BOQ), and select a process that incorporates these factors into the CEEDRW process. Once the model was developed, a focus group interview was conducted to check the validity of the model.

4.1. Focus group results

The participants were asked to consider specific statements regarding the function of the framework and rate them according to their level of agreement. The framework relates to the functions of each section of C-DREEM. The rating scale was scaled from 1 (Strongly Disagree) to 5 (Strongly Agree). Results from the questionnaire are shown in Table 2. More than two-thirds of the participants agreed or strongly agreed that the framework was clear in terms of structure, process, content, input requirements and output requirements. Additionally, two-thirds of the participants agreed that the C-DREEM could increase the speed of estimation and adequately cover all necessary variables required for CEEDRW. More than half of the participants agreed or strongly agreed that the C-DREEM was user-friendly. Furthermore, all participants agreed or strongly agreed that the framework would be useful in improving CEEDRW and that they would like to use a C-DREEM tool. All factors had a weighted average above 3.78, a standard deviation less than 0.83 and skewness between −1.17 and 2.33. Participants also gave comments on each section, which was used to improve the framework and identify the limitations and future research.

4.2. Framework development

The C-DREEM model improves cost estimation accuracy by employing bottom-up methodologies to generate detailed estimates essential for contractor selection. It achieves this by utilising 3 d modelling to determine repair methods based on damage location, building a knowledge base from contractor rate databases, and addressing information gaps using pre-earthquake cost estimation models like PACT and SLAT. Additionally, it integrates key impact factors affecting CEEDRW, continuously refines estimates as new data becomes available, and incorporates a feedback loop to enhance consequence functions within PACT and SLAT models. Its ultimate goal is to produce cost estimates that closely align with final construction costs using the best available data.

The developed C-DREEM framework contains three main divisions: ‘identification’, ‘quantification’ and ‘costing & summarisation’. The ‘identification’ division involves identifying the project and damage details. This division includes three tasks: pre-earthquake state identification, post-earthquake state identification and repair method identification. The subsequent ‘quantification’ division aims to calculate quantities associated with time and cost-related items. This division quantifies the direct repair work, repair time (duration and start date) and preliminaries. The final ‘costing and summarisation’ division refers to applying the rates (including other external costs), summarising the project costs, developing consequence functions and evaluating the output. The high-level design of C-DREEM, as visually presented in Fig. 3.

Taking a view of the lower-level or secondary-level design of the C-DREEM, as expressed in Fig. 4, reveals further details for each section. Each column of Fig. 4 represents a section of the framework. Rows of the framework refer to the section name, description of the section, input requirements for the section, output requirements of the section and factors covered by the sections.

Table 2
Questionnaire results from focus group interview (Participant views).

Evaluation criteria	1 Strongly Disagree	2 Disagree	3 Neither Agree/ Disagree	4 Agree	5 Strongly Agree	Weighted average	Standard deviation	Skewness
C-DREEM framework								
The concept of the framework is clear				5 56 %	4 44 %	4.44	0.53	0.21
The concept of the framework is accurate			1 11 %	2 22 %	6 67 %	4.56	0.73	−1.17
The concept of the framework is buildable			1 11 %	5 56 %	3 33 %	4.22	0.67	−0.20
The concept of the framework is useable				6 67 %	3 33 %	4.33	0.50	0.67
The concept of the framework is reliable			2 22 %	3 33 %	4 44 %	4.22	0.83	−0.39
The concept of the framework can increase the speed of estimation				5 56 %	4 44 %	4.44	0.53	0.21
The concept of the framework adequately covers all necessary variables required for CEEDRW			3 33 %	4 44 %	2 22 %	3.89	0.78	0.17
Overview of the framework								
The framework is user-friendly			4 44 %	3 33 %	2 22 %	3.78	0.83	0.39
The framework will be useful in improving CEEDRW				8 89 %	1 11 %	4.11	0.33	2.33
I would like to use a tool based on the proposed framework				5 56 %	4 44 %	4.44	0.53	0.21

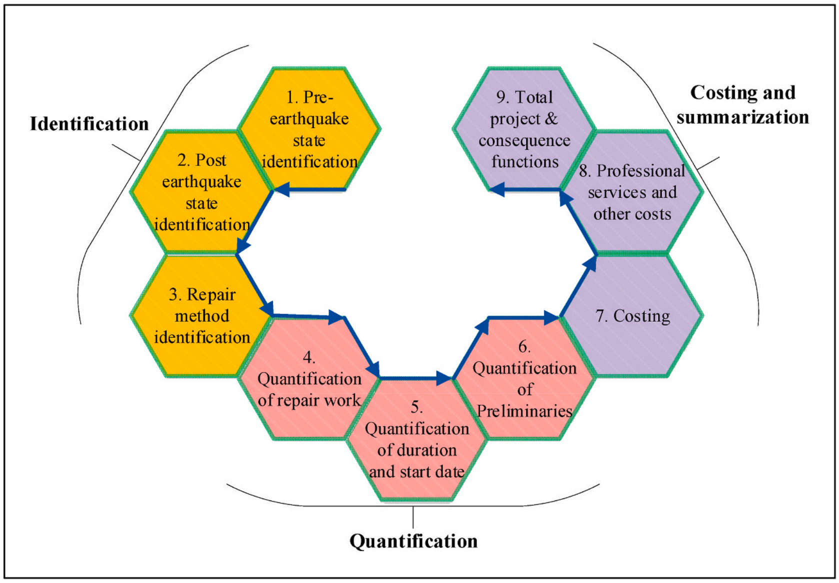
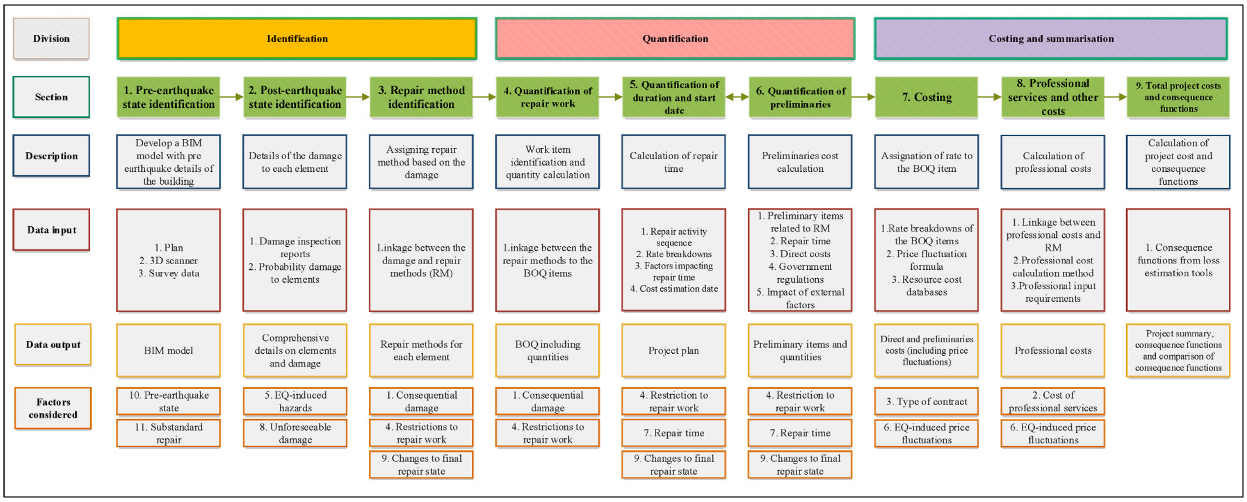


Fig. 3. – High-level design of C-DREEM.



Division	Identification			Quantification			Costing and summarisation		
Section	1. Pre-earthquake state identification	2. Post-earthquake state identification	3. Repair method identification	4. Quantification of repair work	5. Quantification of duration and start date	6. Quantification of preliminaries	7. Costing	8. Professional services and other costs	9. Total project costs and consequence functions
Description	Develop a BIM model with pre earthquake details of the building	Details of the damage to each element	Assigning repair method based on the damage	Work item identification and quantity calculation	Calculation of repair time	Preliminaries cost calculation	Assignation of rate to the BOQ item	Calculation of professional costs	Calculation of project cost and consequence functions
Data input	1. Plan 2. 3D scanner 3. Survey data	1. Damage inspection reports 2. Probability damage to elements	Linkage between the damage and repair methods (RM)	Linkage between the repair methods to the BOQ items	1. Repair activity sequence 2. Rate breakdowns 3. Factors impacting repair time 4. Cost estimation date	1. Preliminary items related to RM 2. Repair time 3. Direct costs 4. Government regulations 5. Impact of external factors	1.Rate breakdowns of the BOQ items 2. Price fluctuation formula 3. Resource cost databases	1. Linkage between professional costs and RM 2.Professional cost calculation method 3.Professional input requirements	1. Consequence functions from loss estimation tools
Data output	BIM model	Comprehensive details on elements and damage	Repair methods for each element	BOQ including quantities	Project plan	Preliminary items and quantities	Direct and preliminaries costs (including price fluctuations)	Professional costs	Project summary, consequence functions and comparison of consequence functions
Factors considered	10. Pre-earthquake state 11. Substandard repair	5. EQ-induced hazards 8. Unforeseeable damage	1. Consequential damage 4. Restrictions to repair work 9. Changes to final repair state	1. Consequential damage 4. Restrictions to repair work	4. Restriction to repair work 7. Repair time 9. Changes to final repair state	4. Restriction to repair work 7. Repair time 9. Changes to final repair state	3. Type of contract 6. EQ-induced price fluctuations	2. Cost of professional services 6. EQ-induced price fluctuations	

Fig. 4. Lower-level design of the C-DREEM.

The arrows in the framework represent the information flow of the C-DREEM. The default information flow is from left to right. However, information flows backwards between sections six (quantification of duration and start date) and seven (quantification of preliminaries). The double-headed arrows depict backward information flows. The process of each section is detailed below.

4.3. C-DREEM framework section explanation

C-DREEM consists of nine main sections. Each section follows a specific process that is detailed in the following sections. Each process explanation includes the data inputs that were considered, the methods used to process the data, the factors considered, and the resulting information outputs. A numerical coding system is employed to reference the items included in the process.

4.4. Pre-earthquake state identification (section 1)

4.4.1. Process of the pre-earthquake state identification (section 1)

The detailed process associated with the first step of the identification stage of the C-DREEM framework involves cumulating and organising the details of an affected building (refer to Fig. 5). The final output of this process is a 3D model updated with the pre-earthquake state and final output specifications for the repair work.

As shown in the figure, the process starts with the identification and use of building plans and specifications available on the building (1.01) to develop a 3D model (1.07) of the building. The use of a 3D model follows principle 17 (dimensionality change - moving an object from a two-dimensional space to a three-dimensional space) of the TRIZ methodology. Floor plans, door window details, finishing details and specifications are examples of some of the information required (1.04) for 3D model development. The resulting 3D model can be further developed through the inclusion of the pre-earthquake state of the building (1.08), using the building survey data (1.02) to extract the information related to the variations between the 'as-built state' and the pre-earthquake state (1.05). The post-earthquake building survey data considers the 'pre-earthquake state of the building' factor identified by the study into consideration (1.06). If available, 3D scans can also be used for the 3D model development process (1.03).

Once the 3D model has been initially developed, current building regulations and standards (1.10) are used to identify changes required to the framework in order to formulate the final repair state (1.09). The factor 'impacts of substandard repair work' are covered, to an extent, by this process (1.12), when the relevant building regulations (1.10) are compared with the current conditions of the building and included in the BIM model. However, this evaluation of the substandard repair work might be limited to visual identification.

The final output produces a BIM model and requires specifications of the final repair work. The BIM model would be developed to suitable LOD (Level of Development) like LOD 350 or above detail, which is the general level of detail required for construction documentation [60] (1.11). The BIM model developed for the LOD 350 level contains the location, size, shape, alignment, quantity and interfaces of the building elements, objects or systems [61]. If either the survey data or the 3D scan is not available, only the building plans can be used, and such an approach might affect the accuracy of the output.

4.5. Post-earthquake state identification (section 2)

4.5.1. Process of the post-earthquake state identification (section 2)

The second section of the identification stage of the C-DREEM framework focuses on identifying probable and actual post-earthquake damage to incorporate into the 3D model (refer to Fig. 6). The final outputs of the section are: the extraction of details of the damaged building elements, which can be used in the later stages of the cost estimation development process; and a model that includes earthquake damage.

Through this section, the C-DREEM continues to update the BIM model that was produced in the first identification section (2.01).

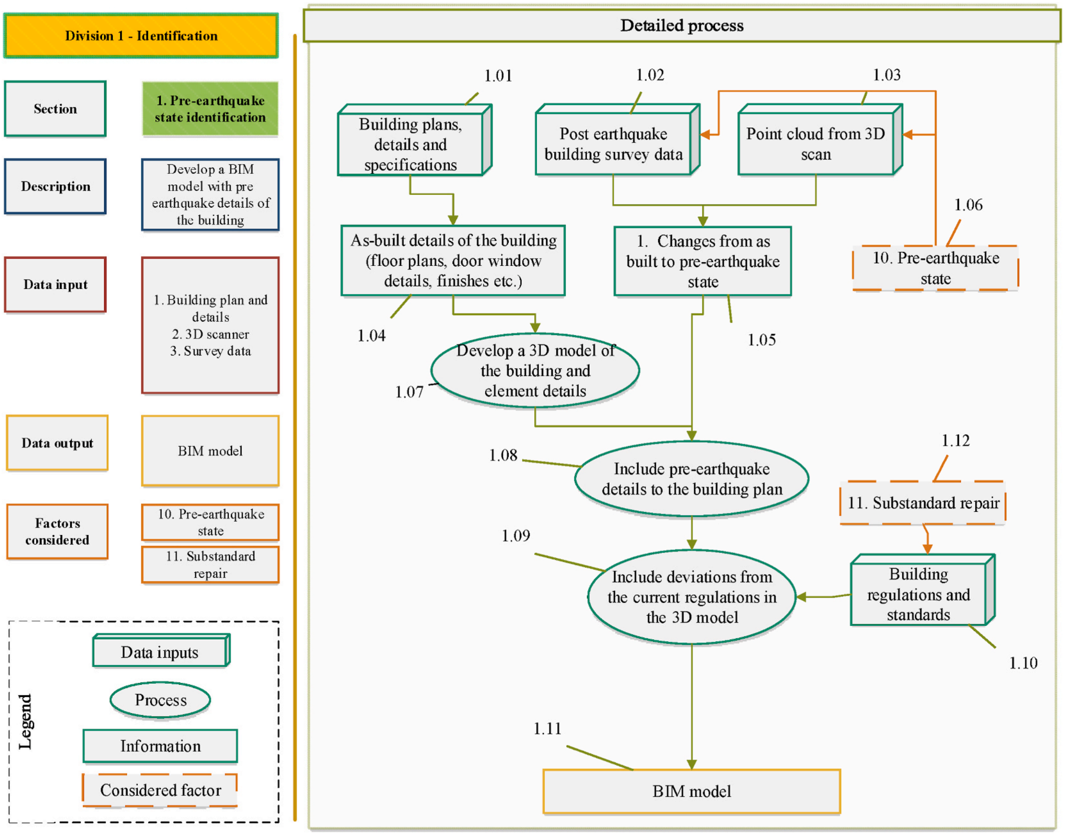


Fig. 5. Pre-earthquake state identification (Section 1).

The process starts with the identification of the probable damage to elements of the building (2.03). These details are extracted from probability-based models (2.04). This integration is based on principle 10 (Perform a function before it is needed) of the TRIZ methodology. The identified probable damages are linked and represented in each element of the BIM model (2.02). Usage of data from the probability-based loss estimation tools (2.04) enables the inclusion of the impact of initially unforeseen damage (2.10) and earthquake-induced hazards (2.11), key factors identified in the research, into the model. It is important to note that the accuracy of the probable damage depends on the accuracy and availability of the data input.

When details of the actual damage become available, this information is then included in the BIM model (2.06). These details would be extracted from the initial and detailed damage survey reports (2.07). These actual damage details would supersede the probable damage inputs. The impact of earthquake-induced hazards (2.12) is thus more accurately included in the model through information acquired from damage inspection reports (2.07).

The resulting updated BIM model contains details of each building element and the relevant damage to that element. Damage details include the location, size and level of damage. Finally, the comprehensive details of the building, its elements and damage to those elements (2.09) are extracted into spreadsheets (2.08). This extraction is required because the cost estimation process is conducted through the use of spreadsheets.

4.6. Repair method identification (section 3)

4.6.1. Process of the repair method identification (section 3)

The third and final section of the identification division (refer to Fig. 7) involves the selection of suitable repair methods, based on the damaged building elements pinpointed in the previous stage. The comprehensive details of damage to building elements (3.01) are used to select a suitable repair method for each. These details of damage and elements are extracted from the BIM model. Details required are project details, element details and damage details.

The data sought for 'project details' refers to the scope of the building. For example, the number of stories and rooms, door and window details and different room finishes (3.02). 'Element details' gather specific information regarding the element. These details supersede the project details when required (3.03). Examples of element details include type, size, properties, location, unique identification number, connected elements (same type and other types) and finishes (if applicable). 'Damage details' specify the extent of the damage to the element (3.04). Damage details include a damage identification number, element type, location of the damage on the element, size of the damage, severity of the damage and other relevant details (3.04).

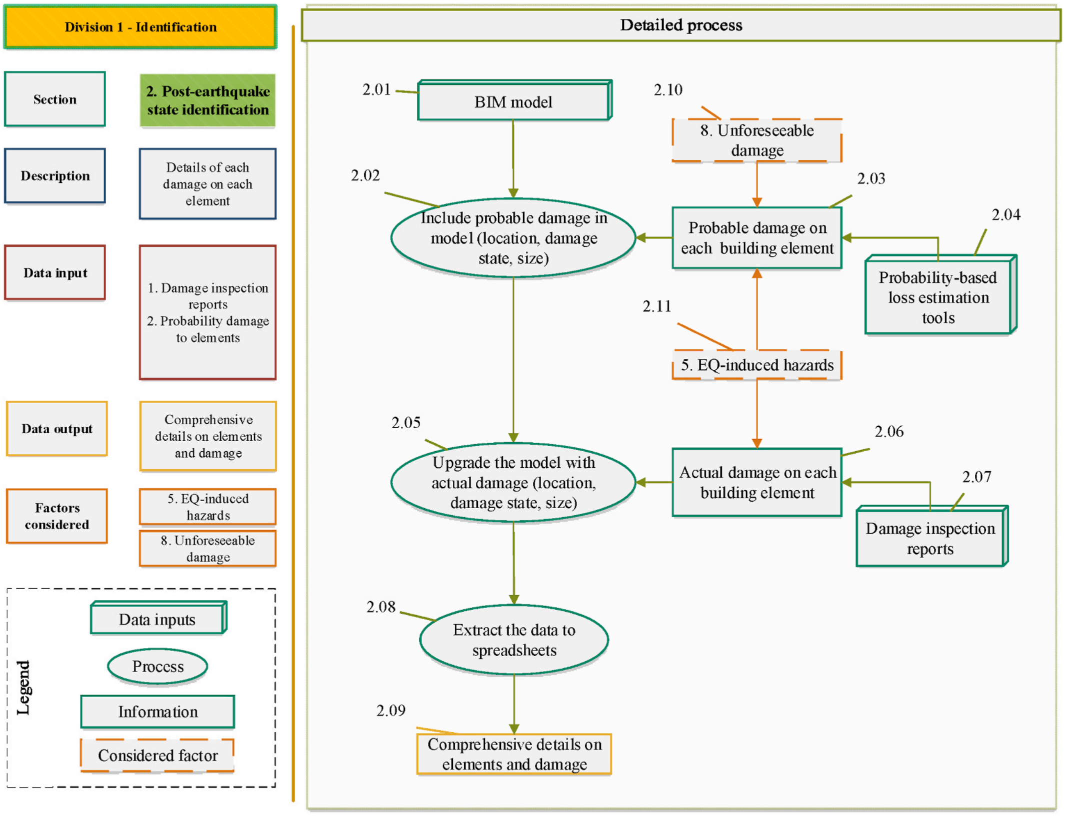


Fig. 6. Post-earthquake state identification (Section 2).

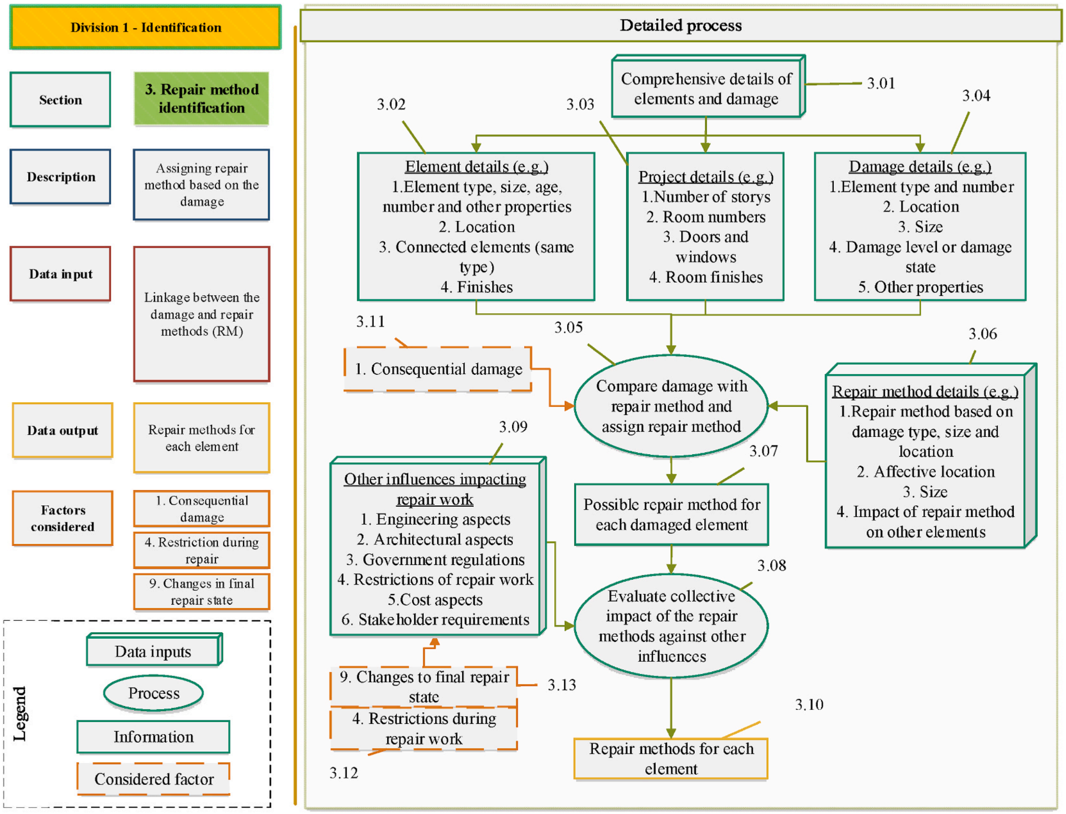


Fig. 7. Repair method identification (Section 3).

The repair method selection process (3.05) is conducted using information included in preloaded functions. Preloaded functions (3.06) define the most suitable repair method based on project, element and damage details.

The selected repair method takes into consideration repair location, method of repair and size of repair (3.07). Additionally, it also considers the impact of consequential damage to attached elements (3.11), another key factor identified in the research. Details of any consequential damage are recorded in the relevant building elements in the BIM model.

Next, the collective impact of all damage repair work on the project is compared against other influences that have an impact on repair work (3.08). These include engineering aspects, architectural aspects, building regulations, restrictions during repair work, cost aspects and stakeholder requirements (3.09). Results from this comparison and evaluation modify the selected repair method, if required. Changes to the final repair state (3.13) and restrictions during repair work (3.12), key factors established by the research, are evaluated through the other influences evaluation (3.08) process. As an example, if there is a change in regulations that will have an impact on the final state of repair work, then the repair methods will be modified accordingly.

The output sought for this section is the repair method(s) selected for each building element (3.10).

4.7. Quantification of repair work (section 4)

4.7.1. Process of the quantification of repair work (section 4)

The fourth section of the framework (refer to Fig. 8) is the first of the three 'quantification' sections, which calculates the quantities of repair work items. Based on the repair methods identified (4.01) in section 3, appropriate BOQ items are selected (4.02). A preloaded function included in the C-DREEM links damage repair methods to required BOQ work items (4.03). Based on the repair method details and BOQ items, the quantities and repair locations associated with each item are calculated (4.04). Selected BOQ items and related quantities also include items related to consequential damage (4.05), another key factor identified in the research.

As the quantities are calculated separately for each damaged element, the next step of the process is to deduct any duplicated quantities, as explained in the system mechanics section (4.07). Any restrictions affecting the repair work not addressed in the repair method selection process are considered during the quantity calculation (4.04) and duplication deduction (4.07) processes. Finally, all the quantities are summarised (4.08), and a BOQ with quantities is produced (4.09).

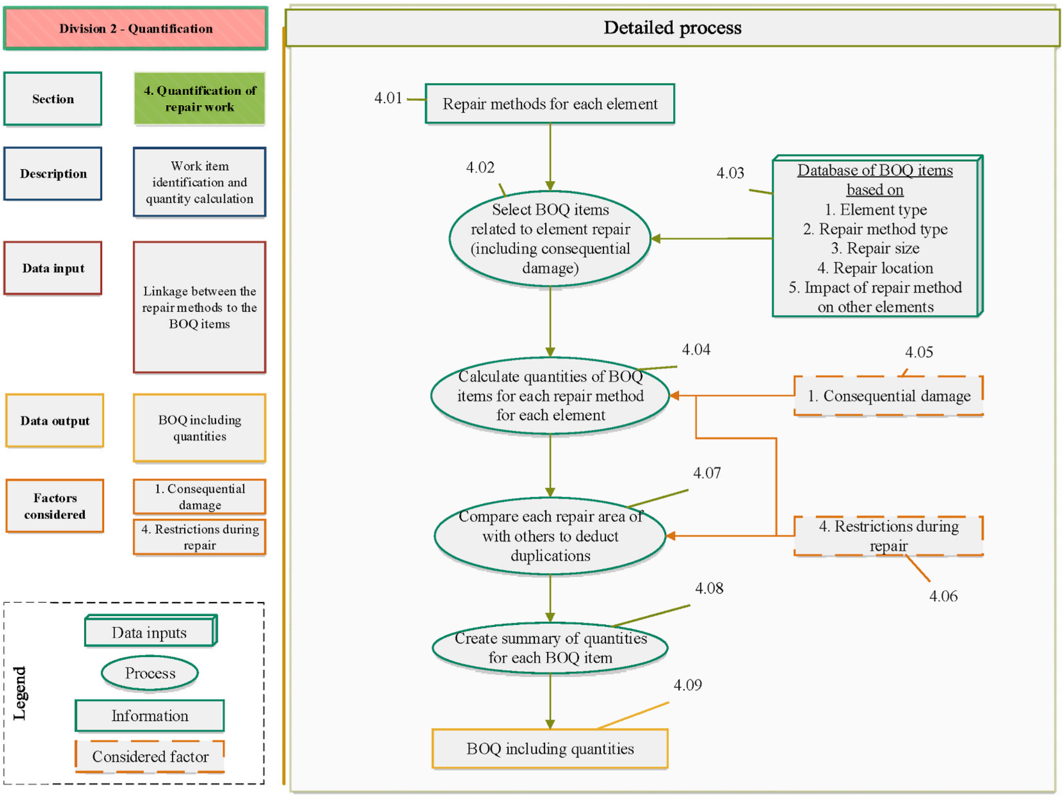


Fig. 8. Quantification of repair work (Section 4).

4.8. *Quantification of duration and start date (section 5)*

4.8.1. *Process of the quantification of duration and start date (section 5)*

The fifth section of C-DREEM establishes the project plan by calculating the repair duration and the start date (refer to Fig. 9). The process starts with sequencing the repair work for each item (5.04) based on the BOQ items and related quantities (5.01). Preloaded functions that contain the general order of work activities (5.03) are used to create the repair work sequence (5.04). The general sequence of work items is superseded by the other influences that have an impact on repair work, which include; engineering requirements, architectural requirements, government regulations, restrictions during repair work and stakeholder requirements (5.05). Other influences that impact repair work (5.05) include factors identified in the research: restrictions impacting repair work (5.02) and changes to the required final repair state (5.12) .

Next, labour requirements for the work items are extracted from the rate breakdowns of each BOQ item (5.06). The quantified labour requirements are then used to calculate the labour needed for each work activity (5.07) and determine the project duration (5.10).

The duration between the start date and cost estimation date (5.13) is based on external factors that affect the start date (5.14) and project-related work items that require long lead times (5.11). Until a separate process is developed, the processes employed by P-58 methodology-based models [43] can be used to calculate the impact of impeding factors that prevent the start of a project (5.14). Material and equipment that require a long lead time are calculated (5.11) using preliminary requirements extracted from section six (Quantification of preliminaries) (5.08), project duration (5.10) and BOQ items and quantities (5.09).

The combination of the project duration (5.10) and start date (5.15) outputs produces the project plan (5.18), which is directly related to repair time (5.19), another key factor identified in the research.

4.9. *Quantification of preliminaries (section 6)*

4.9.1. *Process of the quantification of preliminaries (section 6)*

The sixth section of C-DREEM establishes the process of selecting and quantifying preliminary items based on the identified repair method (refer to Fig. 10). A preloaded function included in the model links repair methods to preliminary item requirements (6.05). The selection of required preliminary items is based on the repair methods (6.01), BOQ item quantities (6.01), and other influences impacting the repair work (6.06), including: engineering requirements, architectural requirements, government regulations, restrictions to repair work, and stakeholder requirements (6.06). As per previous sections, other influences impacting repair work (6.06)

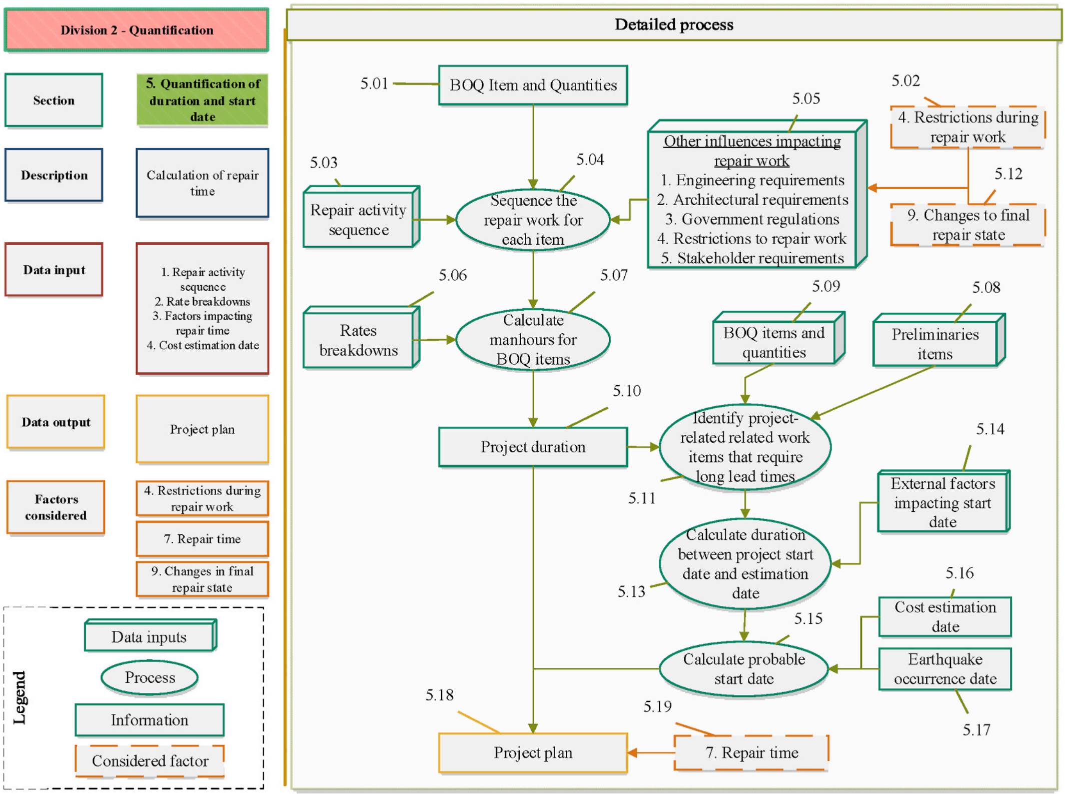


Fig. 9. Quantification of duration and start date (Section 5).

would also take into consideration the impact of restrictions to repair work (6.02) and changes to the required final repair state (6.03).

The quantification of preliminaries is based on the project plan identified in the previous section (6.10), BOQ item quantities (6.10) and the labour required for the repair work (6.11). The use of a project plan (6.09) would include the impact of the repair time (6.08), a key factor identified in the research.

Quantification of the labour required for the project is based on the BOQ item quantities (6.10) and rate breakdowns (6.12). Any preliminary items that require total project costs in order for their quantities to be calculated are considered in the 'costing' section. Calculating quantities for preliminaries also includes the deduction of quantity duplications (6.11). A summary of preliminary items and relevant quantities is the final output of section (6.13).

4.10. Costing (section 7)

4.10.1. Process of the costing (section 7)

The seventh section of C-DREEM, the first of the 'costing and summarisation' division, breaks down the process associated with costing the quantified items and adjusting for price fluctuations.

The process starts by extracting quantities related to direct work items and preliminaries (7.01). Thereafter, suitable rates are assigned to the extracted cost items (7.02) (refer to Fig. 11). The required rates are developed (7.05) using rate breakdowns (7.04) and the current market prices of resources (7.06). Any changes in the cost of resources (7.06) are updated using cost databases (7.07). Any impact from changes to the type of contract (7.03) is included through the rate development process (7.05) whereby profit and overhead percentages are included.

Next, the total direct cost of work items (7.08) is produced, using the rates and quantities. A similar process is used for costing the preliminary items (7.09). The costs of total direct costs (7.08) and preliminary items (7.09) are added together to produce a BOQ with total construction costs (7.10). This total does not reflect the impact of price fluctuations.

Projected price fluctuations that might occur during post-earthquake repair work are calculated with the use of a preload formula (7.15)included in the framework. Calculations from this formula includes earthquake-induced price fluctuations (7.16), another key factor identified in the research. The price fluctuation formula operates on information provided by the construction cost indices (7.13), project plan (7.12), and rate databases (7.14). In this instance, the project plan (7.12) is used to identify the start date and duration of each work item. The output of section (7.17)is an estimate of the total construction costs adjusted according to price fluctuations.

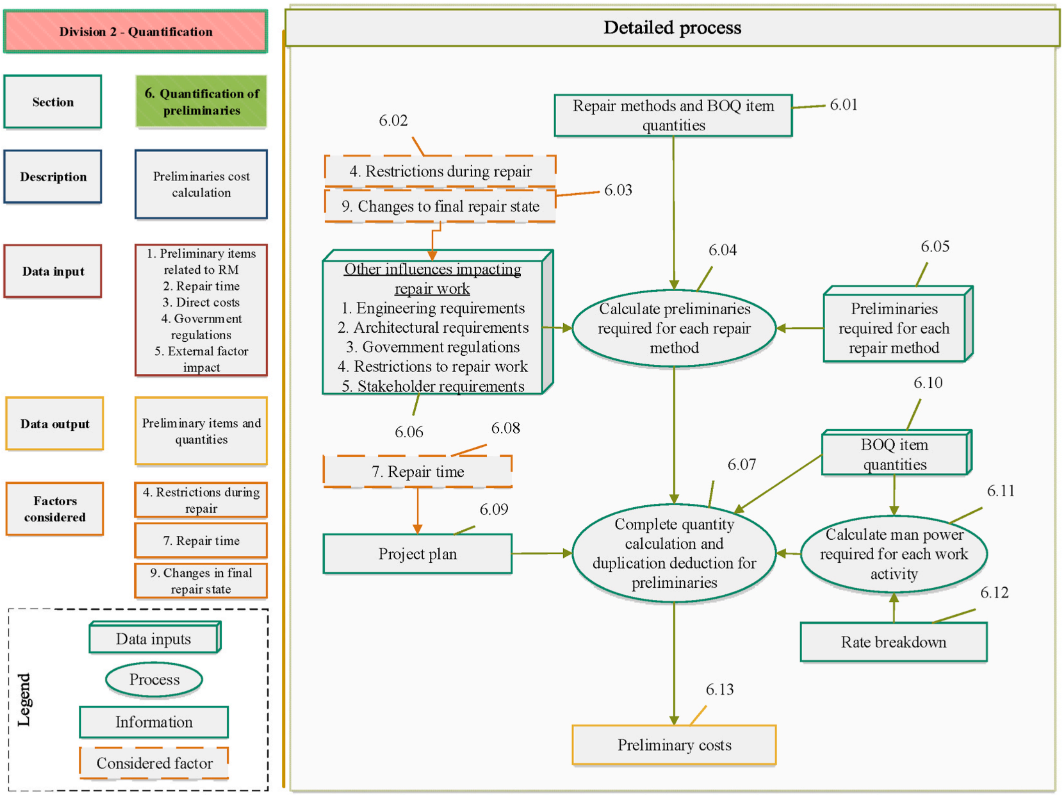


Fig. 10. Quantification of preliminaries (Section 6).

4.11. *Professional services and other costs (section 8)*

4.11.1. *Process of the professional services and other costs (section 8)*

The eighth section of C-DREEM calculates the cost of professional services and other costs (refer to Fig. 12). The process starts with the selection of professional services and other costs required for total repair work (8.02). An inbuilt selection mechanism is included to link damage details to required professional services (8.03) and other costs (8.04). Details required for this function are: damaged element type, size of the element, location of the element, size of the damage, damage severity, damage location and required professional services for each type of damage. The required damage details are extracted from the BIM model (8.01).

Several project details are used to calculate the cost of professional services and other costs (8.04): recommended professional services and costs; project start date and duration, extracted from the project plan (8.07); cost of preliminaries (8.06); and direct costs (8.08). Separate formulas are included in the framework to calculate the professional service costs (8.09) and other costs (8.10).

Next, the costs of professional services and other costs are adjusted according to projected price fluctuations (8.09). As per section 7, a preloaded post-earthquake price fluctuation formula (8.14)is used to calculate the projected price fluctuations, which include earthquake-induced price fluctuations (8.15). As per the previous section, inputs for the price fluctuation formula are the construction cost indices (8.10), the project start date, the project duration and rate databases (8.11).

The project plan is used in this instance to identify the start date and duration of each professional service required and other costs in order to establish a professional cost calculation method (8.09). The final output of section 8is the total cost of professional services and other costs (8.14), and includes another key factor identified in the research: the cost of professional services (8.15).

4.12. *Total project costs and consequential functions (section 9)*

4.12.1. *Process of the total project costs and consequential functions (section 9)*

The ninth and final section of the framework focuses on combining all the previously calculated costs to produce the total cost of the project (refer Fig. 13). Additionally, this section develops consequence functions and compares them with previous versions. The developed consequence functions can be used in the pre-earthquake loss estimation tools that were identified in the literature section.

The total cost of the project contains total direct costs (9.01), costs of preliminaries (9.02) and professional services and other costs (9.03). The total cost of the project is based on both actual damage and projected probable damage. The costs associated with repairing actual damage are extracted into the total verified direct cost (9.06), verified costs of preliminaries (9.07) and verified professional costs (9.08). Costs derived from probable damage are included in the contingencies (9.05). Since C-DREEM adopts the ANZSMM 2022

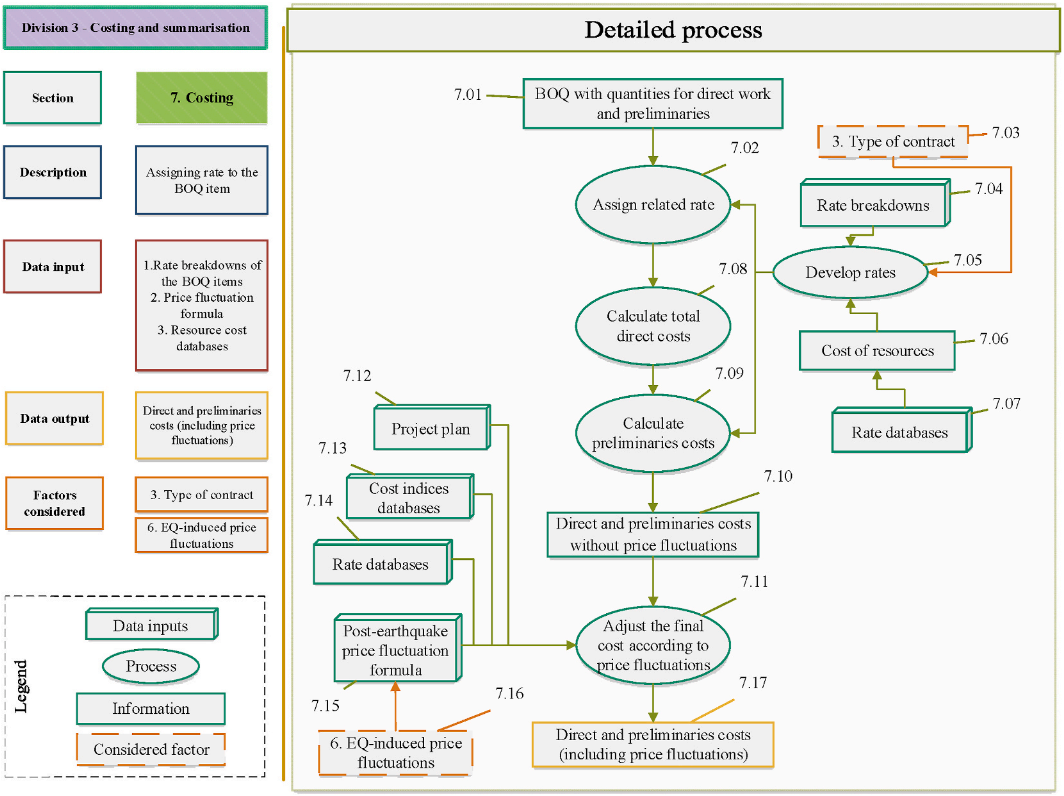


Fig. 11. Costing (Section 7).

standard, costs of contingency items (9.05) are included in the provisional sums (9.09).

Then, the total verified direct costs (9.06), verified cost of preliminaries (9.07), verified professional costs (9.08) and provisional sums (9.09) are summarised in the summary sheet to produce the total project cost summary (9.10).

The next step of the process is to produce consequence functions (9.15). As explained in the literature review, consequence functions link different damage states of building elements to the appropriate repair costs. The first step of the consequence function development process is to link the damage states of the building elements to the appropriate direct costs (9.14) and then develop consequence functions. The information used in this linking process is the repair methods details (9.12), the direct costs of the repair methods (9.13) and the damage states of the elements (9.11). Then, the remaining project costs are added to the consequence functions. A summary of the total project cost (9.10) will be divided and allocated proportionately to the remaining costs for each consequence (9.16). These costs are: the cost of preliminaries, the cost of professional services and other costs (9.15). This process produces the consequence functions for each damage state of all building elements.

Finally, the consequence functions developed from the C-DREEM (9.16) are compared with previously developed consequence functions (9.17), which include data extracted from loss estimation (9.18) and probability-based (9.19) tools. The comparison functions as a feedback procedure for future modifications to C-DREEM. This process follows Principle 28 of the TRIZ methodology, which is to change the method used.

5. Discussion

This study aims to develop a standardised post-earthquake cost estimation mechanism that incorporates the impact of eleven key factors affecting cost estimation and improves the overall process. The C-DREEM framework addresses this gap by integrating these eleven factors into the current CEEDRW, thereby enhancing its accuracy. Additionally, C-DREEM introduces new sources of information for CEEDRW, including probability-based damage prediction data, 3D modelling, and systematic approaches that were not previously used in the existing CEEDRW process.

A major issue in the current CEEDRW process is the time required to obtain accurate earthquake damage assessments for buildings [48]. Probability-based models predict earthquake damage using earthquake forces and building details without the need for on-site inspections [51,52,62]. Although this information is not as precise as actual damage evaluations, it helps bridge the gap when real damage data is unavailable for cost estimation.

Additionally, the C-DREEM framework proposes developing consequence functions at the end of the costing process, establishing a checks-and-balances mechanism for damage estimation while continuously refining consequence functions. Over time, as more

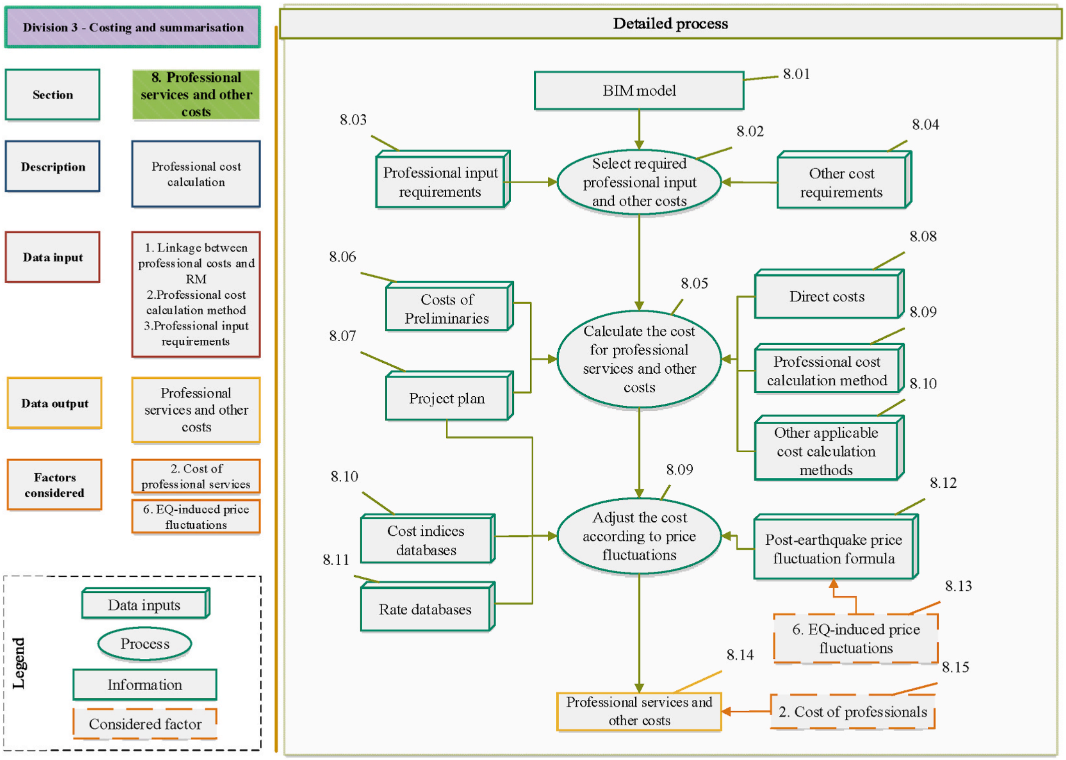


Fig. 12. Professional services and other costs (Section 8).

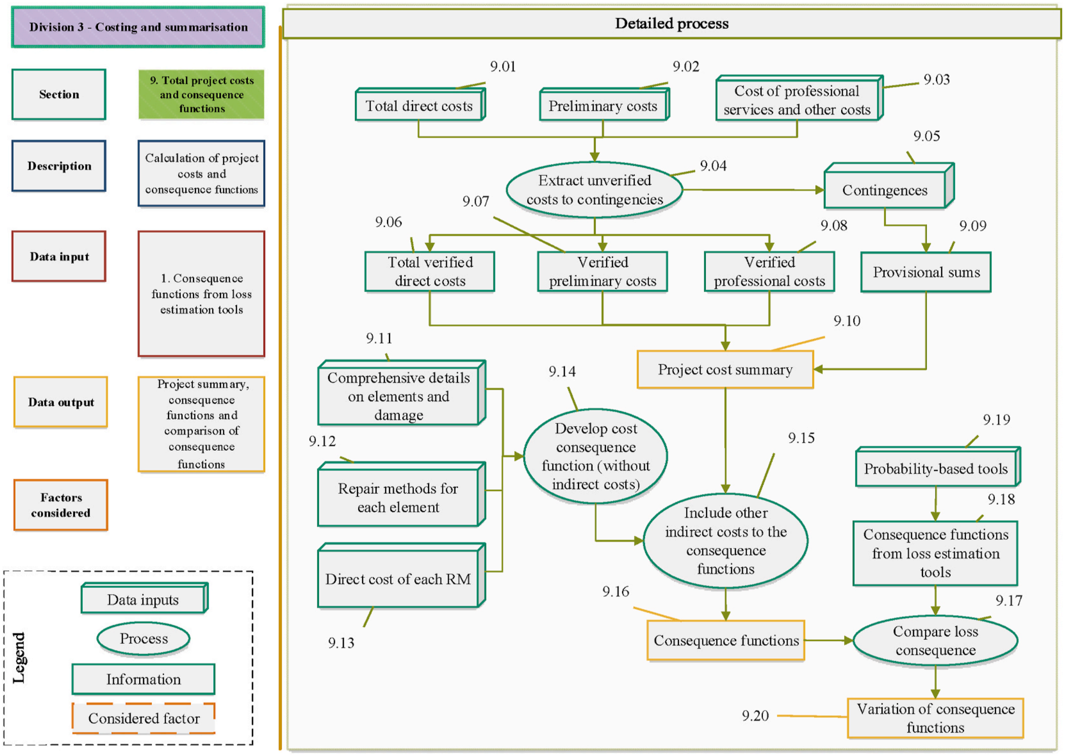


Fig. 13. Total project costs and consequential functions (Section 9).

validations are conducted, the C-DREEM costing process will become increasingly accurate.

Furthermore, 3D models facilitate the digital storage of building damage information, enhancing data visualization and information sharing. C-DREEM also introduces a segmented system that structures the cost estimation process into distinct components, each connected only by inputs and outputs. This modular approach allows individual segments to function independently, enabling easy upgrades and improvements without disrupting the overall system.

Based on participant feedback, three-quarters of respondents agreed that C-DREEM is clear, accurate, practical, useable, reliable, and capable of increasing the speed of cost estimation. Additionally, two-thirds of participants agreed that the model adequately accounts for all necessary variables required for CEEDRW. Quantitatively, the weighted average for all factors was above 3.78, with a standard deviation of less than 1 across all results, indicating strong agreement among participants.

Furthermore, two-thirds of respondents stated that the C-DREEM framework met their expectations, and eight out of nine participants supported its commercialisation. Given that the participants had an average of 26.1 years of industry experience and 6.9 years of CEEDRW experience, these findings suggest that the proposed C-DREEM framework effectively achieves its objective. It provides a more accurate post-earthquake cost estimation mechanism that enhances the speed of estimation while integrating the impact of the eleven key factors influencing earthquake damage repair costs. The coverage of these factors is summarised in Table 3.

However, as suggested by the participants, C-DREEM needs to be developed into software and validated using actual cost data, which remains a limitation at this stage. This can be addressed in future research and development. As mentioned earlier, the software development and validation process will help mitigate most drawbacks, including usability, user acceptance, development time and

Table 3
Method of incorporating the impact of the 11 factors that impact cost in C-DREEM.

Factor no.	Factor	Considered section	Method of coverage (including the model reference numbers)
1	Consequential damage repair	Repair method identification (Section 3)	The repair method and its selection process include the identification of impacts from consequential damage (3.05)
		Quantification of repair work (Section 4)	The quantity calculation process quantifies the impact of consequential damage (4.04)
2	The cost of professional services	Professional services and other costs (Section 8)	The main output of this section is the cost of professional services (8.16)
3	Type of contract	Costing (Section 7)	Profit and overhead percentages in rates are adjusted according to the type of contract (7.05)
4	Restrictions during repair work	Repair method identification (Section 3)	'Other influences' evaluation process considers incorporates the impact of restrictions on the repair method (3.09)
		Quantification of repair work (Section 4)	The quantity calculation and duplication deduction process quantify the impact of restrictions during repair work (4.04 and 4.06)
		Quantification of duration and start date (Section 5)	'Other influences' evaluation process considers the impact of restrictions on start date and duration (5.05)
		Quantification of preliminaries (Section 6)	'Other influences' evaluation process considers the impact of restrictions on preliminary items (6.04 and 6.06)
5	Aftershocks, earthquake-induced hazards and weather conditions	Post-earthquake state identification (Section 2)	Probable damage data gives partial indication of aftershocks and earthquake-induced hazards. Probability-based loss estimation tools will be used to extract the data (2.03). Details from damage inspection reports will be used to extract and include actual damage information (2.06).
6	Earthquake-induced high rates and price fluctuations	Costing (Section 7)	Calculated costs are adjusted according to EQ-induced price fluctuations, which include the impacts of start date and duration (7.11 and 7.15)
		Professional services and other costs (Section 8)	Calculated professional services and other costs are adjusted according to EQ-induced price fluctuations, which include the impact of start date and duration (8.09 and 8.12)
7	Repair time	Quantification of duration and start date (Section 5)	The main purpose and final product of this section is to calculate the impact of the repair time through the calculation of the start date and project duration (5.19)
		Quantification of preliminaries (Section 6)	The impact of the repair time (6.08) will be considered when quantifying the preliminary items that are impacted by repair time (6.07)
8	Initially unforeseen damage	Post-earthquake state identification (Section 2)	Probable damage data gives a partial indication of initially unforeseen damage. Probability-based loss estimation tools will be used to extract the data (2.04).
9	Changes to the required final state of the building	Repair method identification (Section 3)	'Other influences' evaluation process considers the impact of changes to the required final repair state on the repair method (3.08) (e.g., changes in regulations)
		Quantification of duration and start date (Section 5)	'Other influences' evaluation process considers the impact of changes to the required final repair state on the start date and duration (5.05)
		Quantification of preliminaries (Section 6)	'Other influences' evaluation process considers the impact of changes to the required final repair state on preliminary items (6.04 and 6.06)
10	Pre-earthquake state of the building	Pre-earthquake state identification (Section 1)	The post-earthquake survey and 3D point cloud will cover some of the variations between the as-built drawings and the pre-earthquake state. This will lead to the identification of pre-earthquake damage (1.02 and 1.03)
11	Substandard repair work	Pre-earthquake state identification (Section 1)	The relevant building regulations are compared with the current condition of the building to identify substandard repair work (1.10).

cost, and the need for continuous updates to maintain accuracy. To facilitate implementation, an iterative approach has been suggested, starting with a simple manual process using a checklist. This would enhance factor coverage and assign responsibility for each input and C-DREEM action, laying the groundwork for a more advanced system.

Additionally, further research is required to develop methods for quantifying and incorporating the impact of additional factors on repair work, start dates, and duration; sequencing repair methods based on individual projects and on-site construction methods; calculating earthquake-induced price fluctuations; assessing the impact of building regulation changes; and improving inputs and project management processes in response to new aftershocks. These advancements will further enhance the effectiveness of C-DREEM.

5.1. Importance of the C-DREEM

The importance of the C-DREEM can be identified when it is compared with the traditional CEEDRW process and P-58 methodology-based models. Therefore, a comparison was conducted between the C-DREEM, the traditional post-earthquake cost estimation for earthquake damage repair work (PEQ-CEEDRW) process and probability-based models, as expressed in Table 4.

The main differences between the methods are related to the innovations introduced to the C-DREEM system by the TRIZ methodology. These innovations were designed to enhance the speed of the cost estimation process while ensuring that all key factors affecting CEEDRW are considered. To improve estimation speed, C-DREEM incorporates automated processes for (i) damage identification, (ii) repair method selection, and (iii) cost estimation. Validation results confirmed that C-DREEM outperforms PEQ-CEEDRW in terms of speed, making it a more efficient approach to post-earthquake cost estimation. The analysis of P-58 methodology-based models shows that they do not account for building element details, repair methodologies, and all CEEDRW-related factors as comprehensively as C-DREEM. While P-58 models may run slightly faster due to fewer calculation stages, this advantage is marginal and remains unverified through direct comparison. More importantly, C-DREEM provides a detailed cost estimation essential for post-earthquake repair work, making it far more suitable for its intended purpose. Its comprehensive approach ensures greater accuracy and reliability in assessing repair needs, outweighing any potential differences in processing speed.

In terms of output accuracy, C-DREEM offers a significant advantage over other CEEDRW methods. Unlike P-58 methodology-based models, which rely solely on probability-based damage estimation, and PEQ-CEEDRW, which considers only actual damage, C-DREEM integrates both approaches. By incorporating both probable and actual damage assessments, it can cross-validate its results against past data to detect deviations, enhancing reliability. Additionally, C-DREEM accounts for all key factors affecting CEEDRW, further improving estimation accuracy. While P-58 methodology-based models provide less detailed estimates due to their reliance on probable damage, PEQ-CEEDRW generates more precise outputs by using actual damage data and considering most CEEDRW factors. However, by combining the strengths of both methods, C-DREEM produces even more accurate and comprehensive cost estimations.

The complexity of the process is a critical factor in evaluating the C-DREEM framework. Among the compared methods, PEQ-CEEDRW has the lowest complexity as its cost calculations follow a straightforward approach based on multiplying rates by quantities. In contrast, P-58 methodology-based models introduce a higher level of complexity by incorporating fragility curves and consequence functions in the estimation process [46,51,52]. C-DREEM, however, is the most complex system, as it integrates multiple advanced processes, including fragility curves for probable damage estimation, consequence functions for evaluation, automated damage identification and cost estimation, and real-time price updates through cost databases. These features enhance accuracy and efficiency but also contribute to its overall complexity.

Further describing the factors considered by the processes, C-DREEM considers all key factors impacting CEEDRW based on the

Table 4
Difference between P-58 methodology-based models, PEQ-CEEDRW and the C-DREEM.

Characteristics	P-58 methodology-based models	PEQ-CEEDRW	C-DREEM
Speed of cost estimation	The highest is due to the lower number of inputs required.	The lowest is due to the length of time required for manual estimation.	According to the validation results, it is better than the current cost estimation process. Lower than P-58 methodology-based models due to the greater number of inputs required.
Accuracy of outputs from CEEDRW	The lowest is due to the use of probability information and the minimum use of building-specific details and factors considered.	It is better than P-58 due to the use of actual damage. Lower than C-DREEM because of the non-consideration of probable future damage and a smaller number of factors affecting CEEDRW	Higher than all other methods due to the use of both probability predictions and actual damage, and a standard CEEDRW process. Considers all of the factors affecting CEEDRW
Complexity	Requires users to identify the function of fragility curves and consequence functions.	The lowest is due to the use of the simple theory of rates multiplied by quantity equals cost.	Highest. Due to the use of automation processes and other integrated functions.
Provides a standardised process to include the impact of key factors	No	No	Yes
Can be used for post-earthquake CEEDRW	No	Yes	Yes

available information, as outlined in the results section (refer to Fig. 14). In comparison, P-58 models account for earthquake-induced hazards (F 05.1) and the impact of initially unforeseen damage (F 08). However, these models only partially address these factors. However, these models only include the impacts of aftershocks and initially unforeseen damage. Initially, unforeseen damage is only considered by probability-based damage estimation methods, and aftershocks are only one part of earthquake-induced hazards. Therefore, the impact of earthquake-induced hazards and unforeseen damage is, in fact, only partially considered by these models.

PEQ-CEEDRW considers the factors that are identifiable at the cost estimation stage, including the impact of types of contract (F 03), repair time (F 07), and changes required to the final repair state (F 09). However, as demonstrated during the Canterbury earthquake sequence, some other factors were considered at the latter stages of the project when information became available [48]. These factors were: consequential damage repair (F 01); restrictions during repair work (F 04); earthquake-induced high rates and price fluctuations (F 06); and initially unforeseen damage (F 08). Some factors that were identified at the latter stages of the project were considered separate events: earthquake-induced hazards and weather conditions (F 05), the pre-earthquake state of the building

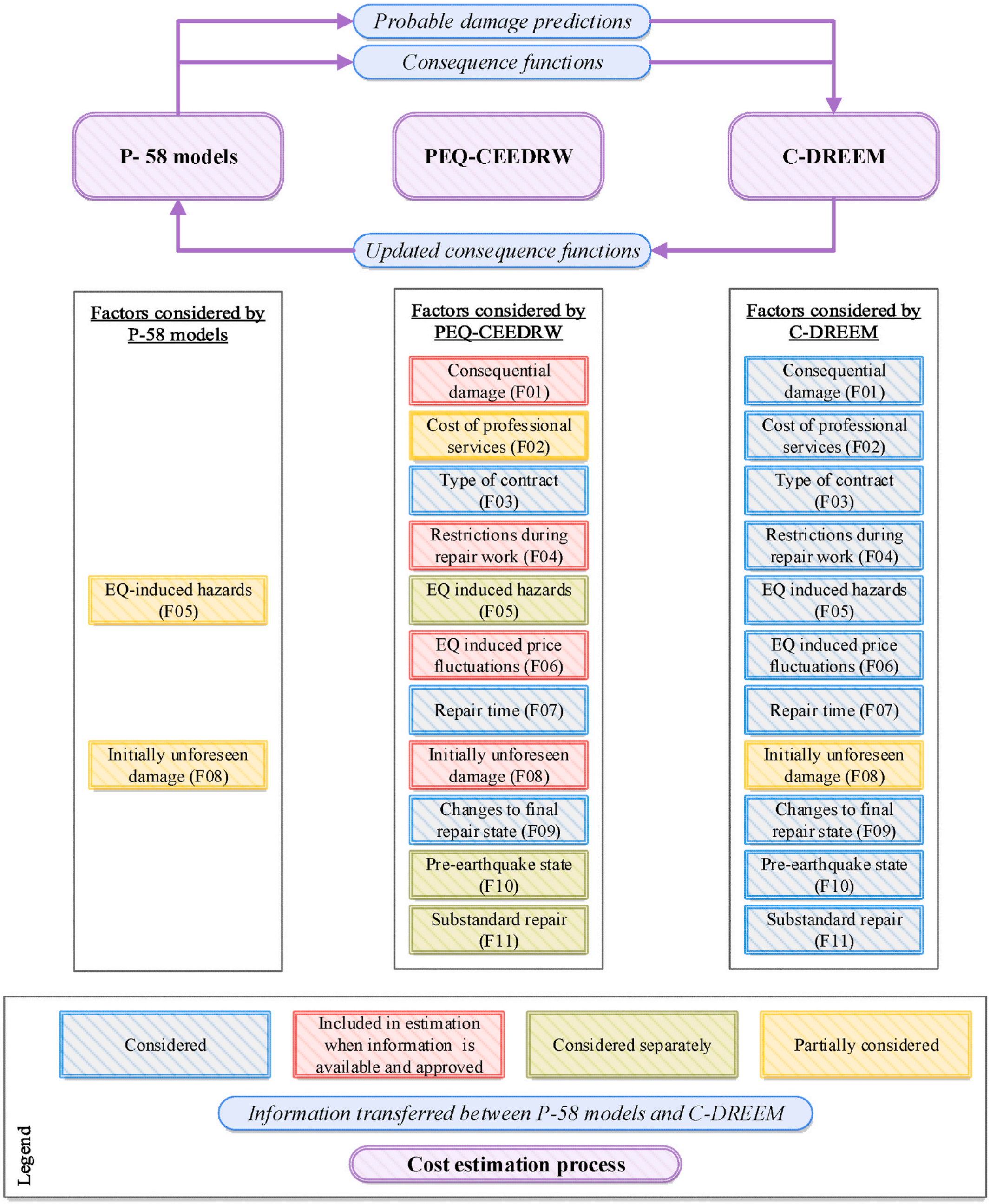


Fig. 14. Comparison between P-58 methodology-based models, PEQ-CEEDRW and C-DREEM in terms of factor coverage and information sharing.

(F 10) and sub-standard repair work (F 11). The cost of legal services was also not considered during the Canterbury earthquake sequence since these costs were not part of the construction costs [48]. Therefore, the total costs of professional services (F02) were not fully considered.

A key feature of C-DREEM is its creation of an information cycle with P-58 methodology-based models. C-DREEM uses probability-based predictions and consequence functions generated by these models in its process. Probability-based predictions identify damage to building elements, while consequence functions evaluate the C-DREEM outputs. In turn, C-DREEM produces updated consequence functions that can be used to refine the P-58 methodology-based models. This information cycle improves the outputs of both C-DREEM and P-58-based models. Another advantage of C-DREEM is that it provides a standard method for incorporating the impact of key factors and defining the procedures by which these impacts should be included. As a result, C-DREEM offers a standardised cost estimation approach.

The C-DREEM model, while more complex than other cost estimation processes, excels in providing highly accurate estimates, effectively incorporates all key factors and surpasses the capabilities of PEQ-CEEDRW methods in both accuracy and speed. Although it may have a slightly lower speed compared to P-58 methodology-based models, C-DREEM offers detailed cost estimates required for coverage of all relevant factors and produces results that were not achieved by P-58 methodology-based models. By creating an information cycle with P-58 methodology-based models, C-DREEM enhances the accuracy and efficiency of both systems, fostering continuous improvement. Moreover, it establishes a standardised process for incorporating these factors into the CEEDRW process. Designed to meet the specific needs of post-earthquake cost estimation, C-DREEM successfully addresses challenges identified through extensive research, fulfilling its intended purpose of improving both the accuracy and speed of cost estimation for earthquake damage repair work.

5.2. Limitations of C-DREEM

The C-DREEM [46] framework is at the theoretical stage, thus containing limitations and requiring further research. The following limitations and further developments were also identified after the author reviewed them and received input from research participants (see Table 5).

6. Conclusion

After devastating earthquakes, an accurate damage estimation method is required to assess the damage in the recovery process. Previous research identified 11 factors that significantly impact cost estimation for earthquake damage repair work. These 11 factors were not fully addressed by the currently available pre-earthquake damage prediction models and post-earthquake cost estimation processes. Therefore, this research developed a post-earthquake cost estimation framework that incorporates the impact of these factors while standardising the cost estimation process. Key improvements included in the C-DREEM are the integration of inputs from pre-earthquake predictions to fill information gaps in post-earthquake CEEDRW, updates to earthquake prediction models for increased accuracy, 3D modelling of buildings to account for deviations from building standards and both earthquake and non-earthquake-related damage, and a systematic segmented process to demonstrate how to cover the factors. According to the findings, C-DREEM will help improve the CEEDRW process by making it both more accurate and faster, as it outlines how to incorporate the 11 factors into the costing process.

However, there are additional functions that need to be incorporated into C-DREEM, which the software platform and future research should address. These include methods for calculating: repair method sequencing, earthquake-related price fluctuations, the impact of other influences on repair work, start date and duration, the effect of building regulation changes, input prioritisation, and responsibility allocation. The software package should be simple, understandable, user-friendly, based on a standardised process, introduced in iterations, and kept up to date. It should also be developed and managed efficiently, minimizing time and cost.

The framework does have some limitations. C-DREEM was developed and validated based on data from New Zealand, so its applicability to other countries requires further verification. Additionally, C-DREEM is a theoretical model, and needs to be developed into software and quantitatively validated with actual data. Therefore, the next logical step is to create a software example to demonstrate how the costing process would work.

6.1. Theoretical implications

Currently, no standardised model exists for post-earthquake cost estimation, and repairs are traditionally assessed using a bottom-up approach. The C-DREEM model addresses this gap by providing a structured framework for estimating earthquake damage repair costs.

Additionally, eleven critical factors significantly impact CEEDRW but are not fully considered in the existing process. C-DREEM introduces a methodology to systematically incorporate these factors, enhancing cost estimation accuracy.

Currently, traditional CEEDRW cost estimation practices and pre-earthquake loss estimation tools operate independently thus lacking integration. C-DREEM bridges this divide by unifying both approaches, allowing them to complement each other. Additionally, P-58 methodology-based tools such as PACT, SLAT, and SP3 will benefit from C-DREEM's structured mechanism, enabling automated updates to consequence functions and a validation process to ensure accuracy.

Table 5
– Limitations of C-DREEM and the method of upgrade.

Limitations	Possible methods of incorporation
Need for clarification regarding the allocation of responsibility for 3D model development, the process of initial assessments and the method to manage mismatches in information from different sources.	The software package can be designed to assign superseding mechanisms based on input type and person and assign responsibility for each data type.
Mechanisms for quantifying and incorporating the impact of other influences on repair work, start date, and duration.	Future research and features in the software
Method of calculating earthquake-induced price fluctuation.	Future research and features in the software
Method sequencing the repair method based on the individual project and on-site construction method.	Future research and features in the software
Method of quantifying and incorporating the impact of building regulation changes.	Future research and features in the software
The process should consider the impact from impact of each new aftershock.	Improving the software to be updated based on new aftershocks can be part of further research.
C-DREEM might require a considerable amount of additional time to create estimates for new projects.	A feature to be included in the software through more processing power
Making C-DREEM simple, understandable, reliable, readily available, user-friendly, useable in the field, and containing an online platform for information-sharing	The software based on should be run online with an interface made more user-friendly and understandable. The software should be compatible with portable devices while providing information sharing.
The C-DREEM process should be standardised, holistic and understood by everyone to reap the framework's benefits.	The software estimation process should be published and explained to the user through guides.
Time and cost required for the C-DREEM software development process.	The software development process can consider how to reduce the time and cost required to develop the model. It can be developed as part of a research project for the benefit of all stakeholders.
The industry may have a low usage of C-DREEM since it is new.	The software can be introduced in iterations to reduce drastic changes through the use of working templates. A checklist can be the first step.
Need to include up-to-date information in C-DREEM	The software should be continuously updated based on professional inputs from industry practitioners. Section 9does have an updating mechanism for the C-DREEM to some extent.
The use of C-DREEM might drastically increase consultant fees due to the time required to become familiar with it.	Introducing the C-DREEM through iteration can improve its understandability.
Usage of the commercialised version depends on its adaptability by the quantity surveyors and alignment with current methods used by quantity surveyors.	Through guides, instruction videos, and induction seminars, the adoption of the C-DREEM can be increased
Requires a method to incorporate damage to the 3D model and a method of outputting repair method required	This will be part of further research.

6.2. Practical and social implications

For homeowners, accurate cost predictions from C-DREEM benefit by aiding negotiations, repair decisions, and demolition considerations. Compared to traditional CEEDRW processes, C-DREEM enables faster cost estimations, reducing repair durations and expediting recovery.

For insurance companies, the model improves cost prediction accuracy, minimizing post-earthquake losses through better-adjusted insurance premiums. Policies can be updated to either include identified factors leading to higher premiums or exclude them from future claims.

For the government, standard cost estimation practices should be enhanced to integrate these factors and adopt an automated C-DREEM-based system. This would lower operational costs and enable proactive measures to mitigate the impact of key factors, ensuring better control over nationwide post-earthquake cost variations.

6.3. Future research

This research has developed C-DREEM as a theoretical framework for generating detailed cost estimations for earthquake damage repair work as part of a PhD study. To maximize its practical application, a software tool should be developed based on C-DREEM and validated through a case study to demonstrate its full potential.

Further research is recommended to develop quantitative mechanisms for measuring and integrating the impact of additional factors on repair work, start dates, and duration. It should also focus on quantifying earthquake-induced price fluctuations, sequencing repair methods based on individual projects and on-site construction approaches, and assessing the impact of building regulation changes. Additionally, future studies should explore ways to account for aftershocks by updating the 3D model and adjusting repair methods accordingly.

Authorship Contribution Statement

Kahandawa Ravindu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Domingo Niluka:** Writing – review &

editing, Validation, Supervision, Resources, Methodology, Funding acquisition. **Chawynski Gregory:** Writing – review & editing, Validation, Supervision. **S.R. Uma:** Writing – review & editing, Validation, Supervision.

Ethics statement

This project has been reviewed and approved as low risk by the Massey University Human Ethics Committee: Northern, Application 4000017232.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:This research was funded by the Massey University Research Fund award to Niluka Domingo. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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