Environmental Research Communications

OPEN ACCESS

RECEIVED
11 October 2023

REVISED
11 February 2024

ACCEPTED FOR PUBLICATION
26 February 2024

PUBLISHED
6 March 2024

PAPER

Estimating construction waste in New Zealand: a focus on urban areas, residential and non-residential building activities

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Keywords: construction waste, New Zealand, residential construction, urban areas, waste estimation, waste generation rate

Abstract

This paper examines the significant increase in construction waste (CW) due to urbanisation and population growth in New Zealand and worldwide. The aim is to estimate CW using available data in New Zealand and identify relevant indicators to employ estimation methods. Various methods and models for estimating CW at the urban level and from building activities are reviewed. According to the best available data, the paper uses the per-capita multiplier and waste generation rate methods to estimate CW in New Zealand. New Zealand's per-capita multiplier for CW is 943.46 kg/per capita. The waste generation method using the floor area indicator is applied at residential and non-residential building levels. The estimated CW in 2021 was 531,109 tonnes for residential and non-residential buildings using the floor area indicator. The findings reveal a positive relationship between residential building activity and population growth, with Auckland generating the highest rate of CW. Because of the limitations of the available data and estimation methods, the paper highlights the need for standardised data collection systems and outreach programs to improve CW estimation practices. Further research is recommended to enhance waste reduction strategies and identify high-waste-generating materials and methods. It is vital to have accurate CW estimations to support project waste management plans and sustainable construction practices and to inform waste management policies and regulations at the regional or national level.

1. Introduction

Increasing construction waste (CW) has become a growing issue, with billions of tonnes of CW estimated to be produced worldwide. Construction generates 100 million tonnes of waste annually in the UK (Alwan *et al* 2017) and 17 million tonnes in Australia (Davis *et al* 2021), with a substantial portion ending up in landfills. The generation of CW entails environmental, economic, and social costs. These costs include pollution, risks to human health, financial losses to businesses and governments, and depletion of natural resources (Hussin *et al* 2013, Li and Du 2015).

Consequently, governments and the industry are urged to develop strategies and management practices to reduce CW effectively. For instance, the European Commission (2008) enacted the waste framework directive with 'prevention' at the top of the waste hierarchy. Furthermore, the framework sets incentives to increase the recycling rate and decrease landfilling. Besides, many fast-growing and highly developing cities, namely Adelaide, San Francisco and Stockholm, have adopted zero-waste policies to avoid waste generation and reduce material consumption (Zaman 2014, Pietzsch *et al* 2017). Likewise, Auckland's waste management and minimisation plan supports reducing, reusing, and recycling waste to achieve a zero-waste goal by 2040 (Auckland Council 2018). Emerging economies like Turkey and Malaysia have introduced regulatory measures to curb the alarming rise in CW generation (Esin and Cosgun 2007, Sabodin and Adeleke 2018).

Along with regulation and control measures, reliable data about generated CW is required to improve CW management planning and strategies like landfill space preparation, levy and subsidy establishment, and designing effective CW policies (Lu *et al* 2021). Previous studies emphasised the significance of estimating the amount of generated CW as a stepping stone for future planning towards establishing recycling and recovery infrastructure and developing CW strategies (Kofoworola and Gheewala 2009, Oyedele *et al* 2014, Maués *et al* 2020).

The construction industry's waste production has been rising globally, driven by urbanisation and population growth (Yang *et al* 2010, Duan and Li 2016, Hao *et al* 2007). New Zealand has experienced prolonged urbanisation and population growth since the 1960s and is anticipated to proceed until 2050 (Stats NZ 2020a). Data from the World Bank (2021) and the United Nations-UN (2018) show that 87% of New Zealand's population lives in urban areas. Moreover, investments in construction work recorded a value of $7.2 billion in 2021, with the highest in Auckland at $2.8 billion (Stats NZ 2021c). Hence, a significant amount of CW is generated in New Zealand due to the rise in construction activities, mainly in urban areas.

There is limited research evidence on estimates of CW quantities in New Zealand. The only recent study focused on residential construction at the project level by Domingo and Batty (2021). The Ministry for the Environment-MfE (2021) acknowledged the need for more information on the composition and quantity of CW in their data, research, and evidence base. Furthermore, government agencies and territorial authorities report national information about CW management and performance planning. However, the reported data only includes an approximate percentage of CW for around 50% of the total waste generated in New Zealand (Building Research Association of New Zealand-BRANZ 2021). One of the reasons for data limitation is that private waste operators manage CW, and it is optional to report qualitatively or quantitatively on collected waste (Auckland Council 2018).

Various methods are available in the literature for estimating CW, which can be determined based on the available data, the purpose of the estimation, and the level of detail required (Wu *et al* 2014). These methods include estimates based on the materials used, weight, volume, and waste generation rate. Studies on estimating CW often use statistics to estimate CW generation, as complicated algorithms may lead to poor results and limited interpretation (Lu *et al* 2021). At the same time, there have been efforts to explore CW estimation at the project level (Li *et al* 2013, Lam *et al* 2019) and regional level (Maués *et al* 2020, Wang *et al* 2020) using several techniques. Variations in CW estimation methods exist due to differences in geographical location and construction practices (Guerra *et al* 2020, Wang *et al* 2023). Additionally, the unavailability of data on CW presents a primary limitation in this research area.

New Zealand has unique geographic characteristics that create notable regional differences compared to other world economies. Due to the economic dynamics and urbanisation trends, exploring the current indicators of CW generation in New Zealand and its correlation with urban areas and residential and non-residential building activities is essential. Therefore, this paper explicitly focuses on New Zealand and explores the escalating CW issue resulting from urbanisation and residential and non-residential expansion in New Zealand. This focused perspective enhances the identification of pertinent indicators for CW, contributing valuable insights for sustainable urban planning and CW management strategies in the construction sector.

2. A review of methods and relevant indicators in estimating CW

Table 1 summarises the previous studies that investigated estimating CW generation at a regional or national level.

Various studies developed methods for CW estimation according to the best available data on relevant indicators. For instance, after analysing 57 studies in CW estimation, Wu *et al* (2014) revealed three main methods to quantify the amount of waste generation at either the project or regional levels, including (i) site visits with direct and indirect measurements, (ii) generation rate method, (iii) material flow analysis (MFA).

The site visit method offers benefits such as accurate data and identifying waste sources and causes. However, the site visit method is limited to time, labour, and feasibility for specific projects or regions (Rašković *et al* 2020). Moreover, the generation rate method calculates waste generation rates (WGRs) per unit of activity (Białko 2018). Calculating WGRs helps better understand CW management between different economies (Lu and Yuan 2011). Furthermore, estimating CW using WGRs is beneficial in benchmarking performance measures for CW management practices (Chen *et al* 2015). While the generation rate method offers a significant advantage because it can be applied at different levels, including the site, regional, and national but can be of limited accuracy because of limitations to the availability and quality of data (Białko 2018).

MFA is a comprehensive approach that considers the entire lifecycle of materials, from their extraction and production to their use and disposal (Westin *et al* 2019). This method can provide detailed insights into the sources and types of waste generated during construction and opportunities to reduce waste through improved design, construction practices, and material selection (Estrada *et al* 2023). However, the limitations of the MFA method are data-intensive and require specialised expertise (Islam and Huda 2019).

Table 1. Review of studies on relevant indicators for estimating CW generation.

Region/Country	Construction activity	Relevant indicators	Estimated quantities of waste	References
US	Construction and renovation for residential and non-residential	Population, financial value, floor area	gypsum board waste in tonnes	Yost and Halstead (1996)
Greece	Construction and demolition in residential and non-residential	Population	191 kg/capita- 2.09 million tonnes	Fatta *et al* (2003)
Florida, US	Construction, renovation, demolition	Floor area, material analysis	3.75 million tonnes	Cochran *et al* (2007)
Thailand	Construction- residential and non-residential	Floor area	21.38 kg m^{-2}	Kofoworola and Gheewala (2009)
Galicia, Spain	Newly constructed buildings, renovations, and demolitions	Floor area, population	New construction 80 kg m^{-2}, demolition 1350 kg m^{-2}	Lage *et al* (2010)
Portugal	Construction and demolition in residential and non-residential	floor area, population	186 kg/person/year	Coelho and de Brito (2011)
Taiwan	Construction and demolition	floor area, material analysis	0.092(t/M^3) with on-site separation, or 0.329 (t/M^3) without on-site separation	Huang *et al* (2011)
Shanghai, China	Construction and demolition	material analysis, floor area	842 kg/capita- 13.71 million tonnes	Ding and Xiao (2014)
Beirut, Lebanon	Construction- residential and non-residential	Floor area, waste quantity and composition	38–43 kg m^{-2}	Bakshan *et al* (2015)
China	Construction and demolition	floor area, financial value	1.13 billion tonnes	Lu *et al* (2017)
Chennai, India	Construction and demolition	Material analysis	1.14 million tonnes	Ram and Kalidindi (2017)
Urban India	Construction and demolition	Material analysis	150 million tonnes	Jain *et al* (2019)
Greater Bay area, China	Construction	population, GDP per capita, total construction output, floor area	364 million m^3	Lu *et al* (2021)
India	Construction and demolition for urban building, rural building, and non-building activities	Population, material analysis	150 million tonnes	Jain *et al* (2021)

Each method of CW estimation requires specific indicators or parameters to be measured or calculated. These indicators may vary depending on the method used and data availability. Relevant indicators in waste estimation methods are classified into two types (Lu *et al* 2021): socioeconomic and construction related. Socioeconomic indicators use population and GDP information, while construction-related indicators consider floor areas, number of building permits, material weight and financial value for construction activity.

Values for relevant indicators can be sourced via site visits (primary data) or stats in official records by local authorities (secondary data). For example, Bakshan *et al* (2015) gathered primary waste data from 28 construction projects on-site to estimate construction WGRs, including material waste quantity and the type and size of the built area. Alternatively, secondary data includes official records maintained by local authorities, such as the population or total built floor area, which can be accessed at either the type of project (residential or non-residential) or regional level (Vilventhan *et al* 2019). Nevertheless, in the cases of not enough information is available, assumptions can be made to provide a more reliable estimation (Coelho and de Brito 2011, Wu *et al* 2014).

Researchers have used various indicators to estimate CW, with some adopted populations as one of the early indicators to estimate CW using the per capita multiplier. The method of per capita multiplier involves using waste generation rates per person per year, along with population data. For example, to estimate construction and demolition waste in Greece (Fatta *et al* 2003) and Portugal (Coelho and de Brito 2011).

Furthermore, McBean and Fortin (1993) utilised a modified version of the per-capita multiplier approach to estimate the total domestic and industrial waste generated annually. On the other hand, some studies argued that the financial value indicator provides a more accurate reflection of construction work. For instance, Yost and Halstead (1996) estimated the amount of gypsum waste by investigating the relationship between gypsum quantity, financial value for construction work, and the built floor area. Besides, Cochran *et al* (2007) used the financial value of construction, demolition, or renovation work divided by the cost per area of each work ($/m^2) to estimate the amount of waste generated.

In addition, some studies have used the floor area indicator to estimate WGRs per unit floor area. For instance, Kofoworola and Gheewala (2009) estimated CW generated by new residential and non-residential construction in Thailand using the floor area indicator. Similarly, Huang *et al* (2011) and Ding and Xiao (2014) quantified the weight of generated waste (tonnes) per unit floor area (m^2) of the constructed or demolished works. In Spain, Villoria Sáez *et al* (2012) created a model to estimate residential CW based on waste accumulation and built area, while Lage *et al* (2010) estimated waste based on the regional information on floor area, population, waste composition, and quantity to determine WGRs.

Construction, demolition, and renovation waste pose significant environmental challenges in urban areas, particularly in rapidly urbanising regions such as China. Given the region's high urbanisation and construction activities, Lu *et al* (2017) sought to estimate the amount of waste generated in urban China. The study drew on indicators from the literature, including area-based waste generation rate (kg/m^2) and information from local authorities such as floor area and construction work financial value. This approach allowed for a more comprehensive estimation of urban China's CW and provided valuable insights into the challenges of managing such waste in rapidly urbanising regions.

Alternatively, Jain *et al* (2021) estimated CW generated in urban and rural areas and from non-building construction activities using the MFA method. The study indicated a higher waste generation in rural areas despite previous per capita waste generation records in India that suggest higher waste in urban areas. The study challenged that by revealing that rural areas in India have a double share of the population as urban areas. Hence, this resulted in higher waste in rural areas. Similarly, using multiple case studies in India, Ram and Kalidindi (2017) used the rates of primary materials to estimate waste generated from construction and demolition works in terms of quantity and composition.

The literature suggests no specific 'best' method for estimating CW. Instead, the choice of waste quantification method depends on the project or regional context and the availability of data and resources. Furthermore, a combination of methods may provide a more comprehensive and accurate assessment of waste generation.

3. Estimating CW in New Zealand

3.1. CW at the urban level

In New Zealand, the available data for urban areas include population statistics, major urban regions, and an estimation of the annual CW amount. Hence, the per-capita multiplier approach is the most appropriate method based on the available data. This approach involves selecting the population indicator to estimate the CW generated in urban areas. As Wu *et al* (2014) described, the per capita multiplier is the weight of waste generated per person. The basic formula of per capita multiplier (capita/year) is to divide the estimated quantity of CW in any given year into the number of populations in a particular region for that year (Fatta *et al* 2003, Dyson and Chang 2005, Ding and Xiao 2014). Hence, multiplying the waste weight per capita by the number of populations in a region quantifies the waste generated per region.

The most recent estimation shows the total amount of waste discarded yearly is 15 million tonnes for 2015, of which discarded CW for all national construction activities is 4.4 million tonnes (Infrastructure Commission 2021). The total populations retrieved from Stats NZ (2021a) for the same year marked 4,663,700. Then, the per capita multiplier of CW is calculated as 943.46 kg capita^{-1}. Therefore, the total national CW generated can be determined by multiplying the CW weight per capita by the total population number. Table 2 presents the estimated total CW generated in New Zealand during 2010–2020 using the calculated per capita multiplier.

Figure 1(a) shows the population growth in New Zealand's major urban areas, in which Auckland is the highest, followed by Christchurch, Wellington, Hamilton, Tauranga, Lower Hutt, and Dunedin. First, the population of major urban areas was sourced from Stats NZ (2020a) using the tool 'NZ.Stats', with the theme of population estimates being selected. Then, subnational population estimates (urban-rural) by age and sex (1962–2021 boundaries) were selected and customised to major urban areas during 2010–2020. Population estimates are provisional and subject to revision each quarter until finalised about six quarters after the reference period. These estimates were as published on 17 August 2021.

As a result, figure 1(b) illustrates the estimated weight of CW generated in the major urban areas of New Zealand between 2010 and 2020. The estimated weight of CW is calculated by using the per capita multiplier of 943.46 kg capita^{-1}. The variation in estimated CW suggests a steady increase in waste generation with projected population growth, with the highest trend observed in Christchurch and Dunedin.

For Christchurch, building activity slowed down due to the Canterbury earthquakes in 2010 and 2011 but increased in response to rebuilding and recovery works (Kachali *et al* 2015). Population in Christchurch also declined during that period due to the interrupted services, rise in migration to other areas, and damaged dwellings. Nonetheless, the 2018 Census revealed that the population of Christchurch has rebounded (Environment Canterbury Regional Council 2023).

The primary trend of urbanisation growth in major urban areas indicates a projection rise in construction activities, causing a similar trend in estimated CW. According to the urban strategy plan by the Tauranga City Council (2018), Tauranga was the place with the highest growing urban cities in New Zealand throughout the period between 1996 and 2013. On the other hand, Auckland has obtained the highest urban growth since 2013; it is expected for Auckland to continue the trend until 2043, with Tauranga in second place (Tauranga City Council 2018). Statistics show that the current population in Auckland is 1.66 million and is projected to reach 2.4 million by 2050 (Auckland Council 2021b).

3.2. CW from building activities

There are two primary types of building activities in New Zealand, namely residential and non-residential building work (Ministry of Business, Innovation, and Employment-MBIE 2020). Alteration and addition works are also included in residential and non-residential building activities.

Stats NZ (2021b) data presented in figure 2 indicate that residential building activities have the highest contribution to the total national building activity. There was a decline in 2020 due to COVID-19 economic challenges. However, in 2021, the value of residential building work reached a record high due to increased housing demand (Ministry of Business, Innovation, and Employment-MBIE 2020).

The national construction pipeline report forecasted that the non-residential activity peaked in 2019 and steadily dropped through 2021. Non-residential building activity is prominently known for fluctuating trends within an interval due to construction work's start, end, or pause in large projects. However, the trend also indicates that the volume of the residential building sector in New Zealand is a significant driver of the total volume of national building work.

For estimating the amount of waste generated from building activities in New Zealand, equations (1) and (2) are initiated for guiding data collection and waste generation estimation.

$$CW_{TB} = CW_R + CW_{NR} \tag{1}$$

$$CW_i = WGR_j \left(\frac{\text{kg}}{\text{m}^2}\right) \times Total \quad floor \quad area \ (\text{m}^2) \tag{2}$$

CW_{TB}: the total estimated amount of CW generated from building activities

CW_R: The waste generated from residential building

CW_{NR}: is the waste generated from non-residential building

To calculate the total estimated amount of CW generated from building activities, equation (1) is utilised. CW_{TB} represents the sum of residential and non-residential building waste. Moreover, equation (2) is initiated

Table 2. Total New Zealand's population during 2010–2020 and estimated CW.

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Population	4,373,900	4,399,400	4,425,900	4,477,400	4,564,400	4,663,700	4,767,600	4,859,500	4,941,200	5,040,400	5,103,700
Estimated CW (tonnes)	4,126,586	4,150,644	4,175,645	4,224,233	4,306,314	4,400,000	4,498,025	4,584,728	4,661,809	4,755,416	4,815,137

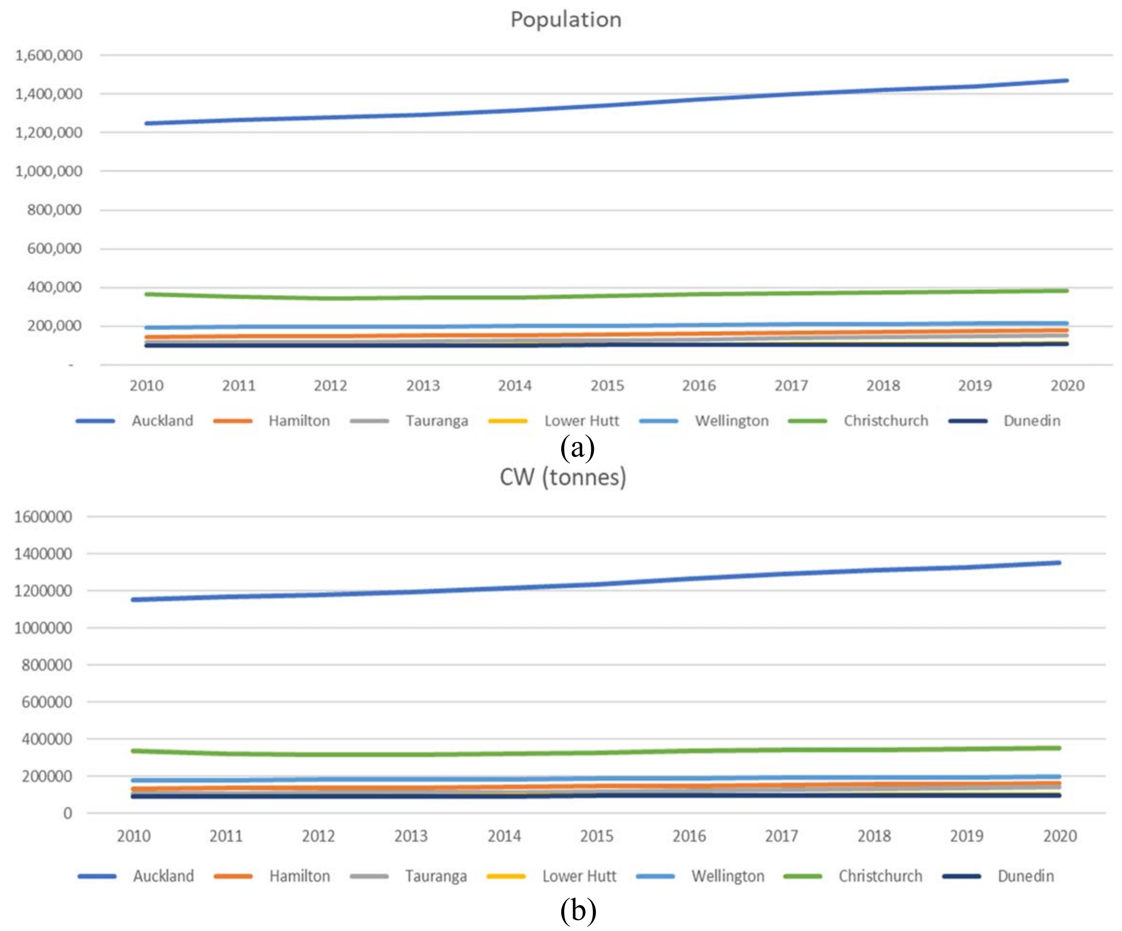

Figure 1. (a) Population growth by major urban area in New Zealand during 2010–2020. (b) CW estimates by major urban areas in New Zealand during the period of 2010–2020.

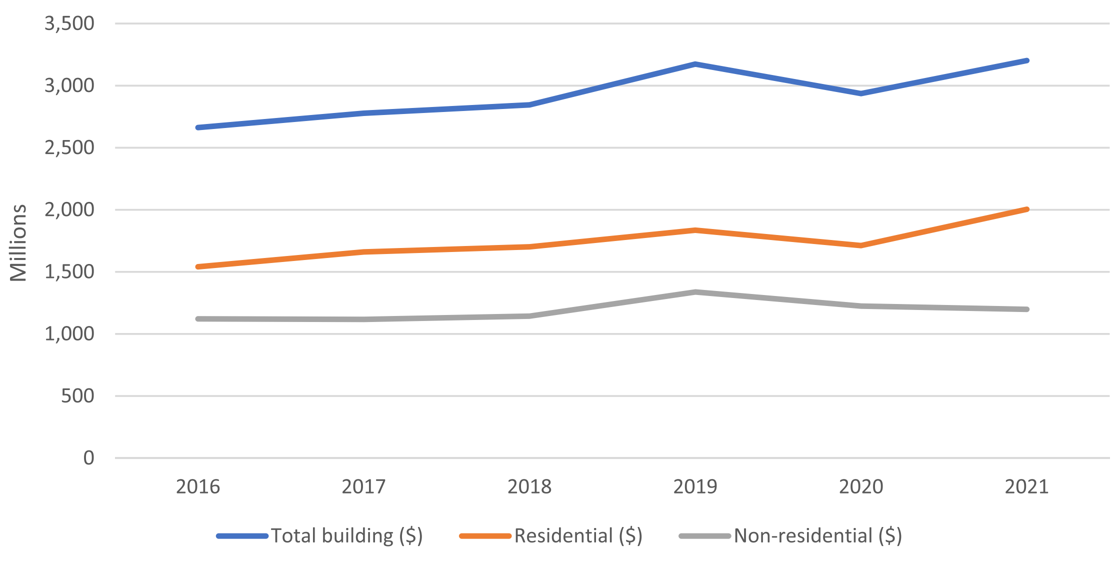

Figure 2. Building work volume ($) during 2016–2021.

to guide the calculation of the amount of CW (CW_i) using the generation rate method and selected indicator floor area (m^2). Index i denotes either the residential (CW_R) or non-residential (CW_{NR}) building waste.

Stats NZ (2021d) provided information on the total floor area (in square meters) for new residential and non-residential buildings at both national and regional levels in New Zealand. For residential construction, the

Table 3. Floor area (m^2) and estimated CW (tonnes) for total New Zealand's residential construction during 2010–2021.

Year	Floor area (m^2)	CW_R (tonnes)
2010	3,113,124	100,243
2011	2,617,526	84,284
2012	3,337,692	107,474
2013	4,085,561	131,555
2014	4,623,823	148,887
2015	4,855,202	156,338
2016	5,470,390	176,147
2017	5,493,159	176,880
2018	5,595,152	180,164
2019	5,946,051	191,463
2020	6,158,238	198,295
2021	7,194,000	231,647

data includes the number of consented dwellings, floor area, and the financial value of building works. For non-residential construction, data includes the financial value and floor area of building work. The financial value refers to the value ($) of finished construction work. However, information regarding floor areas is not consistently available; there is a lack of literature on this research area in New Zealand. A recent study by Domingo and Batty (2021) inspected generated waste from 159 residential projects. The study quantified the waste generation rate by 32.2 kg m^{-2} for timber-framed residential buildings. According to the study and BRANZ (2010), the timber-framed building has been a conventional construction method used since the 1900s and represents 90% of dwellings in New Zealand. That is a reliable source of information that can provide an accurate estimation of CW generated from new residential building works.

3.2.1. Residential building

To determine the total amount of CW generated from new residential construction, we used the NZ-Stats tool to extract the total floor area in square metres of new consented dwellings in each region. Then, the total amount of CW generated was estimated by multiplying the generation rate of 32.2 kg m^{-2} by the total floor area, as outlined in Wu *et al* (2014). Table 3 refers to the calculation of CW_R for the total national residential building activity in New Zealand between 2010 and 2021.

Following the same method, CW_R was estimated in different New Zealand regions for new residential buildings, refer to table 4.

Figure 3 features the floor area (m^2) trends and the estimated CW (tonnes) over time. The average floor area of new houses tends to decline. In contrast, the number of new consented dwellings is maintained to increase. For example, between 2010 and 2019, the area of new houses dropped by 21% (Stats NZ 2020b). Hence, the estimated amount of CW followed a similar trend, reflecting the construction activity due to the increase in dwellings.

As such, regional CW_R generated featured in percentage for 2020 in figure 4, using available data in table 4. It is observed that Auckland has the highest contribution of $CW_{R,}$ followed by the rest of North Island, Canterbury, Waikato, the Rest of South Island, and Wellington, respectively.

3.2.2. Non-residential building

Data on non-residential building activities in New Zealand is scarce. While Stats New Zealand does offer information on the number of consents by building type and value ($), data on floor area ($m^2$) is not consistently accessible at the regional or national level. Furthermore, knowledge about the material flow of non-residential building work in New Zealand is also limited.

According to the New Zealand Green Building Council-NZGBC (2019), the total non-residential buildings comprised 47% multi-story reinforced concrete buildings and 53% single-story steel portal-framed buildings. The average floor areas are 1000 m^2 and 4,247 m^2 for portal framed and multi-story, as provided in table 5. Material wastage is approximately 5% of total material input (New Zealand Green Building Council-NZGBC 2019). The calculated wastage from materials is the resulting waste of 36,870 kg and 283,484 kg for portal-framed and multi-story, respectively.

Following equation (2), waste generation rates are calculated by dividing the total waste into the gross floor area for each portal-framed and multi-story. However, the official statistics for non-residential building work include the number of dwellings and floor area without brief details about the characteristics of the building

Table 4. Floor area (m^2) and CW estimated in different New Zealand regions for new residential buildings during 2010–2020.

Region	Auckland		Waikato		Wellington		Rest of North Island		Canterbury		Rest of South Island	
Year	floor area (m^2)	CW_R (tonnes)	floor area (m^2)	CW_R (tonnes)	floor area (m^2)	CW_R (tonnes)	floor area (m^2)	CW_R (tonnes)	floor area (m^2)	CW_R (tonnes)	floor area (m^2)	CW_R (tonnes)
2010	791,144	25,475	369,666	11,903	269,319	8,672	687,131	22,126	569,801	18,348	426,063	13,719
2011	756,413	24,356	323,440	10,415	212,682	6,848	518,926	16,709	450,410	14,503	354,676	11,421
2012	962,027	30,977	353,265	11,375	228,007	7,342	579,904	18,673	801,125	25,796	413,307	13,308
2013	1,244,881	40,085	425,623	13,705	257,295	8,285	621,784	20,021	1,113,846	35,866	421,794	13,582
2014	1,460,403	47,025	444,374	14,309	255,768	8,236	679,558	21,882	1,330,501	42,842	453,219	14,594
2015	1,663,963	53,580	565,704	18,216	248,183	7,991	793,670	25,556	1,112,950	35,837	470,475	15,149
2016	1,859,864	59,888	683,394	22,005	311,916	10,044	1,031,667	33,220	1,017,161	32,753	565,944	18,223
2017	1,849,426	59,552	649,691	20,920	346,006	11,141	1,100,417	35,433	899,753	28,972	647,335	20,844
2018	2,130,133	68,590	648,596	20,885	401,677	12,934	983,519	31,669	818,122	26,344	612,147	19,711
2019	2,324,290	74,842	693,308	22,325	420,605	13,543	1,000,231	32,207	868,123	27,954	639,387	20,588
2020	2,472,574	79,617	685,244	22,065	408,714	13,161	1,023,224	32,948	963,728	31,032	603,717	19,440

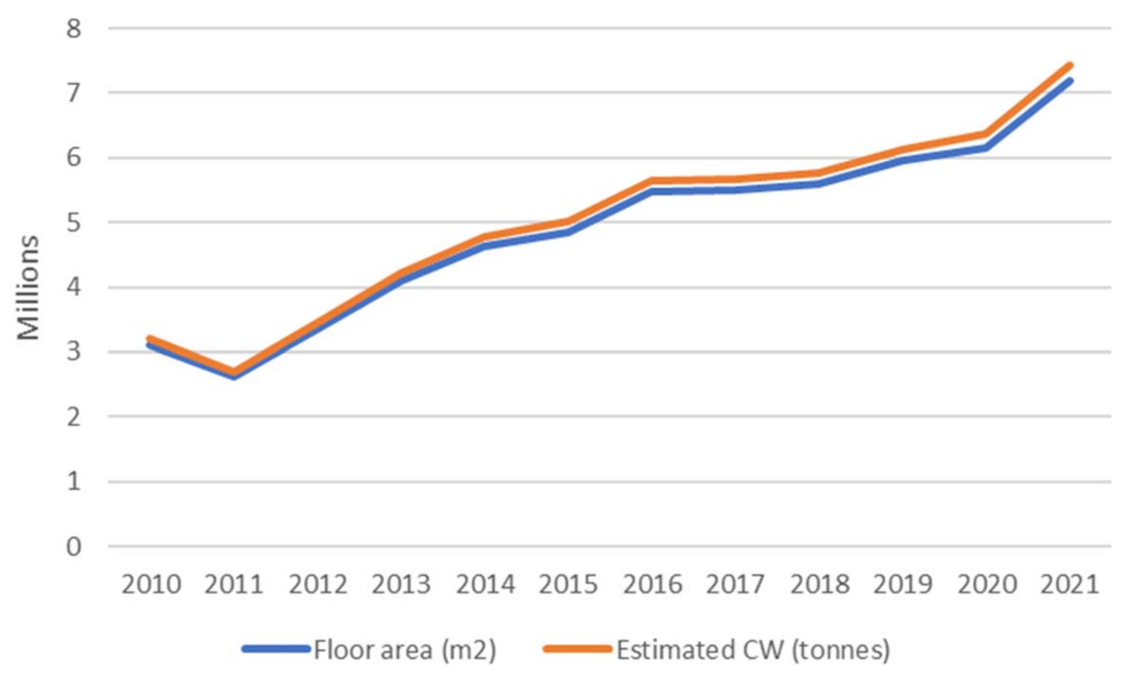

Figure 3. Estimated CW for New Zealand's total residential construction during 2010–2020.

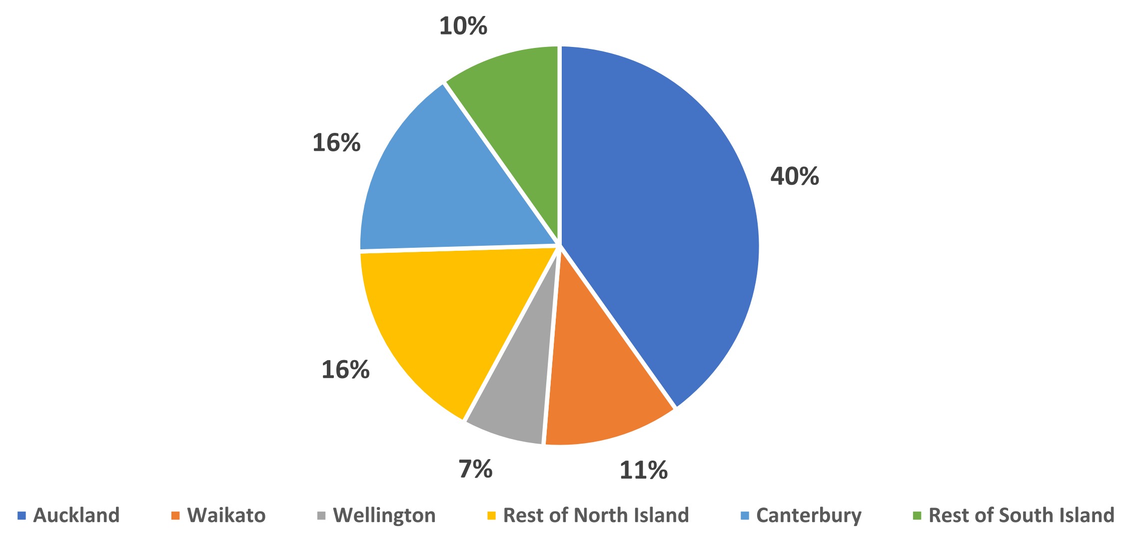

Figure 4. Percentage of CW generated regionally from new residential construction for 2020.

Table 5. Non-residential construction characteristics and estimated waste generation rate.

Non-residential building type	Portal-framed	Multi-story
Gross floor area	1,000 m^2	4,247 m^2
The total quantity of materials (kg)	737,398	5,669,680
Total waste (kg)	36,870	283,484
Waste generation rate (kg/m^2)	36.87	66.75

frame. Therefore, the total estimated amount of CW_{NR} in table 7 is the sum of the CW proportion of framing type and related waste generation rates 36.87–66.75 kg m^{-2}, refer to table 6.

For the total $CW_{TB,}$ equation (1) is applied. A summary of the findings is represented in table 7.

Table 6. Estimated CW generated from non-residential building activities during 2016–2021.

Year	Non-residential building Floor area (m^2)	portal-framed CW (tonnes)	multi-story CW (tonnes)	Total CW_{NR} (tonnes)
2016	2,974,000	109,651	198,515	308,166
2017	2,846,000	104,932	189,971	294,903
2018	3,172,000	116,952	211,731	328,683
2019	3,412,000	125,800	227,751	353,551
2020	2,941,000	108,435	196,312	304,747
2021	2,890,000	106,554	192,908	299,462

Table 7. The total estimated amount of CW generated from building activities during 2016–2021.

Year	$CW_{TB\ (tonnes)}$
2016	484,313
2017	471,783
2018	508,847
2019	545,014
2020	503,042
2021	531,109

4. Discussion

Two methods were used at different levels to estimate CW. The population indicator and the per capita multiplier method were used at the national and urban levels. Meanwhile, the generation rate method and the floor area indicator were used at the building activity level.

The findings highlight the relationship between residential building activity and population growth in New Zealand, suggesting that the rise in residential construction activity is primarily driven by the increase in the country's population. The Reserve Bank of New Zealand- RBNZ (2018) reported a positive correlation between population growth and the number of new dwellings constructed. Estimations in the report suggest that New Zealand's regions experience a percentage increase in new dwellings of 0.25 to 0.30 per additional person.

Thus, the per capita multiplier indicated an increased quantity of the generated CW in New Zealand and the population over time. The trend is not unique to New Zealand but is a global phenomenon. This trend has been consistent with the latent findings reported in China (Lu *et al* 2021) and India (Jain *et al* 2021). As the population grows, so does the demand for housing, which leads to increased construction activity. In New Zealand, this trend has been particularly evident in recent years due to the country's rapidly growing population, emphasising the need for policymakers to consider population growth trends when formulating policies, strategies, and sustainable approaches to decouple CW generation and population growth and ensure a sustainable and resilient industry.

Compared to most OECD countries, New Zealand's 'total' waste is higher because it includes construction and demolition waste sent to landfills. However, most other OECD countries estimate their construction and demolition waste separately, and their 'total' waste only includes municipal waste generated by homes, offices, and small businesses. Hence, the resulting per capita multiplier of 943.46 kg capita^{-1} can contribute to the gap in the estimated CW of New Zealand in the Organisation for Economic Cooperation and Development- OECD (2021) data, figure 5.

However, using the per-capita multiplier (population as an indicator) for estimating the generated CW neither gives insights into the proportion of each building activity nor reflects other construction activities such as demolition and renovation. Moreover, using the population as an indicator in estimating CW does not reflect the differences in the CW management or strategies between different projects or regions. However, it is useful when assessing trends in urbanisation and population growth over the past decade because of the ambiguous definitions and lack of reliable data in New Zealand before 1995.

At the urban level, Auckland's most significant share of total waste generation is from intensified residential building activity. Auckland is the most crucial economic hub in New Zealand, contributing 40% of the total

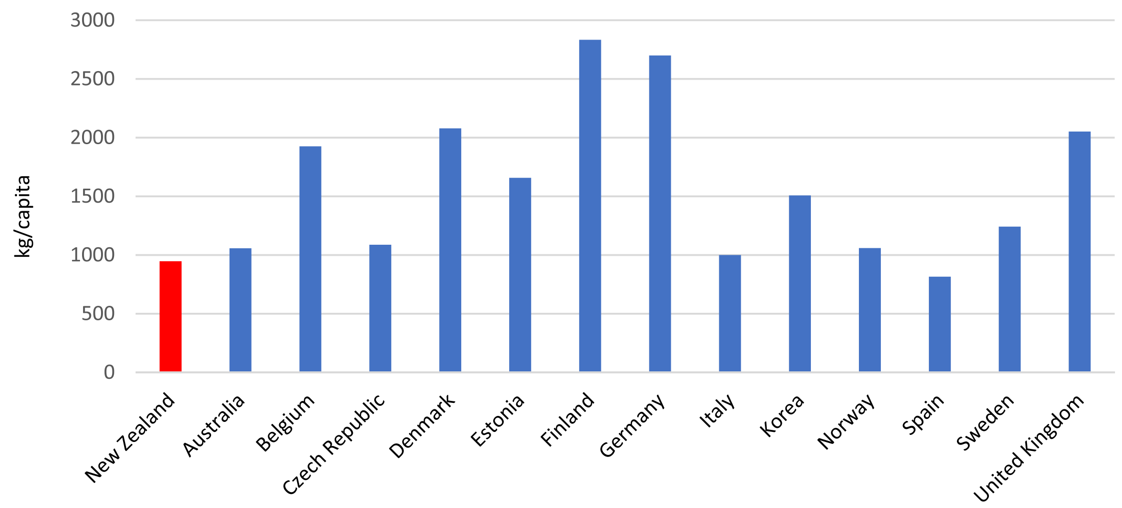

Figure 5. Estimated CW generated (kg/capita) in some OECD countries in 2018.

national GDP (Auckland Council 2021a). A primary component of Auckland's economy is the volume of building work, contributing to 7% of Auckland's GDP and 10% of total employment (Auckland Council 2020a). With these characteristics, Auckland attracts businesses and people to invest and work. The council highlighted that a significant change in the built environment is expected towards building thousands of new homes, infrastructure, and other facilities to adapt to this growth. CW is reported as a significant waste stream that makes up 50% of total generated waste in Auckland (Auckland Council 2019). Building an average house in Auckland is estimated to cause 4.5 tonnes of waste (Auckland Council 2020b), pointing to the need to prioritise Auckland in waste reduction or diversion strategies and resource recovery infrastructure.

On the other hand, at the building activity level, CW estimation involves estimating the amount of waste likely to be generated by a specific construction project, whether residential or non-residential. Building-level CW estimations provide insights into project waste management plans, materials estimates, and sustainable construction practices.

The generation rate method using the floor area indicator offered estimates of the waste produced per unit of construction activity per square meter. This method suggests a relatively simple and accurate estimation based on the quality of the available data used. The trend in floor area in residential buildings is associated with dwelling type. The recent boom in new dwelling construction was coupled with a rise in attached dwellings and a drop in floor area. However, CW generation is more likely to increase in response to the boom cycle. The Ministry of Business, Innovation, and Employment-MBIE (2020) reported residential buildings as the most significant contributor to national construction work. However, the report forecasted a drop by 2022 in residential and non-residential building work due to the challenges of the COVID-19 pandemic.

While urban and building-level CW estimations are essential, they differ in scope and purpose. Urban or regional CW estimations provide an overall picture of the waste generated by all construction activities within a region, which inform waste management policies and regulations at a higher level. Building-level CW estimations are more specific and are used to inform the waste management plan for a particular construction activity. Both estimations are essential to ensure that CW is managed efficiently and sustainably.

Several strategies can be employed to improve CW estimation practices in New Zealand. One strategy is to develop a standardised data collection and reporting system that captures detailed information on waste generation, including waste types, quantities, and disposal methods. This data can inform waste reduction and diversion strategies and improve waste management practices. Education and outreach programs can also be developed to raise awareness of the importance of sustainable construction practices and encourage behaviour change among industry professionals and the general public. For regional variations in CW generation, Wang *et al* (2023) suggested the need for the establishment of cross-regional CW management cooperation and promoting technological innovation in regions with intense CW generation.

5. Conclusion

The increase in building work due to urbanisation and population growth has led to a significant rise in CW in New Zealand and worldwide. This paper aims to estimate CW using available data and identify relevant indicators to employ estimation methods. The paper reviews different methods and models for estimating CW at regional, residential, and non-residential construction levels.

The study used the per-capita multiplier and waste generation rate methods to estimate construction waste at the urban and building (residential and non-residential) levels in New Zealand. The per capita multiplier is the amount of CW produced by each person, which is 943.46kg/per capita for New Zealand. Over time, the estimated trend for residential building activity suggests a positive relationship with population growth. In addition, Auckland has generated the most CW, indicating a greater need for prioritising waste reduction strategies and building resource recovery infrastructure in that region and other areas.

The waste generation method using the floor area indicator was applied at residential and non-residential building levels. The total estimated CW_{TB} for 2021 was 531,109 tonnes, and the trend in estimated CW_{TB} over time is a projection of the increase in building activity. Building-level CW estimations provide insights into project waste management plans and sustainable construction practices. In contrast, urban or regional estimations inform waste management policies and regulations.

The minimum amount of reliable data on the type and quantity of waste generated limits the accuracy of CW estimates in this study. Similarly, using the per-capita method partially accounts for variations in WGRs between demographic groups or regions, potentially limiting the accuracy of estimates at the regional or national level. Therefore, recognising the limitations inherent in the available data and estimation methods emphasises the critical need for standardised data collection systems in New Zealand. The findings demonstrate a forward-looking approach, advocating for better CW estimation practices by implementing advanced data collection techniques. Finally, the paper recommends further research to improve prioritising waste reduction strategies and identifying high-waste-generating materials and construction methods.

Acknowledgments

This research received the 'EOI Cluster Research Support' funding offered by the School of Future Environments at Auckland University of Technology.

Data availability statement

All data that support the findings of this study are included within the article.

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