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A system dynamics framework for whole life costing in seismic and climate-sensitive residential construction in New Zealand

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Abstract

Purpose – This study develops a whole life costing (WLC) framework tailored to New Zealand's residential construction sector, addressing key region-specific challenges such as seismic risks, climate variability, and evolving regulatory conditions.

Design/methodology/approach – A systematic literature review (SLR) was conducted alongside 22 semi-structured expert interviews to identify critical cost drivers influencing WLC in residential buildings. The study applies system dynamics (SD) methodology, using causal loop diagrams (CLDs) and degree centrality analysis to model complex interdependencies and feedback loops among these cost drivers.

Findings – The study identifies 73 key cost drivers across technical, environmental, economic, regulatory and behavioural domains. These drivers are structured into a hierarchical framework that models their interactions across the acquisition, operational and end-of-life phases of residential buildings. The findings emphasise the importance of seismic resilience, energy efficiency, material durability and climate-related impacts in long-term cost planning for residential buildings in New Zealand.

Research limitations/implications – The framework is based on expert interviews and literature review, which may limit the scope of identified factors. The research is conceptual in nature, and empirical validation of the framework is needed to confirm its practical applicability across different residential projects. Future research could include testing the framework in real-world settings or extending it to other geographical contexts.

Practical implications – The proposed WLC framework provides policymakers, developers and architects with a structured tool for evaluating long-term costs and benefits of residential construction projects. It integrates local environmental, economic and regulatory factors, thus promoting sustainable design and more informed decision-making throughout the construction lifecycle. The framework can guide policy development, building regulations and sustainable construction practices in New Zealand and similar regions.

Social implications – The framework promotes long-term affordability, quality and resilience in residential buildings, supporting improved public health, energy equity and disaster preparedness, critical issues for vulnerable communities affected by housing and environmental instability.

Originality/value – This study presents the first context-specific WLC framework for New Zealand's residential construction sector. Unlike global models, it incorporates critical regional factors, such as seismic and climate risks, to offer a more comprehensive and practical tool for enhancing the economic sustainability of residential buildings. The framework's innovative use of system dynamics and causal loop modelling offers new insights into lifecycle cost estimation and long-term sustainability in construction.

Keywords Whole life costing, System dynamics, Residential construction, New Zealand, Seismic resilience, Sustainable design

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1. Introduction

Whole Life Costing (WLC) is a pivotal methodology in the construction sector, enabling stakeholders to comprehensively assess a building's total cost throughout its lifecycle, including capital investment, barrier, maintenance, and eventual decommissioning costs (Flanagan and Jewell, 2008; ISO, 2017). By aligning financial planning with long-term environmental objectives, WLC plays a crucial role in fostering sustainable development within the construction industry. Despite its successful application in larger infrastructure and commercial projects globally, most existing WLC frameworks are generic and inadequately cater to the unique needs of residential buildings (Goh and Sun, 2016; RICS, 2016). These models often lack the adaptability needed for specific regional conditions.

In the context of New Zealand, the absence of a nationally standardised or residential-specific WLC framework creates fragmented practices and hinders effective long-term cost planning (MBIE, 2013; NIWA, 2022). Specifically, New Zealand faces unique challenges, including significant seismic risks, varying climatic conditions, and evolving regulatory requirements, which substantially impact lifecycle costs. Without a robust WLC methodology tailored to these conditions, homeowners, developers, and public sector entities face escalating long-term costs. For instance, estimates from the Ministry of Business, Innovation, and Employment, MBIE (2013) Seismic retrofitting could cost upwards of NZD 100,000 per dwelling in high-risk areas, such as Wellington and Christchurch. Furthermore, climate-related weather events have incurred costs exceeding NZD 1 billion over the past decade, underscoring the urgent need for lifecycle-focused planning in residential development. (NIWA, 2022). **These economic impacts and ongoing affordability pressures highlight the urgent need for lifecycle-conscious planning in residential development.**

This research addresses the gap by developing a WLC framework specifically designed for New Zealand's residential construction sector. The aim of the study is to propose the improvements required in the WLC framework to make it suitable for residential buildings in New Zealand.

The central research question addressed by this study is:

What specific improvements are required to adapt or enhance the whole-life costing approach for residential buildings in New Zealand?

To address this research question, the following objectives were formulated:

Objective 1. To identify the key cost drivers that affect WLC estimation for residential buildings in New Zealand.

Objective 2. Develop a comprehensive WLC framework that integrates these factors, with a particular focus on seismic resilience, energy efficiency, and climate-related impacts.

By identifying and addressing the limitations of existing frameworks, this study aims to provide a robust, region-specific tool that incorporates the unique geographical, environmental, and regulatory factors affecting residential construction in New Zealand. The framework will offer significant value to stakeholders by supporting more accurate long-term cost planning, enhancing decision-making in the design, procurement, and maintenance phases, and ultimately fostering more sustainable and resilient residential buildings.

The methodology used to achieve these objectives includes a systematic literature review (SLR) and expert interviews to identify key cost drivers. Additionally, system dynamics (SD) and causal loop diagrams (CLDs) will be applied to integrate the identified factors into the framework and model their relationships across the lifecycle stages.

2. Literature review

2.1 Global perspectives on WLC and its limitations

Whole Life Costing (WLC) evaluates the total cost of a building throughout its entire lifecycle, encompassing acquisition, operational, maintenance, and disposal considerations (Flanagan and Jewell, 2008; ISO, 2017). Its implementation supports sustainable decision-making, shifting the focus from initial capital expenditure to long-term value. However, high upfront capital costs remain a significant barrier to adopting sustainable practices, highlighting the need for integrated frameworks that address these challenges (Nasereddin and Price, 2021). While international standards, such as ISO 15686-5, and guidelines from organisations like the Royal Institution of Chartered Surveyors (RICS) advocate for structured approaches to lifecycle cost assessments, particularly in commercial and infrastructure projects, these models often remain inadequate for residential applications. (RICS, 2016). These frameworks tend to be generic, failing to account for region-specific risks, local construction practices, and socio-behavioural factors (Goh, 2016).

Several countries, including the UK, Germany, and Japan, have developed extensive WLC databases and tools, but these are often tailored to local construction norms and environmental conditions, which may not translate well to other contexts (ESCAP, 2019; USGBC, 2019). For example, the BREEAM, LEED, and Green Star systems primarily focus on environmental performance during the design stage and lack comprehensive long-term financial planning for the building's entire lifecycle (USGBC, 2019). Furthermore, many established frameworks rely on static estimation methods that fail to account for the evolving nature of construction risks, user behaviour, and long-term asset performance (Goh and Sun, 2016), limiting their applicability in regions like New Zealand, where risk profiles are highly dynamic and influenced by frequent seismic events, climate change, and other factors.

The global research gap lies in the lack of frameworks that integrate dynamic environmental factors, real-time data, and context-specific risks into a comprehensive, adaptable lifecycle cost model for residential buildings. Existing models often neglect the specific challenges faced by countries with highly variable climatic and seismic conditions, which results in fragmented and less reliable long-term cost planning for residential projects. There is a clear need for models that consider evolving risks over time and incorporate local factors, such as seismic resilience and material durability, that significantly affect long-term building costs.

2.2 Contextual challenges and system dynamics in New Zealand residential construction

In New Zealand, the WLC application in the residential sector is minimal. The country faces challenges such as frequent seismic activity, diverse climatic conditions, coastal exposure, and evolving compliance frameworks (MBIE, 2013; NIWA, 2022). Although public sector documents like MBIE's Total Cost of Ownership Guide and the Treasury's Whole of Life Costs Guidance promote life cycle thinking, they primarily focus on public infrastructure and are not consistently applied in residential projects (treasury.govt.nz, 2015). This leads to fragmented long-term cost planning. A study by Samarasekara *et al.* (2024) identified 51 interrelated factors affecting WLC estimations, showing that international models often overlook unique conditions in New Zealand's housing sector, including the costs associated with seismic retrofitting. Similarly, BRANZ (Jaques *et al.*, 2015) indicates the economic benefits of sustainable housing, such as reduced maintenance costs, but these insights have not yet led to a cohesive residential-specific WLC framework. Emerging research emphasises the importance of circular economy strategies, promoting material reuse and recycling to enhance resource efficiency and reduce lifecycle costs (Bao, 2023).

Moreover, traditional WLC frameworks used in New Zealand tend to treat lifecycle costs as static estimates, which hinders their ability to respond to changing environmental conditions or user behaviour over time. There is a growing advocacy for the integration of systems thinking through methodologies like System Dynamics (SD), which can capture interdependencies and feedback loops between cost drivers over time (Seetharaman *et al.*, 2017). SD provides an effective tool for modelling complex, time-delayed relationships that are particularly important in risk-prone regions like New Zealand. For example, Wellington’s lifecycle costs must account for seismic resilience, while high-rainfall regions need to factor in enhanced drainage and weatherproofing costs (Hay and Mimura, 2006; Lakshmanan *et al.*, 2008). Similarly, energy efficiency strategies, such as high-performance glazing and passive heating, can reduce long-term energy demand (Lehmann, 2013), while water-saving features lower utility costs (Memon *et al.*, 2015).

Despite these advantages, SD remains underutilised in the WLC field, particularly for residential buildings. While recent studies have begun to explore Causal Loop Diagrams (CLDs) and degree centrality analysis to model interactions and prioritise influential factors (Crielaard *et al.*, 2024; Samarasekara *et al.*, 2024), these methods have not been fully integrated into existing WLC frameworks. This creates a significant gap in the literature, as the ability to model the dynamic, evolving nature of WLC in residential buildings has been largely neglected. Research gaps in the New Zealand context are clearly defined. While traditional WLC frameworks overlook the complexities of regional risk, material durability, and energy efficiency, there is a need for an integrated approach that combines System Dynamics with local environmental factors, enabling stakeholders to make more accurate long-term predictions. This study fills this gap by proposing a tailored WLC framework that addresses the unique needs of New Zealand’s residential construction sector.

The current literature on WLC frameworks for residential construction is fragmented and often inadequate in addressing context-specific challenges, such as regional risk, construction practices, and environmental conditions. Existing frameworks typically fail to integrate dynamic risks over time, relying on static cost estimations that do not account for the evolving nature of construction projects. There is a clear need for models that integrate System Dynamics, circular economy principles, and region-specific variables to provide more accurate long-term cost predictions. This study fills this gap by proposing a tailored WLC framework that addresses the unique needs of New Zealand’s residential construction sector.

3. Methods

This study adopts a qualitative approach to develop a context-specific Whole Life Costing (WLC) framework for residential buildings in New Zealand. It integrates insights from a systematic literature review (SLR) and 22 semi-structured expert interviews to identify and validate critical cost drivers, which were then modelled using system dynamics tools including Causal Loop Diagrams (CLDs) and degree centrality analysis.

3.1 Systematic literature review

An SLR was conducted in accordance with PRISMA guidelines to identify critical factors influencing WLC estimation in residential construction. Peer-reviewed articles, industry reports, and relevant standards were sourced from databases like Scopus, ScienceDirect, and Google Scholar, covering the period from 2000 to 2024.

While academic databases like Scopus and Web of Science are important for finding widely indexed research, publisher platforms such as Emerald Insight and SpringerLink were specifically included in the search strategy. These platforms provide access to a wider range of peer-reviewed articles and often offer full-text access to journals and resources that may not be fully indexed in traditional academic databases. This choice ensures a more complete and inclusive review, capturing both high-impact and specialised studies that are crucial for understanding the details of WLC in residential construction. The decision to utilise these publisher platforms aimed to enhance the review process and ensure a comprehensive representation of the relevant literature.

Initially, an exhaustive search was performed using a set of specific search strings across academic databases and publisher platforms. This yielded a large number of articles, as summarised in Table 1, which presents the search strings, inclusion and exclusion criteria, and the corresponding database used to identify primary research data. To ensure the quality and relevance of the review, we implemented several screening stages to refine the results, including: Title and Abstract Screening: Articles were first assessed based on their titles and abstracts to determine their relevance to the study's focus on WLC in residential construction, and Full-Text Review: For articles that passed the initial screening, full texts were examined to confirm they offered substantial, original content directly related to the research objectives. The PRISMA Flow Diagram in Figure 1 shows the number of records identified, screened, and included at each phase, in accordance with PRISMA guidelines.

The studies included in this review were published between 2020 and 2024 to ensure the relevance and currency of the data in the context of the rapidly evolving construction industry, particularly regarding emerging methodologies and environmental challenges. This timeframe captures the most recent research, ensuring that the findings reflect the latest advancements in WLC methodologies and their application in residential construction. The exclusion of review articles, book reviews, and other forms of publications, such as product reviews and reference work entries, was implemented to maintain focus on original research that offers empirical data, theoretical development, or novel methodologies directly related to the application of WLC in the context of residential buildings. This approach minimises bias from secondary sources and provides a clearer picture of the current state of research in this field. Furthermore, by excluding these types of publications, we aim to enhance the quality of the review by prioritising studies that directly contribute to the development of the WLC framework, thereby ensuring the transparency and replicability of the review process.

Table 1. Search strings and results of the database search for primary research data

Database	Search strings	Inclusions	Exclusions
Scopus	"whole life cost" OR "life cycle cost" AND "construction" AND "framework"	Subject Area – Engineering Language – English Open access From 2000 to 2024	Review Articles
Science Direct	"whole life cost" OR "life cycle cost" AND "construction" AND "framework"	Subject Area – Engineering Language – English Open access From 2000 to 2024	Review Articles Book Review Product Review
Emerald Insight	abstract: "whole life cost" OR (abstract: "life cycle cost") AND (abstract: "construction") AND (abstract: "framework")	Open Access Content Type – Articles From 2000 to 2024	Review Articles
Springer Link	Construction AND framework AND "Whole life cost" OR "life cycle cost"	Discipline – Engineering Subdiscipline – Building Construction and Design Language – English From 2000 to 2024	Reference work entry Reference work
Google Scholar	allintitle: "whole life cost" OR WLC OR "life cycle cost" OR LCC OR LCA AND "construction" AND "framework"	Only in the title	Review Articles

Source(s): Developed by the authors

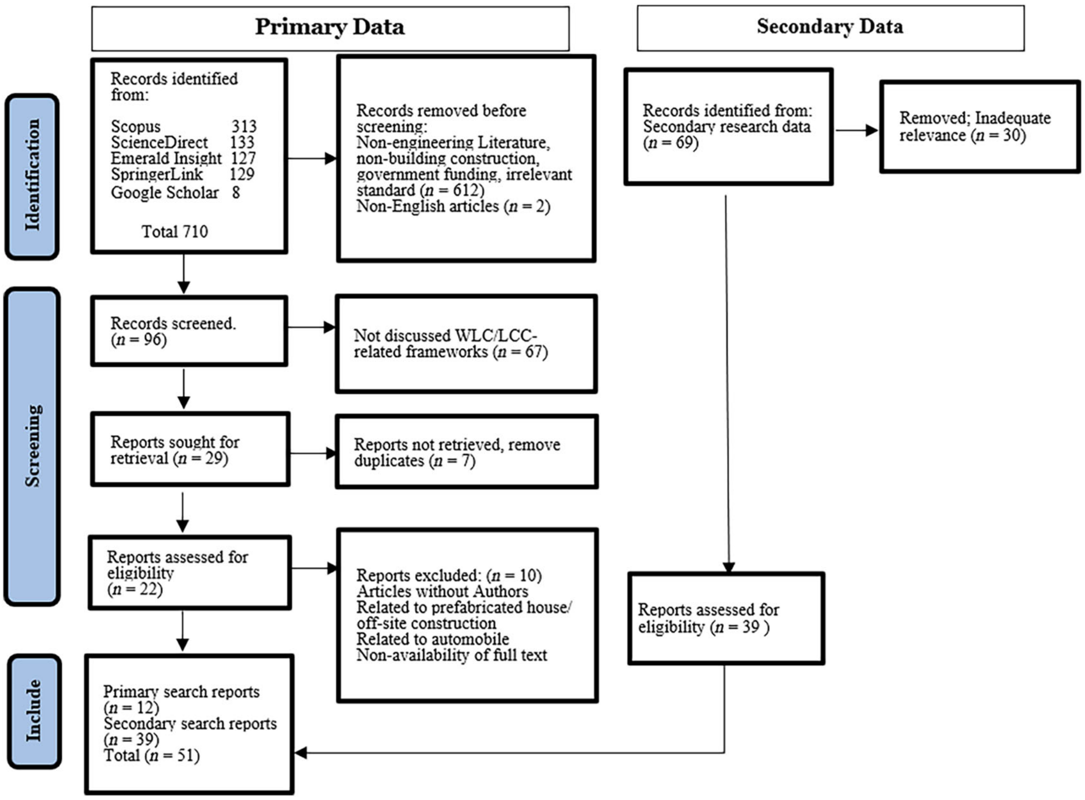


Figure 1. PRISMA flow diagram adapted from PRISMA 2020 statement. Page *et al.* (2021)

The review identified 73 unique influencing factors, categorised into technical, environmental, economic, regulatory, and behavioural domains, providing foundational knowledge for interview design and model development. A literature matrix summarising key contributions from selected studies and how this study builds on or diverges from them has been created and is presented in Appendix 2.

3.2 Semi-structured interviews

To validate the literature-based factor set and gain practical insights, 22 semi-structured interviews were conducted with industry professionals, using an interview guide detailed in Appendix 1. This method was selected for its flexibility in exploring complex topics in depth, enabling clarification of responses and the capture of contextual insights often missed in structured surveys (Kallio *et al.*, 2016). Given the complexity of Whole Life Cost (WLC) factors in New Zealand's residential construction, semi-structured interviews were considered appropriate to ensure robust validation from multiple professional perspectives.

A purposive sampling strategy was employed to recruit participants who represented key stakeholder roles in residential construction, such as quantity surveyors, architects, developers, project managers, engineers, facilities managers, and homeowners (Palinkas *et al.*, 2015). Eligibility requires at least five years of direct professional involvement in residential projects within New Zealand. The principle of thematic saturation guided the sample size; saturation was achieved after approximately 15 interviews, with the remaining seven confirming no substantial new themes. The final sample composition is shown in Table 2. Interviews were conducted online via Microsoft Teams, lasted approximately 30–40 min, and employed open-ended questions covering lifecycle cost components, barriers to WLC adoption, local construction challenges, and feedback on a preliminary factor framework. All interviews were audio recorded with consent, transcribed verbatim, and

Table 2. Demographics of participants in role-wise

Role	No of participants
Government authority	1
Project managers	3
Architects	2
Quantity surveyors	8
Electrical engineers	2
Structural engineer	1
Site manager	1
Facilities managers	2
Homeowners	2

Source(s): Developed by the authors

de-identified to maintain anonymity. Ethical approval was obtained from the Auckland University of Technology Ethics Committee (AUTEC Reference: 24/206).

Recurring themes included the cost burden of seismic retrofitting, the difficulty in accessing long-term cost data, the influence of occupant behaviour on operational costs, the limited use of smart systems, and the gap between capital investment and lifecycle value. Participants emphasised the need for a national framework that integrates lifecycle thinking into residential design and procurement.

3.3 Data analysis

The qualitative data analysis in this study followed Braun and Clarke (2006) six-phase framework for thematic analysis. This approach ensured a systematic and transparent method for coding and developing themes. The process began with familiarisation, during which two researchers read and reread the interview transcripts to understand the content and context thoroughly. This deep dive helped identify preliminary patterns and initial analytical observations.

The next phase involved generating initial codes systematically. Using NVivo qualitative data analysis software, the researchers highlighted relevant features of each transcript and assigned open codes. Both deductive and inductive coding strategies were used. Deductive codes reflected pre-existing categories from the literature review, while inductive codes arose from unexpected issues or new insights during the interviews. In the following phase, the researchers grouped similar codes to form potential themes and explored their relationships to create broader thematic categories. During the fourth phase, the team reviewed, assessed, and refined these candidate themes. This step ensured that each theme was coherent and distinct from the others. The research team held ongoing discussions and conducted multiple reviews of the coded data to resolve any discrepancies or ambiguities in the coding.

Once clear and distinct themes were established, the researchers defined and named each theme. This allowed the team to explain the boundaries and essential qualities of each thematic pattern. The final phase involved creating a detailed report, in which the themes were integrated into the presentation of results and discussion, supported by relevant excerpts from participant interviews. Throughout this process, the team improved reliability through cross-checks among researchers and ensured transparency by carefully documenting coding decisions and theme definitions.

3.4 Development of the WLC hierarchy

The final WLC framework was developed through structured synthesis of evidence from literature, expert interviews, and system dynamics modelling. A five-level hierarchy was created to categorise influencing factors across the lifecycle of residential buildings, serving as both a classification system and the foundation for dynamic modelling. The hierarchy was aligned with the International Construction Measurement Standards (ICMS), which define four levels of cost breakdown (ICMS, 2019):

(1) **Level 1** (Orange): *Whole-Life Cost (WLC)* – representing the total lifecycle cost of the asset.

(2) **Level 2** (Yellow): *Primary Categories* – including non-construction costs, lifecycle costs, income, and externalities.

(3) **Level 3** (Blue): *Subcategories* – acquisition, operational, and end-of-life costs.

(4) **Level 4** (Grey): *Functional Breakdown* – detailing specific project components like site services, utilities, and decommissioning.

To contextualise the framework for New Zealand, a **fifth level** was introduced:

(5) **Level 5** (Green): *Contextual Influencing Factors* – derived from the systematic literature review and expert feedback. This level captures region-specific drivers such as seismicity, regulatory changes, occupant behaviour, energy efficiency, supply chain risks, material resilience, and insurance considerations.

Each level is colour-coded for visual clarity in subsequent modelling diagrams (refer to Section 4.6). The hierarchy provided the structural basis for causal loop diagramming (CLD), enabling the visualisation of feedback mechanisms and interdependencies among lifecycle cost drivers. These insights informed the prioritisation of variables through the degree of centrality analysis, ultimately guiding the design logic of the final WLC framework.

3.5 System dynamics and causal loop modelling

A system dynamics (SD) approach was applied to explore the interrelationships among WLC factors. SD effectively understands non-linear interactions, feedback loops, and time delays in complex systems. Based on the validated factor set, Causal Loop Diagrams (CLDs) were developed to visualise system behaviours and identify feedback patterns. The CLDs illustrated how technical, environmental, and behavioural factors reinforce or balance lifecycle outcomes. For instance, the selection of durable materials positively reinforces lower maintenance costs, while delayed repairs introduce balancing loops through increased degradation and eventual cost spikes. Interviews contributed a nuanced understanding of these interactions, particularly around the long-term effects of seismic planning, energy upgrades, and occupant-led wear and tear.

The polarity of each causal relationship was determined through a combination of evidence from the systematic literature review and validation by semi-structured expert interviews. Positive (+) polarity denotes that the two variables change in the same direction (i.e., an increase in one leads to an increase in the other, or a decrease leads to a decrease). Negative (−) polarity denotes an inverse relationship (i.e., an increase in one leads to a decrease in the other, or vice versa). All polarity assignments were reviewed with domain experts to ensure contextual accuracy for the New Zealand residential construction sector.

3.6 Degree of centrality analysis

To identify the main factors within the Whole Life Costing (WLC) system, we conducted a degree centrality analysis on the directed network formed from the validated causal loop diagrams (CLDs). In this network, each node represents a WLC factor, and each directed link shows a causal influence from one factor to another.

Degree of centrality was calculated in three ways:

(1) Out-Degree Centrality (CD-out) measures the number of direct causal influences a node has on other nodes. High out-degree values suggest potential driver variables that impact many other factors.

(2) In-Degree Centrality (CD-in) measures the number of direct causal influences that a node receives from other nodes. High in-degree values indicate dependent variables that are sensitive to changes in the system.

(3) Total Degree Centrality (CD-total) is the sum of in-degree and out-degree values, showing the overall connectivity of a given node within the network.

The centrality scores were calculated from the binary adjacency matrix of the CLD structure, using an adjacency matrix where each causal connection was coded as a directed edge, following the CLD mapping protocol. We included both reinforcing and balancing loops. The sign of the causal link did not matter in the degree calculations since we focused on structural connectivity rather than polarity.

High out-degree values highlight potential driver variables influencing many others (Borgatti *et al.*, 2024; Freeman, 1978). High in-degree values reveal variables sensitive to external changes (Borgatti *et al.*, 2024; Opsahl *et al.*, 2010). A high total degree indicates systemic importance, capturing overall network embeddedness (Opsahl *et al.*, 2010).

3.7 Framework development

Building upon the established hierarchy, CLD and centrality analysis, a tailored WLC framework has been developed to facilitate lifecycle decision-making within New Zealand's residential construction sector. This framework effectively integrates a five-level hierarchical structure with prioritised cost drivers and feedback pathways identified through rigorous modelling processes. Highly central, high-leverage variables, specifically energy design, seismic strategy, and material durability, are strategically positioned at the framework's core, whilst contextual and outcome-based variables (such as maintenance costs and building performance) extend from these foundational nodes. The framework is meticulously designed to be modular and adaptable, thereby accommodating the diverse needs of a wide range of stakeholders, from early-phase design and procurement to regulatory review and long-term asset management. It promotes lifecycle-conscious decision-making by emphasising variables that yield compounding cost benefits or risks over time. This framework serves as the foundation for the subsequent results and discussion sections, where its application is critically evaluated and refined.

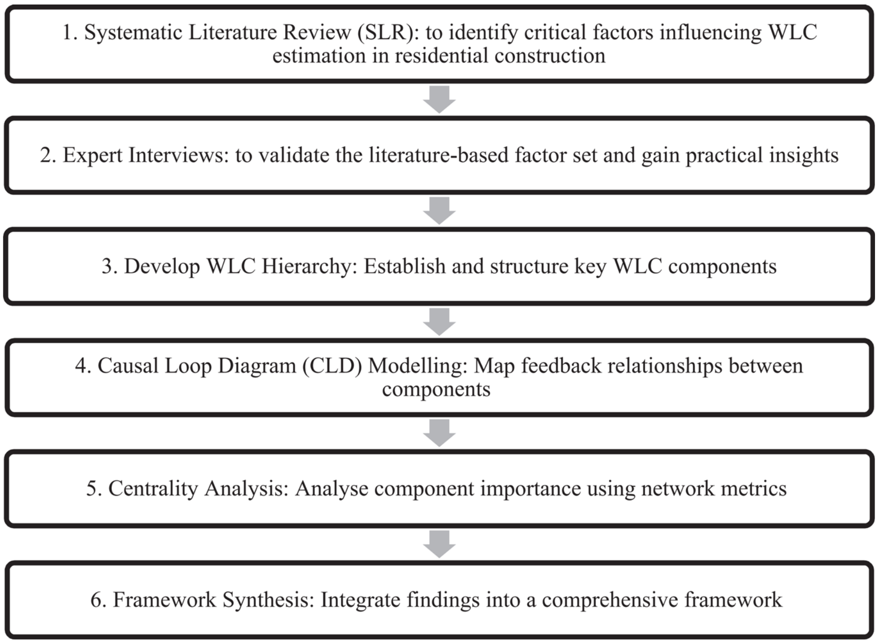
The methodological framework has been summarised in Figure 2.

4. Results

This section presents the study's empirical findings, beginning with insights from industry interviews and summarising the CLD modelling and centrality analysis to prioritise key cost factors. The proposed WLC framework, which integrates interview themes, hierarchical structure, and feedback mapping, is also introduced, with each component described in terms of its relevance supported by figures and tables.

4.1 Geographical representation of WLC and LCC frameworks

Figure 3 illustrates the global distribution of WLC and LCC research, highlighting a predominance in the UK and US, each with six studies, followed by Austria and Denmark with four. Limited contributions from countries like China, Finland, and Italy, and only one article from New Zealand, indicate a significant research gap, particularly for context-specific frameworks in New Zealand's residential sector. This concentration in developed, English-speaking nations reflects challenges in economic capability and governmental support for sustainability.



1. Systematic Literature Review (SLR): to identify critical factors influencing WLC estimation in residential construction

2. Expert Interviews: to validate the literature-based factor set and gain practical insights

3. Develop WLC Hierarchy: Establish and structure key WLC components

4. Causal Loop Diagram (CLD) Modelling: Map feedback relationships between components

5. Centrality Analysis: Analyse component importance using network metrics

6. Framework Synthesis: Integrate findings into a comprehensive framework

Figure 2. Methodology flowchart. Developed by the authors

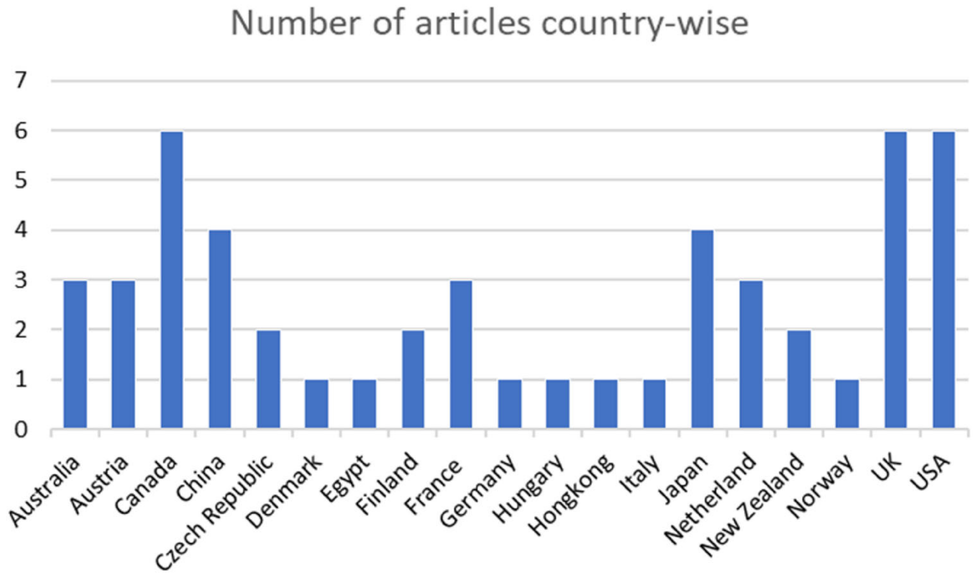


Figure 3. Geographical distribution of reviewed papers. Developed by the authors

4.2 Sectoral focus of existing frameworks

Table 3 shows that LCC frameworks are widely apputilise WLC in public procurement and urban development, most frameworks primarily focus on the commercial and infrastructure sectors, with limitednt, most frameworks focus on commercial and infrastructure sectors, with scarce residential applications. New Zealand notably lacks tailored WLC frameworks for residential buildings, presenting further development opportunities.

4.3 Strengths and weaknesses of existing frameworks

A detailed review of international Life Cycle Costing (LCC) and Whole Life Costing (WLC) frameworks reveals a broad spectrum of strengths and weaknesses that influence their

Table 3. Frameworks and applicable sectors

Framework and applicable sectors	Country																		
	Australia	Austria	Canada	China	Czech Republic	Denmark	Egypt	Finland	France	Germany	Hungary	Hongkong	Italy	Japan	Netherland	NZ	Norway	UK	USA
LCC	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
WLC			x	x										x		x		x	
Number of frameworks associated	3	3	6	4	2	1	1	2	3	1	1	1	1	4	3	2	1	6	6
Residential																			
Commercial							x							x		x		x	
Product-specific tool		x											x	x	x				
Urban development			x				x							x				x	
Public procurement	x	x	x	x	x	x		x	x	x	x		x		x	x		x	x

Source(s): Developed by the authors

applicability across regions and sectors. This variability is particularly pronounced when considering the unique demands of residential construction in high-risk settings, such as New Zealand. Integration of Environmental Metrics – Frameworks from the UK and Denmark successfully incorporate environmental assessments, allowing for more sustainable decision-making processes. These frameworks facilitate the evaluation of environmental impacts, although they may struggle with adaptability in sectors like residential construction.

(1) Incorporation of Climate and Environmental Factors: Frameworks from countries such as the UK, Denmark, and Japan effectively integrate climate-related risks and environmental impact metrics within their costing models. These frameworks embed considerations such as flood mitigation (Abdullah *et al.*, 2025), embodied carbon impacts, and renewable energy systems, offering a more holistic assessment that aligns economic costs with sustainability objectives (UKSI, 2015). For example, Denmark's framework emphasises procurement environmental impacts (Rolfstam and Petersen, 2014), while Japan's models robustly address seismic risks and resilience measures (Akiyama *et al.*, 2020). Such integration is vital for New Zealand, which faces both seismic hazards and climate variability.

(2) User Accessibility and Practical Tools: Robust spreadsheet-based tools and transparent calculation methodologies are characteristic of frameworks from Australia (QTC, 2019), New Zealand (MBIE, 2013), and the USA (ASCE and ENO, 2014). The use of hierarchical cost coding and detailed breakdowns, often following International Construction Measurement Standards (ICMS, 2019), facilitates ease of use among practitioners, including quantity surveyors and project managers, fostering practical uptake. The availability of user-friendly tools, such as Excel templates and modules linked to software like CostX and BIM platforms, reduces barriers to adoption (Purushothaman and Aguas, 2025), enabling smaller firms and non-experts to engage meaningfully with WLC.

(3) Focus on Resilience and Risk: Certain frameworks have advanced the integration of risk-based variables, including seismic strengthening, wind bracing, and flood resilience. This is particularly evident in Japan's and some US models, which set a precedent for embedding risk mitigation costs and insurance implications directly into lifecycle assessments (ASCE and ENO, 2014; Minami, 2003). Such focus is crucial for New Zealand's residential sector, where insurance premiums and retrofit expenses can be significant contributors to total costs.

(4) Structured and Hierarchical Modelling: The adoption of tiered frameworks with hierarchical levels extending from acquisition through operational to end-of-life costs improves transparency and enables detailed scenario analysis (RICS, 2016). Additionally, frameworks incorporating metadata for local factors, such as geographic risk profiles, promote more accurate and tailored cost estimation.

The strengths of these frameworks, summarised in Table 4, demonstrate considerable progress in integrating key environmental and sustainability considerations.

However, alongside these strengths, significant limitations exist across the frameworks, as detailed in Table 5. The main weaknesses are;

(1) Lack of National Standardisation and Consistency: A pervasive issue across many countries, including New Zealand, Australia, and several European and Asian nations, is the absence of unified, nationally recognised methodologies. This fragmentation hinders consistent application and undermines the comparability and credibility of lifecycle cost assessments, leading to disparate industry practices and missed opportunities for economies of scale in data collection and knowledge sharing (Liu *et al.*, 2023).

Table 4. Strengths of the LCC and WLC framework country-wise

Strengths	Australia	Austria	Canada	China	Czech Republic	Denmark	Egypt	Finland	France	Germany	Hungary	Hongkong	Italy	Japan	Netherland	NZ	Norway	UK	USA
Climate change weight					x														
Economic sustainability analysis													x						
Procurement environmental impacts			x										x	x	x				
Infrastructure energy use														x	x				
Flood and storm barriers													x		x				
Energy efficiency, water conservation																			x
Simple calculations										x	x						x		
Environment-material impact database															x			x	
Inflation and discount rate																x		x	
Specific database to compare LCC/WLC																		x	
Project documentation defined																		x	
Budget planning and compliance														x					
Early design decision information																		x	
Spreadsheets available										x	x				x	x			
Easy maintenance, minimal investment										x	x								
Calculation steps are visible																		x	
Hierarchical levels and a unique coding																		x	
Pact on scope and assumptions			x																
Investigating complex issues														x					
Alternatives comparison	x																		
Adverse weather			*x*	*x*							*x*						*x*	*x*	*x*
Seismicity														*x*					*x*

Source(s): Developed by the authors

Table 5. Weakness of LCC and WLC framework country-wise

Weakness	Australia	Austria	Canada	China	Czech Republic	Denmark	Egypt	Finland	France	Germany	Hungary	Hongkong	Italy	Japan	Netherland	NZ	Norway	UK	USA
Includes acquisition cost and income	x																		
Use a series of assumptions		x	x																
Extensive data												x							
Dependence on stakeholders' knowledge			x																
Limited to complex projects	x									x	x					x			
Excludes externalities		x								x	x					x	x		
Site-specificness and local impacts are ignored												x							
Excludes operation, disposal, and residual value																x			
Requires LCC parameter knowledge															x	x			x
Not user-friendly													x					x	
Higher setup and maintenance costs															x				
Significant investment for replication					x								x						
Little public sector incentive																			x
Insufficient published details						x													
There is no national methodology or database	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x		x
Lack of transparency and knowledge																			x
Lack of data or information													x		x	x			x

Source(s): Developed by the authors

(2) Limited Focus on Residential Sector and Local Context: While many frameworks are tailored or primarily designed for commercial infrastructure projects (DGNB, 2022; EU, 2019; ÖBB, 2005), few provide comprehensive, adaptable tools for the residential sector. This gap is pronounced in New Zealand, where unique seismic vulnerabilities, diverse climatic zones, and local market conditions demand specialised modelling approaches. Existing models rarely account adequately for factors such as localised hazard probabilities, region-specific material performance, or the socio-economic dynamics of residential construction.

(3) Inadequate Data Quality and Availability: Many frameworks rely heavily on assumptions or sparse, regionally disaggregated data, weakening the fidelity of lifecycle cost predictions (ASTM, 2020). This limitation is compounded by reliance on expert judgement and often excludes critical cost drivers such as long-term material degradation, maintenance variability, and evolving regulatory requirements (Goh and Sun, 2016). The lack of comprehensive databases hinders model calibration and validation, making it challenging for practitioners to deliver reliable estimates.

(4) Omission of Certain Lifecycle Phases and Externalities: Frequent exclusion of secondary costs such as disposal, residual value, insurance, and social externalities, including health impacts and community displacement, results in partial lifecycle analyses. This narrow scope diminishes the effectiveness of WLC as a holistic decision support tool, particularly when evaluating sustainability and social cost dimensions (Gov.au, 2021).

(5) Usability Challenges and Resource Intensity: Some frameworks impose high setup and maintenance burdens through complex data requirements, sophisticated software integration, or costly implementation (CACQS, 2016; Gov.ca, 2012). These factors disproportionately discourage adoption among small to medium-sized enterprises and owner-builders, who constitute a significant portion of New Zealand's residential construction market (OECD, 2022).

(6) Limited Integration with Emerging Technologies and Incentive Mechanisms: Although tools like BIM and Green Star are gaining traction (Lim *et al.*, 2025), their integration with WLC remains inconsistent. Furthermore, the scarcity of financial incentives or regulatory mandates linking WLC adoption to project approvals or funding constrains market-driven uptake, highlighting the need for policy support mechanisms (USGBC, 2021).

4.4 How the proposed framework addressess identified weaknesses

Building on the identified weaknesses detailed in the previous section, this section explains how the proposed system dynamics-based Whole Life Costing (WLC) framework addresses these critical gaps and enhances lifecycle cost assessment for New Zealand's residential construction sector.

A key issue highlighted was the absence of a nationally standardised methodology, which leads to fragmented practices and undermines consistency and comparability across projects. The proposed framework directly addresses this by offering a unified, structured approach specifically tailored for New Zealand, developed through rigorous empirical research that combines a broad systematic review with extensive consultation of local industry experts. By aligning with international classification systems such as the International Construction Measurement Standards (ICMS), while adding a dedicated fifth level to reflect unique regional factors, the framework facilitates consistent application and benchmarking at a national scale. Furthermore, the envisioned national database for WLC data, including material performance, cost drivers, and risk profiles, intends to foster data harmonisation and knowledge sharing, enabling repeated refinement and greater transparency. This centralised resource is projected to reduce duplication of effort and unlock economies of scale in data collection, reinforcing coherence across the industry.

The framework also overcomes the common shortcoming of inadequate focus on the residential sector and local contextualisation. Many existing models focus on commercial or infrastructure projects and lack relevance to the distinct characteristics of New Zealand's residential construction environment, which is influenced by high seismic risks, varied climate zones, and nuanced market conditions. Drawing on a comprehensive set of 73 validated cost drivers, the framework explicitly incorporates metrics such as seismic resilience, localised hazard probabilities, material durability in diverse climates, and socio-economic impacts. By embedding these factors into the hierarchical structure and dynamic modelling tools, the framework equips stakeholders to capture the complexities and specificities of residential projects, enabling more reliable and context-sensitive lifecycle cost predictions.

Data quality and availability have been pervasive challenges in existing approaches, often relying on sparse datasets, assumptions, or expert judgement without sufficient empirical grounding. This vulnerability is mitigated through the methodical integration of expert insights obtained from industry professionals across disciplines, alongside thorough literature synthesis. The use of system dynamics facilitates modelling feedback loops and delay effects that traditional static models overlook, enhancing robustness in simulating cost trajectories over time. Moreover, the framework advocates for establishing well-maintained, accessible databases that capture regional cost patterns, material degradation rates, and evolving regulatory requirements. These steps are crucial for enabling accurate calibration, validation, and continuous updating of the model parameters, thereby enhancing confidence and practical applicability.

The omission of essential lifecycle phases and externalities in many models diminishes their holistic value as decision-making tools. In contrast, the presented framework broadens the scope to include end-of-life costs such as disposal, residual values, and insurance considerations, as well as social and environmental externalities covering community displacement, public health impacts, and broader societal costs. Incorporating these dimensions enables a for a more comprehensive assessment of sustainability and resilience outcomes, aligning financial analysis with broader policy and community priorities. This is achieved through the multi-level hierarchical classification and feedback-rich causal loop diagrams, which capture complex interdependencies and trade-offs often excluded in simpler models.

Usability concerns and resource intensity, particularly for small and medium enterprises and owner-builders, are directly addressed by designing adaptable model complexity tiers. The framework supports scaled implementation from full-featured BIM-integrated applications suitable for large projects to streamlined, spreadsheet or web-based tools tailored for less-resourced users. Coupled with training initiatives and template provision via government or industry bodies, this accessibility strategy lowers barriers to adoption and democratises advanced lifecycle costing methods. The modular design and clear codification enable users to focus on critical factors, such as material resilience and regulatory compliance, without overwhelming data demands, thereby balancing usability with modelling fidelity.

Finally, to surmount limited integration with emerging technologies and insufficient policy incentives, the framework explicitly promotes embedding WLC workflows within widely utilised digital platforms like BIM and cost estimation software (e.g., CostX), with configurable attributes capturing location-specific and risk-related parameters. Furthermore, it supports linkage to certification systems such as Green Star and advocates for policy mechanisms to mandate or incentivise WLC submissions, especially for developments in high-risk zones. These strides aim to catalyse market uptake through greater visibility, standardisation, and alignment with regulatory compliance, fostering a culture of informed, sustainable investment decisions.

Collectively, these measures ensure that the proposed framework remedies the principal weaknesses of prior WLC models by delivering an empirically grounded, nationally standardised, context-aware, inclusive, user-friendly, and technologically integrated solution tailored to the evolving needs of New Zealand’s residential construction industry. The framework thus lays a foundation for elevating the quality, consistency, and impact of lifecycle cost assessments in pursuit of resilient, sustainable housing outcomes.

4.5 Findings from semi-structured interviews

Semi-structured interviews with 22 industry professionals revealed significant gaps in WLC adoption and offered critical insights into the sector’s current practices, challenges, and improvement needs. Respondents included quantity surveyors, project managers, architects, engineers, and facility managers. While many recognised WLC’s theoretical benefits, most admitted its application in residential projects remains limited and informal.

4.5.1 Adoption and awareness of WLC in residential construction. Most participants reported that WLC is seldom applied in residential projects, which tend to prioritise upfront costs. While WLC is more commonly integrated with commercial and infrastructure projects, residential developments rely heavily on basic cost tools like spreadsheets or quotes. Tools such as Green Star and CostX are occasionally used, but their application to comprehensive lifecycle analysis remains inconsistent.

4.5.2 Variation in WLC tools and methodologies. Interviewees described a fragmented tool landscape. Some quantity surveyors use digital tools like CostX and Primavera in large-scale projects, while residential projects depend on manual estimates or basic software. This inconsistency reflects the absence of a standardised, universally accepted WLC framework for the sector.

4.5.3 Challenges and limitations of existing WLC frameworks. As summarised in Table 6, respondents cited several recurring limitations: lack of standardisation, informal spreadsheet-based methods, narrow cost scopes, and minimal integration with BIM or other digital tools. Quantity surveyors particularly emphasised the omission of key cost elements like insurance, operational, and financing expenses, as well as poor technological integration.

4.5.4 Variations in WLC practices: key insights by profession. Interview data highlighted how regional factors such as seismicity, coastal exposure, and remoteness significantly affect lifecycle costs in Table 7. High-risk areas demand resilient design, increasing both upfront and long-term expenditures. Urban projects benefit from economies of scale, whereas rural developments face higher logistics and labour costs. Sectoral differences also shape WLC adoption; commercial and infrastructure sectors lead implementation due to higher regulatory and financial scrutiny, while residential projects lag due to low awareness and perceived affordability issues.

Each profession approaches WLC differently, shaped by their responsibilities and industry focus. Project Managers prioritise risk management and compliance, considering WLC necessary in high-risk, legally mandated projects. Architects focus on sustainable design and material efficiency, supporting WLC in theory, but acknowledge the slow adoption in residential projects. Quantity Surveyors analyse cost structures and market feasibility, balancing financial viability with long-term cost benefits. Facility managers view WLC as critical for reducing long-term maintenance costs, while electrical engineers and inspectors emphasise its importance in enhancing energy efficiency and supporting infrastructure investments. Site managers and supervisors face practical implementation challenges, arguing that contractors prioritise immediate costs over long-term efficiency. Finally, Homeowners largely ignore WLC due to upfront affordability concerns unless required by regulations or financial incentives.

While all professions recognise WLC’s potential benefits, key differences in priorities create barriers to adoption. Moving forward, financial incentives, standardised cost estimation tools, and regulatory support will be essential for expanding WLC adoption across all sectors.

Table 6. Key challenges and limitations of existing WLC frameworks

Challenges/limitations	GA	PM1	PM2	PM3	SM	A1	A2	SS	QS1	QS2	QS3	QS4	QS5	QS6	QS7
No standardised WLC approach/no unified methodology												✓	✓	✓	✓
WLC frameworks not used in residential projects	✓				✓										
Frameworks are informal or Excel-based				✓								✓			
Limited scope – focus mainly on costs, missing risk analysis							✓						✓		✓
Lack of integration with tools like BIM										✓					
Narrow cost components – missing financing/insurance/operation										✓	✓				

Source(s): Developed by the authors

Table 7. Regional and sectoral variations in WLC adoption

Variations in WLC practices	GA	PM 1	PM 2	PM3	SM	A1	A2	EE	EI	FM1	FM2	HO1	HO2	SS	QS 1	QS 2	QS 3	QS 4	QS 5	QS 6	QS 7	QS 8
Regional differences																						
Differences by project type	✓	✓	✓											✓			✓		✓			
High seismicity areas have stricter costs				✓	✓							✓								✓		✓
Climate impacts long-term costs						✓	✓	✓	✓								✓					
Insurance rates influence cost planning	✓		✓		✓			✓					✓						✓			
Some clients consider WLC; others ignore it				✓		✓			✓	✓				✓							✓	
Variations due to seismic risks, climate, and local standards	✓	✓			✓							✓						✓				
Local material costs affect decisions										✓	✓			✓	✓					✓		
High-risk areas factor in resilience costs	✓	✓											✓			✓						✓
Energy pricing and climate impact cost planning			✓		✓			✓									✓		✓			
Practices vary between urban and rural areas						✓	✓											✓			✓	
Sectorial differences																						
High-seismic regions require extra reinforcements; coastal areas need corrosion-resistant materials										✓	✓			✓						✓		
Green certifications gaining traction		✓										✓		✓						✓		✓
Lifecycle tracking interest is increasing	✓		✓						✓									✓				✓
Commercial projects leading WLC innovation			✓		✓																	✓

Source(s): Developed by the authors

4.5.5 Recent developments in WLC frameworks. Participants reported increased emphasis on sustainability and risk integration within newer WLC models. While Green Star and BIM tools are gaining traction in Table 8, adoption remains patchy. Despite regulatory shifts and growing interest in climate resilience, a unified approach to WLC is still lacking across the industry.

4.5.6 Improvements needed in WLC frameworks. Table 9 captures recommended improvements: better material evaluation, stronger integration with compliance and planning processes, improved data forecasting, and regional risk modelling. Participants advocated for more regulatory support, digital tool adoption, and standardised frameworks. They also noted the lack of NZ-specific cost data, limiting accurate estimations. While some called for government-led initiatives, others suggested voluntary industry reform supported by financial incentives.

4.5.7 The necessity of integrating seismicity and adverse weather in WLC frameworks. A majority of participants supported the integration of seismic and climatic risks into WLC frameworks (refer to Figure 4). These risks significantly impact lifecycle costs in New Zealand. Participants highlighted the need for regionally tailored cost models and better quantification of the long-term value of resilient materials. However, implementation remains a challenge due to limited modelling tools and affordability concerns in smaller projects.

4.5.8 Strategies for incorporating seismicity and adverse weather in WLC frameworks. As shown in Table 10, professionals proposed diverse strategies: mandating risk-based assessments, developing region-specific models, integrating predictive technologies, and incentivising resilient construction. Improved data collection and public awareness were also deemed essential. While opinions differed on the best implementation pathway, a consensus emerged on collaboration among government, industry, and end-users to mainstream WLC in high-risk environments.

4.6 Hierarchical representation of WLC factors

The five-level hierarchical model developed in Section 3.3 methods was applied to classify and visualise key cost components affecting residential building lifecycle outcomes (refer to Figure 5). This structure integrates global best practices via (ICMS, 2019) Levels 1–4 with New Zealand-specific variables at Level 5 identified by this research. It serves as a foundation for identifying feedback loops and centrality-driven priorities. This visual representation illustrates how high-level cost categories are broken down into subcategories and functional tasks, while contextual variables at Level 5 shape dynamic outcomes such as maintenance, insurance, and depreciation. This hierarchy is critical in framing the system dynamics model and informing the final framework design (presented in Table 13).

4.7 System dynamics modelling of WLC influencing factors

To capture the complex interdependencies among WLC factors in New Zealand's residential sector, this study uses a systems thinking approach with Causal Loop Diagrams (CLDs). Existing frameworks like ICMS offer structured cost classifications but often overlook regional challenges such as seismic risks, extreme weather, and evolving regulations. Traditional WLC models isolate cost categories, ignoring early-stage decisions' effects on downstream outcomes. The five-level hierarchy from Section 4.6 serves as a foundation for the CLD, identifying key cost drivers across acquisition, construction, operation, and end-of-life phases, while incorporating unique contextual variables for New Zealand. The CLD maps dynamic feedback relationships among these variables.

This method reveals reinforcing and balancing loops that explain how changes in one factor can amplify or counteract effects in others. This feedback perspective provides a more realistic understanding of lifecycle cost behaviour than linear models. Subsequent subsections present the developed CLD (Figure 5), describe key feedback loops, and show how these insights informed factor prioritisation through centrality analysis.

Table 8. Recent developments in WLC frameworks

Recent developments	GA	PM 1	PM 2	PM3	SM	A1	A2	EE	EI	FM1	FM2	HO1	HO2	SS	QS 1	QS 2	QS 3	QS 4	QS 5	QS 6	QS 7	QS 8
Focus on sustainability and resilience	✓	✓	✓		✓			✓				✓	✓						✓			
Compliance and regulatory changes	✓		✓		✓				✓				✓					✓				✓
Green star as a reference, but limited use		✓										✓		✓								✓
Limited industry-wide improvements			✓			✓	✓								✓					✓		
Integration of sustainability metrics and digital modelling for cost predictions			✓			✓		✓						✓				✓				
Custom modules for regional factors	✓			✓				✓											✓			
Risk assessment and climate data integration	✓	✓	✓		✓			✓	✓							✓						✓
No major initiatives observed				✓					✓	✓				✓								
Interest in AI and data analytics for cost predictions	✓	✓	✓									✓		✓								
AI-driven maintenance prediction models and sustainability tools			✓						✓	✓	✓											
Inclusion in building regulations	✓				✓			✓					✓									✓
More NZ-specific data is needed					✓			✓					✓	✓				✓				

(*continued*)

Table 8. Continued

Recent developments	GA	PM 1	PM 2	PM3	SM	A1	A2	EE	EI	FM1	FM2	HO1	HO2	SS	QS 1	QS 2	QS 3	QS 4	QS 5	QS 6	QS 7	QS 8
Better climate adaptation models	✓		✓				✓					✓										✓
Seismicity and weather resilience integration		✓	✓					✓	✓					✓						✓		
More risk modelling required			✓		✓								✓	✓							✓	
Focus on sustainability and resilience	✓	✓	✓		✓			✓				✓	✓						✓			
Compliance and regulatory changes	✓		✓		✓				✓				✓					✓				✓

Source(s): Developed by the authors

Table 9. Recommended improvements to WLC frameworks

Recommended improvements	GA	PM 1	PM 2	PM3	SM	A1	A2	EE	EI	FM1	FM2	HO1	HO2	SS	QS 1	QS 2	QS 3	QS 4	QS 5	QS 6	QS 7	QS 8
Better material evaluation methods	✓		✓			✓		✓					✓					✓				
More emphasis on compliance costs		✓						✓				✓		✓								
Stronger integration in project planning	✓	✓	✓		✓			✓	✓							✓						✓
Education and advocacy for WLC adoption				✓					✓	✓				✓								
Improvements in data integration and forecasting models	✓	✓	✓			✓		✓						✓				✓				
Regional climate-based modules	✓			✓				✓											✓			
Enhanced regulatory integration	✓	✓	✓		✓			✓	✓							✓						✓
Awareness and standardised software tools				✓					✓	✓				✓								
Better incorporation of geographical risks	✓		✓				✓					✓										✓
More real-time data integration and predictive models		✓					✓					✓				✓						
Climate change adaptation in WLC frameworks	✓		✓				✓					✓										✓
Integration of climate risk and resilience models		✓	✓					✓	✓					✓						✓		
Use of dynamic cost modelling and risk assessment			✓		✓								✓	✓							✓	

Source(s): Developed by the authors

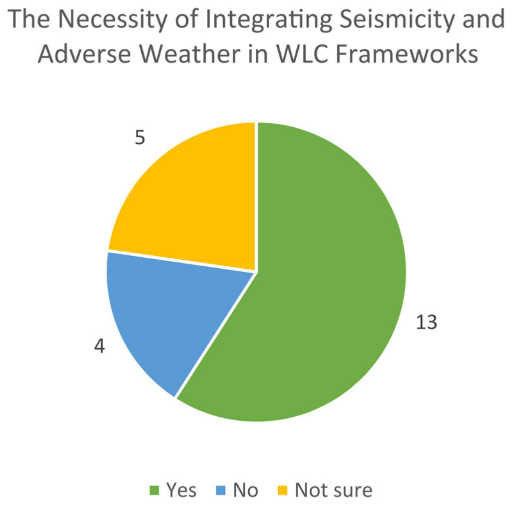


Figure 4. Responses to the inclusion of seismicity and adverse weather factors. Developed by the authors

4.7.1 CLD and loops analyses. With the WLC hierarchy established in Figure 5, the next step is to understand the dynamic interactions over time. A CLD was developed to capture reinforcing and balancing feedback loops influencing long-term cost behaviour in residential projects. This systems-based lens illustrates circular causality, where a change in one variable impacts others and generates feedback that reinforces or counteracts the original change. This insight is vital for accurate WLC estimation and effective decision-making in New Zealand's complex construction environment.

Feedback Polarities and Visual Conventions.

In the CLD:

(1) Positive relationships are shown with blue arrows and a (+) symbol, indicating that a change in one variable leads to a change in the same direction in the connected variable (e.g., increased energy-efficient investment lowers operational costs).

(2) Negative relationships are indicated with red arrows and a (−) symbol, reflecting inverse relationships (e.g., higher upfront costs may reduce long-term maintenance needs).

These conventions help distinguish between reinforcing loops, which amplify changes, and balancing loops, which stabilise the system.

Figure 6 illustrates the dynamic interactions among various variables stemming from the WLC factor hierarchy, highlighting reinforcing and balancing loops. Sixteen reinforcing loops and five balancing loops were identified through qualitative mapping. These loops include material selection, design efficiency, and regulatory compliance.

4.7.2 Degree of centrality and influential factors. A comprehensive centrality analysis was conducted to enhance prioritisation within the proposed WLC framework, grounded in the causal relationships delineated in the CLD and corresponding feedback loops. Each factor was conceptualised as a node, with the directional influences extracted from the CLD structure employed to compute the out-degree, in-degree, and total degree centrality values. This quantitative analysis elucidates which factors exhibit the highest influence (characterised by elevated out-degree), are most susceptible to external influences (indicated by high in-degree), or are systemically essential (denoted by high total degree). Such insights serve to augment the qualitative loop analysis by pinpointing leverage points and response variables within the WLC system. Table 12 articulates the ranked centrality scores for all salient WLC factors.

These results comprehensively understand the structural and dynamic relationships among WLC factors. The Top 10 Whole Life Cost (WLC) Factors by Total Centrality Score are

Table 10. Strategies for incorporating seismicity and adverse weather in WLC frameworks

Strategies	GA	PM 1	PM 2	PM3	SM	A1	A2	EE	EI	FM1	FM2	HO1	HO2	SS	QS 1	QS 2	QS 3	QS 4	QS 5	QS 6	QS 7	QS 8
Develop region-specific WLC models	✓	✓	✓	✓		✓	✓			✓	✓					✓				✓		
Mandate risk-based cost assessments in regulations	✓		✓	✓	✓				✓				✓					✓				✓
Enhance material and design standards for resilience	✓	✓		✓	✓	✓		✓		✓	✓			✓			✓					
Use predictive maintenance and AI-driven risk models		✓	✓				✓	✓	✓													
Improve data collection on climate and seismic risks	✓			✓				✓					✓	✓			✓					✓
Integrate climate resilience costs into project planning and management		✓	✓			✓				✓				✓					✓			
Expand financial incentives for resilient construction			✓			✓			✓	✓								✓				
Adopt lifecycle tracking for high-risk zones	✓		✓		✓		✓	✓	✓		✓				✓				✓	✓		
Increase WLC awareness among stakeholders	✓	✓		✓						✓		✓	✓	✓							✓	

Source(s): Developed by the authors

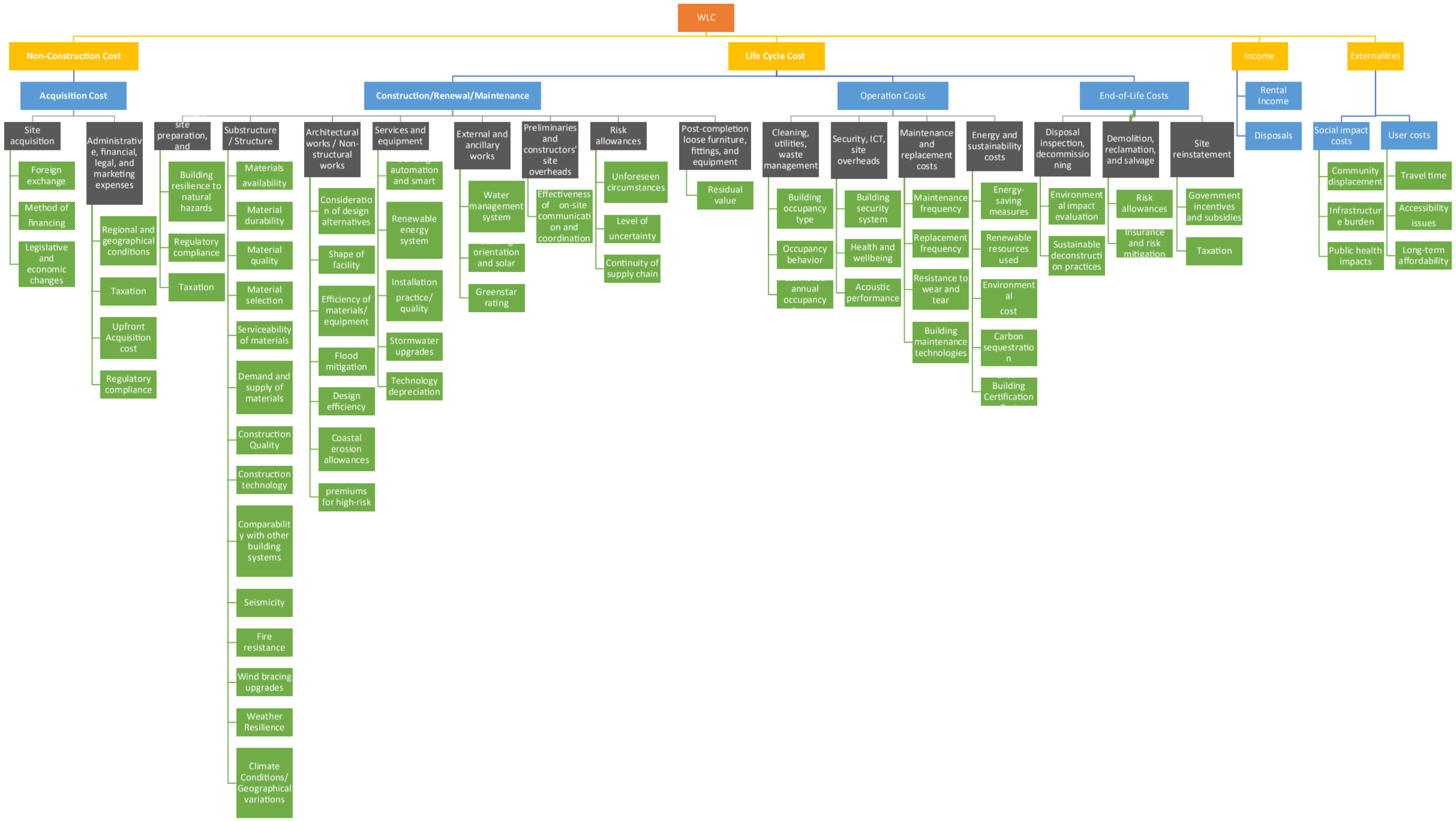


Figure 5. The five-level WLC hierarchy. Developed by the authors

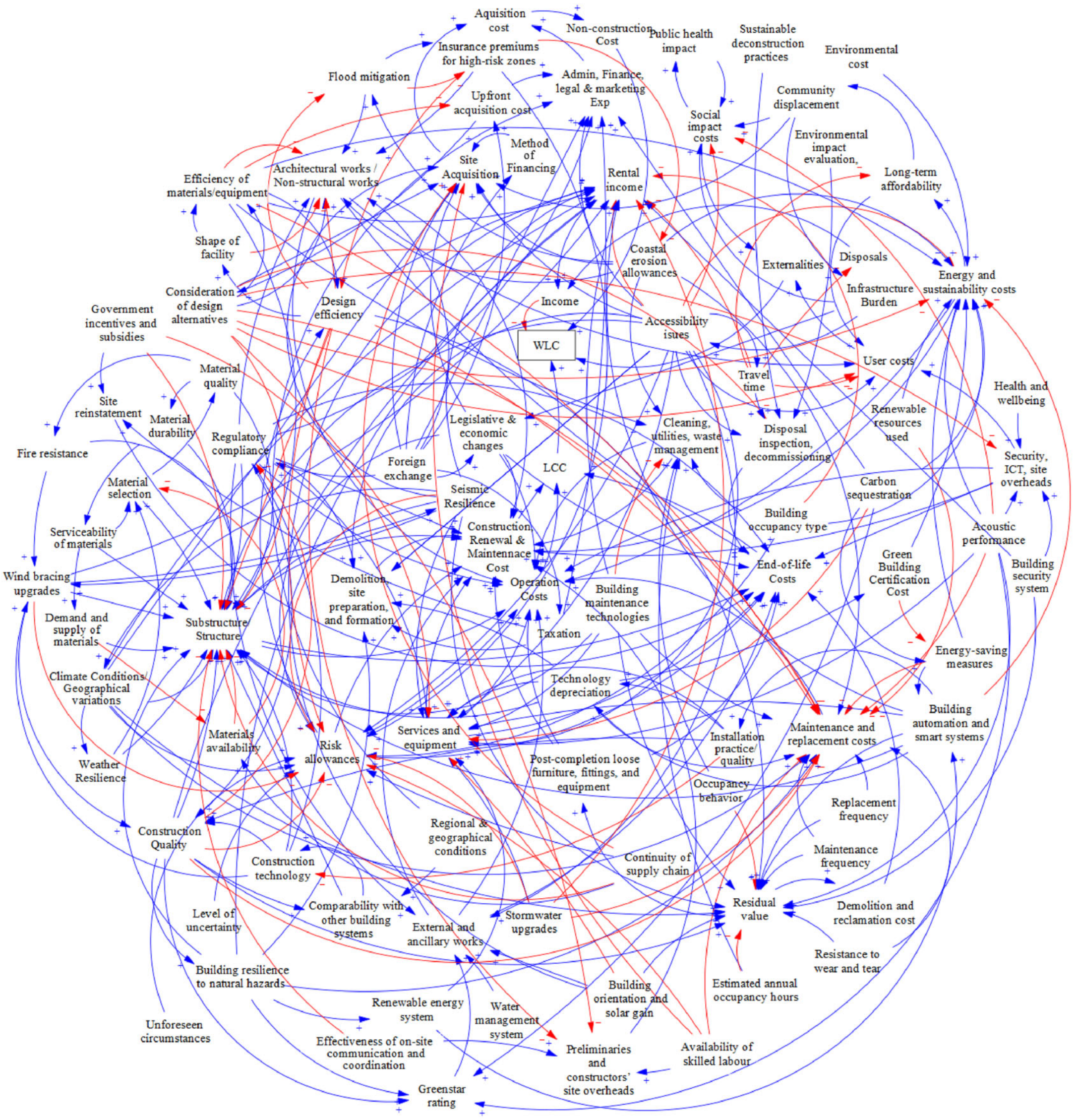


Figure 6. Causal loop diagramme. Developed by the authors

presented in Figure 7 highlighting the most influential variables within the system dynamics model. The following section discusses the implications of these findings, interpreting how feedback mechanisms and centrality patterns influence long-term cost performance and inform the design of a context-specific WLC framework for New Zealand.

5. Discussion

This section interprets the findings in relation to the study objectives and broader WLC discourse, highlighting implications, limitations, and future development directions.

5.1 Insights from the literature review

The literature indicates a lack of geographically tailored WLC frameworks for residential construction in New Zealand. While international standards like ISO 15686 and ICMS are widely adopted, they often generalise conditions and neglect region-specific factors such as seismicity, climatic variability, and compliance differences. Section 4.1 shows that most WLC research comes from the UK and USA, highlighting the need for frameworks that address local

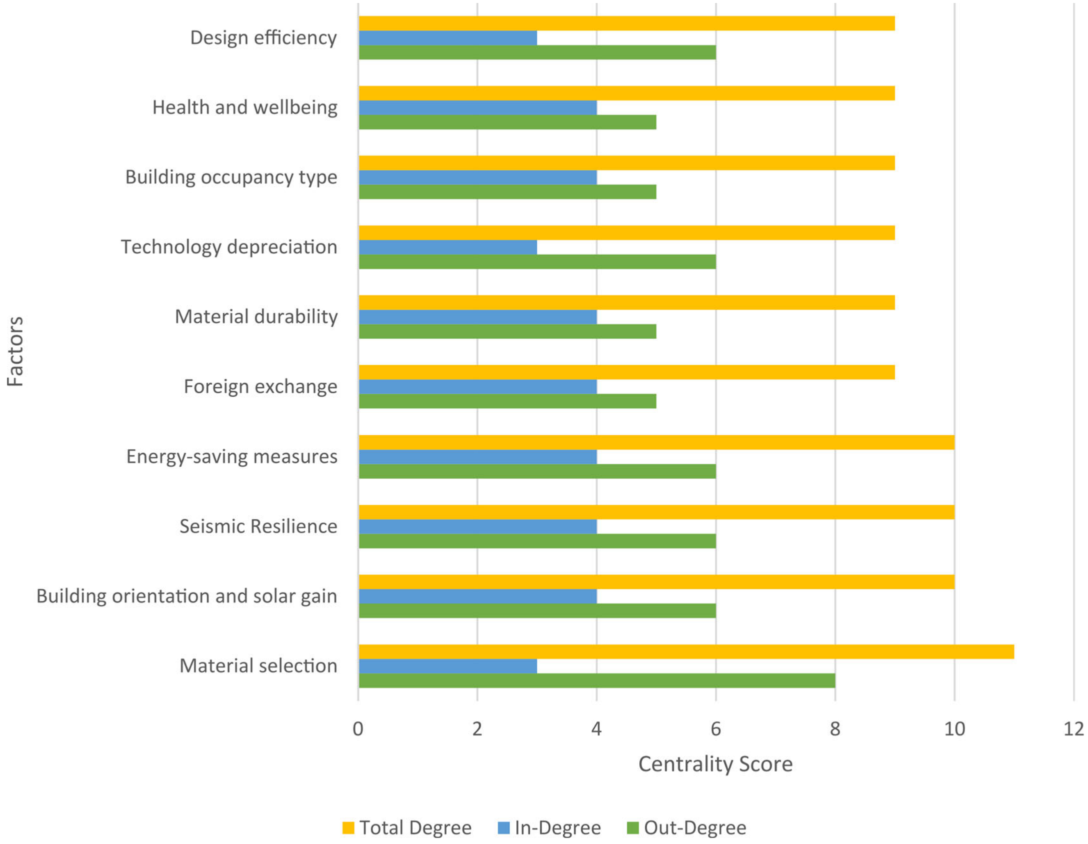


Figure 7. Top 10 WLC factors by total centrality score. Developed by the authors

construction practices and risks. Many current frameworks focus on commercial and infrastructure projects, offering limited relevance for residential developments and often exclude vital factors like long-term energy performance, occupant behaviour, and environmental externalities. This omission detracts from financial planning and the sustainability of housing developments. Countries like Japan and the Netherlands have incorporated seismic and weather risks, while New Zealand's frameworks remain basic. Learning from these nations emphasises the need to integrate durability, sustainability, and regulatory compliance into lifecycle models. Addressing this gap is essential for New Zealand's economic and environmental resilience.

5.2 Expert insights and framework structuring

The semi-structured interviews confirmed literature-based gaps and added practical depth. Industry professionals stressed that current WLC tools are inconsistent, often limited to cost spreadsheets without integration of long-term planning, risk assessment, or digital technologies. Interviewees also noted a lack of alignment between construction decisions and lifecycle outcomes, particularly in residential projects. Key priorities included standardisation, regional risk modelling, better integration of smart systems and material durability. For instance, seismic resilience and compliance were repeatedly flagged as major cost drivers, often omitted in typical models. Regulatory volatility and insurance premiums were also cited as long-term concerns. These themes directly informed the structure of the proposed WLC framework, ensuring its practical relevance and alignment with professional expectations. Refer back to Tables 5–9 from section 4.5 for supportive evidence.

5.3 Interpreting system feedback and centrality prioritisation

This section synthesises the system dynamics findings presented in Section 4.7, focussing on their broader implications for WLC prioritisation in New Zealand's residential construction sector. The feedback loops detailed in Table 11 demonstrate how key WLC variables interact over time. These loops highlight the reinforcing or balancing effects of material durability, seismic resilience, design efficiency, and smart system integration. Instead of repeating those narratives, this section draws attention to the overarching insight: that early-stage design and technology choices significantly influence downstream lifecycle outcomes. For example, investment in resilient materials or flood mitigation measures not only reduces long-term maintenance and insurance costs but also creates positive feedback that enhances building quality and cost predictability.

The centrality analysis executed in this investigation constitutes a pivotal network-based methodology for the identification of the most structurally embedded factors within the WLC system. By scrutinising the direction and density of connections derived from the CLD, this approach quantifies the systemic role of each factor across three dimensions:

(1) Out-degree centrality quantifies the number of other factors influenced by a variable, thereby revealing its potential as a driver or leverage point within the system.

(2) In-degree centrality assesses the number of factors that exert influence upon a given variable, thus indicating its sensitivity to upstream decisions.

(3) Total degree centrality amalgamates both metrics, reflecting a factor's overarching significance within the WLC structure.

This quantitative dimension complements the qualitative insights gained from the feedback loop analysis, elucidating the relative influence and dependency of key WLC factors. The ranked scores—presented in Table 12 (Section 4.7.2)—facilitate a more lucid understanding of which elements warrant prioritisation for intervention, evaluation, or integration within the proposed WLC framework. The results yield several critical insights. Factors such as material selection, seismic resilience, building orientation, solar gain, and energy-saving measures demonstrate the highest total centrality. These variables are deeply embedded within the system and exert substantial influence over a wide array of other cost drivers, performance metrics, and lifecycle outcomes. Their elevated ranking substantiates their placement within the upper tiers of the proposed framework hierarchy, wherein they can function as key levers for achieving systemic improvement.

In terms of out-degree centrality, material durability, design efficiency, and construction quality emerged as significant contributors. Their capacity to influence multiple downstream variables underscores their role as principal enablers of performance and cost-effectiveness over the building lifecycle. These findings accentuate the significance of upstream decision-making in shaping operational and post-occupancy outcomes. Conversely, factors such as occupant behaviour, public health implications, and insurance premiums scored highly in terms of in-degree centrality, indicating their role as indicators of outcomes. These variables are profoundly influenced by decisions made during the design, construction, and material specification processes. Monitoring these factors facilitates feedback-driven refinement of policy and planning practices and supports adaptive lifecycle cost estimation.

Several contextual elements, including foreign exchange rates, climatic variability, and regional conditions, also ranked prominently across centrality dimensions. Their robust systemic positions underscore the need for locally tailored WLC models that can accommodate environmental and economic fluctuations, particularly pertinent within New Zealand's diverse regional landscape. Notably, the findings related to centrality provide a logical foundation for structuring the WLC framework. Variables exhibiting high total centrality are prioritised as core components of system control, directing policy, resource allocation, and design focus. Those with elevated in-degree but diminished out-degree

Table 11. Summary of feedback loops

Loop id	Loop name	Loop variables	Type	Main driver	Main consequence
R1	Social Health Spiral	Social Impact Cost ➔ Public Health Impact ➔ Social Impact Cost	Reinforcing	Social Impact Cost	Increased societal health burden
R2	Material Longevity Loop	Material Selection ➔ Material Quality ➔ Material Durability ➔ Serviceability of Materials ➔ Material Selection	Reinforcing	Material Selection	Enhanced material service life
R3	Market Feedback on Materials	Material Selection ➔ Material Quality ➔ Material Durability ➔ Serviceability of Materials ➔ Demand and Supply ➔ Material Availability ➔ Material Selection	Reinforcing	Material Selection	Stronger supply-demand cycle
R4	Resilience by Material Quality	Material Selection ➔ Material Quality ➔ Fire Resistance ➔ Wind Bracing ➔ Seismic Resilience ➔ Climate Conditions ➔ Weather Resilience ➔ Material Selection	Reinforcing	Material Selection	Improved disaster resilience
R5	Seismic Strengthening Loop	Wind Bracing Upgrades ➔ Seismic Resilience ➔ Wind Bracing Upgrades	Reinforcing	Wind Bracing	Advanced structural integrity
R6	Comparative Quality Cycle	Comparability with Other Systems ➔ Construction Technology ➔ Wind Bracing ➔ Construction Quality ➔ Comparability with Other Systems	Reinforcing	Comparability	Construction quality uplift
R7	Smart Resilience Technology	Construction Technology ➔ Wind Bracing ➔ Construction Quality ➔ Resilience ➔ Renewable Energy ➔ Automation ➔ Installation Quality ➔ Construction Technology	Reinforcing	Construction Technology	Integrated smart-resilient systems
R8	Installation-Performance Loop	Installation Practice ➔ Construction Technology ➔ Construction Quality ➔ Resilience ➔ Renewable Energy ➔ Automation ➔ Installation Practice	Reinforcing	Installation Quality	Reliable technology performance
R9	Regulatory Installation Feedback	Installation Practice ➔ Construction Technology ➔ Regulatory Compliance ➔ Construction Quality ➔ Resilience ➔ Renewable Energy ➔ Automation ➔ Installation	Reinforcing	Installation Quality	Compliance-driven tech adoption
R10	Bracing-Driven Smart Buildings	Installation Quality ➔ Construction Technology ➔ Wind Bracing ➔ Construction Quality ➔ Resilience ➔ Renewable Energy ➔ Automation ➔ Installation Quality	Reinforcing	Installation Quality	Robust and smart residential buildings
R11	Quality-Driven Tech Advancement	Construction Quality ➔ Comparability ➔ Construction Technology ➔ Construction Quality	Reinforcing	Construction Quality	Accelerated technology uptake

(continued)

Table 11. Continued

Loop id	Loop name	Loop variables	Type	Main driver	Main consequence
R12	Seismic Quality Benchmark Loop	Construction Quality ➔ Comparability ➔ Construction Technology ➔ Wind Bracing ➔ Construction Quality	Reinforcing	Construction Quality	Safer, high-performing homes
R13	Compliance-Driven Quality Cycle	Construction Quality ➔ Comparability ➔ Construction Technology ➔ Regulatory Compliance ➔ Construction Quality	Reinforcing	Construction Quality	Stronger compliance and durability
R14	Coastal Insurance Resilience	Coastal Erosion Allowances ➔ Flood Mitigation ➔ Insurance Premiums ➔ Coastal Erosion Allowances	Reinforcing	Coastal Erosion Planning	Lower insurance risk in coastal zones
R15	Flood-Resilient Design	Design Efficiency ➔ Flood Mitigation ➔ Insurance Premiums ➔ Design Efficiency	Reinforcing	Design Efficiency	Lower insurance and flood risks
R16	Form-Based Efficiency Loop	Design Efficiency ➔ Shape of Facility ➔ Material/Equipment Efficiency ➔ Design Efficiency	Reinforcing	Design Efficiency	Improved resource efficiency
B1	Acquisition-Operational Trade-off	Upfront Acquisition Cost ➔ Greenstar Rating ➔ Energy Saving Measures ➔ Operational Cost ➔ Long-Term Affordability ➔ Upfront Acquisition Cost	Balancing	Upfront Acquisition Cost	Controlled lifecycle cost
B2	Repair Risk Control	Maintenance Frequency ➔ Resistance to Wear and Tear ➔ Replacement Frequency ➔ Repair Risk Allowances ➔ Maintenance Frequency	Balancing	Maintenance Frequency	Stability in maintenance cost
B3	Insurance Risk Feedback	Building Security ➔ Risk Allowances ➔ Insurance Premiums ➔ Insurance and Risk Mitigation ➔ Building Security	Balancing	Building Security	Stabilised insurance costs
B4	Environmental Material Loop	Environmental Impact Evaluation ➔ Carbon Sequestration ➔ Renewable Resource Use ➔ Material Selection ➔ Environmental Impact Evaluation	Balancing	Environmental Impact Evaluation	Optimised resource selection
B5	Green Certification Cost-Value Loop	Green Building Certification Cost ➔ Greenstar Rating ➔ Government Incentives ➔ Long-Term Affordability ➔ Green Building Certification Cost	Balancing	Certification Cost	Balanced green certification investment

Source(s): Developed by the authors

Table 12. Degree of centrality rankings for all WLC factors

Factor	Out-degree	In-degree	Total degree
Material selection	8	3	11
Building orientation and solar gain	6	4	10
Seismic resilience	6	4	10
Energy-saving measures	6	4	10
Foreign exchange	5	4	9
Material durability	5	4	9
Technology depreciation	6	3	9
Building occupancy type	5	4	9
Health and wellbeing	5	4	9
Design efficiency	6	3	9
Materials availability	6	3	9
Insurance and risk mitigation	5	4	9
Infrastructure burden	5	4	9
Material quality	4	4	8
Environmental cost	4	4	8
Taxation	4	4	8
Weather resilience	6	2	8
Climate conditions/geographical variations	5	3	8
Renewable energy system	5	3	8
Efficiency of materials/equipment	4	3	7
Estimated annual occupancy hours	5	2	7
Availability of skilled labour	4	3	7
Public health impacts	5	2	7
Acoustic performance	5	2	7
Water management system	4	3	7
Long-term affordability	4	3	7
Construction technology	5	2	7
Legislative and economic changes	5	2	7
Upfront acquisition cost	2	5	7
Wind bracing upgrades	3	4	7
Serviceability of materials	3	4	7
Construction quality	5	2	7
Comparability with other building systems	4	3	7
Community displacement	5	1	6
Carbon sequestration	2	4	6
Regulatory compliance	5	1	6
Building resilience to natural hazards	2	4	6
Maintenance frequency	4	2	6
Building security system	4	2	6
Flood mitigation	2	4	6
Insurance premiums for high-risk zones	2	4	6
Effectiveness of on-site communication and coordination	4	2	6
Building automation and smart systems	5	1	6
Fire resistance	3	3	6
Level of uncertainty	3	2	5
Building maintenance technologies	3	2	5
Accessibility issues	2	3	5
Regional and geographical conditions	3	2	5
Sustainable deconstruction practices	2	3	5
Environmental impact evaluation	1	4	5
Green building certification cost	3	2	5
Stormwater upgrades	4	1	5
Renewable resources used	2	3	5
Resistance to wear and tear	3	2	5
Method of financing	1	4	5

(*continued*)

Table 12. Continued

Factor	Out-degree	In-degree	Total degree
Greenstar rating	4	1	5
Demand and supply of materials	3	2	5
Installation practice/quality	3	1	4
Shape of facility	3	1	4
Unforeseen circumstances	1	3	4
Residual value	3	1	4
Continuity of supply chain	1	2	3
Consideration of design alternatives	1	2	3
Replacement frequency	1	2	3
Risk allowances	1	2	3
Government incentives and subsidies	1	2	3
Coastal erosion allowances	2	1	3
Travel time	1	2	3
Occupancy behaviour	1	1	2

Source(s): Developed by the authors

function as performance measures, which are valuable for evaluating the success of interventions. Conversely, factors characterised by intermediate centrality, exhibiting both in- and out-degrees, serve as systemic enablers, synthesising upstream inputs with downstream outcomes. These mid-network connectors are crucial for maintaining system coherence and enhancing feedback loops.

By aligning the framework with insights derived from centrality analysis, the model achieves both practical clarity and theoretical robustness. It ensures that design decisions, policy interventions, and regulatory efforts are concentrated on areas with the most substantial systemic impact while simultaneously embedding the capability for monitoring, adaptation, and optimisation over time. In the forthcoming section, the prioritised insights from both the feedback loop and centrality analyses will be synthesised into a bespoke WLC framework. This framework is meticulously developed for New Zealand's residential construction sector and aspires to promote durable, affordable, and climate-resilient housing outcomes through strategically aligned lifecycle planning.

5.4 Framework design

To enhance the applicability and contextual relevance of WLC within the New Zealand residential construction sector, a hierarchical framework has been systematically developed in alignment with the International Construction Measurement Standards (ICMS). This approach provides a globally recognised structure for organising construction-related costs and ensures analytical coherence throughout a building's lifecycle. However, while the ICMS classification system traditionally provides a four-level structure, this study introduces a tailored fifth level to account for the unique environmental, seismic, social, and regulatory conditions specific to New Zealand. This new classification layer was necessitated by insights from a rigorous Systematic Literature Review (SLR) and further refined through Semi-Structured Interviews (SSI) with local industry experts and stakeholders.

The inclusion of Level 5 significantly enhances the granularity of the cost framework by integrating critical context-specific variables such as seismic resilience strategies, flood mitigation measures, and evolving regulatory compliance costs. These elements, often underrepresented in international models, are essential for accurately capturing the total cost implications of residential projects in New Zealand. By incorporating them, the framework provides a more accurate representation of real project costs and improves its utility as a

Table 13. Tailored WLC framework structure with levels 1–5, including localised risk factors and additional cost elements

Level 1		Level 2		Level 3		Level 4		Level 5	
1	Whole Life Cost (WLC)	1	Non-Construction Costs	1.1	Acquisition Costs	1.1.1	Site acquisition	1.1.1.1	Foreign exchange
								1.1.1.2	Method of financing
								1.1.1.3	Legislative and economic changes
						1.1.2	Administrative, financial, legal, and marketing expenses	1.1.2.1	Regional and geographical conditions
								1.1.2.2	Taxation
								1.1.2.3	Upfront Acquisition cost
								1.1.2.4	Regulatory compliance
		2	Life Cycle Costs	2.1	Construction, Renewal, and Maintenance Costs	2.1.1	Demolition, site preparation, and formation	2.1.1.1	Building resilience to natural hazards
								2.1.1.2	Regulatory compliance
								2.1.1.3	Taxation
						2.1.2	Substructure/Structure	2.1.2.1	Materials availability
								2.1.2.2	Material durability
								2.1.2.3	Material quality
								2.1.2.4	Material selection
								2.1.2.5	Serviceability of materials
								2.1.2.6	Demand and supply of materials
								2.1.2.7	Construction Quality
								2.1.2.8	Construction technology
								2.1.2.9	Comparability with other building systems
								2.1.2.10	Seismic Resilience
								2.1.2.11	Fire resistance
								2.1.2.12	Wind bracing upgrades
								2.1.2.13	Weather Resilience
								2.1.2.14	Climate Conditions/Geographical variations

(*continued*)

Table 13. Continued

Level 1	Level 2	Level 3	Level 4	Level 5
			2.1.3 Architectural works/Non-structural works	2.1.4.1 Consideration of design alternatives
				2.1.4.2 Shape of facility
				2.1.4.3 Efficiency of materials/equipment
				2.1.4.4 Flood mitigation
				2.1.4.5 Design efficiency
				2.1.4.6 Coastal erosion allowances
				2.1.4.7 Insurance premiums for high-risk zones
			2.1.4 Services and equipment	2.1.5.1 Building automation and smart systems
				2.1.5.2 Renewable energy system
				2.1.5.3 Installation practice/quality
				2.1.5.4 Stormwater upgrades
				2.1.5.5 Technology depreciation
			2.1.5 External and ancillary works	2.1.6.1 Water management system
				2.1.6.2 Building orientation and solar gain
				2.1.6.3 Greenstar rating
			2.1.6 Preliminaries and constructors' site overheads	2.1.7.1 Effectiveness of on-site communication and coordination
				2.1.7.2 Availability of skilled labour
			2.1.7 Risk allowances	2.1.8.1 Unforeseen circumstances
				2.1.8.2 Level of uncertainty
				2.1.8.3 Continuity of supply chain
			2.1.8 Post-completion loose furniture, fittings, and equipment	2.1.9.1 Residual value

(*continued*)

Table 13. Continued

Level 1	Level 2	Level 3	Level 4	Level 5
		2.2 Operation Costs	2.2.1 Cleaning, utilities, waste management	2.2.1.1 Building occupancy type
				2.2.1.2 Occupancy behaviour
				2.2.1.3 Estimated annual occupancy hours
			2.2.2 Security, ICT, site overheads	2.2.2.1 Building a security system
				2.2.2.2 Health and well-being
				2.2.2.3 Acoustic performance
			2.2.3 Maintenance and replacement costs	2.2.3.1 Maintenance frequency
				2.2.3.2 Replacement frequency
				2.2.3.3 Resistance to wear and tear
				2.2.3.4 Building maintenance technologies
			2.2.4 Energy and sustainability costs	2.2.4.1 Energy-saving measures
				2.2.4.2 Renewable resources used
				2.2.4.3 Environmental cost
				2.2.4.4 Carbon sequestration
				2.2.4.5 Green Building Certification Cost
		2.3 End-of-Life Costs	2.3.1 Disposal inspection, decommissioning	2.3.1.1 Environmental impact evaluation
				2.3.1.2 Sustainable deconstruction practices
			2.3.2 Demolition and reclamation cost	2.3.2.1 Risk allowances
				2.3.2.2 Insurance and risk mitigation
			2.3.3 Site reinstatement	2.3.3.1 Government incentives and subsidies
				2.3.3.2 Taxation
3 Income			3.0.1 Rental Income	
			3.0.2 Disposals	
4 Externalities			4.0.1 Social impact costs	4.0.1.1 Community displacement
				4.0.1.2 Infrastructure burden
				4.0.1.3 Public health impacts
			4.0.2 User costs	4.0.2.1 Travel time
				4.0.2.2 Accessibility issues
				4.0.2.3 Long-term affordability

Source(s): Developed by the authors

decision-making tool for project managers, developers, and policymakers. The detailed, tailored framework is presented in Table 12, and its visual hierarchy is illustrated in Figure 4. It provides an explicit, structured reference for how cost components interact and are prioritised across multiple dimensions.

The hierarchical model comprises five distinct levels, each represented by a specific colour to visually denote its place within the structure and differentiate between the original ICMS framework and the bespoke adaptations introduced in this study. At the top of the hierarchy is Level 1 (orange), which classifies costs into four overarching categories: Construction Cost, Non-Construction Cost, Income, and Externalities. These categories encapsulate the broadest understanding of Whole Life Costs, forming the foundation upon which more detailed layers are built. Level 2 (yellow) disaggregates these broad cost categories into primary cost types, such as Acquisition Cost, Operation Cost, and End-of-Life Cost, along with discrete elements of Income (e.g., Rental Income) and Externalities (e.g., Social Impact Cost, User Cost, and Disposal Cost). This layer offers a more nuanced breakdown, supporting informed financial planning across the various stages of a building’s lifecycle.

At Level 3 (blue), the framework transitions into more tangible and operational categories such as construction fees, site acquisition, energy and water consumption, and maintenance frequency. These categories reflect the everyday financial considerations in construction projects and are central to budget development, contract scoping, and risk management. Level 4 (grey) introduces performance-based determinants that influence cost outcomes, including energy efficiency of design, health and well-being impacts, sustainability practices, and the longevity and quality of materials. This layer bridges financial considerations with performance metrics, promoting long-term value creation rather than short-term cost optimisation.

The newly introduced Level 5 (green) reflects the tailored requirements of the New Zealand residential context. It encapsulates variables derived from Sustainable Life-cycle Risk (SLR) assessments and Site-Specific Influences (SSI), such as wind bracing enhancements, embodied carbon thresholds, long-term affordability constraints, and regulatory variations related to environmental and seismic zoning. These elements directly affect capital and operational costs, and their explicit integration into the framework ensures that project evaluations are contextually robust and forward-looking.

The structure and prioritisation of this hierarchical framework were deeply informed by systems-based insights from the CLD developed earlier in the study. The CLD revealed a complex web of interactions comprising sixteen reinforcing and five balancing loops, illustrating the dynamic feedback structures inherent in construction cost behaviours. These feedback loops illuminated how improvements or disruptions in one part of the system, such as investments in energy-efficient design, enhanced material durability, or changes in regulatory pressure, can cascade through other parts of the system and significantly alter whole-life cost outcomes. These interdependencies are directly reflected in the positioning and weighting of factors throughout the five levels of the framework. For example, reinforcing loops that emphasised the benefits of better material selection on long-term maintenance costs and serviceability are operationalised within Levels 3 and 4, while balancing loops involving affordability constraints and policy pressures informed the inclusion of long-term socio-economic impacts at Level 5.

In tandem with the CLD, a comprehensive centrality analysis was employed to quantify the structural importance of each factor within the network. The development of the WLC framework for New Zealand’s residential construction sector was guided by a methodologically rigorous sequence, beginning with the identification of influencing factors through the Systematic Literature Review (SLR) and Semi-Structured Interviews (SSI). After establishing a comprehensive list of context-relevant factors, an ICMS-based hierarchical structure was adapted (ICMS, 2019)and extended with a new Level 5 tier to incorporate specific New Zealand challenges and dynamics. However, the most critical step in aligning systemic interactions with framework design was using a CLD and degree of centrality analysis, which ensured the strategic placement and prioritisation of variables.

To justify the direct use of a degree of centrality in framework development, the centrality scores of each factor and its participation in feedback loops were used to indicate systemic influence and interconnectivity. Centrality analysis, particularly degree centrality, measures the extent to which each factor is well-connected within the causal network. A higher centrality rank implies that a factor has numerous direct relationships with others and potentially acts as a leverage point for systemic change. This measure helped identify essential variables and those that would create cascading impacts throughout the cost structure if managed effectively. For instance, “Energy Use” held the highest centrality rank and featured prominently across six reinforcing loops. Its presence across multiple tiers of the framework (Levels 3, 4, and 5) reflects its strategic importance in shaping operational and environmental costs. Similarly, “Material Durability” and “Affordability” were placed across Levels 4 and 5, or Levels 3 and 5, to reflect their dual influence on both design-level decisions and site-specific contextual factors.

This centrality-informed approach ensured that highly influential factors were embedded in generic cost categories and the newly introduced Level 5, which accommodates unique New Zealand-specific risk factors such as seismic resilience and flood mitigation. For example, “Seismic Resilience” ranked fourth in centrality and is exclusively placed in Level 5, demonstrating how local contextual importance and systemic connectivity converge in the framework. Thus, the final framework is not merely a categorical classification of costs but a dynamic system model where the positioning of each factor reflects its systemic role. The mapping of centrality-ranked factors to their framework placement (see Table below) illustrates the intentional translation of causal dynamics into structural hierarchy. This method ensures that the WLC model is comprehensive, locally relevant and strategically prioritised for maximum cost-effectiveness and resilience.

What distinguishes this framework from conventional cost models is its embedded responsiveness to both dynamic system feedback and context-specific challenges. Rather than treating cost categories as static or mutually exclusive, the framework accommodates the interconnected nature of real-world construction decisions. It provides a structure that aligns technical, financial, and regulatory considerations in a way that is both analytically rigorous and practically relevant to New Zealand. The combined use of CLD and centrality metrics ensures that important cost categories are included, and their placement reflects their dynamic behaviour and systemic importance. This makes the framework a diagnostic and prescriptive tool for guiding investment decisions and managing lifecycle performance in residential construction.

To facilitate practical adoption, the proposed WLC framework can be embedded into existing digital tools such as CostX and Building Information Modelling (BIM) platforms. Specifically, Level 5 context-specific variables, such as seismic risk, climate exposure, and material durability, can be configured as custom attributes within BIM models, enabling automated cost tracking throughout the project lifecycle. For instance, design teams could use BIM-linked cost codes to estimate resilience-related maintenance costs during early design stages. Quantity surveyors using CostX can tag cost items with lifecycle-related metadata, enabling the visualisation of cumulative costs from acquisition to decommissioning. A national WLC database should be developed to support consistent inputs. This database could be hosted by MBIE or BRANZ and populated with verified cost curves, material degradation profiles, and region-specific hazard data. Stakeholders, particularly SMEs, could access simplified templates or plug-ins for mainstream tools, reducing the learning curve and cost barriers associated with WLC adoption.

In summary, the proposed hierarchical framework represents a significant advancement in WLC methodology for the New Zealand residential construction sector. It preserves the global consistency and analytical clarity of the ICMS structure (ICMS, 2019) while enriching it with critical local dimensions by including a bespoke Level 5 classification. Grounded in systems thinking and supported by empirical analysis, this framework provides a robust foundation for lifecycle-informed decision-making, helping practitioners navigate complexity, anticipate risk, and realise long-term value in residential construction projects nationwide.

These findings are consistent with earlier research indicating that WLC adoption in residential construction remains limited compared to commercial sectors (Flanagan and Jewell, 2008; MBIE, 2013), but the results extend the discourse by identifying seismic resilience, coastal exposure, and evolving climate adaptation requirements as critical cost determinants in the New Zealand context. Prior LCC/WLC frameworks, such as those by Goh and Sun (2016) and (Lehmann, 2013), provide comprehensive cost–benefit or sustainability integration, yet often omit hazard-related costs and feedback effects between early design choices and downstream lifecycle performance. The present framework addresses this gap through the combined application of systems thinking, ICMS-aligned cost structuring, and network-based centrality analysis, offering a novel tool for lifecycle-conscious decision-making in hazard-prone residential environments.

5.5 Framework

To successfully implement the Whole Life Costing (WLC) framework in New Zealand's residential construction sector, it's essential to adopt a structured approach that incorporates both the technical aspects of the framework and specific regional needs. This section guides the reader through each step of applying the framework, from initial planning to long-term monitoring, providing practical advice for industry stakeholders.

The first step in using the WLC framework is to define the project's specific context. This means evaluating factors such as location, climate, and seismic risks that could affect construction. For example, residential projects in high-risk seismic areas like Wellington and Christchurch must consider extra costs for seismic safety. Likewise, areas facing severe weather, such as heavy rainfall or coastal conditions, will need cost estimates for improved drainage, protection from the elements, and materials that resist corrosion. By considering these local factors, the framework guarantees that all relevant cost factors are included in the lifecycle planning from the start.

Next, the framework supports a detailed cost categorisation process. The five-level hierarchical structure from Section 5.4 acts as a guide for breaking down various cost components, from acquisition to end-of-life expenses. Stakeholders should start by sorting costs into broad categories like acquisition, operation, and end-of-life, then delve into subcategories that include construction costs, energy expenses, and long-term upkeep. The framework's consideration of local variables (such as seismic risk, material strength, and energy use) within these categories enables more precise and context-specific estimates. For instance, choosing materials in a high-seismic zone may focus on those offering both structural strength and long-lasting durability, impacting both initial costs and future maintenance expenses.

After categorising the cost drivers, the next step is to use system dynamics modelling to examine relationships and feedback loops among the identified variables. By utilising the Causal Loop Diagrams (CLDs) from earlier sections, stakeholders can visualise how a choice in one area (like selecting more energy-efficient materials) might affect other costs throughout the lifecycle. The feedback loops revealed through system dynamics analysis assist users in grasping the long-term results of their choices. For example, investing in durable materials may lower future maintenance costs, but it could require a higher upfront investment. These dynamic connections will lead to more informed decision-making, enabling stakeholders to anticipate potential cost shifts and adjust their plans as needed.

To make the framework usable across different project sizes, it's important to focus on scalability in its application. The WLC framework should be applicable to various stakeholders, ranging from large developers to smaller owner-builder projects. For smaller endeavours, a simplified version of the framework could be adopted, highlighting the most significant factors like material longevity, seismic safety, and energy efficiency. This easier version could be offered through an Excel tool or web calculator, allowing stakeholders with limited resources to perform basic lifecycle cost estimates. This phase also includes collaborating with local organisations, such as BRANZ or councils, to provide training and templates that help stakeholders in underprivileged or remote areas implement the framework effectively.

Additionally, regulatory systems will be crucial in promoting the widespread adoption of the framework. One approach could be to require WLC assessments as part of building consent applications, especially in high-risk seismic regions. For larger residential projects or those with public access, local councils may require the submission of WLC analysis findings, such as 30-year cost projections, as part of the planning documents. By folding WLC assessments into regulations, the framework can standardise lifecycle cost evaluations across the industry and promote more sustainable and resilient design practices.

Lastly, support from policies and incentives will be crucial for motivating the widespread adoption of the WLC framework. Government agencies or public-private partnerships could tie specific housing grants or incentives to meeting minimum WLC compliance standards. For example, programs like KiwiBuild could require developers to monitor and report on energy, maintenance, and resilience costs over a 30-year span to qualify for financial support or increased density allowances. Furthermore, the framework could align with existing sustainability certification programs such as Green Star, facilitating integration into ongoing efforts to improve the environmental performance of residential buildings.

By following these steps, stakeholders in New Zealand's residential construction sector can effectively integrate the WLC framework into their projects, ensuring a focus on lasting financial and environmental sustainability. The framework serves as a solid tool for evaluating costs, predicting future financial responsibilities, and making informed choices that balance initial expenditures with long-term savings.

From an implementation perspective, establishing a national WLC database would be a vital enabler. Such a repository would centralise cost data, material performance insights, and location-specific benchmarks, supporting risk-adjusted financial modelling. This would also enable benchmarking against international systems, such as the UK's Building Cost Information Service (BCIS) and Australia's National Construction Code (RICS, 2016; GBCA, 2021), thereby elevating New Zealand's lifecycle assessment standards. The framework also supports integration into regulatory mechanisms. Mandating WLC assessments for developments in high-risk zones could be complemented by financial incentives such as tax benefits, grants, or reduced insurance premiums. These policy interventions would promote adoption and encourage developers and property owners to invest in long-term resilience and sustainability (NZ Treasury, 2019).

In summary, this section emphasises the tailored WLC framework's strategic and practical relevance to the New Zealand context. While Section 5.4 lays out the structural and theoretical foundation, this section demonstrates how the model can be applied, adapted, and institutionalised to enhance decision-making in residential construction.

6. Practical and policy implications

The enhanced WLC framework developed in this study represents a robust decision-support instrument for stakeholders within New Zealand's residential construction sector. It provides developers and design consultants with a systematic methodology for critically assessing the long-term cost implications associated with early-stage decisions regarding materials, energy systems, and resilience features. This capability facilitates more informed trade-offs between initial capital investment and life-cycle affordability.

Local councils, regulatory bodies, and policymakers, such as the Ministry of Business, Innovation and Employment (MBIE), are well-positioned to leverage the framework to incorporate lifecycle considerations into planning approvals, subsidy design, and compliance regimes. The emphasis on factors such as seismic resilience and energy performance aligns with contemporary national objectives outlined under the Building for Climate Change programme. Furthermore, the modular architecture of the framework enables prospective integration with advanced tools such as Building Information Modelling (BIM), digital twins, and green certification systems (e.g., Green Star NZ).

By actualising long-term cost planning within the context of region-specific risks, the proposed framework contributes to enhanced housing affordability, durability, and climate resilience across New Zealand's residential building inventory.

7. Research limitations

This study acknowledges several key limitations. First, the proposed Whole Life Costing (WLC) framework is conceptual and has not yet undergone empirical validation, such as through case studies, pilot testing, or longitudinal application. These activities are planned as part of future research to assess and refine their real-world performance.

Second, although the framework was informed by expert and stakeholder input to ensure contextual relevance, such qualitative data inevitably reflect a degree of subjectivity and variability in perspectives. Broader engagement and replication with diverse participant groups could strengthen the robustness of the insights.

Third, the development process was constrained by data gaps in current lifecycle cost information, particularly for long-term maintenance expenses, the financial impacts of regulatory changes, and the quantification of social externalities. While the framework highlights the need for improved data infrastructure, effective implementation will require future data acquisition, curation, and calibration.

Finally, the use of a system dynamics (SD) approach, though valuable for mapping complex interdependencies, required simplifying assumptions that may omit specific real-world nuances and nonlinearities. Model accuracy will therefore benefit from iterative updating as more empirical evidence and regional datasets become available.

These limitations underscore that the current framework should be viewed as a validated-by-experts design prototype, requiring further testing, refinement, and integration with empirical datasets before it can be confidently deployed at scale.

8. Conclusion

The primary aim of this study was to develop a refined Whole Life Costing (WLC) framework specifically tailored to New Zealand's residential construction sector, addressing current gaps in national standardisation, data quality, sector applicability, and resilience considerations. This goal was pursued in response to the distinctive environmental, seismic, and regulatory challenges that influence long-term housing costs in New Zealand.

To achieve this aim, we undertook a multi-stage methodology. First, a comprehensive review and comparative analysis of international LCC/WLC frameworks identified strengths and weaknesses relevant to hazard-prone residential environments. Second, sector-specific requirements were gathered through stakeholder engagement, ensuring the framework incorporated New Zealand's unique seismic risk profiles, climatic conditions, and socio-economic factors. Third, system dynamics modelling, causal loop diagrams, and centrality analysis were applied to map interdependencies between lifecycle cost drivers and to prioritise high-leverage variables, such as seismic resilience, material durability, and energy efficiency. These methodological steps informed the creation of a structured, modular, and nationally standardised WLC framework designed for both rigour and practical usability.

The resulting framework provides a dynamic decision-making tool for lifecycle planning in the residential sector, offering actionable insights for developers, designers, policymakers, and other stakeholders. Beyond its contributions to academic discourse, this framework represents a significant innovation over prior WLC approaches by integrating system dynamics modelling, sector-specific resilience variables, and a full lifecycle scope for the New Zealand residential context. This combination of features presents new opportunities for integrating lifecycle thinking into housing policy and practice, provided that it is validated through further applied research. By enabling resilient design and material selection that considers maintenance, it has the potential to achieve lifecycle savings of approximately 15–25% in high-risk seismic zones when early-stage investments are strategically informed.

Theoretically, this study advances the understanding of whole life costing by demonstrating how the integration of system dynamics fundamentally enriches lifecycle costing theory for residential construction. Unlike traditional WLC models, which treat cost elements as largely static, the framework developed in this research enables the analysis of complex feedback loops and dynamic interdependencies among cost drivers, revealing the significant influence of region-specific factors, such as seismic risk and climate variability. By structuring these influences within a hierarchical model, the research not only challenges the universal applicability of global WLC frameworks but also proposes a theoretical shift towards context-sensitive, adaptable approaches that reflect real-world complexity. This work contributes to the ongoing evolution of construction economics by positioning whole life costing as a dynamic, decision-support process rather than a retrospective accounting tool, and underscores the importance of integrating environmental, regulatory, and social dimensions into the theoretical modelling of sustainability and resilience in the built environment. In doing so, the framework provides a conceptual foundation for future research that aims to refine WLC analysis methodologies and adapt them to diverse local contexts.

To foster industry adoption, we recommend piloting the framework within public housing initiatives, such as Kāinga Ora projects, and fostering collaborations between organisations like MBIE, NZIQS, and BRANZ to produce digital templates and training resources. Future research should focus on validation through case studies, integration with BIM platforms, and development of streamlined tools for smaller developers.

As New Zealand continues to face challenges related to housing affordability and resilience, adopting a lifecycle-based cost framework is timely and necessary. The methodology and tools presented here provide a replicable roadmap for embedding long-term cost considerations into residential construction, supporting more equitable, sustainable, and disaster-resilient housing outcomes.

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Appendix 1

Interview guide

Introduction

(1) Greeting:

Good [morning/afternoon], thank you for agreeing to participate in this interview. My name is Herath Mudiyanselage Samadhi Nayanathara Samarasekara, and I’m conducting research at Auckland University of Technology. This study focuses on developing a framework to enhance the accuracy of whole-life cost (WLC) estimations in residential buildings in New Zealand.

(2) Study Overview:

The goal of this study is to identify and understand the factors that impact WLC estimation, with a particular focus on their interrelationships. We aim to propose improvements to the existing WLC frameworks, specifically tailored to New Zealand’s residential construction context.

(3) Confidentiality and Consent:

I assure you that your responses will remain confidential. Your identity will be anonymised in the final report. Do I have your consent to record this interview for research purposes?

Warm-up questions

1. Can you briefly describe your professional background and experience in the construction industry?
2. How did you become involved in whole-life cost estimation for residential buildings?
3. What specific expertise or role do you have in the process of WLC estimation for residential buildings?

Main interview questions

Questions related to the factors influencing WLC estimation

1. From your perspective, what factors influence whole-life cost estimation for residential buildings?
2. How do you prioritise these factors when conducting cost estimations for residential building projects?
3. Can you provide examples of how different factors interact and affect the overall accuracy of whole-life cost estimation?
4. In your opinion, which factors significantly impact whole-life cost estimation, and why?
5. How do economic conditions, market trends, and regulatory requirements in different countries influence the cost estimation process for residential buildings?
6. Have you observed geographical variations in cost estimation methodologies and outcomes for residential building projects?
7. What challenges do you encounter when estimating whole-life costs for residential buildings, and how do you address these challenges?
8. How do advancements in construction technology, sustainable practices, and building materials impact the global accuracy of whole-life cost estimation?

Questions related to system dynamics in WLC estimation

1. What factors interact positively or negatively influence the WLC of NZ Residential Buildings?
2. Have you noticed any patterns where changes in one area, like project decisions or stakeholder interactions, lead to changes in overall cost estimates for residential buildings in New Zealand?
3. How do you think a better understanding of how different factors interact could improve the accuracy of cost estimation for residential buildings in New Zealand?
4. Considering the interrelationships, how do you rank the factors influencing the accuracy of cost estimates for residential buildings in New Zealand?

Questions related to the framework

1. Can you provide an overview of the current framework or methodologies used for whole-life cost estimation in residential building projects in New Zealand?
2. What are the key components or elements included in the existing WLC framework for residential buildings in New Zealand?
3. How are costs typically categorised or segmented within the current WLC framework (e.g., construction, maintenance, operational costs)?

(4) Are there any specific tools, software, or models commonly utilised for whole-life cost estimation in residential building projects in New Zealand?

(5) How do stakeholders typically collaborate or engage in the whole-life cost estimation process for residential buildings in New Zealand?

(6) What are the primary challenges or limitations associated with the current WLC framework for residential buildings in New Zealand?

(7) Are there any notable differences or variations in whole-life cost estimation practices among different regions or sectors within New Zealand?

(8) How do factors such as project size, complexity, or building type influence the application of the WLC framework for residential buildings in New Zealand?

(9) Have any recent developments or initiatives aimed at improving or refining the WLC framework for residential buildings in New Zealand?

(10) Based on your experience or expertise, what areas or aspects of the existing WLC framework do you believe require the most significant improvements or enhancements better to suit the needs of New Zealand residential building projects?

Interview closeout

(1) Do you have any final thoughts or anything else you want to share?

Recording and data management

In adherence to rigorous recording and data management protocols, all interviews will be meticulously documented and stored to ensure the integrity and confidentiality of participant responses. Each interview session will be captured using state-of-the-art recording devices, such as digital audio recorders or secure online platforms of Microsoft Teams. Simultaneously, comprehensive notes will be taken to capture nuanced details and critical insights.

After the interviews, recordings will be transcribed verbatim, maintaining fidelity to the original dialogue. These transcripts and supplementary notes will be securely stored using a sensitive data management protocol that will be filled out and stored during the active data collection stage on https://autuni-my.sharepoint.com. After the analysis, the management protocol will be securely stored in the AUT by the applicant as an encrypted folder. Auckland University of Technology provides a data management tool (DMP) for researchers to store information and download a PDF version when needed. This tool enables researchers to set the information to private, making it completely secure and inaccessible to the public, except to the designated researchers.

Appendix 2

Table A1. Literature matrix

Author(s)	Year	Title	Key contributions	Relationship to this study
Abdullah, A. S., *et al.*	2025	*A geographic information system-based flood risk assessment comprehensive model utilising a multi-criteria decision analysis technique*	Proposed a GIS-based model for flood risk assessment in construction, emphasising the integration of multi-criteria decision analysis	This study employed similar multi-criteria approaches to incorporate climate risks into WLC frameworks
Akiyama, M., *et al.*	2020	*Toward life-cycle reliability-risk- and resilience-based design and assessment of bridges and bridge networks*	Introduced a resilience-based framework for assessing infrastructure risks, focussing on earthquake, tsunami, and corrosion hazards	This study extended resilience-based approaches into residential building design, particularly in seismic regions
ASCE and ENO	2014	*Life Cycle Cost Analysis*	Provided guidelines for conducting life cycle cost analysis (LCCA) in civil engineering projects	This study built on LCCA by incorporating system dynamics and adapting it for residential buildings with regional considerations
ASTM	2020	*Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems*	Developed a standardised approach to LCCA for assessing the long-term costs of building systems	This study referenced ASTM’s framework by integrating New Zealand-specific risks, including seismic activity and climate change
Bao, Z.	2023	*Developing circularity of construction waste for a sustainable built environment in emerging economies*	Focused on circular economy strategies for reducing construction waste and promoting sustainability in emerging economies	This study incorporated similar sustainability principles but with a focus on WLC and resilience in the New Zealand context
Crielaard, L., *et al.*	2024	*Refining the causal loop diagram: A tutorial for maximising the contribution of domain expertise in computational system dynamics modelling*	Emphasised the importance of domain expertise in system dynamics modelling, particularly for causal loop diagrams (CLDs)	This study used CLDs to model WLC factors, enhancing them with New Zealand-specific data and risks
DGNB	2022	*Important Facts about DGNB Certification*	Described the DGNB certification system for sustainable building, which includes environmental and social criteria	This study integrated these criteria into a WLC framework tailored for New Zealand’s residential buildings
Goh, B. H.	2016	*Designing a whole-life building cost index in Singapore*	Developed a cost index for building life-cycle management specific to Singapore’s building sector	This study adapted the index to New Zealand’s residential buildings, taking into account the country’s unique seismic and climate risks

(*continued*)

Table A1. Continued

Author(s)	Year	Title	Key contributions	Relationship to this study
Goh, B. H., and Sun, Y.	2016	*The development of life-cycle costing for buildings*	Explored the development and application of life-cycle costing in building projects, focussing on long-term economic considerations	This study expanded on this by integrating regional factors, such as seismic resilience and climate impacts
ISO	2017	*ISO 15686-5: Buildings and Constructed Assets—Service Life Planning—Part 5: Life Cycle Costing*	Standardised life-cycle costing for buildings, focussing on systematic cost management and service life planning	This study followed the ISO standard while incorporating context-specific factors, such as seismic and climate-related risks, relevant to New Zealand
Jaques, R. A., *et al.*	2015	*Valuing sustainability and resilience features in housing*	Focused on valuing sustainability features in residential buildings, specifically in the context of New Zealand	This study considered sustainability and resilience, emphasising their role in whole-life costing for New Zealand homes
Kallio, H., *et al.*	2016	*Systematic methodological review: developing a framework for a qualitative semi-structured interview guide*	Developed a framework for semi-structured interviews in qualitative research, focussing on systematic data collection	This study employed a similar qualitative framework to conduct expert interviews, validating cost-driving factors in New Zealand's residential buildings
Lakshmanan, N., *et al.*	2008	*Experimental investigations on the seismic response of a base-isolated reinforced concrete frame model*	Investigated the seismic response of reinforced concrete frames, focussing on base-isolation techniques	This study incorporated seismic resilience as a key cost driver, aligning with findings from Lakshmanan *et al.* on seismic risk management
Lehmann, S.	2013	*Sustainable building design and systems integration: combining energy efficiency with material efficiency*	Discussed the integration of energy efficiency and material efficiency in sustainable building design	This study integrated energy efficiency and material durability as central factors influencing the WLC of residential buildings
Lim, J., *et al.*	2025	*Evaluating green building certification criteria for small health care centres in the Jakarta area – from GREENSHIP to Puske-GREENSHIP framework*	Evaluated the criteria for green building certifications, focussing on health care centres	This study incorporated similar certification criteria into the WLC framework for New Zealand's residential sector
Liu, J., *et al.*	2023	*Life cycle cost modelling and economic analysis of wind power: A state of art review*	Reviewed life cycle cost modelling in wind power, offering insights into renewable energy systems	This study incorporated similar life cycle cost models, focussing on the residential sector and integrating energy-efficient technologies and renewable systems

(*continued*)

Table A1. Continued

Author(s)	Year	Title	Key contributions	Relationship to this study
MBIE	2013	*Total cost of Ownership: An Introduction to Whole-life cost*	Introduced guidelines for considering whole-life cost in public procurement for infrastructure	This study extended these principles to residential buildings in New Zealand, incorporating seismic and climate risks into cost estimations
Memon, F. A., *et al.*	2015	*Energy and carbon implications of water saving micro-components and greywater reuse systems*	Investigated the energy and carbon savings associated with water-saving systems	This study extended water-saving systems into a broader WLC framework, focussing on their impact on long-term building costs in New Zealand
Minami, K.	2003	*Whole life cost of post offices in Japan, based on a survey of actual conditions and consideration of investment correction*	Explored the whole life cost of post offices in Japan, particularly regarding investment correction	This study extended these cost estimation techniques to the residential sector in New Zealand, incorporating local seismic risks
Nasereddin, M., and Price, A.	2021	*Addressing the capital cost barrier to sustainable construction*	Discussed how to overcome the capital cost barrier in sustainable construction practices	This study addressed similar barriers by incorporating long-term WLC considerations and seismic resilience into New Zealand’s residential building practices
NIWA	2022	*Climate change and possible impacts for New Zealand*	Provided an overview of potential climate change impacts specific to New Zealand	This study directly incorporated the climate risks identified by NIWA into the WLC framework for residential buildings
Opsahl, T., *et al.*	2010	*Node centrality in weighted networks: Generalising degree and shortest paths*	Expanded the understanding of centrality in social networks, focussing on weighted connections	This study applied centrality analysis to model the dynamic interactions of cost drivers in residential buildings
Page, M. J., *et al.*	2021	*The PRISMA 2020 statement: an updated guideline for reporting systematic reviews*	Provided updated guidelines for conducting systematic literature reviews	This study adhered to the PRISMA guidelines to conduct a systematic review of factors influencing WLC in residential buildings
Purushothaman, M. B., and Aguas, A. B.	2025	*Cognitive biases that shape the drivers and barriers to embracing green construction practices*	Explored cognitive biases affecting the adoption of green construction practices	This study incorporated insights from cognitive biases to analyse barriers to WLC adoption in New Zealand’s residential sector
QTC	2019	*Whole-Of-Life Costing: A QUICK REFERENCE GUIDE FOR ELECTED OFFICIALS AND STAFF*	Provided a practical guide to understanding and applying whole-of-life costing in public projects	This study followed similar guidelines, applying WLC specifically to residential buildings in New Zealand

(*continued*)

Table A1. Continued

Author(s)	Year	Title	Key contributions	Relationship to this study
RICS	2016	*Life Cycle Costing*	Provided a comprehensive guide to life cycle costing in construction, with an emphasis on cost management	This study adapted RICS guidelines, focussing on the integration of system dynamics for residential buildings in New Zealand
Rolfstam, M., and Petersen, O. H.	2014	*Denmark. In Public Procurement, Innovation and Policy: International Perspectives*	Focused on public procurement and innovation in Denmark, with an emphasis on lifecycle considerations	This study built on these principles, incorporating regional factors like seismic resilience and climate change into the WLC framework for New Zealand
Seetharaman, A., *et al.*	2017	*The impact of property management services on tenants' satisfaction with industrial buildings*	Explored the role of property management in tenant satisfaction in industrial buildings	This study extended these findings by focussing on lifecycle cost factors in residential buildings, with a particular emphasis on long-term sustainability and resilience
Sterman, J.	2002	*System Dynamics: systems thinking and modelling for a complex world*	Provided a comprehensive approach to system dynamics, focussing on modelling and feedback loops	This study adopted system dynamics and causal loop diagrams (CLDs) to model the dynamic interactions of cost drivers in the WLC of residential buildings
treasury.govt.nz	2015	*Whole of Life Costs Guidance*	Guided considering whole-of-life costs for public procurement in New Zealand	This study incorporated this guidance to model long-term costs for residential buildings, taking into account seismic and climate-related risks
UKSI	2015	*The Public Contracts Regulations 2015/102*	Provided regulations for public procurement, emphasising lifecycle costs and sustainability	This study aligned with UKSI's regulations by applying lifecycle cost modelling to residential buildings in New Zealand
USGBC	2019	*LEED v4.1 Building Design and Construction Beta Guide*	Provided a guide to LEED v4.1 for building design and construction, focussing on sustainability	This study incorporated LEED v4.1 criteria for building sustainability and applied them to the WLC framework for New Zealand homes
USGBC	2021	*LEED v4.1 Reference Guide for Building Design and Construction*	A comprehensive guide for achieving LEED certification in building projects, focussing on green building standards	This study followed LEED criteria for sustainability and integrated them into the whole-life costing model for New Zealand's residential sector

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