





# Integrating occupancy density into the environmental assessment of residential buildings: Towards embodied impact reduction at both building and urban level

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## ABSTRACT

Life Cycle Assessments (LCA) of buildings typically use gross floor area (GFA)-centric functional units, while urban-scale assessments use occupancy-centric ones. This mismatch reflects the dual functions of buildings (providing space and shelter) and can lead to conflicting strategies, where reducing impacts per GFA at the building level may increase impacts per occupant at the urban level. This study compares these assessment approaches and introduces a dual-functional unit approach that evaluates buildings across both functions. Eight detached houses are assessed using LCA across four impact categories and ranked using a multi-criteria decision-making (MCDM) method for each approach. Results show significant variation in rankings among the established approaches, with several buildings having completely opposite outcomes (e.g., ranked 1st in the GFA-centric assessment but 6th in the occupancy-centric assessment), while the proposed approach produces more consistent rankings, representing both functions. Moreover, a scenario-based analysis compares the three assessments to a control (no-assessment) scenario, considering all detached houses built in Aotearoa New Zealand over the past 5 years. The GFA-centric assessment resulted in increased total impacts (mean difference +0.20% across the four impact categories) by promoting larger and less dense buildings (+0.70 m<sup>2</sup> per occupant), while the occupancy-centric assessment led to mean impact reductions of -1.98%, while significantly reducing the space per occupant by 0.98m<sup>2</sup>. The proposed approach achieved even greater impact reductions (-2.22%) while reducing space by only 0.31m<sup>2</sup> per occupant. Finally, a correlation with national climate goals was made, showing the approach could achieve 71.65% of the national carbon reduction target.

## 1. Introduction

Human activity and anthropogenic pollution have led to severe degradation of natural ecosystems. As the global population grows and resource demand increases, optimizing resource use to balance human needs with environmental sustainability has become essential. The construction industry is one of the most resource-intensive sectors due to the recent rapid urbanization and the increasing need for infrastructure globally [1]; the most widely used material of the sector, concrete, is, after water, the second most consumed product by mankind [2]. Therefore, the construction sector is the largest emitter of greenhouse gases (GHG), accounting for approximately 37 % of global GHG emissions [3], as well as for one-sixth of the world's freshwater withdrawals

and one-quarter of the wood harvested [4]. Among the several sub-sectors of the construction industry, the residential sector is responsible for a significant share of these emissions while also being vital for humanity's wellbeing. It is estimated that buildings, both residential and commercial, are responsible for approximately 16 % of global GHG emissions. Of these emissions, residential buildings alone contribute 64 % [5]. Therefore, research and policy efforts have been increasingly focusing on examining the life cycles of residential buildings and investigating ways to regulate resource use and improve energy efficiency.

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### 1.1. Environmental impact assessment of buildings

The environmental impacts of buildings are generally grouped into two main impact categories: the embodied and operational impacts. Operational impacts refer to the energy and water consumed while a building is in its use phase, such as electricity for heating, cooling, lighting, and everyday appliances. Operational impacts occur gradually over the building's lifespan. Embodied impacts on the other hand, refer to all the impacts related to manufacturing, transporting, assembling, maintaining, and disposing of the building's materials. In other words, they refer to the sum of the infrastructure's components and the impacts related to them. Therefore, embodied impacts can be identified throughout the whole building's life cycle, from the extraction of raw materials to the processing of building waste. It is widely supported that as buildings become more energy efficient, and energy decarbonization gradually occurs, the embodied impacts will dominate the life cycle impacts [6], and therefore recent research focus has shifted towards potential embodied impacts reductions. Finally, the importance of upfront embodied impacts (those that occur before the use phase) and their reduction is highlighted in the literature [7–9]. This is especially true for impact-intensive product systems with big lifespans such as buildings. Unlike later-stage embodied impacts, upfront impacts are sealed into the building's life cycle from the beginning—often viewed as an impact investment—meaning they are not affected by future technological advancements. Moreover, since upfront impacts make up a significant share of emissions within the critical timeframe for climate change mitigation, reducing them is essential to achieving climate goals [8].

With regards to developed methodologies for impact assessment, Life Cycle Assessment (LCA) is the most widely used for quantifying environmental impacts, often complemented by economic and, more recently, social assessments. In the building sector, the integration of Building Information Modelling (BIM) with LCA has gained attention, offering comparative insights across materials and designs in the early-design stage of buildings, and therefore considered a milestone in the sustainability assessment of the built environment [10]. Various studies have investigated the effects of different designs and structures [11,12], materials [13,14], or both [15] in different buildings and contexts, thus providing insight for designers, policymakers, and stakeholders in sustainable decision-making. The BIM-LCA integration is largely enabled by the introduction of Environmental Product Declarations (EPDs), which provide standardized, locally relevant data that improve assessment accuracy over generic datasets. The offered data granularity also enables faster assessments, making the approach more conducive to industry adoption. Several impact assessment tools have been developed for various regions [16]. *Tally LCA* is among the most popular in the literature, focusing on the context of the United States, using the U.S. Life Cycle Inventory (USLCI) [17], while *Athena Impact Estimator* and *Embodied Carbon in Construction Calculator (EC3)* are also popular for the broader context of North America [18]. In the context of Aotearoa New Zealand, *LCAQuick* [19] was developed and released in November 2016 by the Building Research Association of New Zealand (BRANZ) [20]. It consists of an EPD-database integrated in an excel-based interface for impact analysis. A study, for example, used *LCAQuick* to assess the benefits of energy retrofitting heritage buildings in the New Zealand context [21], while another study [22] compared three different window refurbishment scenarios, focusing on improving the efficiency of historic buildings. Finally, environmental impact assessments of residential buildings [9,23] have been performed using *LCAQuick*, to compare how different structural systems, materials and designs perform in the context of New Zealand.

Conflicting criteria are often present in impact assessment and decision-making in the building sector, as well as in other sectors. One of the most popular methodologies to deal with those is the multi-criteria decision-making (MCDM) methods which are preferred over single- and multi-objective optimisation strategies [24] or single sustainability

indices [25]. For buildings, some of the most used methodologies are the *Analytical Hierarchy Process (AHP)*, the *Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)*, the *Weighted Arithmetic Mean/Simple Additive Weighting (WAM/SAW)*, the *Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE)*, and more [25, 26]. Combined versions of these methodologies, as well as combinations with different weighting methods, are also popular depending on the problem. By using such approaches, studies have explored several building characteristics and their effect on the environmental performance of buildings; from optimizing the selection of building and insulation materials [27–29], assessing building designs regarding energy consumption [30], assisting decision-making in municipal residential investments and management [31] and analysing system dynamics to identify the most efficient pathways towards a sustainable built environment [32], to combining economic and environmental criteria [33] alongside with social criteria [34] in multi-dimensional sustainability assessments.

### 1.2. Sustainable housing and density

Urban density has emerged as a key characteristic of the residential building stock towards reducing the environmental impacts of the residential sector and is considered essential for sustainable urban development [35]. Urban density can be described by several indicators such as *site coverage* (ratio of building footprints to site area) and *plot ratio* (ratio of total floor area to site area) [36], as well as more complicated indicators depending on the scope of study [37]. Higher urban density is associated with reduced environmental impacts as it requires less infrastructure per capita and results in lower energy consumption [38–40]. From a social perspective, higher density offers several advantages, including improved access to services [35], greater support for local stores and facilities, typically within walking or biking distance [41], and a more vibrant social life. On the other hand, higher urban density is often common in low-income neighbourhoods where some of the aforementioned advantages are not realized due to social challenges [41,42]. The latest international urban planning guidelines mention the term *appropriate density*, which refers to a well-considered urban form that enhances connectivity, prevents urban sprawl, and combines social and economic uses in built-up areas [43]. While research has examined the benefits and drawbacks of higher density at the urban level, investigations at the individual building level remain limited. Research in this area is mainly focusing on how more compact building designs can contribute to its energy efficiency [37,44,45], and thus its potential for reducing operational impacts. Especially in climatic zones with high demand for either cooling or heating loads, occupancy density is identified as a vital building design aspect for environmental efficiency [46]. The effect of occupants' behaviour in the energy performance of buildings (especially residential but also commercial) is also a research topic that is gaining attention with various studies correlating behavioural patterns such as clothing, HVAC (Heating, Ventilation and Air Conditioning) systems usage, usage of building openings, and more, with energy consumption [47].

### 1.3. Literature gap & research contribution

Fundamentally, anthropogenic pollution (environmental impact) has been described by [48] as dependent on three factors: population, affluence, and technology ( $I=PAT$  equation). Population refers to the number of people consuming resources and therefore generating impacts; affluence refers to the amount of impact generated per unit of population; and technology refers to the efficiency of consumed products—the ratio of impact per unit of consumption (product). Current literature focuses on reducing anthropogenic pollution via improving technology, while affluence remains largely unaddressed, despite being identified as the most influential factor [49]. It is also noted that, at the global level, the increase in affluence (and to a lesser extent population)

has already outweighed the environmental gains achieved through technological improvements over the past decades, making it clear that humanity will likely not reach a sustainable future if affluence is not included in sustainable development assessments and strategies [49].

In the context of buildings, sustainability frameworks continue to emphasize technological advancement. This focus is evident in the widespread use of gross floor area (GFA)-centric functional units in building life cycle assessments (LCAs) [50,51], revealing that the efforts are oriented toward enhancing the technological performance of buildings—making the product (i.e., space) more sustainable. In contrast, urban-scale sustainability studies, which assess broader systems composed of multiple buildings, adopt occupancy-based functional units [52–55]. These studies prioritize the primary societal function of buildings: to provide shelter/accommodation. This divergence in functional units, not only potentially leads to contradicting strategies for impact mitigation [38], but also highlights two fundamental distinctions. First, it reflects the dual function of buildings—as both spatial products and shelters. Second, it mirrors the deeper impact drivers identified by the  $I=PAT$  framework: technology and affluence. This discrepancy can also be understood in terms of relative and absolute sustainability. While technology-centric assessments often aim to reduce environmental impacts per unit of product (relative reduction), a growing body of research is pushing toward absolute sustainability [56, 57]—evaluating whether a building’s impacts are within the *safe operating space* assigned to it according to the Planet’s limits. This perspective emphasizes whether buildings (or any product) are actually sustainable (instead of more sustainable), with recent research in New Zealand’s buildings showing that current practice exceeds the safe operating space by more than 10 times, in some cases [58].

All these points lead to the conclusion that the current orientation of sustainability assessments lacks comprehensiveness and fails to integrate the actual drivers of environmental pollution. This fact is further supported by recent research suggesting that buildings with larger GFA tend to show lower environmental impacts per GFA [59]—a finding that embodies the paradox highlighted here, while there are warnings from previous literature arguing that certain functional units may promote further consumption of the assessed product [60]. Therefore, considering the need for absolute impact reductions due to the Earth’s defined tolerance for anthropogenic pollution [61] and the call for affluence-related environmental assessments across sectors [49,62], this work introduces a novel dual-functional unit LCA framework for residential buildings to ensure impact reduction potential at both levels: building (technology-related) and urban (affluence-related).

## 2. Methodology

The methodological steps followed in this work are presented below and consist of the following: a) estimating the upfront impacts (Global

Warming Potential, Eutrophication Potential, Ozone Depletion Potential, and Acidification Potential) for eight residential buildings and for the two different functional units (GFA and occupancy), b) applying a multi-criteria decision-making methodology to identify the most sustainable options according to the two different functional units alongside the proposed dual-functional unit approach, c) performing a scenario-based analysis to identify how the different approaches perform in terms of absolute impacts (in a 5-year timeframe) and correlation of the results with national climate change mitigation goals.

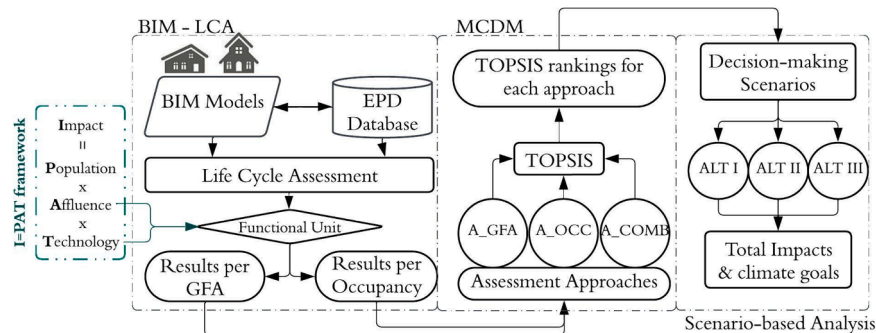
### 2.1. Data collection & preprocessing

The study’s workflow is presented in Fig. 1. To ensure coherent data collection and comparable results, only buildings designed for New Zealand were considered. This is due to regionality being perceived as particularly crucial for assessing sustainability in New Zealand as the country’s remoteness results in unique characteristics related to building materials, their production, manufacturing, and transportation. The data collection of this study consists of 8 case-study BIM models provided by the Building Research Association of New Zealand (BRANZ) which represent 1-storey and 2-storey detached houses. The bills of quantities (BoQs) were obtained from the BIM models using the *material take-off* function of *Autodesk Revit 2023* [63] software. All the buildings were developed in a BIM-LCA context; thus, the materials used for the models correspond to locally used materials and their corresponding EPDs, which are included in the *LCAQuick* database.

Table 1 shows the buildings under study and their characteristics (more information with regards to design and bills of quantities can be found in supplementary material SM1). The occupational load factor (OLF) is derived from Eq. (1) and is a factor usually used in risk assessments in commercial and residential buildings [64,65]. In this study, the OLF is used as a metric to express each building’s occupancy density—that is, the number of occupants per unit of space. It reflects how spatially compact a building is relative to its occupants, and therefore how efficient it is in delivering its accommodative function. The total GFA for each building was obtained from the BIM models whereas the

**Table 1**  
Characteristics of buildings.

ID	Type	Storeys	GFA (m <sup>2</sup> )	Occupants	OLF
D1	2-storey Detached	2	106	4	0.03774
D2	2-storey Detached	2	186	5	0.02688
D3	2-storey Detached	2	194	5	0.02577
D4	2-storey Detached	2	190	4	0.02105
S1	1-storey Detached	1	113	4	0.03540
S2	1-storey Detached	1	146	4	0.02740
S3	1-storey Detached	1	194	5	0.02577
S4	1-storey Detached	1	166	4	0.02410



**Fig. 1.** Workflow of the presented work. A\_GFA refers to the TOPSIS dataset that considers the LCA results per gross floor area (GFA), while A\_OCC considers the results per occupant. A\_COMB considers both. ALT I, ALT II & ALT III refer to decision-making scenarios that incorporate A\_GFA, A\_OCC and A\_COMB rankings respectively. Abbreviations: BIM-LCA, Building Information Modelling-Life Cycle Assessment; EPD, Environmental Product Declaration; GFA, Gross Floor Area; TOPSIS, Technique for Order of Preference by Similarity to Ideal Solution.

number of occupants is derived from Eq. (2) [66,67].

$$\text{Occupational Load Factor (OLF)} = \frac{\text{Number of Occupants}}{\text{Gross floor area (GFA)}} \quad (1)$$

$$\text{Occupants} = \text{Number of Bedrooms} + 1 \quad (2)$$

Finally, data preprocessing was carried out before the LCA to ensure that the results are comparable. Impact-intensive material inputs that were found to be present only in individual buildings (e.g. landscaping materials such as sand and granular fill) were removed from the BoQs, assuming that all buildings may have used such materials, but only a few included them in the BIMs due to different level of detail among models.

## 2.2. Life cycle assessment (LCA)

According to ISO 14,040 and 14,044 standards [68,69], LCA follows four key steps: the goal and scope definition, the life cycle inventory (LCI) analysis, the life cycle impact assessment (LCIA) and the interpretation of the results. The goal of the LCA study is to quantify the upfront embodied environmental impacts of the eight buildings for two functional units and observe how these compare with each other. The scope of the study is limited to the context of New Zealand while the buildings were designed specifically for the city of Auckland. This makes the buildings under study even comparable since New Zealand hosts several climates and the building code specifies different required characteristics (e.g. insulation levels) for the different regions. The scope of the study includes the impact categories of Global Warming Potential (GWP with a unit of  $kgCO_2eq$ ), Eutrophication Potential (EP with a unit of  $kgPO_4^{3-}eq$ ), Ozone Depletion Potential (ODP with a unit of  $kgCFC-11eq$ ) and Acidification Potential (AP with a unit of  $kgSO_2eq$ ). Four impact categories were selected to minimize potential trade-offs and ensure a comprehensive assessment of environmental sustainability [70], with GWP being the most used in sustainability studies [16], and the remaining categories being among those included in EN15804+A2 [71]. Two functional units were used: GFA ( $m^2$ ), and occupancy (number of occupants), while the lifespan of the buildings was considered the same (50 years according to New Zealand's building code regulations [72]) for all buildings. Finally, modules A1-A5 (upfront embodied impacts) are included in the scope of this study (Fig. 2), due to the importance of these modules for long-lifespan products such as buildings (as mentioned in 1.1).

For the Life Cycle Inventory (LCI) development, the data collection was used and BoQs of the case-study buildings were extracted from the BIM models and inserted as inputs into the *LCAQuick* excel-based interface. This process also requires assigning a dependency factor to each input which determines whether the impacts are calculated at a per area, weight, volume or item basis in the corresponding EPDs. The impact assessment was performed next, by calculating each module with the corresponding EPD from the *LCAQuick* database. While modules A1-

A2-A3 are provided by the EPDs directly, modules A4 and A5 were estimated according to BRANZ's assumptions [73]. Specifically, A4 includes both ship and road transportation impacts, tailored to each EPD's origin and specifically for delivery in Auckland [73] and A5 refers to the construction waste generated for each input material which is calculated with correspondence to the *co-ordinated building information (CBI)* specification system of New Zealand. The absolute values of impacts for each building were obtained and normalized using both GFA and occupancy as functional units.

## 2.3. Sustainability assessment using TOPSIS

TOPSIS was selected as one of the most popular objective-weighted MCDM methods in the literature regarding sustainability of buildings [25,26,74,75]. Three different datasets were created (see Fig. 1) for the three assessment approaches with each one containing different criteria. The first one (A\_GFA), includes the four impact categories (GWP, EP, ODP, AP) normalized by the GFA and represents the conventional assessment approach. The second (A\_OCC) includes the four impact categories but normalized by the occupancy of the buildings rather than GFA. The third dataset (A\_COMB) refers to the proposed approach, which includes both normalizations in a single dataset (thus eight criteria instead of four).

### Step 1: Normalized Evaluation Matrix

First, each decision matrix (Eq. (3)), where  $i$  are the several criteria and  $j$  the alternative building designs, for the three TOPSIS scenarios, was normalized using *vector normalisation* (Eq. (4)) [75,76], given that  $j = 1, \dots, m$  and  $i = 1, \dots, n$ .

$$X = \begin{bmatrix} x_{11} & \dots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{mj} & \dots & x_{jn} \end{bmatrix} \quad (3)$$

$$z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^m x_{ij}^2}} \quad (4)$$

### Step 2: Weighting and determination of the normalized weighted matrix

The *criteria importance through intercriteria correlation* (CRITIC) weighting method was chosen for this study. CRITIC considers both variation (more weight for criteria with more dispersion) and correlation (lower weight for criteria that behave similarly to others) [77]. At first, impact scores for each criterion and building are normalised using *min-max normalisation* (Eq. (5)) [76]. Then, the standard deviation of each criterion was calculated using Eq. (6) along with the correlation coefficients (Eq. (7)), where  $i$  and  $k$  represent two different criteria and

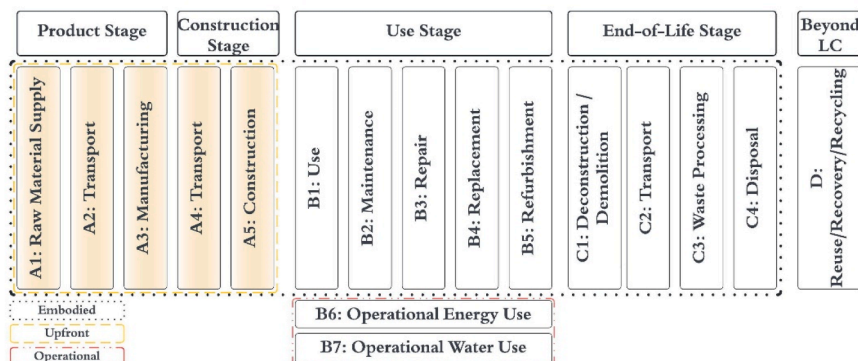


Fig. 2. Life Cycle Stages of Buildings & those included in the study (yellow).

$\bar{r}_i, \bar{r}_k$  the mean of all  $r_{ij}$  for criterion  $i$  and  $k$ , respectively. Standard deviation expresses the degree of variation while correlation coefficients express correlation between criteria.

$$r_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (5)$$

$$\sigma_i = \sqrt{\frac{1}{m} \sum_{j=1}^m (r_{ij} - \bar{r}_i)^2} \quad (6)$$

$$corr_{ik} = \frac{\sum_{j=1}^m (r_{ij} - \bar{r}_i)(r_{kj} - \bar{r}_k)}{\sqrt{\sum_{j=1}^m (r_{ij} - \bar{r}_i)^2 \sum_{j=1}^m (r_{kj} - \bar{r}_k)^2}} \quad (7)$$

Then the information content is calculated using Eq. (8) and it is normalised for each criterion using Eq. (9) to obtain the assigned weighting factors, given that  $i = 1, \dots, n$ .

$$C_i = \sigma_i \sum_{k \neq j} (1 - corr_{ik}) \quad (8)$$

$$w_i = \frac{C_i}{\sum_{i=1}^n C_i} \quad (9)$$

Next, the weighted normalized matrices were created using Eq. (10):

$$v_{ij} = w_i \times z_{ij} \quad (10)$$

where  $\sum_{i=1}^n w_i = 1$

#### Step 3: Determination of ideal solutions

The positive and negative ideal solutions for each TOPSIS criterion were found (Eqs. (11) and (12)):

$$V^+ = \{v_1^+, v_2^+, \dots, v_n^+\} \quad (11)$$

where  $v_i^+ = \min v_{ij}$ , for all  $j$

$$V^- = \{v_1^-, v_2^-, \dots, v_n^-\} \quad (12)$$

where  $v_i^- = \max v_{ij}$ , for all  $j$

#### Step 4: Calculation of Euclidean Distances from ideal solutions

The distances from the positive and negative ideal solutions were calculated using Eqs. (13) and (14):

$$S_j^+ = \sqrt{\sum_{i=1}^n (v_{ij} - v_i^+)^2} \quad (13)$$

$$S_j^- = \sqrt{\sum_{i=1}^n (v_{ij} - v_i^-)^2} \quad (14)$$

#### Step 5: Relative proximity to ideal solution and ranking

Finally, the relative proximity of the alternatives to the ideal solution (TOPSIS score) were calculated using Eq. (15):

$$C_j = \frac{S_j^-}{S_j^+ + S_j^-} \quad (15)$$

Where  $0 \leq C_i \leq 1$

The alternative building options were ranked from 1 to 8 according to their assigned  $C_j$  (higher  $C_j$  means higher ranking), for the several assessment approaches.

#### 2.4. Scenario-based analysis

To validate the proposed framework, we perform a scenario-based analysis for the New Zealand context. 109,333 consents for detached houses were approved across New Zealand from 2019Q2 to 2024Q2 (5 years) [78] while we assume that the percentage share of 1-storey and 2-storey houses among those is 73.7 % and 26.3 % respectively based on 2023 census data [79] that also align with earlier reports from BRANZ [80].

The eight case-study buildings are extrapolated to cover those 109,333 newly built houses with equal percentage distribution within each typology (73.7 % of the total consents among the four 1-storey buildings and 26.3 % of the total consents among the four 2-storey options). This is the no-assessment (NA) scenario and serves as a control scenario for comparison with the following hypothetical scenarios. Next, we assume that a percentage of designers and stakeholders use the LCA-TOPSIS methodology to select more sustainable building designs as part of reducing the sector's impacts. The percentage of those is set at 11.7 % and is based on a recent study that investigated the construction sector's stakeholders' engagement in sustainability assessments in New Zealand and found that 88.3 % of those never used *LCAQuick* while the rest used it from a rare to a consistent basis for their projects [81]. We assume that these designers will choose the most sustainable option for each typology (1-storey – 2-storey) based on the LCA-TOPSIS results. Therefore, three alternative scenarios are created according to the functional unit these designers could use. ALT I refers to A\_GFA from TOPSIS using GFA as functional unit, ALT II to A\_OCC using occupancy and ALT III to A\_COMB using the proposed approach. The quantified absolute impacts of those different scenarios alongside the no-assessment scenario were estimated and a comparison of their outcomes was conducted to evaluate the potential of the proposed integration at reducing the impacts at both the building (per GFA) and the urban (per occupancy) level.

#### 2.5. Correlation of the GWP results with national climate goals

A correlation of the total impacts with national climate change goals was conducted to highlight the impact of the proposed integration. Global Warming Potential (GWP) is the impact category of interest, as it is the only impact category included in national environmental strategies with quantified goals. The national carbon reduction plan for buildings sets a target of 0.9–1.7 MtCO<sub>2</sub>eq for the 2022–2025 period, which translates to annual reductions of 0.3–0.57 MtCO<sub>2</sub>eq [82]. This estimated amount is based on historical sector activity and refers to both commercial and residential buildings and the whole-building life cycle (operational impacts and embodied impacts). To modify the target to the scope of the performed analysis that refers to detached houses and upfront impacts (A1-A5), Eq. (16) was developed and used:

$$\text{Target}_{\text{modified}} = f_{\text{residential}} \times f_{\text{detached}} \times f_{\text{upfront carbon}} \times \text{Target}_{\text{initial}} \quad (16)$$

where  $f_{\text{residential}}$  refers to the share of building carbon emissions that are related to residential buildings,  $f_{\text{detached}}$  refers to the share among the residential emissions that are related to detached houses,  $f_{\text{upfront carbon}}$  refers to the share among the detached houses emissions that are upfront (A1-A5 in Fig. 2) and  $\text{Target}_{\text{initial}}$  refers to the initial target set by the carbon reduction plan for the whole sector [82].

The share of carbon emissions between commercial and residential buildings is assumed to be 36 %–64 % [5] (global estimation as mentioned in 1), therefore  $f_{\text{residential}}$  is set at 0.64. Detached houses represent approximately 66.7 % of the residential gross floor area consented in the last 5 years nationally [78] and by assuming that residential typologies have the same GWP per GFA,  $f_{\text{detached}}$  is set at 0.667. Finally, upfront carbon (A1-A5) represents approximately 20.4 % of whole life cycle's carbon in the New Zealand context, specifically for detached houses [23,58] (thus  $f_{\text{upfront carbon}} = 0.204$ ). This provides a modified reduction target ( $\text{Target}_{\text{modified}}$ ) of 0.0261–0.0496 upfront

MtCO<sub>2</sub>eq per year in detached houses in New Zealand.

### 3. Results & discussion

#### 3.1. Life cycle assessment (LCA) results

Fig. 3 shows the LCA results for the eight analysed buildings and the two different functional units. Overall, results align with recent findings regarding buildings in New Zealand's building sector. The upfront GWP was found to be between 177.14 and 266.88 kgCO<sub>2</sub>eq/GFA (reported 252.02 kgCO<sub>2</sub>eq/GFA in the literature [23] for a similar timber-frame residential building). The same applies for the other impact categories which were found to be in the ranges of 0.17 – 0.25 kgPO<sub>4</sub><sup>3-</sup>-eq/GFA, 4.5e-06 – 8.5e-06 kgCFC-11-eq/GFA and 1.07 to 1.61 kgSO<sub>2</sub>-eq/GFA, for EP, ODP and AP respectively, and are similar to values reported in the literature [83] in New Zealand. Therefore, it can be concluded that the LCA results are valid and depict the current performance of residential buildings in New Zealand.

It can be observed that in the GFA-centric analysis (Fig. 3a, c, e, g) buildings S1 and D1 are among the most impact-intensive while D3 is performing the worst in the impact category of ODP (Fig. 3e) followed by S3. On the other hand, D4, S2 and S4 perform the best for GWP, EP, AP (Fig. 3a, c, g), with S2 performing the best in both GWP and AP. In the impact categories of GWP, EP and AP (Fig. 3a, c, g), a similar relative performance of the buildings can be observed while ODP results (Fig. 3e) differ from that. This is mainly due to the extensive brick use in S3 and D3 in comparison to the rest of the buildings that use fibre-cement and timber weatherboards as cladding elements. Further analysis of the contributions of materials is beyond the scope of this study, but more information can be found in the supplementary material SM1.

LCA results that use occupancy as a functional unit are presented in Fig. 3b, d, f, h. D4 and S4 are the overall most impact-intensive alternatives in this assessment approach, while D3 and S3 continue to perform the worst in the ODP category (Fig. 3f). D1 and S2 perform the best for GWP, EP and AP with D1 having the best performance across 3 out of the 4 impact categories due to its high OLF. It is also interesting that S1, while having the second biggest OLF among the buildings (Table 1), does not outperform S2 in the occupancy-centric analysis (Fig. 3b, d, h), due to its higher impact intensity per GFA, as shown in Fig. 3a, c, e, g. Similar relative performance amongst the buildings is observed in this assessment approach in the impact categories of GWP, EP and AP (Fig. 3b, d, h), in the same manner as in Fig. 3a, c, g for the GFA-centric assessment.

When comparing the two assessment approaches, it can be observed that the trendline from the 2-storey buildings for the impact categories of GWP, EP and AP shifts from slightly reducing in the GFA analysis (Fig. 3a, c, g) to aggressively trending upwards for the occupancy-centric analysis (Fig. 3b, d, h). In a similar but milder way this applies to 1-storey buildings for GWP, EP and AP where trendlines in both assessments have an upwards tendency, but the rate shifts significantly. This difference depicts how functional unit selection is essential for interpreting LCA outcomes, and the potential limited depth of single-functional unit assessments. Relating this observation to the impact drivers of technology and affluence discussed in Section 1.3, D4 emerges as one of the most technologically advanced buildings, achieving low impacts per unit of space. However, its low OLF (Table 1) reflects extreme affluence, signifying excessive resource use per occupant. The opposite applies for D1.

The overall results between the two assessments are shown in Fig. 4. Both GFA-centric and occupancy-centric results were normalized using vector normalisation (Eq. (4)) so that they can be compared when visualized [76]. The corresponding OLF for the building stock is also normalised and depicted in Fig. 4 and how the buildings' impacts correspond to OLF can be observed. D1, D4, S1 and S4 are the buildings with the highest and lowest OLFs for the two typologies and are characterized by the biggest shifts in terms of performance across the two

assessments, while D1's performance has the most significant variation. This is due to D1 having a relatively poor performance in the GFA analysis while having the highest OLF among all.

#### 3.2. TOPSIS results

TOPSIS results can be seen in Fig. 5. Fig. 5a shows the TOPSIS scores deriving from Eq. (15) (relative proximity to ideal solutions), while Fig. 5b shows the rankings according to relative proximity sorted from highest to lowest ranking according to A\_GFA. A\_GFA and A\_OCC provided controversial TOPSIS rankings and scores that reflect the LCA results for each functional unit. D3 performed poorly for both due to high ODP impacts (Fig. 3e, f), the high weighting factor that CRITIC assigned to ODPsqm and ODPocc for A\_GFA and A\_OCC, respectively (APPENDIX Table A1), alongside average performance in the rest of the impact categories (Fig. 3). CRITIC assigned high weighting factors for ODP impacts due to the negative correlation of this criterion with the others. As mentioned in 3.1, ODP was the only impact category where the relative performance of buildings differed from GWP, EP, and AP. As a result, a higher weighting factor is assigned to ODP, to ensure that this negative correlation is reflected in the TOPSIS scores/rankings, without being overshadowed by the more homogenous results of the other three criteria (GWP, EP, AP). In the case of A\_COMB, CRITIC assigned ODPgfa and ODPocc weighting values similar to the other criteria, resulting in a more even weight distribution (APPENDIX Table A1). This is due to more criteria in the A\_COMB's decision matrix having negative correlation with each other in comparison with A\_GFA and A\_OCC; GFA-centric criteria (GWPgfa, EPgfa, ODPgfa and APgfa) have a negative correlation with the occupancy-centric ones (which can be also seen in the LCA results of Fig. 3 as discussed in 3.1). Although ODP criteria were not weighted more heavily, A\_COMB ranked D3 last and S3 6th (similar to A\_GFA). Therefore, it can be concluded that D3 had the worst overall performance among the building options.

On the other hand, D1 had the best performance for A\_OCC and A\_COMB, while S1 and D2 were ranked second in the two assessments, respectively. This underscores the potential of the proposed integration; A\_OCC ranked S1 2nd, despite its significantly poor performance in the GFA-centric assessment (7th), while A\_COMB performed better by ranking D2 2nd, which had a satisfactory performance in both GFA and occupancy-centric assessments (ranked 3rd in both (Fig. 5b)).

TOPSIS scores for A\_GFA and A\_OCC had relatively big variations in comparison to A\_COMB (Fig. 5a) (in the 0.28–0.92 range for A\_GFA and 0.16–0.99 for A\_OCC). On the other hand, A\_COMB's scores were between 0.35–0.69. This is due to A\_COMB's decision matrix containing more criteria than the other assessment's matrices (eight criteria instead of four), as well as more negative correlation among them, therefore resulting in more even distribution of scores. The dual-functional unit (A\_COMB) approach adds an additional layer of multidimensionality, resulting in greater comprehensiveness. For example, an assessment examining a single criterion (e.g. GWP) will have far more clearly differentiated results in comparison to one that examines 2 or more (e.g. GWP and cost). Therefore, the results of TOPSIS are more evenly distributed, representing both of the buildings' functions. This is also depicted in A\_COMB's rankings (Fig. 5b), which are often in between the rankings of A\_GFA and A\_OCC.

#### 3.3. Scenario-based analysis results

The scenario-based analysis examined the outcomes of the three presented LCA-TOPSIS assessment approaches. ALT I promoted the construction of S4 and D4. ALT II promoted D1 and S1, while ALT III promoted D1 and S2. Fig. 6 presents the percentage difference of the average impact values both per GFA and occupancy for each alternative scenario compared to the no-assessment (NA) scenario. ALT I performed well in the GFA-centric criteria and had the best performance for EPgfa and ODPgfa where the average values were reduced by 0.56 % and 2.58



Fig. 3. Environmental Impacts per gross floor area (GFA) and per occupancy for each building.

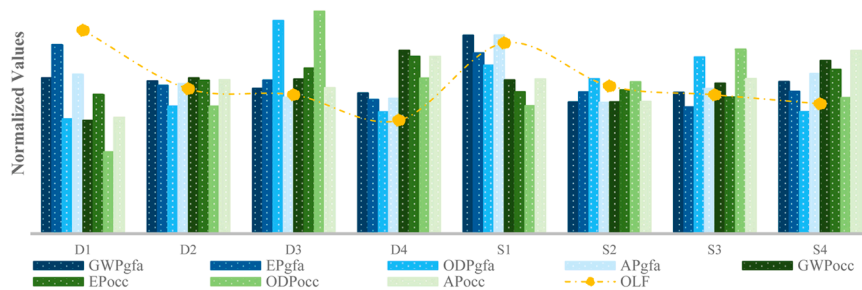


Fig. 4. Impact categories(per gross floor area (GFA) & per occupancy & occupational load factor (OLF) normalised using Eq. (4).

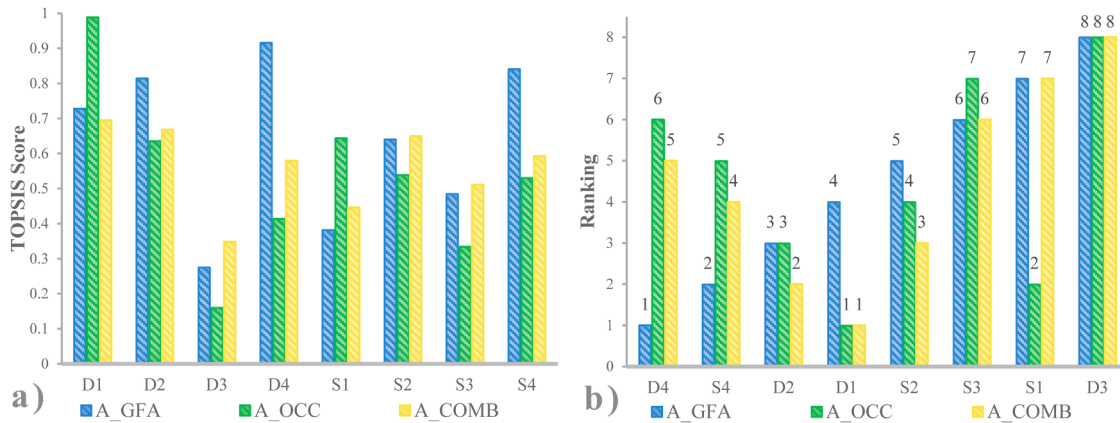


Fig. 5. TOPSIS scores (a) and TOPSIS rankings (b) for the three assessments.

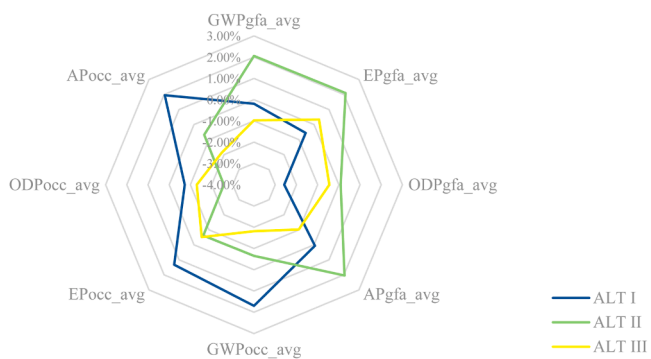


Fig. 6. Percentage difference of average impacts per gross floor area (GFA) and per occupancy for the alternative scenarios compared to the no-assessment scenario (NA).

% respectively in comparison to the NA scenario. On the other hand, ALT II had the best performance in EPocc and ODPOcc with reductions of 0.62 % and 2.58 % respectively. ALT III performed the best, with reductions in 7 out of the 8 criteria and only one positive percentage difference (EPgfa) (Fig. 6). For GWPgfa, APgfa, GWPOcc, and APocc, the reductions were 0.97 %, 1.02 %, 1.81 %, and 1.86 %, respectively. The mean percentage difference for the eight criteria, compared to the no-assessment scenario, is  $-0.95\%$  for ALT III. For ALT I and ALT II this number equals  $+0.12\%$  and  $+0.22\%$ .

Fig. 7a shows the percentage difference of total cumulative impacts and occupational load factor (OLF) for alternative scenarios I, II, and III in comparison to the NA scenario (deriving from Table 2). As hypothesized in 1.3, the selection of GFA as a functional unit, led to more total impacts in 3 out of 4 impact categories. Only reductions in total ODP were achieved, which is due to fewer D3s being built (D3 having the highest ODP impacts, see Fig. 3) compared to the NA scenario (a trend

observed in all ALT scenarios, explaining the relatively high reductions in ODP). In ALT I, the OLF was decreased by 1.86 % (approx. providing  $0.7\text{m}^2$  more space per occupant) which is also shown in Fig. 7b where ALT I had the most built gross floor area, while also accommodating less occupants in comparison to NA. This was due to promoting D4 and S4, both of which are larger buildings with lower OLFs. For the case of ALT II, reductions in total impacts were achieved across all criteria (Fig. 7a) while the OLF was increased by 2.73 % (providing approximately  $0.98\text{m}^2$  less space per occupant in comparison to NA). Regarding ALT III, impact reductions were the greatest in GWP and AP (Fig. 7a), alongside the greatest mean percentage reduction of total impacts ( $-2.22\%$ ) (ALT I's and ALT II's mean percentage difference was  $+0.19\%$  and  $-1.98\%$  respectively) (APPENDIX Table A2). Furthermore, ALT III provided more space per occupant in comparison to ALT II ( $0.67\text{m}^2$  per occupant more, compared to ALT II— $0.31\text{m}^2$  per occupant less, compared to NA). The total number of occupants for all alternative scenarios was the same and 0.86 % less than NA (Fig. 7b), due to the promoted buildings (S1, D1, S2, D4, S4) by ALT scenarios having the same occupancy (Table 1).

Overall, the results of the scenario-based analysis indicate that excluding occupancy-centric metrics in the LCA of buildings can result in higher total impacts in the long term. On the other hand, using occupancy as a functional unit may lead to suboptimal strategies where denser buildings (regarding space/occupant) are promoted, without considering their efficiency as space providers (e.g. S1 in Fig. 3). Essentially, this translates to suboptimal performance of products when they are assessed and promoted based on only one of the two identified environmental impact drivers that relate to their functions (technology-space, affluence-shelter). The proposed approach (ALT III) offered a balanced evaluation of the buildings across the two functions and therefore yielded the best results.

### 3.4. Correlation of the results with national climate goals

The quantified total impacts of the different alternatives and the NA

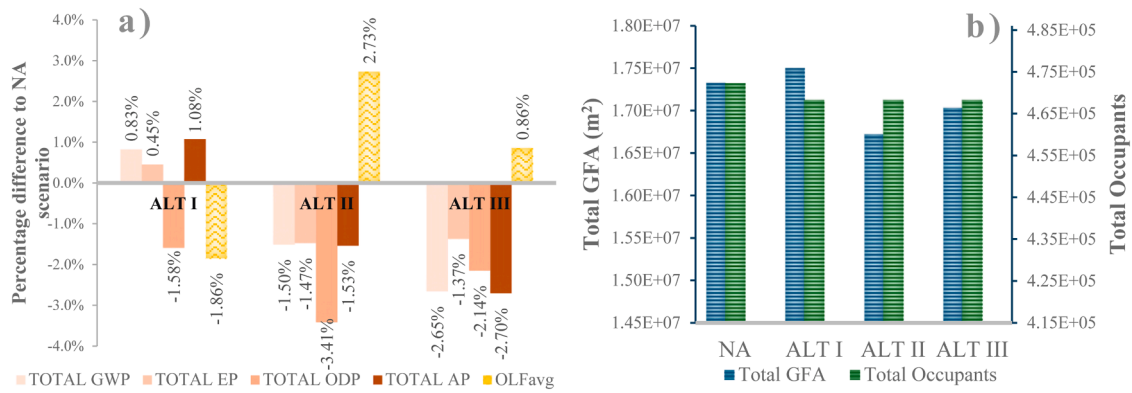


Fig. 7. Percentage difference of total impacts for the alternative scenarios compared to the no-assessment scenario (NA) (a) and total gross floor area & occupancy of the different scenarios (b).

Table 2  
Total quantified environmental impacts (2019Q2–2024Q2) and average OLF per scenario.

Scenario	Total GWP (MtCO <sub>2</sub> eq)	Total EP (kg PO <sub>4</sub> <sup>3-</sup> -eq)	Total ODP (kgCFC11-eq)	Total AP (kgSO <sub>2</sub> -eq)	OLFavg (occupants/GFA)
NA	3.5204	3.3585E+06	1.0587E+02	2.1448E+07	0.02723
ALT I	3.5495	3.3738E+06	1.0420E+02	2.1680E+07	0.02672
ALT II	3.4674	3.3092E+06	1.0226E+02	2.1120E+07	0.02797
ALT III	3.4269	3.3127E+06	1.0360E+02	2.0869E+07	0.02746

scenario are presented in Table 2. Regarding GWP, NA resulted in a total of 3.5204 MtCO<sub>2</sub>eq which corresponds to approximately 0.704 MtCO<sub>2</sub>eq per year (for the 5-year period under-study). This amount aligns with the projected emissions (prior to reduction strategies) reported in the national carbon reduction plan when Eq. (16) is used for modification [82] (0.705 MtCO<sub>2</sub>eq per year prior to reduction strategies). Therefore, NA acts as the control scenario and is assumed to have 0 % reduced carbon. By correlating the modified GWP target with the study’s results, it can be observed that ALT I fails to achieve any reduction and instead emits an additional 0.00582 MtCO<sub>2</sub>eq per year. ALT II results in a reduction of 0.0106 MtCO<sub>2</sub>eq per year (40.61 % of the target’s low end), whereas ALT III results in a reduction of 0.0187 MtCO<sub>2</sub>eq per year (71.65 % of the target’s low end) and provides 0.67 m<sup>2</sup> more space per occupant compared to ALT II. The results can be seen in Fig. 8. Considering that the national guidelines involve several actions to achieve the proposed carbon reduction targets, the results underscore the importance of including occupancy-centric metrics, and therefore the effect of affluence, in building LCAs to achieve environmental goals while highlighting the GFA-centric approach’s inefficient performance. The results also highlight the importance of early design and stakeholder engagement in sustainability strategies. The 11.7 % of stakeholders assumed to participate in sustainability practices for this analysis would have been sufficient to achieve 71.65 % of the national climate goal by

assessing and promoting specific buildings, and without the need to develop, adapt, or use any high-end materials or systems. Ultimately, it becomes clear that single-dimensional assessments fail to capture the full picture—tending to favor either more technologically advanced or denser options, which lead to suboptimal outcomes.

### 3.5. Limitations

With regard to environmental impact categories, the four selected are among the most commonly used, resulting in a more accurate data representation in the EPDs. On the other hand, other impact categories relevant to human health, such as Human Toxicity Potential (HTP) and Particulate Matter Formation (PMF), could have added more value to the LCA results due to concerns about construction materials and their effect on residents’ health [84]. These were not included due to their unavailability from LCAQuick. In the same realm, the exclusion of operational impacts (B6, B7 modules in Fig. 2), limited the value of the LCA results with regards to the specific building designs. Unfortunately, no energy-modelling data were available for the case-studies. The exclusion of the above modules and impact categories does not affect the main finding of the study but limits the depth of the LCA results—and their correlation with the national carbon reduction plan regarding building design and material selection. The scenario-based analysis and its results is subject to several limitations and assumptions. The eight building designs were extrapolated to cover the detached building consents of the last 5 years in New Zealand. The extrapolation method is widely used for building stock modelling but also known for its limitations which relate to the sample’s representativeness [85]. In this study, buildings recently designed in the last six years for the context of Auckland were used, and thus the extrapolation’s accuracy is considered satisfactory. Additionally, it was assumed that the stakeholders who performed the sustainability assessment would eventually choose the best design for each building typology. This assumption ignores the importance of criteria beyond the ones included in this study such as economic and social which may have altered the selection’s outcome in some cases. Furthermore, a *fixed-consents* approach was adopted in this study rather than a *fixed-GFA* or *fixed-occupancy*. This means that the residential buildings market is assumed to be unaffected by demand or



Fig. 8. TOTAL GWP reduction per year compared to NA and national GWP reduction targets per year for 2022–2025 [82].

other socioeconomic factors during this period. For example, the fact that the alternative scenarios provided shelter to fewer occupants is not considered in Fig. 7a (the total impacts refer to fixed number of new built buildings rather than occupants). Each alternative scenario's efficiency to provide housing per occupant (alongside per gross floor area) is depicted in Fig. 6 though, where ALT III performed similarly to ALT I and ALT II in the GFA-centric and occupancy-centric criteria, respectively, while performing superiorly when all criteria are considered. Finally, the results from 3.4, present the scenarios' performance only for GWP due to a shortage of quantified national targets for the other impact categories. Similar results are expected for AP, but not for EP and ODP. For those, ALT II is expected to have better relative performance compared to ALT III in terms of total impact reduction, while the difference in average OLFs is expected to remain the same.

#### 4. Conclusions & future research

It was identified that current sustainability frameworks in Life Cycle Assessment (LCA) of buildings fail to account for both functions of residential buildings—providing space and shelter—by adopting single-dimensional functional units and promoting impact reductions either at the building or urban level. The two identified functions of buildings were then correlated with the environmental impact drivers from the  $I=PAT$  equation. By doing so, it was concluded that current frameworks orient themselves towards technological improvements at the building level, while urban-scale studies use occupancy-centric units—not primarily to address affluence, but because this function aligns with their scope. The study's results showed that GFA-centric assessments, that orient themselves towards solely technological advances, may lead to greater absolute impacts by excluding the key factor driving building stock development: occupancy. Conversely, occupancy-centric assessments, fail to offer valuable insights at the building level as they may inadvertently promote densely packed buildings that are inefficient in terms of space provision. This study proposes an integrated assessment approach that incorporates occupancy density into building LCA, considering both functional units and applying a multi-criteria decision method for optimal building design selection. The proposed approach yielded the best results by promoting buildings that demonstrate balanced performance across both functions for the four impact categories under study, resulting in the lowest absolute impacts and more available space per occupant. As the human population increases and resources deplete, it is crucial for humanity to develop optimal resource allocation strategies that ensure both human well-being and environmental sustainability. Finally, by integrating occupancy density into building LCA, this study highlights affluence as a potential key driver of future residential development—one whose strategic inclusion in assessments could enable more effective environmental impact mitigation, whereas its neglect may accelerate resource depletion and hinder the transition to a sustainable future. It is essential for future research to apply the proposed framework to larger datasets with regard to building alternatives. By doing so, a better understanding of how the occupational load factor (OLF) affects the environmental performance of buildings at the urban level can be gained, potentially leading to the identification of optimal OLF ranges—aligning with planetary boundaries—for the residential sector. OLF ranges could be further refined by research examining social impacts of density, such as

mapping the effect of higher or lower occupancy densities on the social wellbeing of occupants. Additionally, research regarding space allocation in relation to socioeconomic criteria would provide a baseline upon which future policies can be shaped to promote densification strategies that enhance socially sustainable outcomes, rather than making both dense and non-dense neighbourhoods equally denser (e.g., densification scenarios only for areas with extremely low OLFs and therefore high impacts per capita). Finally, and beyond buildings, further research should apply dual or multi-functional unit assessments in other impact-intensive sectors to identify the effect of functional unit selection on absolute impacts and the potential for integrating affluence-related metrics towards absolute impact reductions. Since the planet has defined limits that anthropogenic pollution should not surpass, it is essential to include affluence in the environmental performance of products, rather than focusing solely on technology by adopting relative indexes that could promote further consumption of resources per capita (as established by ALT I scenario in this study—promoting more spatially-efficient buildings that lack affluence-related efficiency).

#### Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT-4 by OpenAI & DeepseekV3.1 in order to improve the clarity, grammar, and overall readability of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

#### CRediT authorship contribution statement

**Gerasimos Christoforatos:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Kim Pickering:** Writing – review & editing, Supervision, Funding acquisition. **Christian Gauss:** Writing – review & editing, Validation, Methodology. **Krishanu Roy:** Writing – review & editing. **Mohammad Dalour Beg:** Writing – review & editing.

#### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Gerasimos Christoforatos reports financial support was provided by BRANZ. Gerasimos Christoforatos reports financial support was provided by New Zealand Ministry of Business Innovation and Employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.buildenv.2025.113559](https://doi.org/10.1016/j.buildenv.2025.113559).

#### APPENDIX

Table A1,A2

**Table A1**  
CRITIC weighting factors for each assessment.

Criterion	A_GFA	A_OCC	A_COMB
GWP <sub>gfa</sub>	0.15277113	x	0.106747
EP <sub>gfa</sub>	0.24016499	x	0.1648
ODP <sub>gfa</sub>	0.42674838	x	0.137822
AP <sub>gfa</sub>	0.1803155	x	0.120626
GWP <sub>occ</sub>	x	0.162263087	0.102677
EP <sub>occ</sub>	x	0.266745867	0.138268
ODP <sub>occ</sub>	x	0.354099168	0.117844
AP <sub>occ</sub>	x	0.216891878	0.111216

**Table A2**  
Percentage differences of alternative scenarios' total impacts to the no-assessment (NA) scenario.

Scenario	TOTAL GWP	TOTAL EP	TOTAL ODP	TOTAL AP	Mean
ALT I	0.83 %	0.45 %	-1.58 %	1.08 %	0.20 %
ALT II	-1.50 %	-1.47 %	-3.41 %	-1.53 %	-1.98 %
ALT III	-2.65 %	-1.37 %	-2.14 %	-2.70 %	-2.22 %

## Data availability

Data will be made available upon reasonable request and in accordance with the data-sharing agreement between the provider and the authors

## References

- [1] K. Govindan, K.Madan Shankar, D. Kannan, Sustainable material selection for construction industry - a hybrid multi criteria decision making approach, *Renew. Sustain. Energy Rev.* 55 (Mar. 2016) 1274–1288, <https://doi.org/10.1016/j.rser.2015.07.100>.
- [2] B. Regúlez, D.M.V. Faria, L. Todisco, M.Fernández Ruiz, H. Corres, Sustainability in construction: the urgent need for a new ethics, *Struct. Concr.* 24 (2) (Apr. 2023) 1893–1913, <https://doi.org/10.1002/suco.202200406>.
- [3] United Nations Environment Programme, *Building Materials and the Climate: Constructing a New Future*, 2023. Nairobi Accessed: Mar. 14, 2025. [Online]. Available: <https://wedocs.unep.org/20.500.11822/43293>.
- [4] M.S. Sandanayake, Environmental Impacts of Construction in Building Industry—A Review of Knowledge Advances, Gaps and Future Directions, *Knowledge 2* (1) (Mar. 2022) 139–156, <https://doi.org/10.3390/knowledge2010008>.
- [5] Shobhakar Dhakal, Jan Christoph Minx, Ferenc L. Toth, Emissions Trends and Drivers, in: B. Amon, D. Stern (Eds.), *Climate Change 2022 - Mitigation of Climate Change*, Cambridge University Press, 2023, pp. 215–294, <https://doi.org/10.1017/9781009157926.004>.
- [6] B. Goldstein, F.N. Rasmussen, *LCA of Buildings and the Built Environment. Life Cycle Assessment*, Springer International Publishing, Cham, 2018, pp. 695–722, [https://doi.org/10.1007/978-3-319-56475-3\\_28](https://doi.org/10.1007/978-3-319-56475-3_28).
- [7] S. Kechidi, N. Banks, Minimising upfront carbon emissions of steel-framed modular housing: a case study, *J. Build. Eng.* 72 (Aug. 2023), <https://doi.org/10.1016/j.job.2023.106707>.
- [8] M. Röck, et al., Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation, *Appl. Energy* 258 (Jan. 2020), <https://doi.org/10.1016/j.apenergy.2019.114107>.
- [9] A.A. Dani, R. Feng, Z. Fang, K. Roy, Life Cycle Assessment of a Structural Insulated Panel Modular House in New Zealand, *Buildings* 15 (1) (Jan. 2025), <https://doi.org/10.3390/buildings15010146>.
- [10] T. Bruce-Hyrkäs, P. Pasanen, R. Castro, Overview of Whole Building Life-Cycle Assessment for Green Building Certification and Ecodesign through Industry Surveys and Interviews. *Procedia CIRP*, Elsevier B.V., 2018, pp. 178–183, <https://doi.org/10.1016/j.procir.2017.11.127>.
- [11] Q. Tushar, M.A. Bhuiyan, G. Zhang, T. Maqsood, An integrated approach of BIM-enabled LCA and energy simulation: the optimized solution towards sustainable development, *J. Clean. Prod.* 289 (Mar. 2021), <https://doi.org/10.1016/j.jclepro.2020.125622>.
- [12] A. Mohammed, I. Elmasoudi, M. Ghannam, Life cycle environmental impact assessment of steel structures using building information modeling, *Innov. Infrastruct. Solut.* 10 (1) (Jan. 2025), <https://doi.org/10.1007/s41062-024-01840-8>.
- [13] M. Najjar, K. Figueiredo, M. Palumbo, A. Haddad, Integration of BIM and LCA: evaluating the environmental impacts of building materials at an early stage of designing a typical office building, *J. Build. Eng.* 14 (Nov. 2017) 115–126, <https://doi.org/10.1016/j.job.2017.10.005>.
- [14] L. Ma, R. Azari, M. Elnimeiri, A Building Information Modeling-Based Life Cycle Assessment of the Embodied Carbon and Environmental Impacts of High-Rise Building Structures: a Case Study, *Sustain.* (Switz.) 16 (2) (Jan. 2024), <https://doi.org/10.3390/su16020569>.
- [15] H. Feng, M. Kassem, D. Greenwood, O. Doukari, Whole building life cycle assessment at the design stage: a BIM-based framework using environmental product declaration, *Int. J. Build. Pathol. Adapt.* 41 (1) (Mar. 2023) 109–142, <https://doi.org/10.1108/IJBPA-06-2021-0091>.
- [16] C.K. Anand, B. Amor, Recent developments, future challenges and new research directions in LCA of buildings: a critical review, *Renew. Sustain. Energy Rev.* 67 (Jan. 2017) 408–416, <https://doi.org/10.1016/j.rser.2016.09.058>.
- [17] National Renewable Energy Laboratory, U.S. Life Cycle Inventory Database, 2012. Accessed: Mar. 25, 2025. [Online]. Available: <https://www.lcacommons.gov/nrel/search>.
- [18] T.D. Nguyen, P. Pishdad-Bozorgi, A Review of Life Cycle Assessment Tools for Measuring the Environmental Impact of Building and a Decision Support Framework for Choosing Among Them, *EasyChair* (Dec. 2023) 816, <https://doi.org/10.29007/pcmw.-806>.
- [19] Building Research Association of New Zealand, “LCAQuick.” Accessed: Apr. 08, 2025. [Online]. Available: <https://www.branz.co.nz/environment-zero-carbon-research/framework/lcaquick/version-history/>.
- [20] D. Dowdell, B. Berg, J. Butler, A. Pollard, Study report SR418 New Zealand whole-building whole-of-life framework: ICAQuick v3.4 – a tool to help designers understand how to evaluate building environmental performance [Online]. Available, [www.branz.co.nz/co2nstruct](http://www.branz.co.nz/co2nstruct), 2020.
- [21] R. Paschoalin, N. Isaacs, F. Chicca, *The Environmental Impact of Retrofitting Heritage Buildings in New Zealand*, in: L.L. Wang, H. Ge, Z.J. Zhai, D. Qi, M. Ouf, C. Sun, D. Wang (Eds.), *Proceedings of the 5th International Conference on Building Energy and Environment*, Springer Nature Singapore, Singapore, 2023, pp. 443–451.
- [22] R. Paschoalin, N. Isaacs, *Historic Buildings and Energy Efficiency in New Zealand: A theoretical Study of a Holistic Refurbishment of a 1930s Heritage Building's Windows*, EEHB, 2020.
- [23] A.A. Dani, K. Roy, R. Masood, Z. Fang, J.B.P. Lim, A comparative study on the life cycle assessment of New Zealand residential buildings, *Buildings* 12 (1) (Jan. 2022), <https://doi.org/10.3390/buildings12010050>.
- [24] I.J. Navarro, V. Yepes, J.V. Martí, A review of multicriteria assessment techniques applied to sustainable infrastructure design, *Adv. Civ. Eng.* 2019 (2019), <https://doi.org/10.1155/2019/6134803>.
- [25] P. Ziemba, Application framework of multi-criteria methods in sustainability assessment, *Energ.* (Basel) 15 (23) (Dec. 2022), <https://doi.org/10.3390/en15239201>.
- [26] B. Mecca, Assessing the sustainable development: a review of multi-criteria decision analysis for urban and architectural sustainability, *J. Multi-Criteria Decis. Anal.* 30 (5–6) (Sep. 2023) 203–218, <https://doi.org/10.1002/mcda.1818>.
- [27] A. Ulutaş, F. Balo, K. Mirković, Z. Stević, M.M.H. Mostafa, MCDM model for critical selection of building and insulation materials for optimising energy usage and environmental effect in production focus, *J. Civ. Eng. Manag.* 29 (7) (Aug. 2023) 587–603, <https://doi.org/10.3846/jcem.2023.19569>.
- [28] I. Emovon, O.S. Ogheniyerovwho, Application of MCDM method in material selection for optimal design: a review, *Results Mater.* 7 (Sep. 2020), <https://doi.org/10.1016/j.rinma.2020.100115>.
- [29] A. Fazeli, F. Jalaei, M. Khanzadi, S. Banihashemi, BIM-integrated TOPSIS-Fuzzy framework to optimize selection of sustainable building components, *Int. J. Constr. Manag.* 22 (7) (2022) 1240–1259, <https://doi.org/10.1080/15623599.2019.1686836>.

- [30] M. Kabak, E. Köse, O. Kirilmaz, S. Burmaoğlu, A fuzzy multi-criteria decision making approach to assess building energy performance, *Energy Build.* 72 (Apr. 2014) 382–389, <https://doi.org/10.1016/j.enbuild.2013.12.059>.
- [31] E. Klumbyte, R. Blüdzius, M. Medineckienė, P.A. Fokaides, An MCDM model for sustainable decision-making in municipal residential buildings facilities management, *Sustain.* (Switz.) 13 (5) (Mar. 2021) 1–16, <https://doi.org/10.3390/su13052820>.
- [32] A. Francis, A. Thomas, System dynamics modelling coupled with multi-criteria decision-making (MCDM) for sustainability-related policy analysis and decision-making in the built environment, *Smart Sustain.* Built Environ. 12 (3) (Apr. 2023) 534–564, <https://doi.org/10.1108/SASBE-09-2021-0156>.
- [33] A.T. Balasbaneh, W. Sher, Economic and environmental life cycle assessment of alternative mass timber walls to evaluate circular economy in building: MCDM method, *Env. Dev Sustain* 26 (1) (Jan. 2024) 239–268, <https://doi.org/10.1007/s10668-022-02707-7>.
- [34] G. da M. Passos Neto, L.H. Alencar, R. Valdes-Vasquez, Multiple-criteria methods for assessing social sustainability in the built environment: a systematic review, *Sustain.* (Switz.) 15 (23) (Dec. 2023), <https://doi.org/10.3390/su152316231>.
- [35] G. Bramley, S. Power, Urban form and social sustainability: the role of density and housing type, *Env. Plann B Plann Des* 36 (1) (2009) 30–48, <https://doi.org/10.1068/b33129>.
- [36] V. Cheng, K. Steemers, M. Montavon, R. Compagnon, Urban form, density and solar potential, *PLEA 2006* (Jan. 2006).
- [37] E. Ahmadian, B. Sodagar, C. Bingham, A. Elnokaly, G. Mills, Effect of urban built form and density on building energy performance in temperate climates, *Energy Build.* 236 (Apr. 2021), <https://doi.org/10.1016/j.enbuild.2021.110762>.
- [38] J. Norman, H.L. Maclean, M. Asce, C.A. Kennedy, Comparing high and low residential density: life-cycle analysis of energy use and greenhouse gas emissions, *J. Urban Plan. Dev.* (2006), <https://doi.org/10.1061/ASCE0733-94882006132:110>.
- [39] A. Kamal, et al., Impact of urban morphology on urban microclimate and building energy loads, *Energy Build.* 253 (Dec. 2021), <https://doi.org/10.1016/j.enbuild.2021.111499>.
- [40] J. Allan, et al., Operational and embodied emissions associated with urban neighbourhood densification strategies, *Energy Build.* 276 (Dec. 2022), <https://doi.org/10.1016/j.enbuild.2022.112482>.
- [41] N. Dempsey, C. Brown, G. Bramley, The key to sustainable urban development in UK cities? The influence of density on social sustainability, *Prog. Plann.* 77 (3) (Apr. 2012) 89–141, <https://doi.org/10.1016/j.progress.2012.01.001>.
- [42] S. Dave, High Urban Densities in Developing Countries: a Sustainable Solution? *Built Env.* 36 (1) (2010) 9–27. Accessed: Mar. 14, 2025. [Online]. Available: <https://www.jstor.org/stable/23289981>.
- [43] United Nations, New Urban Agenda, United Nations, 2017. Accessed: Mar. 14, 2025. [Online]. Available: <https://www.urbanagendaplatform.org/nua>.
- [44] E. Trepci, P. Maghelal, E. Azar, Effect of densification and compactness on urban building energy consumption: case of a Transit-Oriented Development in Dallas, TX, *Sustain. Cities. Soc.* 56 (May 2020), <https://doi.org/10.1016/j.scs.2019.101987>.
- [45] C. Marincu, D. Dan, L. Moga, Investigating the influence of building shape and insulation thickness on energy efficiency of buildings, *Energy Sustain. Dev.* 79 (Apr. 2024), <https://doi.org/10.1016/j.esd.2024.101384>.
- [46] H.L. Gauch, C.F. Dunant, W. Hawkins, A.Cabrera Serrenho, What really matters in multi-storey building design? A simultaneous sensitivity study of embodied carbon, construction cost, and operational energy, *Appl. Energy* 333 (Mar. 2023), <https://doi.org/10.1016/j.apenergy.2022.120585>.
- [47] H.T. Ebuy, H.Brill El Haouzi, R. Benelmir, R. Pannequin, Occupant Behavior Impact on Building Sustainability Performance: a Literature Review, *Sustain.* (Switz.) 15 (3) (Feb. 2023), <https://doi.org/10.3390/su15032440>.
- [48] J.P. Holdren and P.R. Ehrlich, “Human Population and the Global Environment: population growth, rising per capita material consumption, and disruptive technologies have made civilization a global ecological force.” [Online]. Available: <https://about.jstor.org/terms>.
- [49] T. Wiedmann, M. Lenzen, L.T. Keyßer, J.K. Steinberger, Scientists’ warning on affluence, *Nat. Commun.* 11 (1) (Dec. 2020), <https://doi.org/10.1038/s41467-020-16941-y>.
- [50] H.H. de Simone Souza, et al., Functional unit influence on building life cycle assessment, *Int. J. Life Cycle Assess.* 26 (3) (Mar. 2021) 435–454, <https://doi.org/10.1007/s11367-020-01854-1>.
- [51] M.R.M. Saade, G. Guest, B. Amor, Comparative whole building LCAs: how far are our expectations from the documented evidence? *Build Env.* 167 (Jan. 2020) <https://doi.org/10.1016/j.buildenv.2019.106449>.
- [52] M. Lavagna, et al., Benchmarks for environmental impact of housing in Europe: definition of archetypes and LCA of the residential building stock, *Build Env.* 145 (Nov. 2018) 260–275, <https://doi.org/10.1016/j.buildenv.2018.09.008>.
- [53] S. González-García, M.R. Caamaño, M.T. Moreira, G. Feijoo, Environmental profile of the municipality of Madrid through the methodologies of Urban Metabolism and Life Cycle Analysis, *Sustain. Cities. Soc.* 64 (Jan. 2021), <https://doi.org/10.1016/j.scs.2020.102546>.
- [54] M. Lotteau, P. Loubet, M. Pousse, E. Dufrasnes, G. Sonnemann, Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale, *Build Env.* 93 (P2) (Nov. 2015) 165–178, <https://doi.org/10.1016/j.buildenv.2015.06.029>.
- [55] J. Alberti, C. Brodhag, P. Fullana-i-Palmer, First steps in life cycle assessments of cities with a sustainability perspective: a proposal for goal, function, functional unit, and reference flow, *Sci. Total Environ.* 646 (Jan. 2019) 1516–1527, <https://doi.org/10.1016/j.scitotenv.2018.07.377>.
- [56] S.C. Andersen, S. Petersen, M. Ryberg, L.L. Molander, M. Birkved, Ten questions concerning absolute sustainability in the built environment, *Build Env.* 251 (Mar. 2024), <https://doi.org/10.1016/j.buildenv.2024.111220>.
- [57] L.Hvid Horup, et al., Evaluating mitigation strategies for building stocks against absolute climate targets, *Build. Cities* 5 (1) (2024) 117–132, <https://doi.org/10.5334/bc.413>.
- [58] S.J. McLaren, C. Chandrakumar, D. Dowdell, L. Bullen, R. Jaques, Application of absolute sustainability assessment to new zealand residential dwellings, in: *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Nov. 2020, <https://doi.org/10.1088/1755-1315/588/2/022064>.
- [59] B. Tozan, E. Hoxha, C. Ole Olsen, C. Grau Sørensen, H. Birgisdóttir, Exploring the relationship of building area and GHGe: a mitigation strategy? *IOP Conf Ser Earth Env. Sci* 1402 (1) (Oct. 2024) 012048 <https://doi.org/10.1088/1755-1315/1402/1/012048>.
- [60] S.J. Kim, S. Kara, M. Hauschild, Functional unit and product functionality—Addressing increase in consumption and demand for functionality in sustainability assessment with LCA, *Int. J. Life Cycle Assess.* 22 (8) (Aug. 2017) 1257–1265, <https://doi.org/10.1007/s11367-016-1233-3>.
- [61] J. Rockström, et al., Planetary boundaries: exploring the safe operating space for humanity [Online]. Available: <https://about.jstor.org/terms>, 2009.
- [62] F. Creutzig, et al., Towards Demand-Side Solutions for Mitigating Climate Change, *Nature Publishing Group*, Apr. 01, 2018, <https://doi.org/10.1038/s41558-018-0121-1>.
- [63] Autodesk, Autodesk Revit, 24, Autodesk, San Rafael, CA, 2023.
- [64] L.T. Wong, Occupant load assessment for old residential high-rise buildings, *Arch. Sci Rev* 46 (3) (Sep. 2003) 273–277, <https://doi.org/10.1080/00038628.2003.9696994>.
- [65] G. De Sanctis, J. Kohler, M. Fontana, Probabilistic assessment of the occupant load density in retail buildings, *Fire Saf. J.* 69 (2014) 1–11, <https://doi.org/10.1016/j.firesaf.2014.07.002>.
- [66] B. Harley, A. Gifford, Field guide residential new construction, NJ, USA, <https://n.jcleanenergy.com/>, 2008.
- [67] D. Enz, R. Hastings, Proven designs for very low energy housing – swiss experience, in: *EUROPEAN CONFERENCE AND COOPERATION EXCHANGE - Sustainable energy systems for buildings: challenges and changes*, Vienna, Austria, 2006.
- [68] International Standards Organization, “International Standard ISO 14044 (2006) Environmental management — Life cycle assessment — Requirements and guidelines,” 2006.
- [69] International Standards Organization, “International Standard ISO 14040 (2006) Environmental Management—Life Cycle Assessment—Principle and Framework,” 2006.
- [70] A. Petit-Boix, et al., Application of Life Cycle Thinking Towards Sustainable Cities: A Review, Elsevier Ltd, Nov. 10, 2017, <https://doi.org/10.1016/j.jclepro.2017.08.030>.
- [71] European Committee for Standardization (CEN), “EN 15804:2012+A2:2019 - sustainability of construction works – environmental product declarations – Core rules for the product category of construction products,” Brussels, Belgium, 2019. Accessed: Mar. 14, 2025. [Online]. Available: <https://standards.cencenelec.eu/>.
- [72] New Zealand Government, “Clause B2 durability – building code 1992.” Accessed: May 19, 2025. [Online]. Available: <https://www.legislation.govt.nz/regulation/public/1992/0150/latest/whole.html>.
- [73] Building Research Association of New Zealand, “Data,” BRANZ. Accessed: Mar. 04, 2025. [Online]. Available: <https://www.branz.co.nz/environment-zero-carbon-research/framework/data/>.
- [74] D.Y. Zhao, Y.Y. Ma, H.L. Lin, Using the entropy and TOPSIS models to evaluate sustainable development of islands: a case in China, *Sustain.* (Switz.) 14 (6) (Mar. 2022), <https://doi.org/10.3390/su14063707>.
- [75] S. Chakraborty, TOPSIS and Modified TOPSIS: a comparative analysis, *Decis. Anal.* J. 2 (Mar. 2022) 100021, <https://doi.org/10.1016/j.dajour.2021.100021>.
- [76] S.R. Sousa, S.R. Soares, N.G. Moreira, R.M. Severis, L.A. de Santa-Eulalia, Internal Normalization Procedures in the Context of LCA: a Simulation-Based Comparative Analysis, *Environ. Model. Assess.* 26 (3) (Jun. 2021) 271–281, <https://doi.org/10.1007/s10666-021-09767-5>.
- [77] D. Diakoulaki, G. Mavrotas, L. Papayannakis, Determining objective weights in multiple criteria problems: the critic method, *Comput. Oper. Res.* 22 (7) (1995) 763–770, [https://doi.org/10.1016/0305-0548\(94\)00059-H](https://doi.org/10.1016/0305-0548(94)00059-H).
- [78] Interest.co.nz, “Residential building consent analysis tables.” Accessed: Mar. 12, 2025. [Online]. Available: <https://www.interest.co.nz/property/residential-building-consent-analysis>.
- [79] Figure N.Z., “Occupied dwellings in New Zealand .” Accessed: Apr. 02, 2025. [Online]. Available: <https://figure.nz/chart/EL2pqSJSQ3ijKOP2>.
- [80] I. Page, New Zealand new Housing Characteristics and Costs, *Building Research Association of New Zealand (BRANZ)*, Wellington, New Zealand, 2012.
- [81] B.K.S.N. Nidhin, N. Domingo, T.T.P. Bui, S. Wilkinson, Construction stakeholders’ knowledge on zero carbon initiatives in New Zealand, *Int. J. Build. Pathol. Adapt. ahead-of-print (ahead-of-print)* (2023), <https://doi.org/10.1108/IJBPA-08-2022-0119/FULL/XML>.
- [82] H.P. Williams, C. Tremain, Chapter 12: building and construction, Accessed: Apr. 07, 2025. [Online]. Available: <https://environment.govt.nz/publications/aotea-roa-new-zealands-first-emissions-reduction-plan/building-and-construction/>, 2022.

- [83] S. Ganda, A Life Cycle Assessment of Medium Density Houses in New Zealand, Open Access Te Herenga Waka-Victoria University of Wellington, 2019, <https://doi.org/10.26686/WGTN.17142437>.
- [84] E.K. Petrović, 5 - A lack of recognition of potential health risks from building materials, in: E.K. Petrović, B. Vale, M.P. Zari (Eds.), *Materials For a Healthy, Ecological and Sustainable Built Environment*, Woodhead Publishing, 2017, pp. 139–154, <https://doi.org/10.1016/B978-0-08-100707-5.00005-8>.
- [85] M. Brøgger, K.B. Wittchen, Estimating the energy-saving potential in national building stocks – a methodology review, *Renew. Sustain. Energy Rev.* 82 (Feb. 2018) 1489–1496, <https://doi.org/10.1016/j.rser.2017.05.239>.