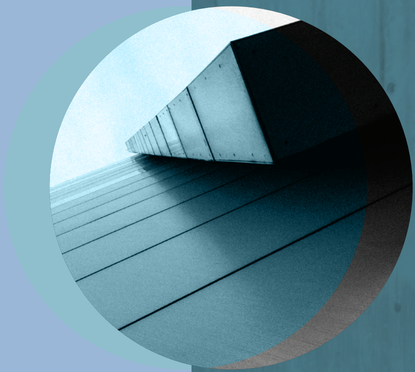
ISSN 2815-9616



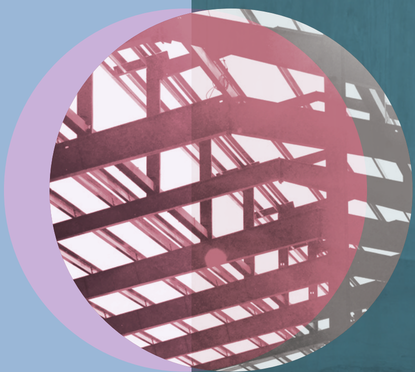
Āmiomio Aotearoa

Preliminary Materials Flow Analysis
for
Aotearoa New Zealand's Building Construction Sector

A sub-project of

Āmiomio Aotearoa: A circular economy for the wellbeing of New Zealand

September 2022



Jacob Nelson

Grace Elliot

Professor Kim Pickering

Dr Mohammad Dalour Beg

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

DOI: 10.15663/Amiomio.MFA

Contents

1 | Abstract

This report describes the methodology used to produce a database of construction material flow in Aotearoa New Zealand and summarises the contents of that database. The database was produced as part of a wider research programme, Āmiomio Aotearoa, which aims to help New Zealand transition to a circular economy.

In order to assess the materials flowing through the building construction sector, the research focussed on residential dwellings, which constituted a larger proportion of the sector than commercial construction in terms of number of new buildings, floor area of new buildings, and the value of new buildings.[1] The building envelope, including the foundations, structure, cladding, roofing, insulation, and lining of the structure, was examined as it accounted for the largest portion of materials in each dwelling. The data was assessed through the four key stages of material flow: material input, construction, demolition and material output.

In terms of material input, timber was the most thoroughly documented material used in construction. An estimated 1.98 million tonnes of timber and timber-based products were supplied to the New Zealand market through local production and imports in 2021. Furthermore, it was estimated that roughly 10.4 million tonnes of ready-mix concrete were used in 2021. Meanwhile, approximately 850 thousand tonnes of steel are consumed within New Zealand annually. However, the amount of concrete and steel that is consumed in the building construction sector specifically is unknown.

An estimation of the materials used in the envelope of residential buildings, based on consent data, New Zealand building reports and standard residential building designs, suggested that concrete and masonry were the most used materials in construction, followed by timber, plasterboard, and metals. In total, it was estimated that 2.07 million tonnes of material were consumed in 2021 in the residential construction sector. A case study using purchase order data validated this estimation, showing that the key materials studied were all of the same magnitude.

Data on the number of demolitions in New Zealand was very limited, largely because consents are not required for the demolition of houses under three stories.[2] However, using some assumptions around census and new building consent data, it was calculated that roughly 5,488 residential demolitions occur annually in the current state of the industry.

Waste from the building construction sector was studied in terms of the whole construction and demolition sector, as well as the expected waste from residential construction and demolition. It was expected that the total construction and demolition sector produces roughly 3.6 million tonnes of waste annually, with an additional 1.4 million tonnes of material from construction being recovered. However, the study found that the differentiation between infrastructure, commercial, and residential construction waste was largely unmeasured.

The residential construction sector was estimated to produce 347 thousand tonnes of waste in 2021, of which 267 thousand tonnes was expected to go to landfill. This waste was produced from: The building envelope (147 thousand tonnes); the rest of the construction (49 thousand tonnes); alterations of residential buildings (25 thousand tonnes); and demolition of residential structures (126 thousand tonnes). Estimations indicated that concrete was the largest contributor to waste, followed by plasterboard and then timber.

The report also includes comments from industry experts to further portray the picture of the current state of material flow in the construction and demolition sector, and the issues faced with the production of waste.

Overall, this report is a first attempt to provide a picture of materials flowing through New Zealand's building construction sector. Due to limitations of data currently being collected within NZ and available to the team within the timeframe of the project, the report has focused on estimating the materials used in the shell of residential buildings; detailing where and how materials are being recycled was out of scope. Contradiction with perceived state of the art recycling is likely due, at least in part, to assumptions that because materials can be recycled, they are indeed being recycled (as per our domestic recycle bins). Despite the data limitations, this report and associated database usefully indicate prime waste materials for incorporation into novel building materials and therefore provide insight to support the direction of future research. The report and associated database also provide a foundation which could be used to support further enterprise to provide a clearer picture of materials flows within the building construction sector.

2 | Acknowledgements

The Āmiomio Aotearoa team would like to acknowledge the invaluable contributions from the following people and organisations:

Annette Day – Naylor Love

Ella van Gool – Ministry for the Environment

Gemma Gloyne – Fletcher Living

Kevin Golding – Skip the Skips

Mark Roberts – Waste Solutions, Auckland Council

Naomi Pocock – University of Waikato

Nicola Tagiston – Fletcher Living

Vagn Lewisham – GJ Gardner

This research was funded through the Ministry of Business, Innovation and Employment under Āmiomio Aotearoa, UOWX2004.

3 | Introduction

The environment can be regarded as "the foundation and support of human existence and survival".[3] Globally, humanity is causing environmental issues such as climate change, mass pollution, resource depletion, ocean acidification, and declining biodiversity.[3, 4] Environmental degradation has become a global concern, resulting in research into new societal, legal, and technological solutions for environmental sustainability.[5]

The current societal norm for material consumption can be considered linear, from resource extraction to waste disposal. The linear economy model is fundamentally unsustainable; the earth's natural resources are being depleted and landfill waste is increasing. One potential solution for improving environmental sustainability is the circular economy concept. In contrast to the linear model, the circular economy concept uses a cyclic consumption of materials and products to keep materials in use for as long as possible, therefore extending the life of materials, reducing reliance on virgin materials, and decreasing mass pollution at end-of-life. The ability to draw on the circular economy model for guidance with new engineering solutions provides the potential to reduce societies' environmental impact.[5]

The building sector is one of the most significant contributors to the arising environmental impact. Globally, the construction industry consumes more than 32 % of the world's resources, produces more than 25 % of the planet's solid waste, and emits about 35 % of the world's greenhouse gasses.[6] The environmental impact of the building sector is no different in New Zealand. For example, the national construction and demolition industry is expected to contribute 40-50 % (presumably by weight) of New Zealand's landfill waste.[7] Adopting ideas from the circular economy model to the building industry could see the reuse of waste materials from construction and demolition at their end-of-life as raw materials for further construction. In a long-term scenario, this could include using materials and design processes that lend themselves better to circularity than the current system allows. The transition into the circular economy could also include the use of materials from current waste streams from the building construction sector for further application. The circular economy concept could help mitigate waste streams, reliance on resource extraction, and the corresponding emissions of processing virgin material, thus, reducing the industry's environmental impact.[5]

Āmiomio Aotearoa is an MBIE-funded project designed to help Aotearoa New Zealand transition to a circular economy. This project, hosted by the University of Waikato, crosses institutions and disciplines to move beyond linear extract-produce-use-dispose material and energy flow models in order to optimise the value and use of products, components and materials over time, for the wellbeing of Aotearoa New Zealand.

One sub-project of Āmiomio Aotearoa endeavoured to develop a database of construction material flow, to assess state of art materials utilisation and waste for building construction, and identify prime waste material candidates for incorporation into novel building materials. To this end, the material flow analysis (MFA) informs and supports further research within the wider Āmiomio Aotearoa project and other academic and industry initiatives, to improve the circularity of material consumption and environmental sustainability in the building construction sector.

This report describes the methodology for producing this database and summarises the findings of this MFA project. The specific objective of the MFA project was to evaluate the currently available data on the flow of material through the building construction sector in Aotearoa New Zealand (NZ). This objective was achieved through an analysis of quantitative and qualitative data measuring the mass of construction materials at four key stages: Material input, construction, demolition and material output (***Figure 1***).

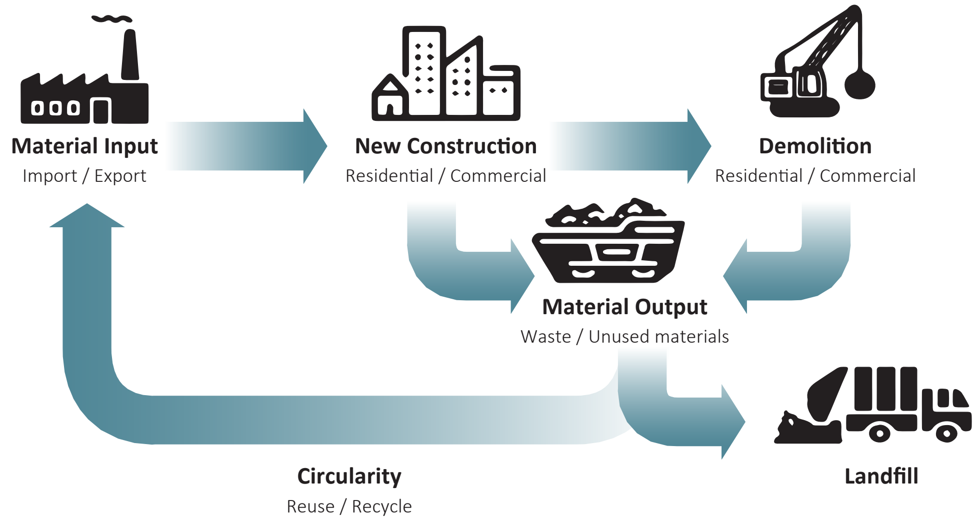


Figure 1*: Simple model of material use in the building construction sector.*

Estimating the total flow of material in the commercial building construction sector was considered out of the scope of this study due to the diversity of building types and a lack of data available, as well as the limited time frame available for this study. Where commercial data was available, it was included in the report. However, residential dwellings account for the vast majority of construction in NZ (88 % of all new buildings by quantity, 75 % by value, and 71 % by floor area).[1] Therefore, as residential dwellings are the biggest consumer of materials and contributor of construction and demolition waste (excluding infrastructure), the project team decided to focus on residential dwellings.

The project team discovered that concrete, masonry, timber, steel, cement-based claddings (including fibre-cement, autoclaved aerated concrete (AAC)), plasterboard, aluminium, glass, and plastic are the primary materials used in the construction of residential building envelopes, in addition to being expected to be the largest contributors of construction and demolition waste. Therefore, the MFA project team decided to focus on building envelope materials to estimate the material flow.

The following sections describe and analyse the available data across the key stages. Where data is unavailable, extrapolation techniques are described to somewhat compensate for these gaps. Data quality and limitations are also described. Despite these gaps, this report gives a useful current state picture of material flows for the residential construction sector in NZ, and informs focus for future data collection to improve this picture.

4 | Material Input

The following section outlines the collection and analysis of data for materials entering the building construction sector, including the quantity (mass) and the source of these materials (imports and local production). For some key materials, the consumption was assumed to be the same as production and supply in NZ. This assumption was made as the stock of materials was expected to be relatively constant over time, and therefore, the production and import of materials was estimated to be relatively constant with the material consumed. Timber was the most thoroughly documented material with regards to use in the building construction sector, while all other materials had large gaps in the data available.

4.1 Timber

Timber and timber-based products for use in NZ's construction sector are produced by local mills and timber product manufacturers, in addition to imports. In the last financial year (2021), there was an estimated 37 million cubic meters of timber harvested in NZ, of which 8 million cubic meters went to NZ sawmills.[8] There are 39 timber mills in NZ with output capacities ranging from 25,000 to 500,000 cubic meters of sawn timber annually, producing a total of 4.5 million cubic meters of sawn timber in 2021.[8, 9] The flow of timber supply in NZ is shown in ***Figure 2***. The consumption of NZ grown and harvested timber is further represented in ***Figure 3***.

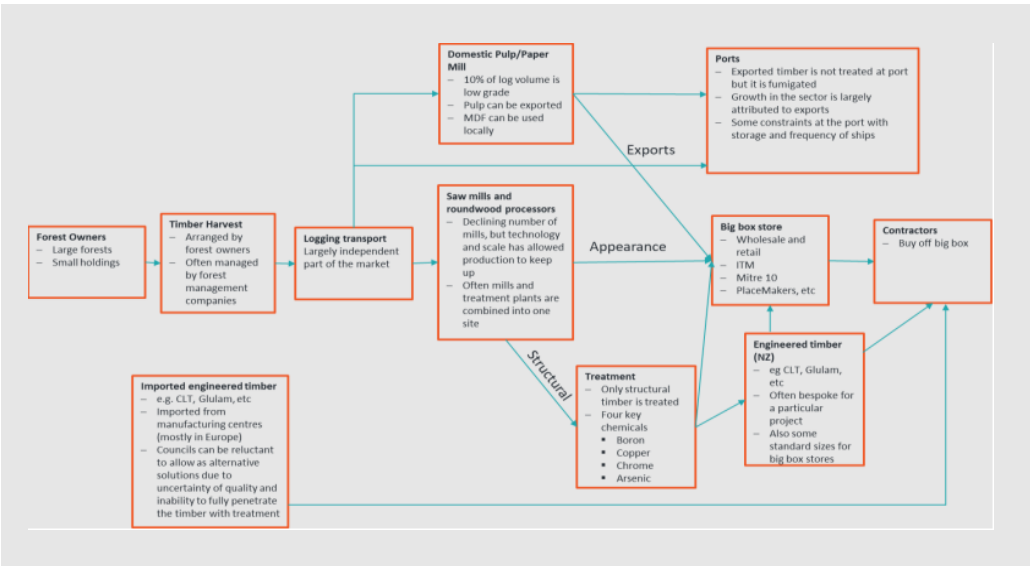


Figure 2: *Flow diagram of timber consumption in NZ.*[10]

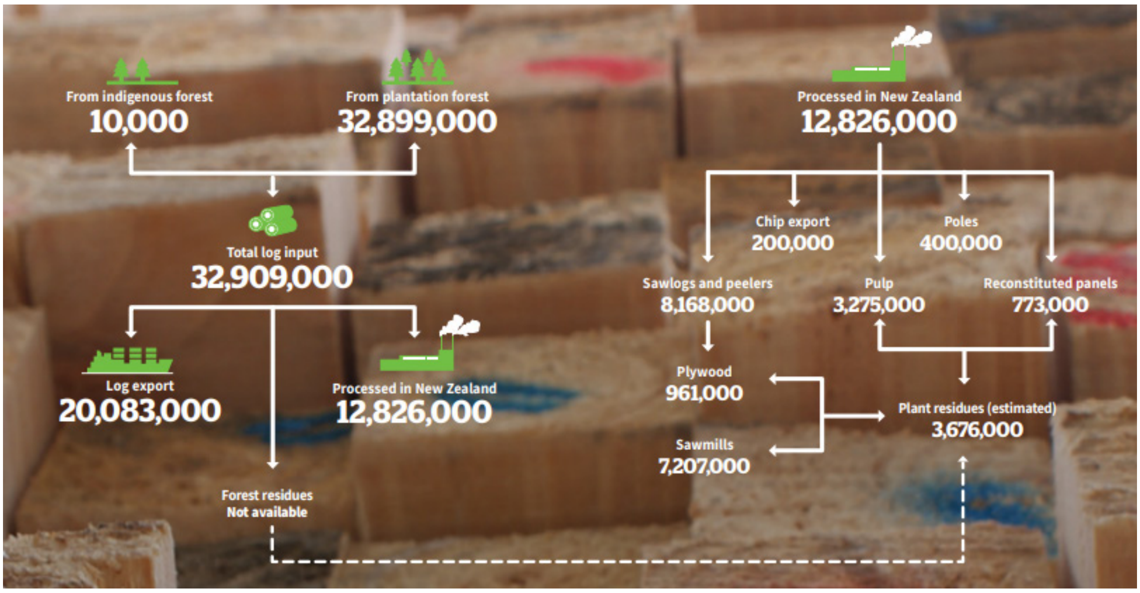


Figure 3: *Consumption of timber harvested in 2020 in NZ (m³).* [11]

The Ministry for Primary Industries (MPI) provides data for timber harvesting, processing, imports, and exports of timber and timber-based products in NZ by volume.[12-15] Collating this data using a mass balance provides an understanding of the consumption of timber for a given year (all timber and timber-based products used in NZ were assumed to have a density of 425 kgm^{-3}, the density of dry radiata pine).[a] It was assumed that the timber supply (from NZ harvesting and imports) in a given year is representative of the timber consumption for that year. Furthermore, an estimated 81 % [b] of timber is used in the residential construction sector, while the remaining 19 % is used in commercial construction.[10] Evaluating this information indicates that 1.6 million tonnes of timber and timber-based products were consumed in 2021 by the residential sector and a further 0.38 million tonnes consumed by the commercial building sector.[c] The timber and timber-based products consumed in 2021 included (***Figure 4*** and ***Figure 5***):

- 1.25 million tonnes of sawn timber produced in NZ
- 50,600 tonnes of imported sawn timber
- 513,900 tonnes of locally produced timber products (panels and engineered timber)
- 169,500 tonnes of imported timber products.

Overall, 88.8 wt.% of timber consumed in NZ was locally produced in 2021. The consumption of local and imported timber products from 1990 to 2021 is summarised further in ***Figure 4, Figure 5*** and ***Figure 6***. [12-15]

a Logs from harvesting are expected to be significantly heavier with a density of roughly 1.04 tonnes/m³. (Personal Communication)

b Presumably by weight. However, the density was considered constant for all timber and timber based products, so the percentage being by weight or volume will not affect the evaluation of the timber used in residential or commercial construction.

c A small percentage of timber is expected to be consumed by other industries, which these estimates have not accounted for. Furthermore, it is expected that these figures include timber used for all parts of construction, including the building envelope, fit-out, renovations, decking, landscaping, and furniture.

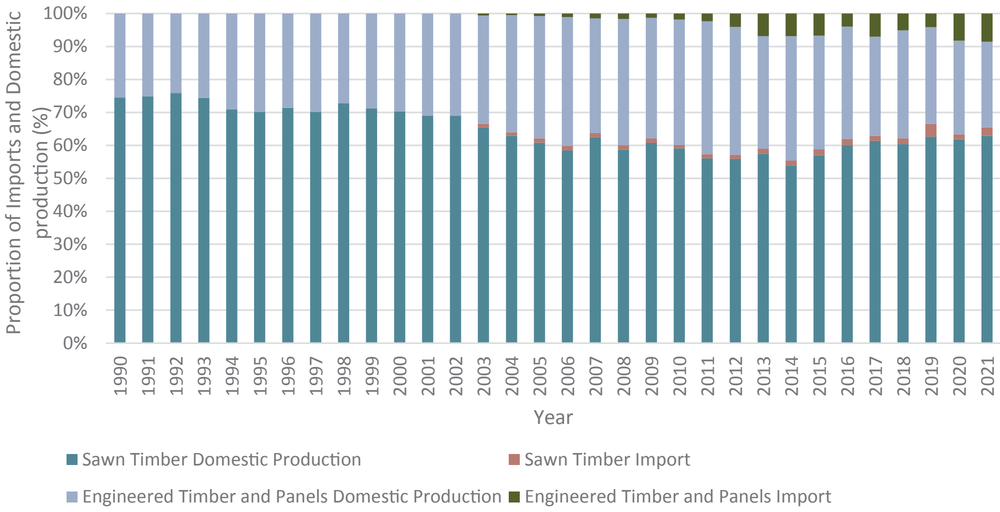


Figure 4*: Proportion of imports and domestic production for sawn timber and timber-based products for use in New Zealand.*

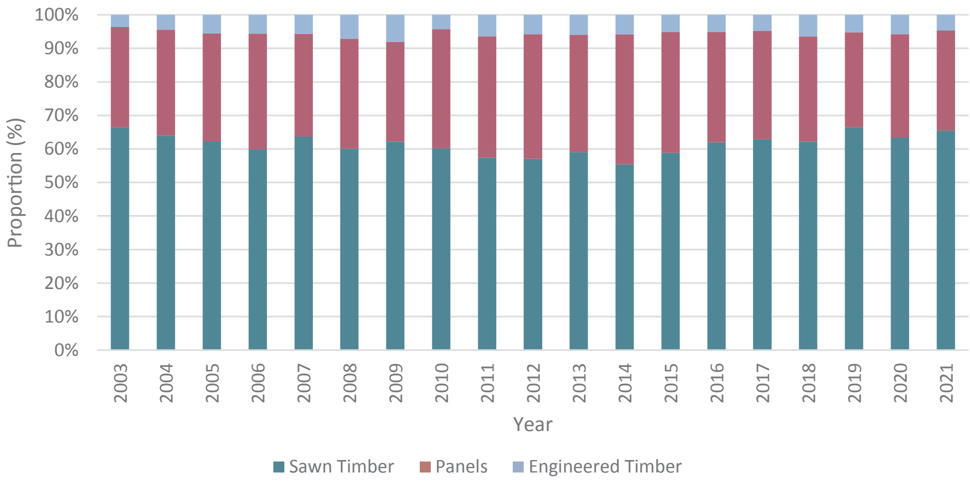


Figure 5*: Proportion of timber consumption, including sawn timber, timber-based panels, and engineered timber products.*

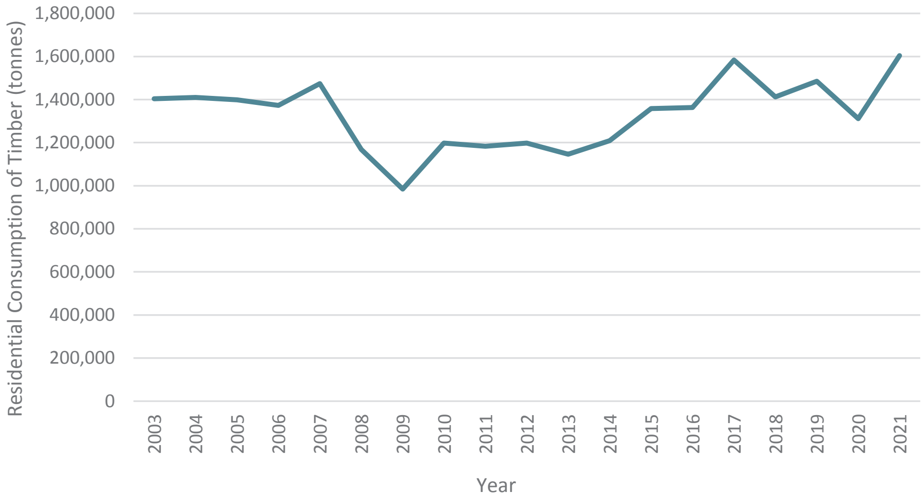


***Figure 6**: Estimate of residential timber consumption in New Zealand from 2003 – 2021, based on MPI data and the assumption that residential buildings consume 81 % of the timber in New Zealand.*

The timber and timber-based products used in residential construction include sawn timber, fibre board, veneer, plywood, particle board, glulam, and laminated veneer lumber (LVL).[12-15] The proportion of timber and timber based products is only known for the timber consumed in NZ. The consumption of timber in residential construction (and in general) appears to be relatively constant (***Figure 6***). The consistency of timber supply is expected to be due to larger forests (making up roughly 60 % of the forestry market) run by managed funds focusing on providing a steady rate of return; therefore, maintaining a consistent rate of harvesting.[10] The timber milling and treatment market is largely dominated by Carter Holt Harvey and Redstag.[10]

4.2 Concrete

The consumption of concrete in NZ is well documented, as Statistics NZ measures the production of ready-mix concrete (assuming production and consumption are roughly the same).[16] However, the proportion of concrete used in infrastructure versus construction (whether residential or commercial) is unknown.[17]

Concrete is produced with three primary ingredients: Cement, aggregate and water. Aggregate makes up the majority of concrete at 60 – 75 wt.% and is all produced locally due to the availability and the high cost of transportation.[10, 18] Aggregate is produced by several companies across NZ and is typically consumed in the area it is produced. In 2018, 50 million tonnes of aggregate were estimated to be consumed in NZ.[10] Of this, 65 wt.% was expected to have been directly consumed by roading and infrastructure. Cement typically makes up 10 – 15 wt.% of concrete and is supplied by three companies. Golden Bay Cement is the largest supplier of cement in NZ, providing 61.7 wt.% of the market. Golden Bay cement produces all of its cement in NZ. Holcim is the next largest supplier of cement in NZ (30.9 wt.%) and imports all of it. HR cement makes up 7.4 wt.% of cement supplied in NZ. HR cement imports clinker (an intermediary product in cement production) and uses it to produce cement in NZ. The total cement supply in NZ is estimated to be 1.62 million tonnes. The expected flow of material input for aggregate and concrete are shown in ***Figure 7*** and ***Figure 8***.[10, 18]

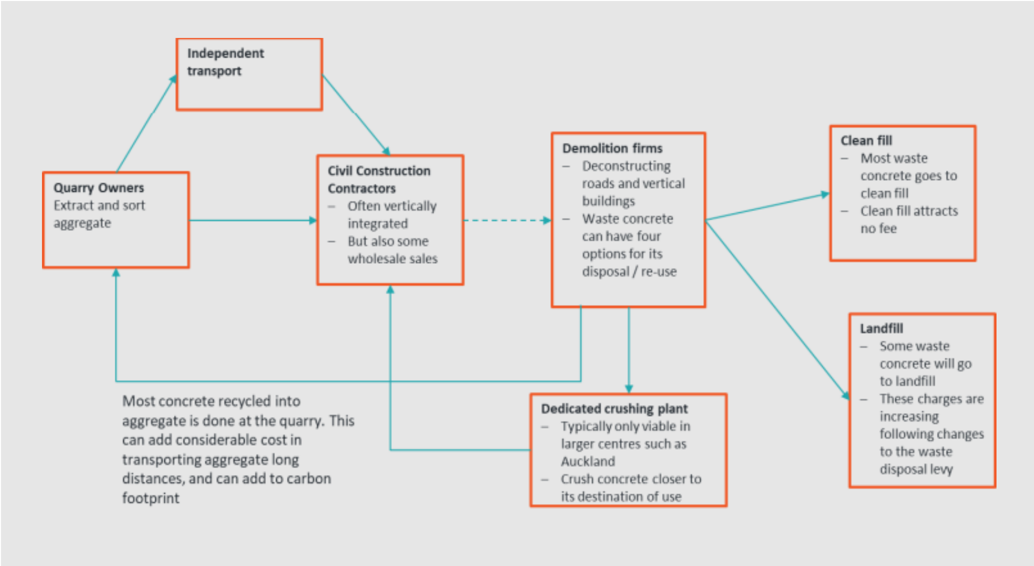


Figure 7*: Flow of aggregate*[10]

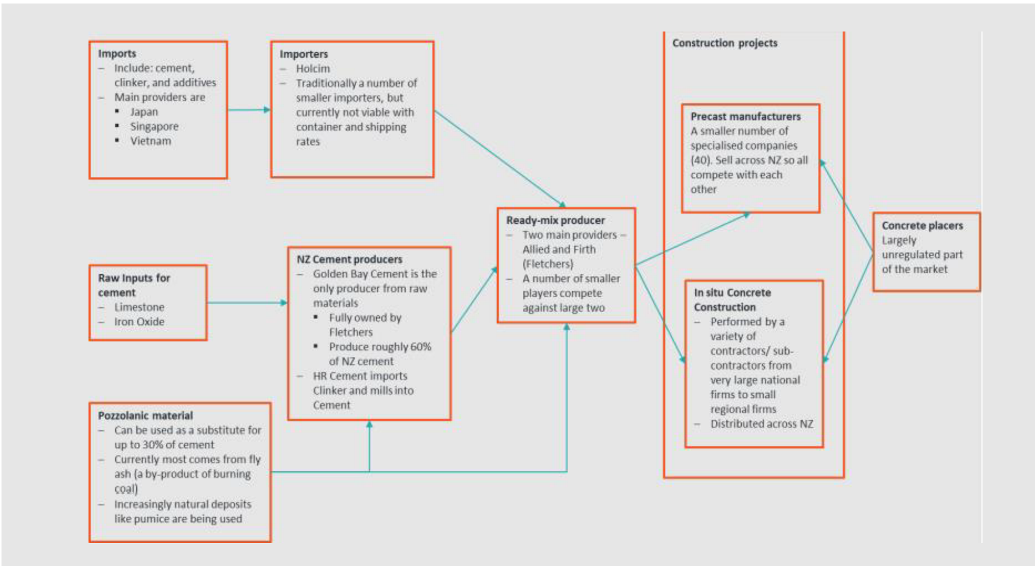


Figure 8*: Flow of concrete*[10]

The consumption of concrete in NZ is assumed to be roughly the same as production. ***Figure 9*** shows the consumption of ready-mix concrete for from 1992 - 2021. Ready-mix concrete includes all forms of concrete, including in-situ concrete, concrete blocks and masonry. In 2021, it was estimated by Statistics NZ that 4.5 million cubic meters of ready-mix concrete was consumed, equating to roughly 10.8 million tonnes (assuming an average density of 2.4 tonnes per cubic meter).[16]

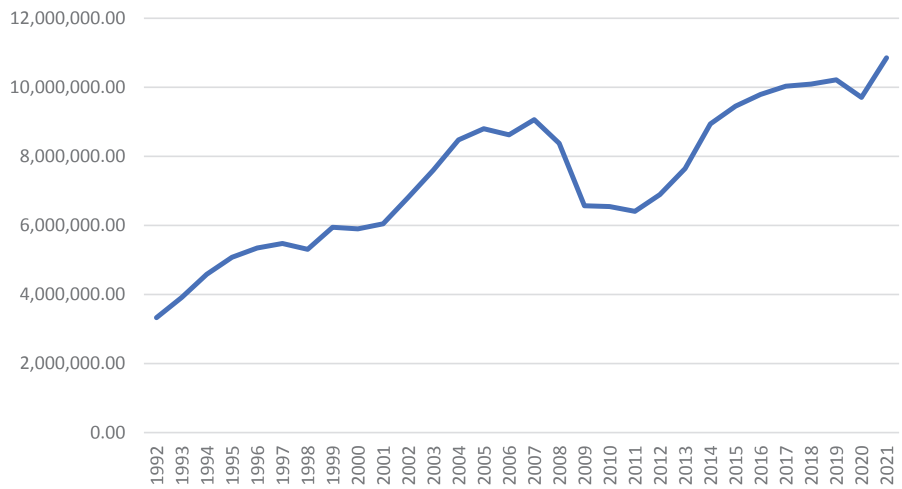


Figure 9: *production of ready-mix concrete for 1992-20201, based on volume statistics and an average density of 2,400 kg/m3.*[10]

4.3 Steel

Steel consumption in NZ is less reported than the consumption of timber and concrete. The material flow for the consumption of steel in NZ is shown in ***Figure 10***.

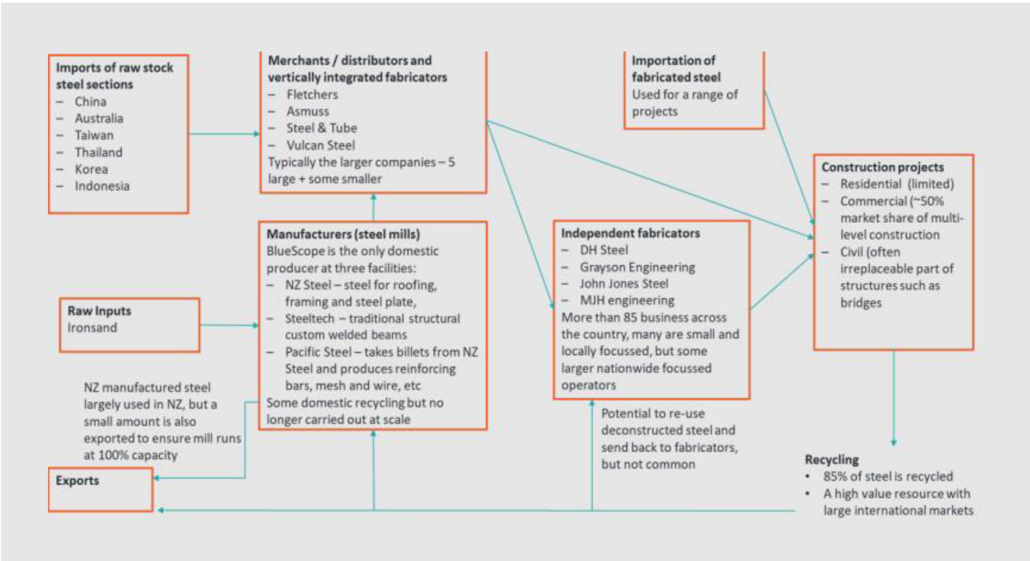


Figure 10: *Flow of steel consumption in NZ*[10]

Steel is only produced by one company in NZ (BlueScope), and all other steel is imported. It is expected that 850,000 tonnes of steel are consumed annually in NZ, and half of the steel is produced locally.[10, 19] Although there is only one producer of steel in NZ, there are several suppliers. The proportion of steel in NZ that is used for residential and commercial buildings is unknown.

4.4 Plasterboard

Plasterboard in NZ is primarily produced by Winstone wallboards (a Fletcher Building company) under the brand name GIB®. GIB® supplies 90 – 95 % (market share) of the plasterboard in NZ.[20, 21] In 2022 a report from Winstone Wallboards indicated that the plasterboard production was at an all-time high, relating to a production rate of 236,600 tonnes per annum.[17, 22]

4.5 Other

Data regarding the input of other materials into the building construction industry could not be found with sufficient detail to be useful for this MFA. The mass of material entering the building construction sector for all materials other than timber and concrete is unknown. Therefore, to predict how much of each material is input into the building construction sector, various extrapolation techniques were used based on further estimations and information explained throughout the report (see the Discussion ***section 9.1***).

5 | New Construction

An estimation of the quantity of materials used in the construction of new residential buildings in NZ on an annual basis was calculated using existing data from the Building Research Association of NZ (BRANZ) and Statistics NZ. Calculating this total quantity of materials used enabled the Āmiomio Aotearoa team to then estimate the associated waste from the residential construction sector. Waste was estimated as the difference between the quantity of materials going into the residential construction sector and the total quantity used in newly constructed dwellings.

The quantification of construction materials used in new commercial buildings was not possible within the scope of this project due to the limited data available regarding the breakdown of materials for various types of commercial buildings. Furthermore, the large variability in the construction of commercial buildings adds to the difficulty of material quantification. However, residential dwellings make up 88 % of all new buildings in NZ by quantity, 75 % by value, and 71.0 % by floor area (***Table 1***).[1] Therefore, residential dwellings are likely to be the biggest consumer of building materials and contributor of construction and demolition (C&D) waste in NZ (excluding infrastructure). For the purpose of this report, it has been assumed by the project team that all new consents lead to new builds in the given year.

Table 1: The Value, Floor area and Numbers of consents for residential and commercial construction in NZ for 2021. Value, and number include residential and commercial alterations, whereas the floor area does not as the data is not available.[1]

	Residential Construction	Commercial Construction	Total
Value ($)	21,190,036,770	8,190,310,679	29,380,347,449
Value (%)	75	25	
Floor Area (m^2)	7,523,585	3,069,321	10,592,906
Floor Area (%)	71	29	
Number (#)	79,963	10,708	90,671
Number (%)	88	12	

5.1 Material Estimation for Residential Housing

As the building envelope accounted for the largest portion of materials used, this was the focus of the residential construction material estimation. The building envelope was defined as the foundations, subfloor, flooring, structural framework, roof coverings, cladding, windows, insulation, and internal wall linings. Other materials, such as electrical wiring, plumbing, internal fixings, or componentry used in kitchens or bathrooms were excluded from the scope of this MFA project.

5.1.1 Quantity and Average Floor Area of New Residential Dwellings

The number of new residential dwellings constructed each year and the average floor area of these were obtained from Statistics NZ consent data (***Table 2***).[1] Residential buildings were separated into Low and Medium Density Housing (L/MDH see ***Glossary***) due to the significant differences in the floor area and quantity of materials used in construction. The number of new dwellings has increased from 17,518 in 1991 to 48,899 in 2021, with MDH making up 29 % and 48 % of all new dwellings in 1991 and 2021, respectively (***Figure 11***). The average floor area of LDH dwellings also increased from 153 m^2 in 1991 to 195 m^2 in 2021, while the floor area of MDH has remained relatively stable over the past three decades (***Figure 12***).

Table 2: *Summary of residential consent data 1991-2021.*[1]

		1991	1996	2001	2006	2011	2016	2021
Low Density Housing (LDH)	**No. New Dwellings**	12,380	17,142	15,805	19,996	11,112	21,310	25,564
	Average Floor Area (m^2)	153	184	198	215	212	209	195
	Total Floor Area (m^2)	1,892,978	3,158,622	3,122,871	4,307,106	2,350,223	4,446,668	4,982,505
Medium Density Housing (MDH)	**No. New Dwellings**	5,138	5,681	4,734	5,956	2,550	8,756	23,335
	Average Floor Area (m^2)	105	134	114	111	105	117	109
	Total Floor Area (m^2)	541,023	760,732	540,428	660,053	267,303	1,023,722	2,541,080
All Dwellings	**No. New Dwellings**	17,518	22,823	20,539	25,952	13,662	30,066	48,899
	Average Floor Area (m^2)	139	172	178	191	192	182	154
	Total Floor Area (m^2)	2,434,001	3,919,354	3,663,299	4,967,159	2,617,526	5,470,390	7,523,585

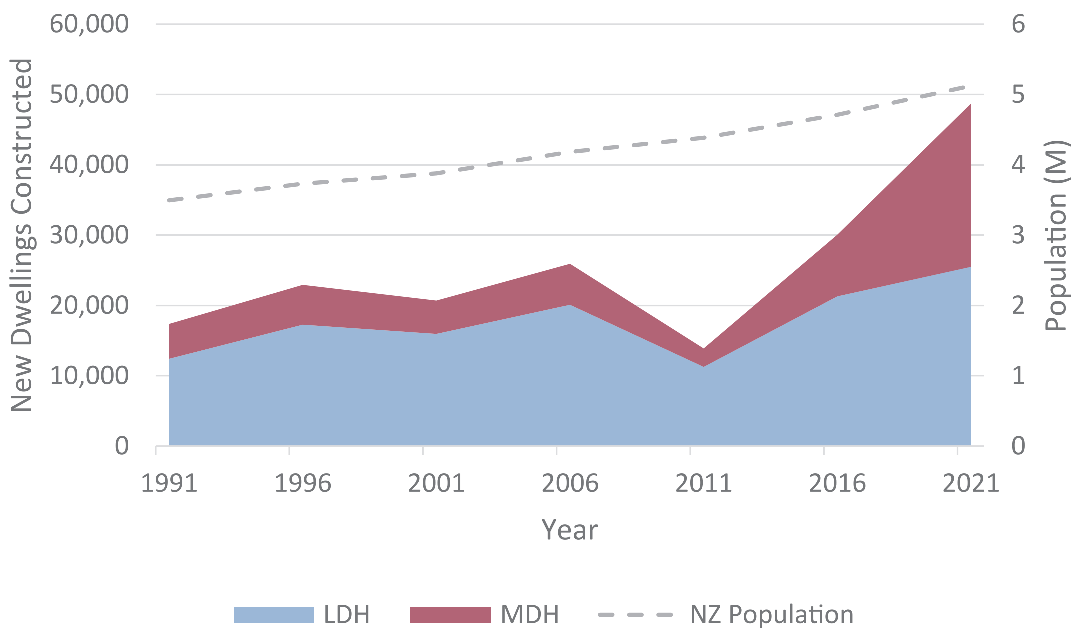


***Figure 11**: Number of new LDH and MDH dwellings constructed from 1991-2021 and NZ population.*

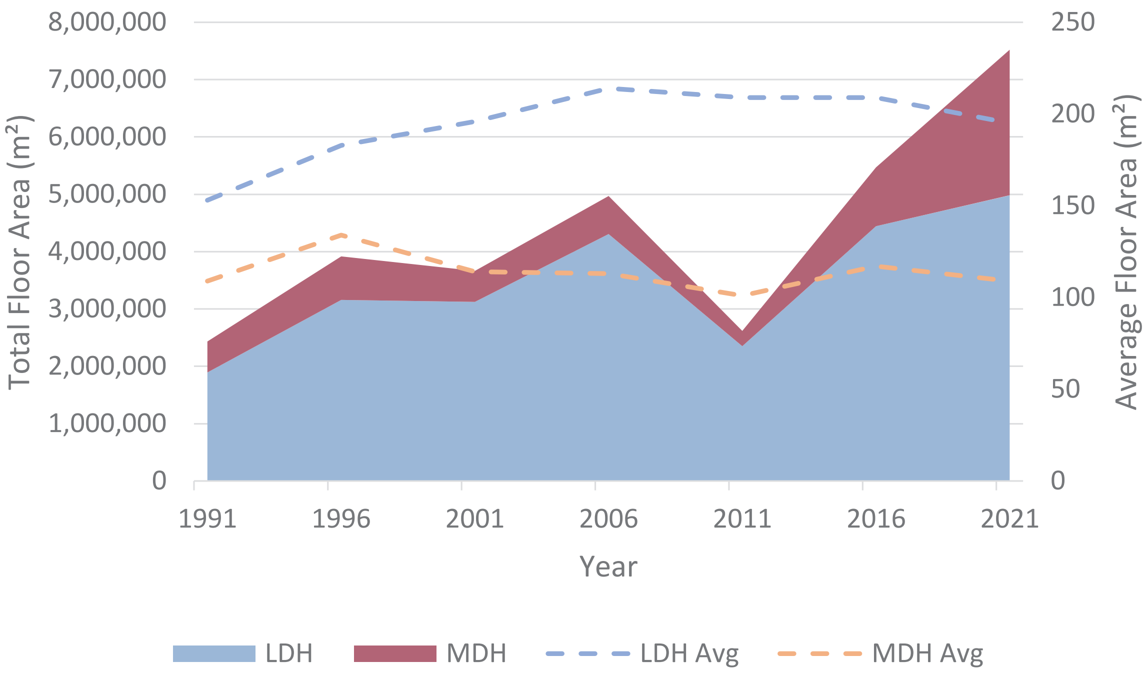


***Figure 12**: Average and total floor area of LDH and MDH dwellings from 1991-2021.*

5.1.2 Residential Dwelling Material Proportions

The proportion of materials used in new residential dwellings has changed over time. Data regarding the typical proportion of different materials used in the envelope of new dwellings between 2010-2019 was obtained from a BRANZ report published in 2020, while additional BRANZ reports provided data for 2002-2010 (***Table 2***).[23] For the periods 1991-2001 and 2020-2021, the data was taken as the last known value to estimate the distribution of materials.

	Roof Cladding			Wall Cladding			Wall Framing		Flooring		Floor Joist		Insulation (wall, ceiling)		Insulation (timber floor)			Insulation (concrete slab)
Year	Sheet Metal	Tiles	Plastic/ Membranes	Bricks	Timber	Fibre Cement/ AAC/Stucco	Timber	Steel	Concrete	Timber	Timber	Steel	Fibreglass	Polyester	Polystyrene	Polyester	Foil	Polystyrene
1991	0.40	0.53	0.07	0.43	0.07	0.50	0.98	0.02	0.79	0.21	0.82	0.18	0.82	0.18	0.20	0.08	0.72	0.24
1996	0.40	0.53	0.07	0.43	0.07	0.50	0.98	0.02	0.79	0.21	0.82	0.18	0.82	0.18	0.20	0.08	0.72	0.24
2001	0.40	0.53	0.07	0.43	0.07	0.50	0.98	0.02	0.79	0.21	0.82	0.18	0.82	0.18	0.20	0.08	0.72	0.24
2002	0.40	0.53	0.07	0.43	0.07	0.50	0.98	0.02	0.79	0.21	0.82	0.18	0.82	0.18	0.20	0.08	0.72	0.24
2003	0.43	0.47	0.10	0.46	0.09	0.45	0.97	0.03	0.79	0.21	0.78	0.22	0.95	0.05	0.20	0.08	0.72	0.24
2004	0.49	0.38	0.13	0.46	0.12	0.42	0.96	0.04	0.79	0.21	0.70	0.30	0.94	0.06	0.20	0.08	0.72	0.24
2005	0.46	0.38	0.16	0.50	0.13	0.37	0.90	0.10	0.81	0.19	0.70	0.30	0.91	0.09	0.20	0.08	0.72	0.24
2006	0.45	0.42	0.13	0.51	0.14	0.35	0.91	0.09	0.81	0.19	0.64	0.36	0.94	0.06	0.20	0.08	0.72	0.24
2007	0.54	0.37	0.09	0.44	0.18	0.38	0.85	0.15	0.78	0.22	0.69	0.31	0.95	0.05	0.20	0.08	0.72	0.24
2008	0.47	0.36	0.17	0.43	0.19	0.38	0.86	0.14	0.73	0.27	0.69	0.31	0.94	0.06	0.32	0.05	0.63	0.38
2009	0.48	0.35	0.17	0.42	0.19	0.39	0.85	0.15	0.78	0.22	0.71	0.29	0.94	0.06	0.52	0.12	0.36	0.42
2010	0.53	0.39	0.08	0.46	0.20	0.34	0.90	0.10	0.81	0.19	0.69	0.31	0.96	0.04	0.65	0.13	0.22	0.45
2011	0.53	0.42	0.05	0.44	0.22	0.34	0.84	0.16	0.80	0.20	0.74	0.26	0.96	0.04	0.69	0.09	0.22	0.48
2012	0.49	0.43	0.08	0.45	0.23	0.32	0.87	0.13	0.80	0.20	0.79	0.21	0.96	0.04	0.34	0.37	0.29	0.49
2013	0.52	0.36	0.12	0.47	0.23	0.30	0.94	0.06	0.79	0.21	0.62	0.38	0.96	0.04	0.53	0.25	0.22	0.50
2014	0.53	0.38	0.09	0.38	0.24	0.38	0.94	0.06	0.77	0.23	0.71	0.29	0.97	0.03	0.13	0.25	0.62	0.63
2015	0.54	0.39	0.07	0.38	0.27	0.35	0.93	0.07	0.76	0.24	0.74	0.26	0.95	0.05	0.70	0.15	0.15	0.45
2016	0.56	0.32	0.12	0.35	0.27	0.38	0.92	0.08	0.77	0.23	0.75	0.25	0.94	0.06	0.66	0.26	0.08	0.63
2017	0.55	0.31	0.14	0.31	0.30	0.39	0.90	0.10	0.74	0.26	0.77	0.23	0.93	0.07	0.80	0.16	0.04	0.57
2018	0.70	0.24	0.06	0.28	0.25	0.47	0.94	0.06	0.69	0.31	0.73	0.27	0.93	0.07	0.85	0.15	0.00	0.61
2019	0.71	0.17	0.12	0.25	0.32	0.43	0.86	0.14	0.65	0.35	0.55	0.45	0.90	0.10	0.77	0.23	0.00	0.61
2020	0.71	0.17	0.12	0.25	0.32	0.43	0.86	0.14	0.65	0.35	0.55	0.45	0.90	0.10	0.77	0.23	0.00	0.61
2021	0.71	0.17	0.12	0.25	0.32	0.43	0.86	0.14	0.65	0.35	0.55	0.45	0.90	0.10	0.77	0.23	0.00	0.61

= Taken as last known value (no data available)

5.1.3 Estimation of Material Quantity

The quantity of each material used in the construction of a new residential dwelling can vary greatly depending on the design of the building (e.g. timber vs. steel framing) and floor area, among other factors. Material quantities were estimated based on NZ Standards (NZS 3604), in addition to the average weights of construction materials.[24-26] In order to represent the varying designs of new residential buildings, the proportion of materials displayed in ***Table 3*** was applied to the total quantity of dwellings built each year (***Table 2***).

Construction materials were categorised into eight main areas of focus, as follows:

- Concrete & masonry (including bricks, blocks, stone, tiles etc…)
- Timber & timber-based products
- Metals (including steel and aluminium)
- Cement-based claddings (including autoclaved aerated concrete (AAC) panels, fibre-cement weatherboards and panels, stucco etc…)
- Glass
- Plastic (including polyester and polystyrene)
- Plasterboard
- Insulation

A standard set of assumptions was also applied in calculating material quantities. Dwellings were assumed to be single storey with a hip roof profile (where all sides of the roof slope downwards towards the walls) and built on good ground as defined by New Zealand building standards.[24] The following sections outline how the material quantity for key areas of the building envelope were calculated. A ***Glossary*** has also been included for common construction terms.

5.1.3.1 Foundations

Dwelling foundation requirements are highly dependent on specific wind and earthquake loadings, shape of the structure, and weight of the wall and roof claddings. The Āmiomio Aotearoa team estimated average quantities of foundation materials with assumptions that would be representative of most NZ dwellings, as follows:

Assumptions

- *Live load of 2 kPa*
- *Wind Zone - Medium*
- *Earthquake Zone 2*
- *Single storey*

Concrete slab foundations were assumed to have the minimum[d] depth of 100 mm and an area equal to the floor area of the dwelling. The density of concrete used to calculate mass was 2400 kg/m^3. The steel reinforcement required for concrete slabs was also calculated using the floor area and the minimum mass of 2.27 kg/m^2.

Pile foundations were assumed to be constructed of 125x125 mm square sawn timber piles, with a minimum height of 300 mm above ground level. Ordinary piles were assumed to extend 100 mm below ground into the concrete footing, while anchor piles were assumed to extend 800 mm below ground, as per NZS3604. The concrete footing for each pile was assumed to have a cross-sectional area of 350x350 mm and a depth extending 100 mm below the base of the pile from ground level. The total number of piles required was calculated using the maximum span (1.65 m) and spacing (2.00 m) of bearers. These dimensions were used to define an area unit (2.00 x 1.65) with one pile on each corner. The number of units required for the floor of a typical NZ house was then found by dividing the floor area by this unit to obtain the variable A. The number of piles was then calculated assuming a rectangular floor area with the same length to width ratio as the unit defined above (2.00 : 1.65). The derivation of the second equation is shown in ***Appendix I - Equation Derivation***.

d The building standard (NZS3604) often defines a minimum value. These minimum values were used in the calculations, unless further information was available.

$$A = \frac{floor\ area}{1.65 \times 2.00}$$

$$No.piles = A + 2\sqrt{A} + 1$$

The bracing units (BUs) required for pile foundations was calculated using the floor area and a weighted average of light (9.6 BUs/m^2) and heavy (12.7 BUs/m^2) roofing, corresponding to ***Table 1***, to give 10.2 BUs/m^2. The number of anchor piles could then be calculated by dividing the total BUs required by 120 BUs (for earthquake loading), while the number of ordinary piles was taken as the remaining piles.

5.1.3.2 Wall Framing & Trusses

The quantity of material required for internal and external wall framing was estimated using standard dimensions from NZS3604. The standard stud height in NZ is 2.4 m, placed vertically and spaced 600 mm centre-centre, with dwangs placed horizontally between studs, spaced 800 mm centre-centre. All timber framing was assumed to be 90x45 mm, including the top and bottom plates, where the top plate of load bearing walls must then be a lamination of two 90x45 mm. For simplicity, all external walls were assumed to be loadbearing (transferring the load of trussed roofs), while the internal walls were assumed to be non-loadbearing. Furthermore, window and door openings were disregarded in the wall framing estimation due to variability in dwelling designs and internal layouts. However, it was estimated that the additional lintels and trimming studs required for these openings would result in a similar amount of framing material required. For simplicity, the same framing dimensions were used in timber and steel framing.

Using the above framing outline and an estimated density of 425 kg/m^3 for *Radiata pine*, the average mass of internal and external wall framing per square meter was found to be 8.01 kg/m^2 and 8.72 kg/m^2, respectively. The predominant framing section for steel-framed dwellings was assumed to be a lipped channel section '89LC75 G550', with a depth of 89 mm, base metal thickness (BMT) of 0.75 mm, and a density of 7850 kg/m^3.[27] Steel sections with a slightly wider flange were used for the top plate in accordance with the National Association of Steel Framed Housing (NASH) standards.[28]

Existing data could not be found regarding the typical wall area of a residential dwelling. Therefore, average data regarding wall area was calculated by collating nine standard house designs from a prominent NZ residential building company, ranging from 175-216 m^2 in floor area. The external and internal wall areas were then divided by the corresponding floor area to calculate an average wall:floor area ratio. The total mass of wall framing for a single dwelling could then be calculated from the floor area and the average mass per square meter previously calculated.

Roof trusses are typically constructed off-site by an independent manufacturer and are highly dependent on the dwelling shape, location, and subsequent wind and snow loadings. It is therefore difficult to accurately determine an average quantity of material required for trusses in new residential dwellings. However, by assuming a square dwelling shape and using comparable roof framing requirements from NZS3604, a rough estimation was calculated.

The top and bottom chords were assumed to be constructed of 190x45 mm members, while the webbing was assumed to be 90x70 mm. The length of the bottom chord was calculated using the square root of the floor area. A standard pitch of 25° was then used to calculate the length of the top chords. Four webbing sections were estimated for each truss using an angle of 60° between the web and bottom chord, arranged in a Fink profile. Trusses were assumed to be placed every 1.2 m, with purlins running the length of the dwelling at 800 mm. Using a timber density of 425 kg/m^3, the total mass of trusses could be calculated for each dwelling. For steel framing, the same assumptions were applied using '89LC75 G550' sections and a density of 7,850 kg/m^3.

5.1.3.3 Subfloor

The subfloor of a dwelling sits on pile foundations and is typically constructed from timber or light steel. As with many other structural elements of a residential buildings, the subfloor design is dependent on the dwelling geometry and loadings from internal and external walls.

Bearers were assumed to have a maximum span of 1.65 m and spacing of 2.00 m, while joists were assumed to have a maximum spacing of 600 mm.[24] To calculate the volume of material required, timber sections measuring 140x90 mm and 140x45 mm were used for bearers and joists, respectively. The volume of material was then multiplied by the density of Radiata pine to obtain the mass of the subfloor per square meter. For steel subfloors, the same assumptions were applied using '89LC75 G550' sections, where each bearer was composed of two C-sections.

5.1.3.4 Flooring

Concrete floors were assumed to be the top surface of concrete slab foundations and therefore not recalculated as further material. Wooden flooring was assumed to be constructed from particleboard sheets with a depth of 15 mm and mass of 9.9 kg/m^2.[23] The total mass was calculated using the floor area of the dwelling. Other flooring surfaces, such as timber floorboards, carpets, tiles, and vinyl were not analysed.

5.1.3.5 Wall Cladding

Wall claddings were assumed to cover the external wall area excluding the window area. Timber cladding was assumed to be weatherboards, with a thickness of 15 mm and density of 425 kg/m^3.[26] Metal cladding was assumed to be corrugated steel with an average BMT of 0.48 mm (average of standard 0.40 and 0.55 mm BMT) and density of 10,000 kg/m^3, accounting for the corrugated profile.[29] Brick claddings were assumed to have an average depth of 70 mm and mass of 1679 kg/m^2, including mortar.[30] Finally, fibre cement was assumed to have an average mass of 13.6 kg/m^2 based on several products from the dominant NZ supplier of fibre cement cladding.

5.1.3.6 Roof Cladding

The mass of roof cladding required for a dwelling is dependent not only on the material used, but also the geometry of the dwelling, roof pitch, and size of the overhang. In order to provide an estimate of material quantity, the following calculation was used to find an average roofing area, assuming a typical pitch of 25°.[31]

$$Roof\ area = A \times R \times E$$

Where A is the total floor area of the dwelling, R is a roof pitch factor (R=1.1034 for a 25° pitch) and E is an excess factor to account for hip, valleys, and ridges (additional 17 % for hip roof).[31] Overhangs were not accounted for as this area would vary significantly depending on the geometry of the dwelling and size of the overhang.

Metal cladding was assumed to be corrugated steel with an average BMT of 0.48 mm (average of standard 0.40 and 0.55 mm BMT) and density of 10,000 kg/m^3, accounting for the corrugated profile. The mass of tiled roofing was taken as an average of terracotta and concrete tiles, at 55 kg/m^2.[26]

5.1.3.7 Plasterboard

It is estimated that 90-95 % (market share) of plasterboard in NZ is manufactured by Winstone Wallboards.[20, 21] Therefore, the density of GIB® plasterboard was used to calculate the mass of plasterboard in new residential dwellings. While varying types of plasterboard are available for different areas (e.g. Standard vs. Aqualine), it was assumed that the majority of plasterboard used in new builds would be 10 mm Standard GIB®, with a nominal mass of 6.5 kg/m^2.[32] The area of plasterboard was estimated as the external wall area excluding windows plus twice the internal wall area, to account for lining on both sides of internal walls. It was also assumed that an average two car garage door measuring 4.75x2.10 m could be subtracted from the wall area for an LDH dwelling, and a single car garage door measuring 2.55x2.10 m could be subtracted for an MDH dwelling.

5.1.3.8 Insulation

Insulation was calculated using the minimum R-values required for floors (R=1.3), walls (R=2.0), and ceilings (R=3.3) for 'Climate Zone 3', as this was the upper value for all areas.[33] The density and thickness of fibreglass insulation was calculated as a weighted average of comparable products from the three most prominent NZ suppliers; Tasman Insulation (Pink® Batts®, 54 % market share), Knauf (25 % market share), and Bradford Insulation (10 % market share).[20] The average density was found to be 7.44 and 11.29 kg/m^3 ceiling and wall insulation respectively, with corresponding average thicknesses of 180 and 90 mm.[34-36] The density and thickness of polyester insulation was taken as an average of Mammoth® and GreenStuf® brands. The average density was found to be 7.5, 16.7, and 13.1 kg/m^3 for floor, wall, and ceiling insulation respectively, while the corresponding thickness was found to be 100, 115, and 175 mm. Polystyrene insulation data was taken from Expol®, a prominent NZ manufacturer. Concrete slab underfloor insulation was found to have a density of 16 kg/m^3 and thickness of 50 mm polystyrene, while timber underfloor insulation was found to have a density of 12 kg/m^3 and thickness of 60 mm polystyrene. Finally, although banned in 2016, foil underfloor insulation was used in new residential dwellings until 2017 and was therefore included in the material estimation. Foil insulation was assumed to be aluminium with a mass of 0.27 kg/m^2.[37]

The insulation area for walls was taken as the exterior wall area excluding window area, assuming internal walls were not insulated. The floor area was used to calculate the mass of floor and ceiling insulation.

5.1.3.9 Window Framing & Glass

Windows in new residential dwellings in NZ are typically double glazed with a glass thickness of 4-5 mm (average of 4.5 mm).[38] The area of windows in a dwelling can be highly variable depending on the design; however, the maximum allowed value is 30 % of the external wall area. Furthermore, industry estimations predicted an average of 35-45 m^2 of windows in a typical house, while online architectural platforms suggested a window area relating to 15-25 % of the floor area.[38, 39] Collating these values, it was estimated that the average window area would correlate to ~20 % of the floor area, giving 39 m^2 of windows in a 195 m^2 dwelling. For dwellings built prior to 2009, it was estimated that 30 % would be double glazed, while the remaining would be single glazed.[38]

The mass of aluminium window joinery in a dwelling is dependent on the number, size, and shape of its windows, in addition to the type of extrusion used. Therefore, it is difficult to give an accurate quantity of aluminium window joinery. However, in order to provide a rough estimate, purchase order data from a prominent residential builder was collated and adjusted for floor area, to obtain an average mass of aluminium window joinery based on the size of the dwelling. This estimation resulted in 8.6 kg of aluminium per square meter of floor area.

5.2 Total Quantities of Residential Construction Materials Over Time

The total quantity of materials going into the construction of new residential dwellings was estimated for the years 1991-2021 (***Table 4***). Overall, the quantity of materials going into the building construction sector has increased from approximately 820,000 to over 2 million tonnes in the 30-year period from 1991-2021.

Table 4: *Total quantity of construction materials going into new residential dwellings 1991-2021.*

Material (Tonnes)	1991	1996	2001	2006	2011	2016	2021
Concrete & Masonry	658,131	1,055,823	986,321	1,348,563	690,951	1,334,385	1,522,961
Timber	67,671	108,910	101,879	128,657	65,197	150,801	208,278
Metal	15,854	25,529	23,861	38,980	23,922	45,073	74,802
Plastic	3,929	6,380	6,044	7,630	5,893	15,569	27,387
Glass	7,119	11,464	10,715	14,529	11,779	24,617	33,856
Plasterboard	52,652	85,054	79,531	107,948	56,868	118,854	163,312
Fibreglass	4,018	6,471	6,048	9,401	5,059	10,353	13,633
Fibre-cement	11,045	17,785	16,623	15,986	8,033	18,762	29,307
Total	**820,420**	**1,317,415**	**1,231,022**	**1,671,694**	**867,702**	**1,718,414**	**2,073,537**

As expected, the total quantity of materials was found to be highly dependent on the number of new dwellings built each year (***Figure 13***). However, trends in the proportions of construction materials used in building envelopes have also impacted the materials going into the residential building sector. While most materials increased in quantity with the increasing number of dwellings, the quantity of bricks and tiles remained relatively steady as they decreased in popularity as a wall and roof cladding, respectively (***Figure 14***). Subsequently, corrugated steel increased in popularity as a roof cladding option, with a large growth in quantity over the 1991-2021 period. Cement-based claddings such as fibre-cement and AAC also grew in popularity as a substitute for brick after the Christchurch earthquakes in 2011. Furthermore, an increase in polyester and polystyrene insulation occurred following the ban of underfloor foil insulation in 2016, while the quantity of glass increased due to the double-glazing requirements introduced in 2009.

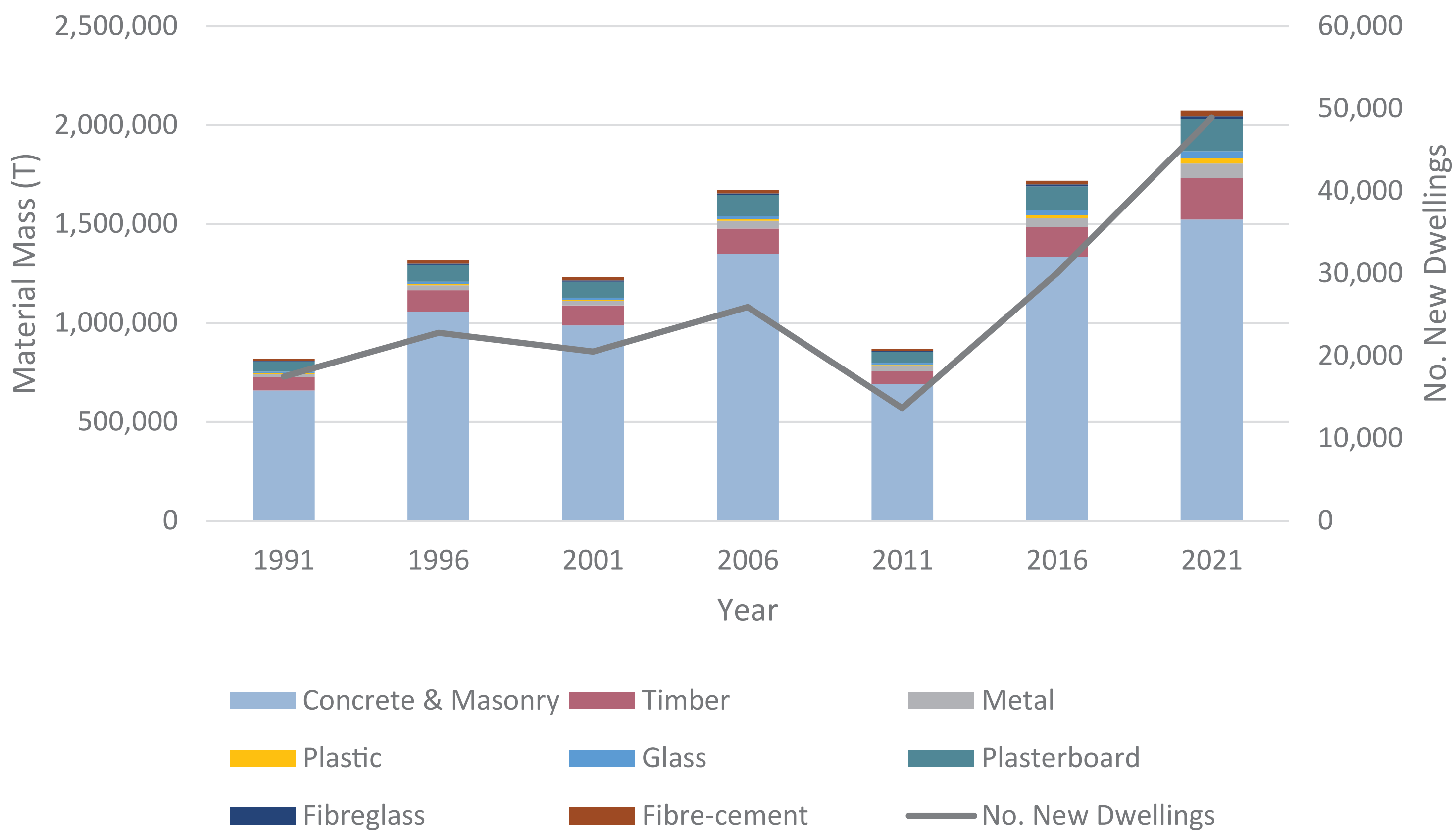


Figure 13: *Total quantity of construction materials estimated for new residential dwellings 1991-2021.*

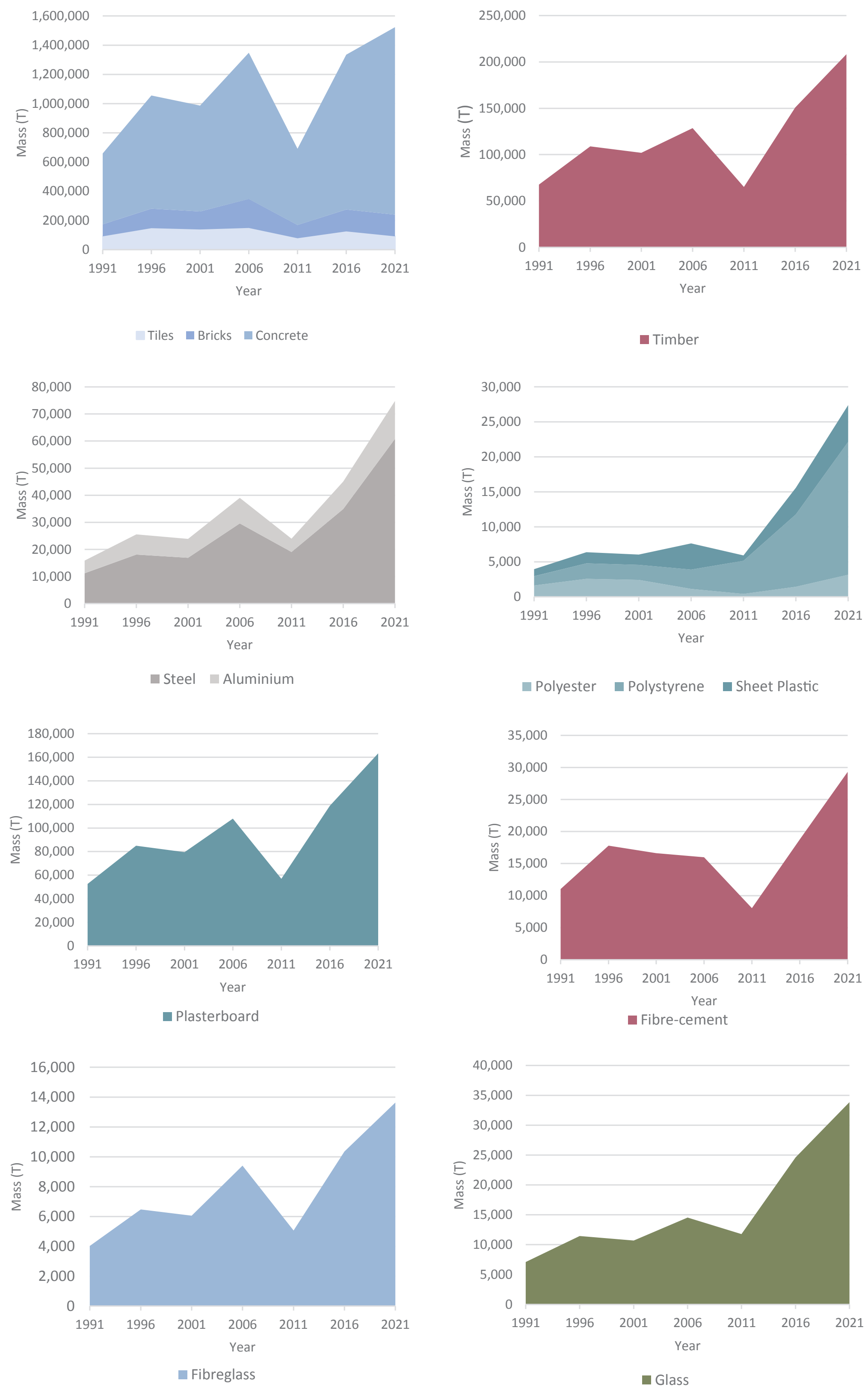


***Figure 14**: Total quantity of each construction material by category from 1991-2021*

5.3 Data Limitations

The above estimations are only representative of the main elements of a new residential building envelope with an average floor area. More complicated or variable elements, such as linings, bracing, fasteners, waterproofing, decking, landscaping, wiring, and plumbing were not accounted for. Therefore, it is likely that the quantity and variety of material required for the construction of a new residential dwelling exceeds that estimated in this report.

5.4 Reconciliation of Residential Material Estimation with Case Study Data

Case studies were undertaken based on data provided by two large residential building companies in NZ. The data included purchase orders for materials for the building envelope, which were used to evaluate the mass of materials purchased per house and extrapolated for the number of residential buildings built in NZ. The first case study used data for the whole company for a financial year and is expected to give a much better indication of representative masses of materials required in the building construction sector due to the high number of new residential builds the data represents (over 1000 residential buildings). The second case study is based on purchase order data for some key materials for two MDH builds. The comparison of case study data with material estimations will be discussed in ***section 9***.

5.4.1 Company-Wide Purchase Order Data for a Large Residential Construction Company

(Case Study 1)

A case study was undertaken in partnership with a major residential construction company in NZ. The company provided purchase order data for all of the residential buildings produced in the previous financial year, as well as details on the average floor area of the houses, and the number of houses built for the same period. Based on the average floor area of the houses it is expected that the majority of the buildings were standalone houses.

The data was assessed to find the mass of materials purchased in order to understand any differences in the material estimation as outlined above and the purchase amounts for this residential building company. The focus of this case study was on the mass of timber, bricks, plasterboard, fibre cement, and aluminium joinery purchased. The purchase order data for other materials, such as concrete and insulation, included supply and installation information where the mass of material could not be determined. Despite this limitation, this case study reconciliation was deemed worthwhile to provide an understanding of the accuracy of the data produced from the residential material estimations.

The following assumptions were used in the assessment of the purchase order data:

- The purchase order information was not assessed for the mass of timber used in framing and trusses due to the lack of data relating to timber volume or mass provided. Instead the timber used in frame and trusses was based on the estimation of 15 m3 of radiata pine used in frame and trusses for a 220 m2 house in NZ provided by one of the major suppliers of framing and trusses to the construction company.
- Timber was assumed to have a standard density of 425 kg/m3 including timber and timber products (e.g. plywood and LVL). This is an accurate density for dry radiata pine. However, timber and timber-based products are likely to have variable densities, and undried timber is expected to have a significantly higher density.
- Timber volume was typically calculated using the cross-sectional area multiplied by the number of lineal meters. Some timber was given in lengths (e.g. 4.2 meters), and volume was found by multiplying the cross-sectional area by the length and the number of lengths. Timber volume for panels (e.g. plywood) was calculated using the area of plywood multiplied by the thickness.
- Aluminium joinery data was provided by two suppliers. One supplier provided joinery sales in mass (kg) sold, while the other supplier provided details in lineal meters. Personal communication with the second supplier provided an estimation for the mass of aluminium joinery in one house. This estimation was used to calculate the mass of aluminium joinery provided by the supplier to the construction company.
- Brick data was provided for the number of standard bricks by three NZ suppliers. The mass of standard bricks was established through personal communication with each supplier to find the typical properties of bricks for each supplier.
- Plasterboard and fibre-cement mass was calculated using the number of sheets and the area or volume of each sheet multiplied by densities from the manufacturers in kg/m2 or kg/m3. For sheets manufactured by companies where densities were not supplied, the density was based on equivalent products from GIB® (for plasterboard) or James Hardie (for fibre-cement), as these were the most common products.

- There were some materials provided in the categories assessed that could not be evaluated due to unknown units or quantities. These are expected to be small portions of the materials assessed due to the small number of purchases.
- The mass of materials for an average 195 m2 house (the average size for a stand-alone house based on consent data for 2021)1 was found using the purchase orders for each branch of the construction company. The mass for each branch was divided by the number of houses built, and the average floor area of the houses built to find the material used per square meter, and then multiplied by 195 to find the material consumption for a typical NZ house in 2021.
- The total mass of materials used in NZ was approximated using the total mass of material used by the construction company multiplied by the ratio of the number of houses produced by the company and the number of residential consents for the whole of NZ in 2021. It is likely that this estimation is higher than the actual consumption of materials in NZ as the proportion of standalone to medium density housing built by this construction company is likely higher than that of the general building construction sector (assumption made from the average floor areas provided with purchase order data).

The mass of materials for a standard stand-alone house and the mass of materials extrapolated for the number of residential consents in 2021 for the year ending in December are shown in ***Table 5.***

Table 5: *Summary of purchase order data assessment for case study 1.*

	Bricks	Timber	Plasterboard	Fibre Cement	Aluminium
Mass used per House (tonnes)	6.87	7.40	3.90	1.04	0.345
Mass used in NZ (tonnes)	306,357	337,056	156,602	42,641	15,928

5.4.2 Purchase Order Data for Two Medium Density Units

(Case Study 2)

A second case study was undertaken using the purchase order amounts for two medium-density buildings. The data was assessed to find the mass of timber (excluding framing and trusses), bricks, plasterboard, fibre cement, and insulation. The assumptions made during the assessment of the purchase order data followed those of the first case study where applicable. ***Table 6*** shows a summary of the purchase order data for the two buildings. Due to the data only being for two buildings it was considered impractical to extrapolate for all of the residential construction in NZ in a year due to the lack of different construction materials and methods (e.g. the buildings only appear to use bricks and fibre cement for cladding, and extrapolating would not allow for other construction methods used). However, the data is useable to make direct comparisons with calculations in the material estimation.

Table 6: *Summary of purchase order data for case study 2*

	Bricks	Timber	Plasterboard	Fibre Cement	Insulation
Mass Per Building (tonnes)	3.15	11.10	6.17	3.52	0.38

6 | Demolition

Residential demolition is largely undocumented in NZ due to a lack of consent data; consent is not required for any demolition of detached buildings under three stories.[2]

The number of demolitions per year was estimated using census and new building consent data. The latest census taken in 2018 estimates that there was an increase of 108,558 residential dwellings between 2013 and 2018. Whereas consent data suggests that there were 145,998 residential buildings built between 2013 and 2018 (consents were used for 2014, 15, 16, 17, and 18).[1, 40] The total number of demolitions was estimated using the following equation:[41 e]

$$Demolitions = \Delta\ building\ stock - consents$$

Using this equation, it is estimated that there were 37,440 demolitions between 2013 and 2018. However, the change in houses from 2013 to 2018 is likely to be distorted by the 2010/2011 Christchurch earthquakes resulting in more demolitions being required. A report in 2013 indicated that in the year of 2013, 10,000 houses still required demolition as a direct result of the earthquakes.[41, 42] Accounting for the 10,000 houses requiring demolition due to the earthquakes, it is expected that 27,440 residential demolitions occurred between 2013 and 2018, resulting in 5,488 annual residential demolitions as a norm in the NZ building sector. BRANZ estimated in 2009 that housing demolitions would rise to about 4,000 per year by 2019, with only half being related to physical failure, and the rest being re-development of the site for higher housing density, or a single house rebuild to a higher level of amenity.[41] Given recent drives for intensity of housing, particularly in Auckland, it appears reasonable to expect 5,488 residential demolitions in 2022.

e The demolitions in the equation are expected to be a negative number as they represent a reduction in the building stock.

7 | Material Output

7.1 Introduction

The C&D industry is expected to be one of the most significant contributors to waste in NZ, producing an expected 40 – 50 % (presumably by weight) of waste in NZ.[7] The primary focus of this study was to understand the production of waste from the construction and demolition of building envelopes, including the foundations, structure, and cladding. Material output or 'waste' is typically defined as *"waste produced directly or incidentally by the construction and demolition industries. This includes building materials such as insulation, nails, plasterboard and timber, roofing materials, as well as waste originating from site preparation, such as dredging materials, tree stumps, and rubble".*[43] For the purpose of this report, waste includes all material that is output from the C&D sector including waste to landfill, clean fill, or recovered through reuse or recycling.

7.2 Data and Estimations

Data was collected through several sources, including government organisations, large residential building companies, and personal communication with experts in the industry. The aim of this section was to represent the data currently available and produce estimations for more specific sections of the building construction sector that were not accounted for in the available data. Firstly, the overall C&D waste data was assessed. The residential sector was then analysed for the expected waste associated with C&D. The expected waste streams associated with each material investigated were summarised. NZ reports for packaging and plastic waste were investigated to understand the sources of plastic waste from C&D and the types of plastic waste being produced. Finally, case studies were presented.

7.2.1 Total Construction & Demolition Waste

Construction and demolition is regularly accredited with producing 40 – 50 % (presumably by weight) of total waste disposed of in NZ.[7] However, this overall waste data is rarely categorised to understand exactly where the waste is coming from. An estimation of the total C&D waste produced in NZ in 2019 is provided by the Ministry for Environment (MfE), summarised in ***Table 7***.[44]

Table 7: *Estimates of C&D waste provided by MfE (2019).* [44]

Construction and Demolition Waste						
Landfill Class	1	2	3/4	5	Recovered	Total Waste
Annual Disposal (tonnes)	661,474	1,765,904	55,185	1,120,374	1,409,808	3,602,937

In 2019, it was estimated that a total of 9.07 million tonnes of waste was disposed of in NZ including managed and unmanaged landfills (i.e. class 1- 5 and farm fills).[29] Therefore, the estimated 3.6 million tonnes of C&D waste fits with the estimation at 40 wt.% of the total waste disposed of in NZ.

For the year of 2021, the Auckland Council expected 398,875 tonnes of landfill waste to be produced by C&D.[45] The estimated C&D waste included waste from infrastructure, commercial and residential buildings, including all related processes such as site preparation. The Auckland Council reports included the expected proportions of C&D waste being sent to Class 1 landfills. The proportions of materials supplied by Auckland Council were applied[f] to the data in ***Table 7*** to produce an estimation for the composition of the total C&D Class 1 landfill waste in NZ (summarised in ***Table 8***).[45] The proportions of materials that are sent to Class 2-5 landfills, are largely unknown, and unmeasured.

f Using the percentage of 398,875 of each material expected as C&D waste by Auckland Council multiplied by the 661,474 tonnes estimated for NZ to get the mass of each material expected in NZ.

Table 8: *Expected composition of C&D waste in NZ based on Auckland Council data for 2021 and MfE Construction and Demolition landfill waste estimate.*[44, 45]

Material	Mass (tonnes)	Proportion (wt.%)
Paper	6,465	0.98
Plastics	17,542	2.65
Ferrous metals	3,035	0.46
Non-ferrous metals	1,996	0.30
Glass	1,695	0.26
Rubble, concrete, etc.	374,957	56.69
Timber	205,856	31.12
Special / potentially hazardous	49,928	7.55
Total	**661,474**	**100**

The construction and demolition waste estimations provided by MfE, and Auckland Council all include waste from infrastructure (e.g. roads and bridges), and processes related to construction such as site preparation, and earthworks. These processes are expected to contribute a large portion of the C&D waste in NZ. The waste produced from construction and demolition of residential and commercial structures appears to be largely unknown and required further estimations.

7.2.2 Residential Construction Waste

Residential waste estimations from the building envelope were calculated using the material estimation (see ***section 5.1***) and an approximation by BRANZ of the mass of waste produced in construction as a percentage of overall mass of materials consumed (***Table* 9**).[47] The BRANZ data is produced for several common building materials and products. The data was simplified for the key materials studied for the envelope of residential houses (***Table 9***). This included taking averages where multiple products or materials fit within the category being assessed. Specifically, timber was calculated by taking an average of engineered timber, engineered timber panels, timber, and plywood; steel used an average of stainless steel, steel reinforcing mesh, steel sheet, and structural steel; and concrete was based on in-situ concrete.

Table 9: *Waste estimates per the mass of material used in construction. All values are provided as percentages.*[47]

Main materials/ products	Construction site waste (% by mass over mass in building)	Fate of construction site waste (% material by mass)			
		Reuse	Recycling	Recovery (Energy)	Landfill/ Clean fill
Aluminium	1	0	95	0	5
Bricks/blocks/tiles	5	90	0	0	10
Concrete	4	0	10	0	90
Fibre cement	18	25	0	0	75
Glass	1	0	0	0	100
Insulation	15	0	0	0	100
Plastics	5	0	0	0	100
Timber	8.75	0	37.5	0	62.5
Steel	2	1.25	95	0	3.75
Plasterboard	23	0	10	0	90

The material estimations for residential building envelopes above were calculated based on the mass of materials utilised in NZ houses, excluding waste such as offcuts, damaged materials, or over-ordering. Therefore, the waste was assumed to be additional to the material estimation, such that:

$$\textit{Material estimation} + \textit{Waste} = \textit{Total material used in construction}$$

Therefore, the waste was calculated as a percentage of the total material used in construction, and not the ***Estimation of Material Quantity*** (***section 5.1.3***) for residential structures. The waste can also be calculated as the total material used in construction multiplied by the percentage of material that is produced as waste. Using abbreviations, the following two equations were produced,

$$M + W = T$$

And,

$$W = T * p$$

Where M is the material estimation, W is the waste, T is the total material used, and p is the construction site waste as a percentage of the material used in construction. Thus, the total material consumption was formulated as,

$$T = \frac{M}{1 - p}$$

And the waste was formulated as,

$$W = T - M$$

Thus, using the information in ***Table 9*** and the material estimations, the waste from the envelope of residential buildings was estimated as shown in ***Table 10***.

Table 10: Estimated mass of construction waste from the envelope of residential buildings. Mass in tonnes.

Materials	Material Estimate	Total Material Use	Waste Material
Aluminium	13,994	14,135	141
Bricks/blocks/tiles	238,926	251,501	12,575
Concrete	1,284,035	1,337,537	53,501
Fibre cement	29,307	35,741	6,433
Glass	33,856	34,198	342
Fibre Glass	13,633	16,039	2,406
Plasterboard	163,312	212,094	48,782
Plastics	27,387	28,828	1,441
Steel	60,808	62,049	1,241
Timber	208,278	228,250	19,972
Total			**146,835**

With a total of 48,899 residential dwellings built in 2021, the above estimations of 146,835 tonnes of waste produced from the construction of residential envelopes indicates that on average three tonnes of waste is produced during the construction of the envelope of each dwelling in NZ. This estimate fits suggestions by BRANZ and industry experts, which suggest that four to five tonnes of C&D waste are expected per residential building, which is expected to include plumbing, electrical, kitchens, bathrooms, carpet, and landscaping.[7] Therefore, it is expected that 60 - 75 wt.% of residential construction waste is produced from the construction of the building envelope alone.

Using the estimation from BRANZ of four tonnes of waste per residential building and the number of residential consents in NZ, it can be predicted that 195,596 tonnes of waste was produced from new residential buildings in 2021. BRANZ has also estimated the proportions of materials from construction waste shown in ***Figure 15.***[44] However, the composition shows that 45 % of the construction waste is unknown (mixed materials), and is expected to be comprised largely of the other materials shown.[17] Therefore, due to the large unknown of 45 % mixed material in the BRANZ assessment, the Āmiomio Aotearoa team made the assumption that the proportion of materials in the estimation of waste from the building envelope (***Table 10***) was a more accurate estimation of the proportions of waste materials from the residential building sector.

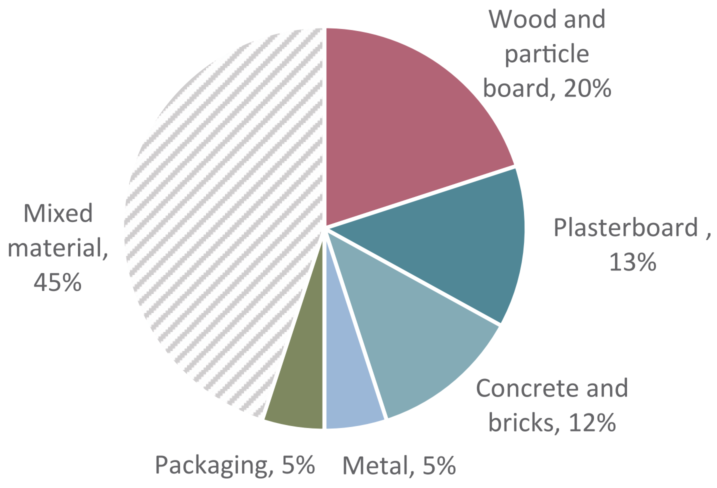


Figure 15*: Proportion of materials in construction.*[44]

Therefore, using the proportion of waste materials in ***Table 10*** the remaining mass of building waste was estimated as shown in ***Table 11***. The total remaining mass of waste was found through a mass balance using the building waste calculated for the building envelope (***Table 10***) and the building waste predicted through the BRANZ estimate of four tonnes per house.

Residential alteration waste was assumed to be generated at the same rate as residential construction for the value of building work required. Therefore, using the estimated mass of waste generated by the residential construction (***Table 11***), and the ratio of new build and alteration consent values ($) for 2021 (***Table 1***), the residential alteration waste was estimated. Thus, the residential construction waste estimate of 195,596 tonnes was extrapolated to find an expected waste of 25,064 tonnes of waste in from residential alterations in NZ (summarised in ***Table 11***). This is likely lower than the actual alteration waste due to the removal of old materials from the building resulting in excess waste. However, this was unable to be accounted for in the estimations.

Communication with industry experts suggested that residential demolition generates anywhere between 11.5 – 26 tonnes of waste per demolition.[17, 48] However, the report that indicated 11.5 tonnes of waste material also weighed the house as 20 tonnes (when removing it from the section) and calculated the 11.5 tonnes by adding the mass of waste and recovered materials when they were removed in deconstruction, suggesting some materials were missed in the process.[48] Therefore, it is expected that the actual typical waste produced from demolition is in the range of 20 – 26 tonnes of waste.

Multiplying the estimated number of residential demolitions of 5,488 per annum and the expected waste (using an average of 23 tonnes) per demolition provides an estimate of 126,224 tonnes of residential demolition waste produced annually in NZ. The proportions of waste materials produced from demolition were based on the materials required for construction of residential buildings in NZ (***Table 4***). Therefore, applying the proportions of materials used for the construction of the building envelope to the estimated demolition waste, the composition of residential demolition building waste was estimated (***shown in Table 11***). ***Figure 16*** further summarises the sources of waste materials from residential construction and demolition.

These demolition waste estimates are limited, because the proportions of materials used were based on material estimations for the building envelope of the residential building stock in 2021; whereas, residential demolition is likely to be primarily houses built from much earlier periods. Furthermore, demolition waste will include the whole building, not just the shell, which is expected to alter the proportion of materials in the waste stream. Nevertheless, these estimates paint a useful picture of the waste expected from residential demolition, given the absence of demolition consent data for buildings under three storeys, to inform future research in this area.

Table 11: Summary of estimated residential C&D waste sources including material types. Mass in tonnes.

Materials	Envelope Waste	Other Building Waste	Alteration Waste	Demolition waste	Total
Aluminium	141	47	24	852	1,064
Bricks/blocks/ tiles	12,575	4,176	2,147	14,544	33,442
Concrete	53,501	17,767	9,133	78,164	158,565
Fibre cement	6,433	2,136	1,098	1,784	11,452
Glass	342	114	58	2,061	2,575
Fibre Glass	2,406	799	411	830	4,445
Plasterboard	48,782	16,199	8,327	9,941	83,249
Plastics	1,441	479	246	1,667	3,833
Steel	1,241	412	212	3,702	5,567
Timber	19,972	6,632	3,409	12,679	42,692
Total	**146,835**	**48,761**	**25,064**	**126,224**	**346,884**

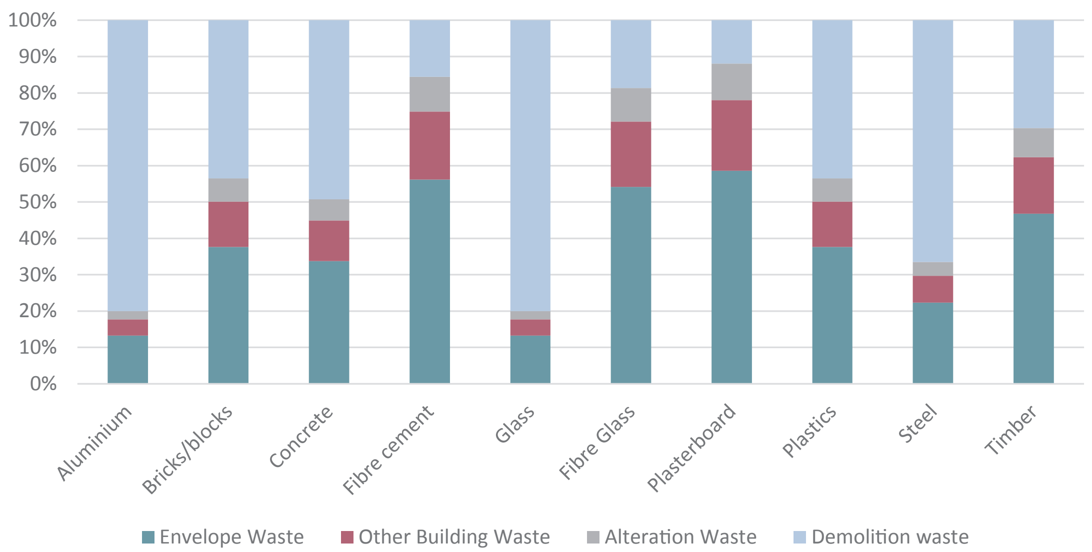


***Figure 16**: Estimated sources of residential C&D waste.*

Waste from C&D incorporates all the material outputs including materials that are sent to landfills, reused, and recycled. The waste streams for C&D shown in ***Table 12*** were estimated by applying the understanding of waste flow from the building construction sector provided by BRANZ in Table 9 to the mass of material waste predicted in ***Table 11***. The proportions of C&D waste sent to landfill, recycled, and reused is summarised in ***Table 12***.[47]

Table 12: Expected waste streams for residential C&D waste. Mass in tonnes. [47]

Materials	Total waste	Landfill/ Clean fill	Reuse	Recycle
Aluminium	1,064	53	0	1,011
Bricks/blocks/tiles	33,442	3,344	30,098	0
Concrete	158,565	142,708	0	15,856
Fibre cement	11,452	8,589	2,863	0
Glass	2,575	2,575	0	0
Fibre Glass	4,445	4,445	0	0
Plasterboard	83,249	74,925	0	8,325
Plastics	3,833	3,833	0	0
Steel	5,567	209	70	5,288
Timber	42,692	26,682	0	16,009
Total	**346,884**	**267,364**	**33,030**	**46,490**

7.2.3 Commercial Construction Waste

The commercial building construction sector is much less understood due to a large variety of different building types, and limited information on the materials consumed or waste produce by the sector. It was decided that the best means to predict the total waste generated by the commercial building construction sector was to assume that waste is produced in the same ratio of waste mass to consent value for the commercial building construction sector and the residential sector. Other known consent data was considered too limited, as the number of consents is expected to be unrepresentative due to typically larger footprints of commercial buildings, and the floor area does not account for alterations. Thus, the waste produced by commercial construction was estimated using a ratio of the value ($) of commercial construction and residential construction and multiplying it by the total construction and demolition waste produced by the residential sector. Thus, it was estimated that commercial construction projects for new builds and alterations produce 134,077 tonnes of waste annually. However, the proportion of materials was not accounted for due to the large variances in construction types (within commercial construction and in comparison to residential construction). Commercial demolitions are unknown; therefore, the waste produced from commercial demolitions was not estimated.

7.2.4 Plastic and Packaging Waste

Plastic waste from the building construction sector is expected to be considerable due to plastic use in construction components, building protection and the packaging of building materials. A recent set of studies has worked on auditing plastic waste produced on construction sites in NZ, monitoring the sources of plastic, as well as the contribution from different stages of building (foundations, exterior façade, and interior fitout).[49, 50] These reports give insight into the types of plastics being produced as waste from C&D.

The first report suggested that a total of 769 kg of plastic waste was produced for a 4800 m^2 build; however, due to covid restrictions only 541.1 kg of plastic waste was audited. The plastic was audited to find the sources and types of plastic waste produced, summarised in ***Table 13***. The report noted that an extra 15 – 20 wt.% of waste was expected due to contractors and workers not separating the waste during the study. Furthermore, the report indicated that residential construction projects would expect more plastic waste than commercial construction projects.

Table 13: *Summary of plastic waste from a 4800 m^2 build. The table includes plastic sources and plastic types, including polyvinyl chloride (PVC), polyethylene (PE), polycarbonate (PC), polyvinyl chloride + calcium carbonate (PVC + $CaCO_3$), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), ethylene/propylene copolymers (EPC), ethylene/vinyl acetate copolymers (EVC) and others.*[g]

	Plastic sources (wt.%)			Polymer types (kg)									Total (kg)
	Construction components	Building protection	Product packaging	PVC	PE	PC	PVC + CaCO3	PP	Other	PS	PET	EPC	
Foundations and concrete	36.8	3.2	60.0	0.1	29.9	-	13.0	23.0	5.1	15.9	2.8	9.9	100.4
Exterior façade and roofing	11.0	10.8	78.2	0.0	32.8	0.0	4.6	7.5	5.9	-	1.0	-	51.8
Interior fitout	84.0	6.7	9.3	217.0	44.9	58.2	31.2	10.6	12.4	2.0	11.1	-	388.9
Average/ Total	67.6	25.7	6.7	217.1	107.6	58.2	48.8	41.1	23.4	17.9	14.9	9.9	541.1

The results of the audit were used to calculate the mass of plastic waste produced per square metre of floor area in commercial construction. The results are summarised in ***Table 14.***

***Table** 14: Production of plastic waste in kg/m^2*

Plastic Source	Kg/m^2
Product Packaging	0.0029
Construction Components	0.075
Building Protection	0.0075
Total	**0.0854**

A second plastic waste study audited four different commercial construction sites in different stages of construction. The four different sites included one construction in the exterior and weatherproofing stage, a demolition site, and two sites in the services and cladding stage of the build. The study followed a similar methodology as the first report, where plastic waste was audited based on the sources and was assessed for different types of plastics used. A summary of the study's findings is shown in ***Table 15***.

g Some numbers are modified slightly from the report; however, the changes to any numbers are minor and do not affect the trends of the report.

Table 15: *Summary of plastic waste from four commercial builds in different stages. The table includes plastic sources, and plastic types, including polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), ethylene (ET), polyamides (PA), and others*

	Plastic source (wt.%)				Plastic type (kg)									Total (kg)
Build #	**Build stage**	**Product packaging**	**Building protection**	**Construction components**	**P**	**BP**	**CC**	**PE**	**PVC**	**PP**	**ET**	**PA**	**Other**	**(Plastic types)**
1	**Exterior and weather proofing**	15.0	84.0	1.0	0.2	0.8	0.0	35.8	0.0	0.4	-	-	0.1	36.2
2	**Demolition**	100.0	0.0	0.0	1.0	0.0	0.0	6.3	-	-	-	-	-	6.3
3	**Services and cladding**	24.0	23.0	53.0	0.2	0.2	0.5	33.5	2.0	1.6	0.7	0.0	0.3	38.1
4	**Services & cladding**	24.0	23.0	53.0	0.2	0.2	0.5	11.0	19.1	0.5	-	0.7	-	31.3
	Total	**25.3**	**41.5**	**33.2**	**1.6**	**41.5**	**33.2**	**86.4**	**21.1**	**2.5**	**0.7**	**0.7**	**0.4**	**111.8**

Both reports indicated that additional plastic waste would be expected, due to plastic missed in the auditing process. The second report proposed that extrapolating the plastic waste based on the values ($) of the construction for the entire NZ building construction sector would result in 534 tonnes of plastic waste produced annually. However, using the plastic produced per square meter from the first report (***Table 14***) and extrapolating the total floor area of new construction in NZ produces an estimated 904 tonnes of plastic waste produced annually for the building construction sector. Using the data in the first report is arguably better as the data is based on measuring all of the plastic from one construction site. The first report also indicated that a further 15 – 20 wt.% of waste is expected and that the residential sector would produce more waste than the commercial buildings. Therefore, adding an additional 20 wt.% to the estimated plastic waste production by the NZ building construction sector suggests that roughly 1,100 tonnes of plastic waste are produced annually from new builds. The estimate of 1,100 tonnes of plastic waste does not include plastic waste produced from demolition or alteration; however, the second study shows that only 6.3 kgs of plastic waste were produced from a commercial demolition site, which is a very small percentage of the total plastic evaluated. Therefore, this report estimates that 1,100 tonnes of plastic waste are produced annually from the building construction sector in NZ (including product packaging).

7.3 Waste Survey

This section assesses the results of a survey produced in collaboration between the Āmiomio Aotearoa team and a large residential construction company in NZ in May/June 2022. The survey was produced to gain an insight into the waste produced on residential building sites in NZ.

7.3.1 Method

The survey was distributed through the company to building site managers, and the results were provided for analysis.

The survey was split into a number of sections based on material types, to get an understanding of building material and packaging waste produced. This list of material types comprised the following categories: Timber, steel, plasterboard, insulation, and packaging, with opportunities for further comments. The questions used in the survey can be seen in ***Appendix II - Waste Survey Used to Collect the Data on Residential Waste.***

The survey responses related to values of waste were converted to appropriate units such as volume in m^3 or mass in kg. For values that were provided as a range (e.g. 0 – 0.25 m^3), the value was taken as the midpoint of the two limits. All other required calculations are provided in the respective sections. Responses that appeared to be unrelated to the question were not included in the assessment.

7.3.2 Results

The survey had 28 responses from builders, with 27 being based on standalone houses and one for a terraced townhouse. The average floor area for the standalone houses was 198.0 m^2 and 115 m^2 for the terraced townhouse. All of the buildings used a concrete slab foundation. For the purpose of this section, the term 'house' refers to standalone houses if it is not distinguished otherwise.

7.3.2.1 Timber

For standalone houses, 25 of the 27 surveyed gave usable responses, and no useable responses for the terraced town house. The average of the timber waste estimates was 1.38 m^3. The estimated waste timber was adjusted for each response to find the expected timber waste for a 198 m^2 house (average of all houses) by multiplying the responses and a ratio of the floor area for the response to the average floor area. The expected timber waste was therefore found to be 1.42 m^3 for a 198 m^2 house. The survey also found that an average distribution of 7 wt.% untreated (UT), 77 wt.% H1.2 treated, 11 wt.% H3.2 treated, 1 wt.% H4 treated, and 4 wt.% H5 treated timber was expected in the waste timber (***Figure 17***).

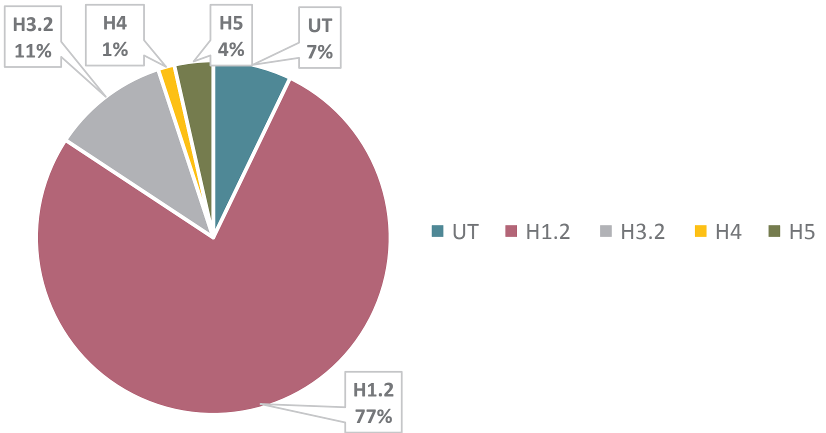


Figure 17*: Proportion of timber waste based on treatment, including Untreated (UT), H1.2, H3.2, H4, and H5.*

Multiplying the percentages of timber waste by the expected timber waste for the average 198 m^2 house provides an expected waste of 0.1 m^3 UT, 1.1m^3 H1.2, 0.15m^3 H3.2, 0.01 m^3 H4, and 0.06 m^3 H5 treated timbers.

The survey further asked what was expected to be done with the waste timber. ***Figure 18*** summarises the responses.

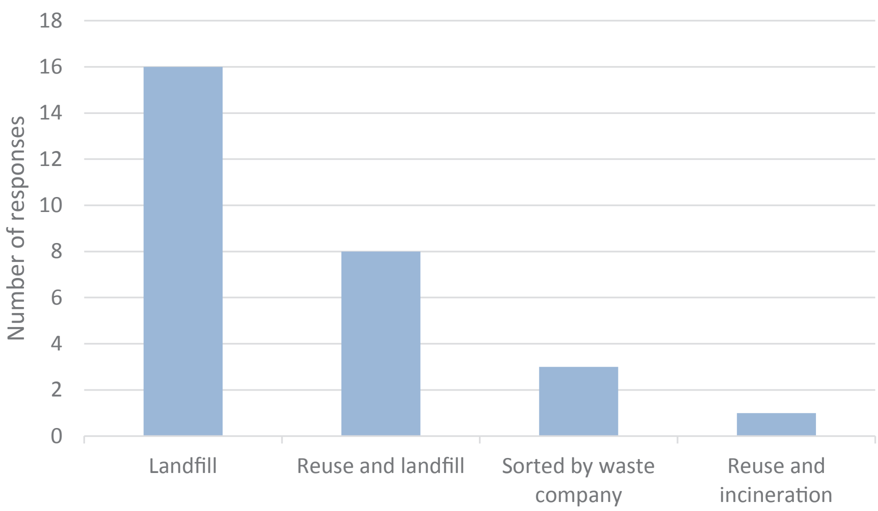


Figure 18*: Summarised survey responses for what is done with waste timber*

The responses that indicated reuse (reuse and incineration/reuse and landfill) typically noted that long pieces of timber were kept for reuse, whereas short offcuts were sent to landfill or incineration. The 'sorted by waste company' responses included sorted by Waste Management, Green Gorilla, and 'unknown once put in the skip'.

The waste survey also asked what parts of the building produced the most waste. Of the 28 surveyed, 18 indicated that frame and trusses were one of the largest producers of timber waste. This is expected to be related to timber used for practices such as bracing of the frames and trusses, where the timber is used temporarily. Furthermore, another five responses indicated that the majority of the waste came from boxing and bracing. Other responses included "framing", "rondo and soffit", and "packaging".

7.3.2.2 Steel

Steel waste was assessed using the same methods as timber waste. The survey found 26 out of 27 usable responses for the volume of steel waste were from standalone houses. The average steel waste was adjusted for the average 198 m^2 house and found to be 0.23 m^3 (1806 kg assuming an average density of 7850 kg/m^3). The terraced townhouse expected between 0 – 0.25 m^3 of steel waste. ***Figure 19*** shows a summary of the expected waste streams of the steel.

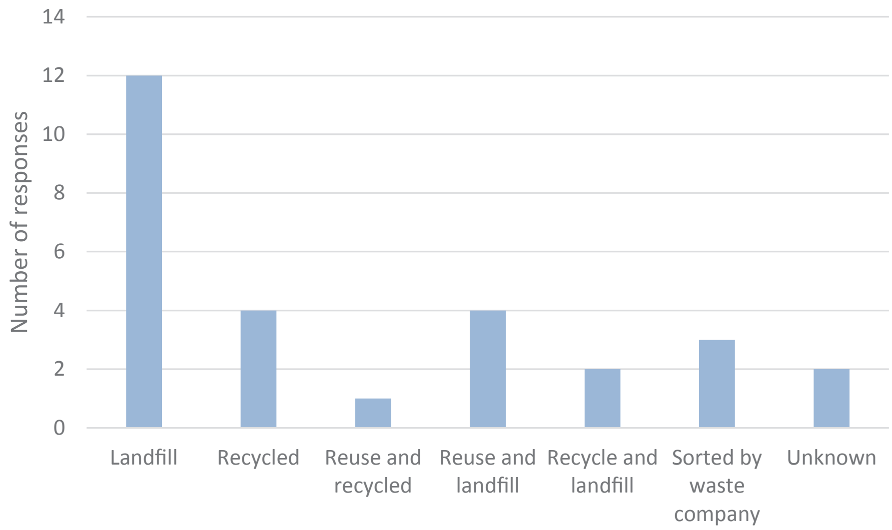


Figure 19*: Summarised survey responses for what is done with waste steel*

Interestingly, 12 of the responses indicated that all steel waste on site was sent to a landfill. This is an extremely different result than the indicated 85 wt.% of steel waste that is expected to be recycled by HERA, or the 96.25 wt.% of the steel that is suggested to be recycled or reused by BRANZ.[47, 51]

The question about the most common source of steel waste produced 27 responses. Of these 27 responses, 26 reported single sections of the building, whereas one response noted two sections as providing the most waste. Most responses (n=21) specified that the primary source of steel waste was reinforcement for concrete in the flooring/ foundations of the building. Four of the responses indicated roofing was the largest producer of steel waste, and three of the responses mentioned rondo/steel battens as the largest producers of metal waste.

7.3.2.3 Plasterboard

Plasterboard was also assessed using similar survey questions. The weight of the plasterboard was calculated by assuming that all plasterboard was 10 mm thick with a nominal weight of 6.5 kg/m^2.[32] This assumption is based on case study data where 10 mm thick plasterboard with a nominal weight of 6.5 kg/ m^2 was the most common. However, this is likely to lead to an underestimate due to being lower than average for a range of different plasterboards in NZ. The survey indicated that, on average, 155 kg of plasterboard waste would be produced for an average 198 m^2 house. The survey further indicated that 6.5 kg of plasterboard waste was expected for the terraced townhouse; however, this cannot be taken as representative of townhouses with only one survey response. The plasterboard survey also shows the expected waste streams for the plasterboard, as shown in ***Figure 20***.

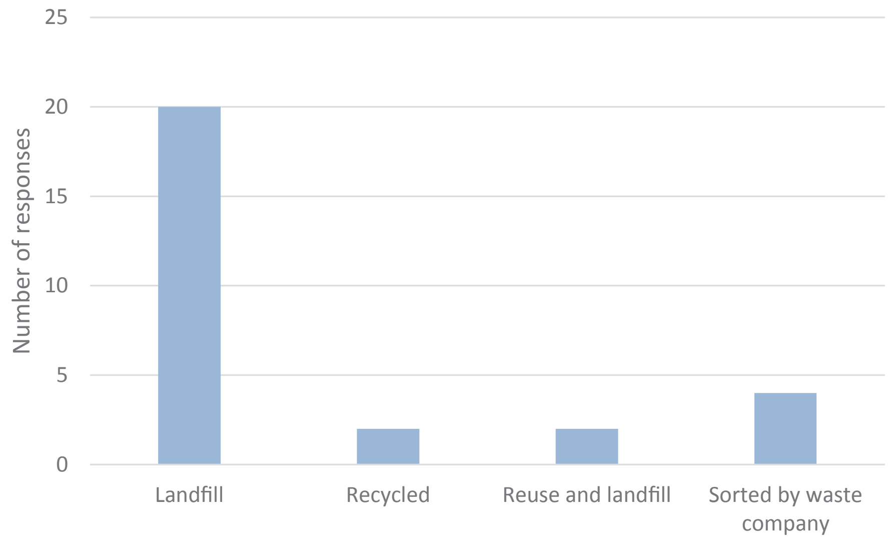


***Figure 20**: Summarised survey responses for what is done with waste plasterboard.*

The results from the plasterboard survey indicate that almost all plasterboard is sent to landfills from construction sites. The category 'sorted by waste company' includes responses such as 'skip', which could further include plasterboard being sent to landfills.

7.3.2.4 Insulation

Insulation was split into fibreglass and polystyrene. After adjusting for the average size house of 198 m^2, the survey found, on average, 0.5 m^3 of fibreglass waste and 0.35 m^3 of polystyrene waste from the construction of standalone houses. In comparison, the building manager for the terraced townhouse predicted more waste polystyrene than fibreglass with an expected 0.5-0.75 m^3 and 0 – 0.25 m^3, respectively. The survey combined polystyrene and fibreglass to assess waste streams, and a summary of the results is shown in ***Figure 21***.

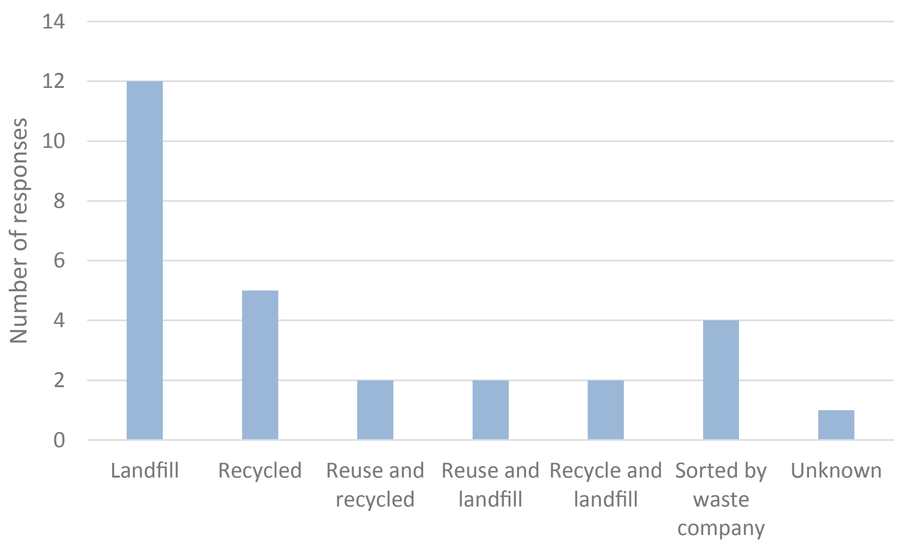


***Figure 21**: Summarised survey responses for what is done with waste insulation*

The survey responses included three comments on the end-of-life of the waste insulation that distinguished between polystyrene and fibreglass. All three comments indicated that polystyrene was sent back to the supplier for recycling, whereas fibreglass was either reused or sent to landfills. This suggests that polystyrene has more recycling potential than fibreglass, which is typically sent to landfill if it cannot be reused in further building projects.

7.3.2.5 Packaging waste

The packaging waste survey questions were based on the packaging related to the different sections or materials used in construction. ***Figure 22*** shows the expected packaging waste for the concrete foundation, timber, roofing, cladding, joinery, insulation, and interior lining in the building. The packaging includes a number of different materials including plastic, timber, carboard, paper, and metal packaging. The packaging survey responses were the least complete, and on average, only 14 responses provided expected quantities of waste (averaged over the 7 categories of packaging waste) which was provided in terms of volume.

Some responses also provided square metres of waste plastic produced. This was accounted for by calculating the volume of the plastic, assuming an average film thickness of 100 µm. It is likely that the film thickness actually varies significantly in both thinner and thicker films. [52] The thickness of film was based on some typical film thicknesses from a NZ plastic packaging company for timber products. The volume was then converted to an estimated volume expected for waste plastic, thus, allowing for free space (or air) in the skip around the plastic. This conversion was completed using a ratio of the typical density of 940 kg/m^3 for polyethylene and a typical waste density for plastic of 38 kg/m^3.[53] Standard deviations and the median were also calculated and added to the graph. For every category, the median is significantly lower than the average, and for some, the standard deviation is larger than the average. The results shown in ***Figure 22*** show a large range of responses for each packaging category, representing a large variance in packaging waste between different construction sites.

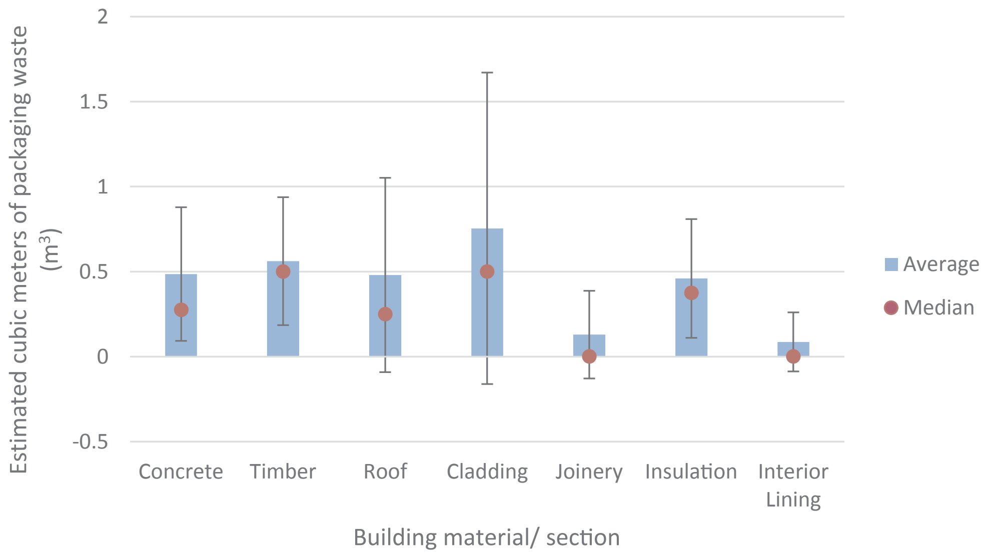


Figure 22*: Average estimated packaging waste for packaging associated with concrete, timber, roofing, cladding, joinery, insulation, and interior lining.*

The responses further indicated the different packaging materials used for the different sections/ materials of the building. ***Figure 23*** summarises the responses to indicate the different materials used for packaging products in the building sector. Unfortunately, the survey did not lead to data that provided a composition of the packaging waste.

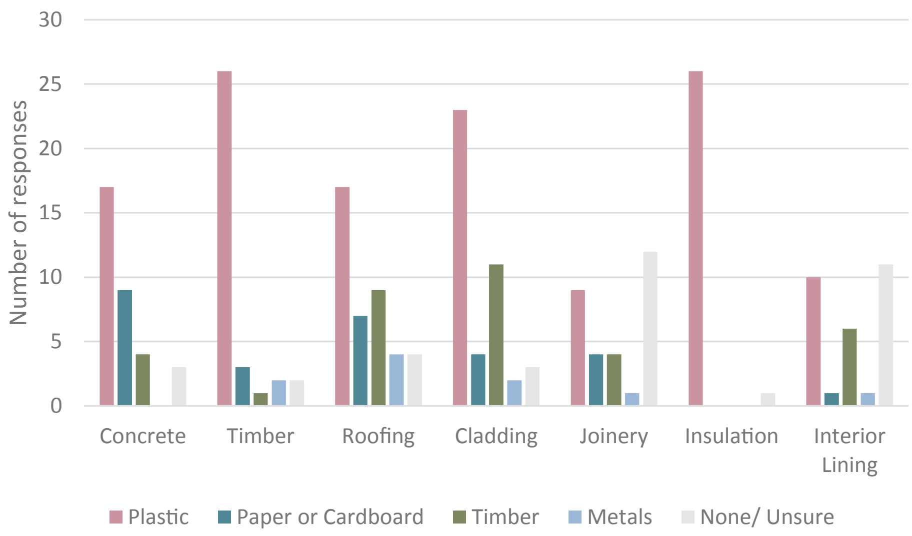


Figure 23: *Packaging materials based on the different building materials used on site.*

The waste survey also questioned the disposal methods of plastic, paper and cardboard, timber, metal and other packaging materials. The results are summarised in ***Figure 24*** indicating that landfill is the most typical disposal method used for all waste packaging materials.

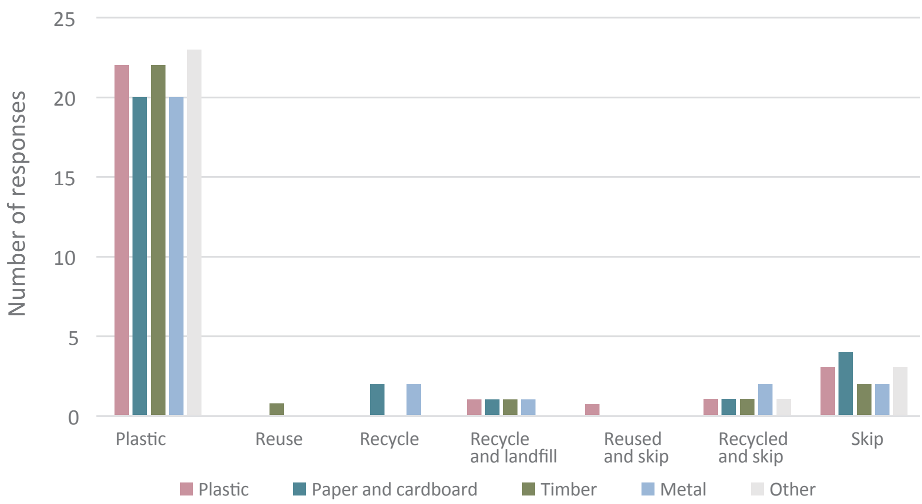


Figure 24: *Summarised survey responses for what is done with waste packaging, including plastic, paper and cardboard, timber, metal, and other packaging materials. The graph also includes the number of responses for each material.*

7.3.3 Overall

The masses of all material waste streams were calculated and compared based on an average floor area of 198 m^2. The results are shown in ***Figure 25***. All materials that were provided as expected volume of waste (m^3). However, the density of waste is expected to be significantly different to the density of the material due to the amount of free space in skips and landfill, leading to much lower densities. Therefore, the waste was calculated using estimated waste densities for the different materials, where possible.[53, 54] The insulation waste was calculated using an average of the expected typical densities for wall and ceiling insulation for both fibreglass and polystyrene. The packaging waste was based on the waste plastic and paper density, as plastic was indicated as the largest contributor to packaging waste. The plasterboard mass was based on the calculations outlined above in the plasterboard section (***section 7.3.2.3***).

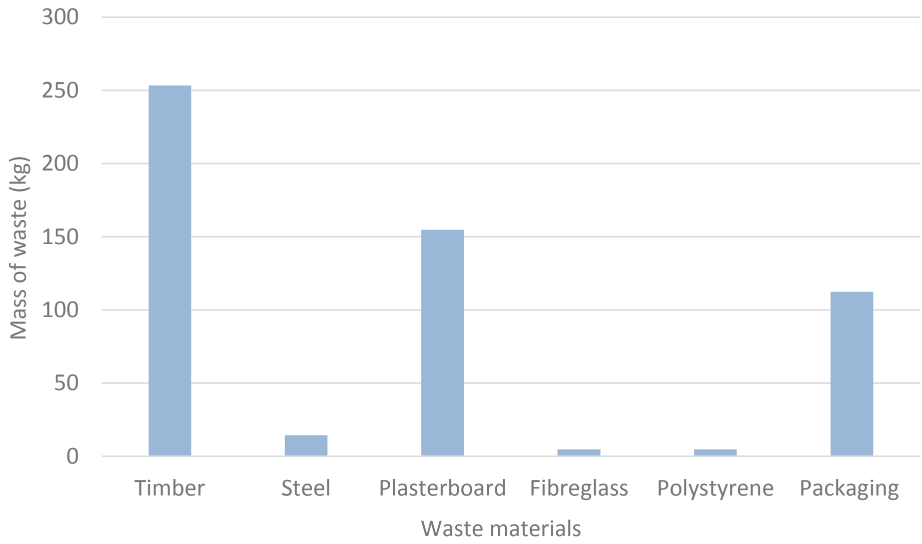


***Figure 25**: Summary of waste survey data showing the estimated mass of waste from an average 198 m² house.*

7.3.4 Comments

The survey question on whether there were any other major waste sources on the construction site produced from the structure of the building elicited the following responses:

- “PVC pipes, electrical cabling”
- “James Hardie, fibre cement products, Offcuts”
- “Metal tiles from the roof, Plastic polythene from floor”
- “Cement sheet offcuts (James Hardie soffit linings & claddings)”
- “Bricks and brick cement”
- “Fibre cement waste”
- “Over ordered materials often end up damaged and thrown in the skip”
- “Paint and plastering buckets can be numerous at times up to 6-7 per house”
- “Hardies product”
- “Bricks”
- “Brick linea and other associated hardies products”
- “Supply of showers, vanities, bath, plumbing supplies, tiles, paint tins, etc. Primarily Cardboard and Plastic”
- “Fibre cement”
- “Neighbours dumping old beds, matrasses, broken toys, household rubbish in our skip bins after hours and weekends”
- “James hardie off cuts”
- “Fibre cement products- James Hardie”
- “Linea of cuts and brick of cuts”

The following comments were provided when asked if there were any further comments on the waste produced on the construction site:

- “Needs to be addressed as it can be recycled.”
- “Gib board would be the biggest, bricks would be the second biggest skip filler.”
- “The main issue is all the packaging, unfortunately it all goes into a skip and then to landfill”
- “We need to be better at the recycling aspect.”
- “It embarrassing seeing all the plastic and polystyrene getting blown away from site .... Into the lake.”
- “Packaging accounts for 80% of the skip bin volumes. Averaging 4-5 bins per build each 7 cubic metres in size.”
- “There needs to be recycling.”
- “We have no method of recycling for our sites. This is something we should be doing.”
- “Would be good if there was an option for segregated bin in the residential building industry and an affordable one.”
- “It can be hard to recycle at times due to availability of space on sites for separate collection bins.”
- “Off cuts of bricks, off cuts of cedar, linea.”
- “Cardboard around white wear and baths. Mostly cardboard.”
- “A certain demographic of builder does not have bins on their sites so dumps their waste in other builders bins. Shocking really.”
- “Massive amount of cardboard from appliances.”
- “By working with Green Gorilla we have approx 85% diversion from landfill.”

7.4 Waste Report from the Construction of Two Medium Density Units

The same commercial building company that provided the purchase order data for two medium density houses, provided waste reports from the construction sites. The reports were assessed to find the total mass of waste produced, and the mass of material in landfills and clean fills. Masses were found using density estimates for waste materials.[53, 54] ***Table 16*** summarises the mass of waste produced from the building sites.

Table 16: *Summary of waste case study information.*

	Waste (tonnes)	Recovered (tonnes)	Landfill (tonnes)	Clean fill (tonnes)
Site 1	6.6	3.37	3.23	0
Site 2	8.0	3.46	4.59	0.026

8 | Insights from Industry Experts

During the project, the Āmiomio Aotearoa materials flow analysis project leads talked with industry experts including people from governmental organisations, construction companies, and building product manufacturers. These discussions often led to noteworthy comments about the building construction sector. The following section summarises some of these comments that directly relate to the flow of materials in the building construction sector.

Several personal communications indicated a concern with over-ordering of materials in the industry. It was explained that over-ordering takes place to ensure there are no delays due to lack of materials on-site; however, this leads to a large amount of unnecessary material waste. One discussion suggested that over-ordering could make up 20 % of materials purchased. Furthermore, with the lack of materials, and the long lead times for materials and products in the current state of the building sector, over-ordering is expected to be more common as a lack of material on-site would significantly delay a project- "Quantity surveyors, don't want to be the quantity surveyor, that didn't order enough."

The production of building products potentially generates a large amount of waste (e.g. the manufacturing of plasterboard and fibre cement). These waste quantities are unknown, and the waste is typically considered commercial waste and not C&D waste, even though it is directly related to the C&D sector.

The majority of frame and trusses used in the building construction sector are built off-site in frame and truss factories. This system is expected to be very efficient and waste from the construction of frames and trusses is expected to be less than 10 wt.%, and as low as 4 wt.% in best-case scenarios. However, when the frame and trusses are delivered to the site, extra timber is typically sent with it to be used to brace and support the frame as the house is constructed. All of this excess timber is wasted in a typical scenario.

Packaging of timber for frames and trusses is also expected to generate waste. Timber is delivered from mills to the frame and truss factories in wrapped packages, to ensure the timber is dry and can be worked with straight away. Frame and trusses are then constructed and re-wrapped with plastic packaging to be delivered to construction sites. This leads to a large amount of plastic packaging waste from some of the largest components of residential buildings. A further comment suggested when builders were given the option of plastic packaging when the frame and truss were delivered to site, as few as 3 % asked for plastic wrapping. Therefore, a simple process of asking whether builders want their frame and trusses wrapped could significantly reduce this waste stream.

Incineration of all grades of timber (treated and untreated) is expected to consume a large portion of timber waste from the Auckland and Northland regions to help produce energy for cement production. However, other regions of NZ typically send all timber to landfills.

A large plasterboard manufacturer is opening a new manufacturing plant, which should be able to recycle 10 wt.% or roughly 20,000 tonnes of its annual output into new plasterboard.

Experts suggested roughly four to five tonnes of waste per new residential dwelling, or roughly 32 kg/m^2. Of the waste produced, roughly two tonnes is expected to be timber waste, and one tonne would be plasterboard. Steel was expected to be the third-largest contributor to construction waste by weight.

There is a concern regarding the attitude of builders and contractors which leads to throwing away a huge amount of material that is not required. Better practices on site are expected to be able to reduce a large portion of construction waste.

The current development of suburbs in Auckland is expected to increase waste further. For example, the Tamaki Regeneration project is removing roughly 2,500 homes to be replaced with a new 10,500 homes.[48] Although this work is being done with sustainability at the top of their priorities, this construction and demolition project is likely to increase the annual waste produced by the sector.

There appears to be a shift for major housing projects to employ the use of a demolition hierarchy. This hierarchy prioritises relocation, deconstruction by hand, deconstruction by machine (demolition and then salvage), and finally demolition and landfill. Decisions are made due to financial and health and safety factors, such as the difficulty of removing asbestos. Trials of deconstruction projects are currently underway, and some results show that in ideal scenarios it can be financially viable to use a deconstruction process, and reuse and recycle most materials over demolition. However, the norm for demolitions in NZ is expected to be machine demolition and sending all materials to landfills. For buildings under three stories, there are currently no consent requirements for demolition in NZ.

9 | Discussion

While the previous section described the methods the Āmiomio Aotearoa project team used to calculate estimations of material flows, this section discusses these results in more depth including limitations and validations of the data.

9.1 Material Input

Publicly available data and information on the materials input for the C&D sector in NZ is only available for the mass of timber used in commercial and residential construction. Ready-mix concrete is also relatively well documented and provides insight into the concrete consumed in NZ annually. All other materials of interest have significant gaps in the data, in terms of the amount of material input into the NZ building construction sector. Nevertheless, the relationship between the timber and concrete consumed in the residential sector (from the material estimation and the feedstock of timber and concrete for construction) can be used to provide an estimation of the mass of other materials feeding into NZ's building construction sector.

The timber in the feedstock of materials in 2021 was estimated to be 1.98 million tonnes for all construction, whereas the timber consumed in the residential building sector from material estimations was 208 thousand tonnes. This large difference in the feedstock of timber and the consumption for residential envelopes is expected, as timber is used for a number of other applications, including timber used in other parts of the building, such as stairs and doors, and other areas such as kitchens, bathrooms, furniture, decking, fencing, retaining walls, and landscaping. Furthermore, timber is expected to be used in residential alterations and commercial construction projects.

The ready-mix concrete produced in NZ was found to be roughly 10.8 million tonnes, the majority of which is expected to end up in construction (including infrastructure). The material estimation was for 1.5 million tonnes of concrete consumed in residential buildings. Using the relationship between the 208,000 tonnes of timber estimated to be in new buildings in NZ and the 1.98 million tonnes of timber expected to be in the NZ timber supply, and the 1.5 million tonnes of concrete in the material estimation and the 10.4 million tonnes of concrete in the concrete produced in NZ suggest that there is roughly eight times more material in the building construction sector than there is in the material estimations (using the average of timber and concrete). Assuming the available timber and concrete is equal to the material consumption it was estimated that the feedstock of major materials in construction is roughly eight times more than the material estimates for residential building envelopes. It is expected that this is most relevant to timber, concrete and masonry, and steel and aluminium as they are widely used in other applications of residential buildings and are expected to be the most commonly used materials in commercial construction and infrastructure.

For the other materials considered in this study, it was expected that the feedstock was likely to be significantly lower than eight times the material used in residential construction. Therefore, the total material consumption estimated in the waste section for plasterboard, fibre cement, glass, fibreglass and plastic was extrapolated to consider residential alterations and new commercial buildings and alterations based on consent values shown in ***Table 1***.[1] It is expected that some commercial buildings will not include any of these materials; however, this is likely to somewhat balance out material consumption due to situations such as over-ordering. The feedstock of plastic only includes plastic used as building products in the building envelope (sheet plastic, and polystyrene and polyester insulation).

Collating these assumptions provides a summary of the estimated mass of timber, concrete and masonry, steel, aluminium, plasterboard, fibre cement, glass, and insulation, in the feedstock of building materials in NZ, shown in ***Table 17***. The data for plasterboard reinforces these assumptions as a report in 2022 indicate that plasterboard was being produced at a rate of 236,000 tonnes per annum.[22 17]

Table 17*: Estimation of the feedstock of building materials in 2021 (including infrastructure). Masses in tonnes.*

Timber	Ready Mix Concrete	Masonry	Steel	Aluminium	Plaster-board	Fibre Ce-ment	Fibre Glass	Plastic	Glass
1,980,225	10,853,426	1,911,407	486,465	111,951	255,452	45,842	21,325	42,838	52,957

9.2 Residential Construction

The residential sector makes up 88 % by number 71% by floor area and 75% by the value of the building construction sector (not including infrastructure), ***Table 1***. Therefore, residential builds were the focus of this study. [1]

The material estimation was based on consent data for residential dwellings and BRANZ reports on the market share of building materials and methods used in residential construction (e.g. 86 % of the residential building market used timber framing in 2019).[1, 23] Material estimations were produced through a set of calculations built on assumptions outlined in ***section 5.1***. This data is considered to be the best indication currently available for the materials used in residential construction and the parts of the building envelope they are used in.

However, the data is limited as only major components of the house were included. Furthermore, the data is limited as it is an estimate of the material that makes up the envelope of a finished building and not the total mass of material required for the construction of the envelope. It was reported to the Āmiomio Aotearoa team that overordering during purchasing of materials could account for up to 20 % (presumably by weight) of the material used in some circumstances.[17] Furthermore, many materials such as timber, or plasterboard, require ordering more than required to account for off cuts, as materials are supplied in a set of standardised sizes.

When comparing the purchase order data and the material estimation, it is clear that for most materials, the material estimation masses are lower than the purchase order data. The extrapolation of purchase order data in case study 1 for timber, plasterboard, fibre cement, bricks, and aluminium came out as 62 %,-4 %, 45 %, 107 %, and 14 % higher than the material estimation, respectively. The large differences in some of these materials are expected, for example, timber is used throughout the construction of most buildings for more than just the building envelope. Furthermore, all of the buildings were expected to be timber framing without any steel framing in the case study. The use of bricks were also considerably higher in the case study than in the material estimations. However, the proportion of houses built with brick cladding in the case study was unknown and could have been significantly higher than the market share of bricks in cladding materials in New Zealand. ***Table 18*** summarises the results of the material estimation for 2021 and shows the case study results as a comparison. ***Table 18*** shows there is good agreement with the case study data and the material estimations, as the masses predicted for consumption for the New Zealand residential sector are all of the same magnitude for both methods used. Thus, the case study validifies the material estimation.

Table 18: *Estimation of material consumption from the residential building sector for 2021. Mass in tonnes.*

Materials	Residential building sector consumption (material estimation)	Residential building sector consumption (case study 1)
Concrete & Masonry	1,522,961	306,357 (bricks)
Timber	208,278	337,056
Metal	74,802	15,928 (aluminium)
Plastic	27,387	-
Glass	33,856	
Plasterboard	163,312	156,602
Fibreglass	13,633	
Fibre-cement	29,307	42,641
Total	2,073,537	-

9.3 Commercial Construction

In comparison to the residential sector, commercial buildings make up a small percentage, by the number of consents (12%), floor area (29%) and value (25%) of the total construction (excluding infrastructure) in NZ (***Table 1***).[1] Furthermore, commercial buildings are expected to have a much wider variety of building methods used, making the material estimation much more complex. Therefore, it was decided that making an estimation for the materials being used in the commercial building sector was out of scope for this study. At this stage, the mass of materials and the proportion of materials consumed in commercial buildings in NZ are unknown.

9.4 Demolition

The number of demolished, deconstructed, or relocated houses in NZ is unmonitered, and there is no consent required for the demolition of buildings under three stories.[2] However, using a set of assumptions outlined in ***section 6***, it was approximated that 5,488 houses underwent demolition or deconstruction annually. From discussions with industry experts, it is expected that the majority of houses at their end-of-life go through demolition as it is typically seen to be cheaper than deconstruction. However, a number of large-scale projects in Auckland, such as the Tamaki Regeneration, show a shift is starting to occur to ensure houses are relocated or deconstructed to keep materials in use for as long as possible. From conversations with industry experts and reports, it is expected that 20 – 26 tonnes of waste are produced from a typical residential demolition site. Therefore, for an estimated 5,488 houses that are expected to undergo demolition, it can be assumed that 134,944 tonnes of waste are produced annually.

Commercial demolition was also considered outside this project's scope, and the number of demolitions and mass of materials produced as waste are currently unknown.

9.5 Material Output

The construction and demolition sector is expected to contribute 3.6 million tonnes of waste to class 1-5 landfills in NZ. However, this waste is expected to be produced from infrastructure (roads and bridges) and residential and commercial construction. Furthermore, the waste is expected to include soil, aggregate, concrete and rubble from site preparation for infrastructure and building sites, which is expected to be a large portion of the construction and demolition waste estimated.

Waste from residential construction of structures was estimated to be 195,596 tonnes for 2021. Of the waste produced from residential construction 146,835 tonnes are expected to be produced from the construction of building envelopes. Furthermore, residential demolition was estimated to produce 126,224 tonnes of waste in 2021. Extrapolating the quantity of waste to commercial construction indicated the construction and demolition of the commercial building sector produced 134,077 tonnes in 2021. These assumptions are very limited and are based on material estimations produced for residential construction and estimations for the number of annual demolitions and the amount of waste produced. It is expected that the material estimations made for residential construction are lower than the materials consumed by the residential construction sector, as shown by the purchase order data. Therefore, it is likely that the waste could be higher than estimated.

The material waste for all residential construction was based on an expected four tonnes of waste per house. This is on the lower side of the expected waste for a complete residential building, and some industry experts indicate up to five tonnes of waste could be produced per house. This is further suggested in the production of two medium-density houses where 6.6 and 8.0 tonnes of waste were produced, and 3.2, and 4.6 tonnes of it were sent to landfills. Furthermore, it is expected that these waste estimates do not account for site preparation, and waste soil and aggregate could further contribute to waste produced from residential construction sites.

Focussing on the building envelope also impacted the estimated proportion of materials used (and associated waste) for the construction of residential dwellings. Assumptions were made regarding the overall waste from residential construction that did not account for waste from materials that were not used in the envelope, for example, plumbing and electrical. However, the approximately 50,000 tonnes of material waste from residential construction that was not from the building envelope is a small portion of the total residential waste and is not likely to have any significant effects on the estimations of the total waste from residential construction and demolition.

The waste data from the residential construction sector suggests that concrete and rubble waste are the largest contributors to waste by weight, which aligns with the construction estimated by the Auckland Council (***Table 8***). This result does differ from some suggestions from people in the industry, which indicated that timber, plasterboard, and metals were the largest contributors of construction waste (see ***sections 7.3*** and ***8***). However, this could be due to oversights in evaluating waste streams, such as not considering waste to clean fill as waste, or waste that is not removed from site using typical methods such as in a skip. Furthermore, the differences could be due to differences in measuring waste proportions i.e. if waste was measured by volume, or cost. Timber and plasterboard were considered to be the next largest contributors of waste, which aligns with comments from people in the industry. This is very interesting as the country currently has a shortage of plasterboard. However, it appears that the shortage of plasterboard has had a negative effect on the production of plasterboard waste, as the large lead times appear to have resulted in over ordering to minimise any chances of delays in construction, thus causing extra waste to be produced. Timber waste was estimated to be produced in lower masses than plasterboard, which also goes against the comments from industry. However, this is likely to be due to large amounts of timber that are used in construction that were not accounted for in areas such as kitchens, bathrooms, stairs, decks, retaining walls, and landscaping. Industry experts further suggested that steel is the next largest contributor to waste from construction. However, our estimates indicate that fibre cement is a larger contributor to waste. This is potentially due to a lack of differentiation between fibre cement and other panel products when assessments have been made within the industry. Fibre cement was also regularly commented on in the waste survey as being a large contributor to waste produced on site. The extra fibre cement is potentially a much larger issue as fibre cement is primarily expected to be sent to landfills, whereas steel is considered by HERA and BRANZ to be primarily recycled, and reused. [47, 51]

A total of 3,833 tonnes of plastic waste was estimated for residential construction alterations and demolitions based on the ***Material Estimation for Residential Housing*** (***section 5.1***) and BRANZ data (***Table 9***), whereas the plastic reports found an estimated waste of 1,100 tonnes for both commercial and residential structures ***(section 7.2.4)***. This difference can be explained through the plastic waste predictions produced as part of this study being primarily from plastics used within the building envelope such as insulation, and plastic roofing materials, and not including plastic waste from packaging, as this waste was not accounted for in the proportions of materials in the envelope of the building. In comparison, the case studies on plastic waste include the use of product packaging, and materials used for the fitout of the structure, such as plastic piping, and flooring. The numbers are both of the same magnitude, which implies some assurance that the prediction of 3,833 tonnes of plastic waste is in an appropriate range for the predicted plastic waste from the residential construction sector. The case study reports are likely to give the best indication of the amount of packaging waste, and types of plastic waste produced in the building construction sector.

The materials were all evaluated using mass as a working unit. However, this is likely to distort the material waste to show denser materials as the largest contributors to waste. In contrast, volume has the potential to show the contribution and issues of lightweight materials that end up as waste from the C&D sector. Using predicted densities for waste materials it can be seen in ***Figure 26*** that the waste composition based on volumes is significantly different than by mass, emphasising that some of the lighter weight materials are large issues in NZ landfills.[53, 54] ***Figure 26*** summarises the expected waste of the residential construction and demolition sector with both mass and volume.

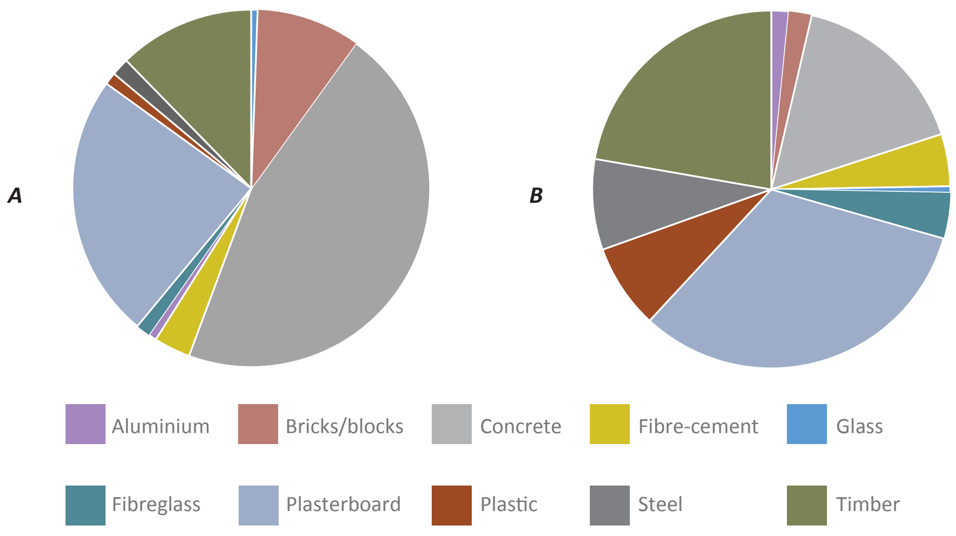


Figure 26: *Composition of building waste based on A) mass (tonnes) and B) volume (m3).*

To summarise, the following Sankey diagrams show the flow of materials through the C&D sector. ***Figure 27*** shows the proportion of materials flowing into the residential construction sector from the material input, while ***Figure 28*** shows the flow of residential building waste.

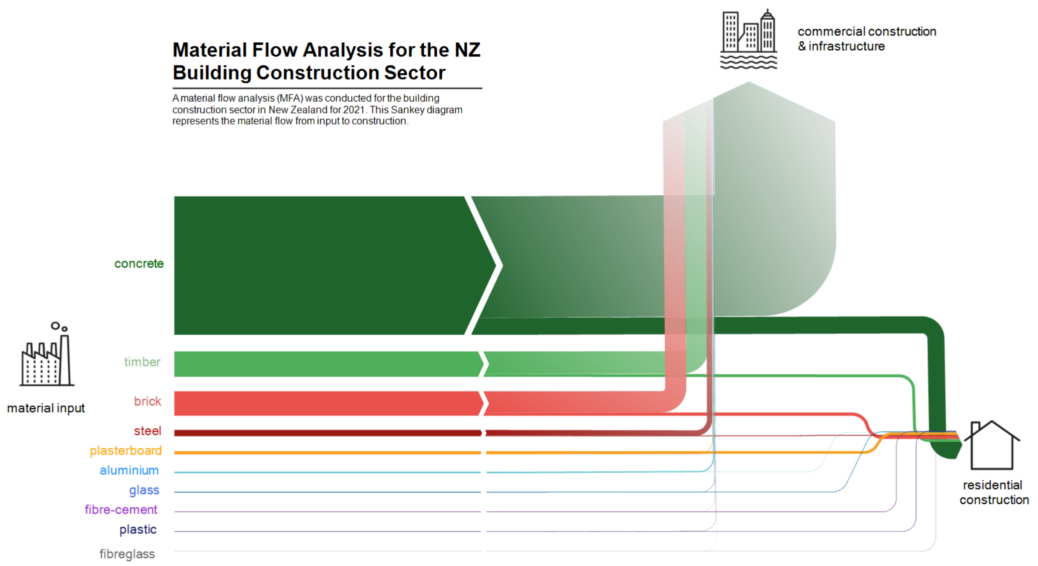


Figure 27*: Sankey diagram showing material flow into the building construction sector in 2021 (the size of the arrows represents the mass of the material).*

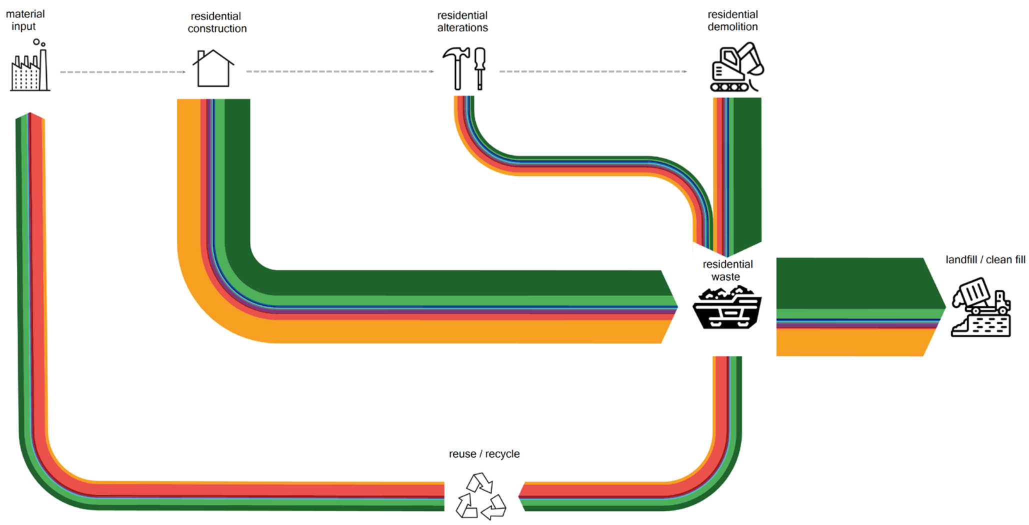


Figure 28*: Sankey diagram showing waste from the residential construction and demolition sector in NZ in 2021 (the size of the arrows represents the mass of the material). The legend for the figure is shown in Figure 27.*

10 | Conclusion

The objective of this project was to assess the material flow through the Aotearoa New Zealand's (NZ's) building construction sector based on four key stages: Material input, construction, demolition, and material output (***Figure* 1**). Residential construction makes up a significantly greater amount of new consents in NZ by number, floor area, and value. [1] The envelope of the building is also expected to be the largest use of materials in new builds including the foundations, structure, cladding, and lining. Thus, the primary focus of the study was to investigate the material flow relating to construction and demolition of the envelope of residential buildings. This report is intended to inform opportunities for further research to deepen the understanding of materials flowing through the building construction sector.

To streamline the material flow analysis, eight material groups were defined as key areas of focus, including:

- Concrete & masonry (including bricks, blocks, stone, tiles etc…)
- Timber & timber-based products
- Metals (including steel and aluminium)
- Cement-based claddings (including autoclaved aerated concrete (AAC) panels, fibre-cement weatherboards and panels, stucco etc…)
- Glass
- Plastic (including polyester and polystyrene)
- Plasterboard
- Insulation

Investigating the material input identified significant gaps in the public information regarding the feedstock of materials into the building construction sector. Timber was found to be the most thoroughly documented material, with an estimated 1.98 million tonnes of timber and timber-based products produced for consumption by the building construction sector in 2021. Furthermore, timber and timber-based products are largely produced in NZ, with an estimated 88 wt.% of timber consumed in 2021 derived from local sources. Concrete was the next best documented material input, followed by steel; however, there was very little data to suggest how much of each material was consumed by residential or commercial construction versus infrastructure and other industries.

Material estimations were used to predict the total quantity of materials used in the construction of new residential building envelopes in NZ. Based on these predictions, it was clear that concrete and masonry made up the largest contribution of residential construction materials (by mass), followed by timber, plasterboard, and metals (***Table 4***).

Data and information on demolition in NZ was very limited, as consents are not required for the demolition of buildings under three stories. However, by making some assumptions (outlined in ***section 6***), it was estimated that 5,488 demolitions would occur on an annual basis in the building construction sector (excluding the impact of the Christchurch earthquakes).

Waste from construction and demolition (C&D) is also very poorly documented in NZ. Several reports indicate that C&D contributes 40 – 50 % (presumably by weight) of waste.[7] However, further investigation found that this is likely to be heavily influenced by waste produced by infrastructure and processes related to the wider building site, such as site preparation and earthworks. Using the material estimations, residential construction waste was estimated for building envelopes, building structures, residential alterations, and demolitions. This project estimated that approximately 347,000 tonnes of waste would be produced from residential construction in 2021. Overall concrete and masonry were expected to be the largest producers of waste, followed by plasterboard, timber, fibre-cement and metals. From the residential waste, approximately 267,000 tonnes of waste were expected to be sent to landfills and clean fills, 33,000 tonnes were expected to be reused, and 46,000 were expected to be recycled. Of the materials being sent to landfills and clean fill, concrete was the largest contributor (142,708 tonnes), followed by plasterboard (74,925 tonnes) and timber (26,682 tonnes). These results are limited due to the methods used to find the proportions of materials used. However, this is expected to be the best currently available estimate of waste produced from the residential construction sector.

Reports on plastic waste indicated that between 6.7 – 25.3 wt% of plastic waste in the building construction sector is produced from packaging of building products. The reports also indicated that up to 1100 tonnes of plastic waste could be produced annually from the building construction sector, which implies that up to 275 tonnes of plastic waste could be produced annually from packaging of building products alone. Furthermore, our research indicated that the plastic waste could be as high as 3,833 tonnes in residential C&D, thus suggesting plastic waste could be even higher. Studies have also shown that the packaging waste is largely not needed or wanted by builders. For example, one industry expert reported via personal communication that when given the option of packaging timber frame and trusses, only 3 % of builders requested the plastic wrapping.

This project has highlighted the lack of information in the current state of material use and disposal in the construction industry. Discussions with industry experts revealed that several projects are underway in NZ, which will contribute to our understanding of construction and demolition waste in the near future. Some of these projects include the creation of a tool to estimate construction waste based on site plans, mandatory site waste management plans by some councils, and large construction projects with a focus on measuring material waste and evaluating how much material can be reused in the construction and what is required to be wasted.

In summary, this research has highlighted large amounts of material waste, within the current trend of linear extraction-use-disposal material use in the building construction sector. The project intended to influence further research into: Material sciences and engineering that could present new materials with improved circularity; opportunities for regulatory, policy or business practice changes; and options for reusing or recycling current waste streams from the building construction sector. It is hoped that this information can be used to help influence further research for the purpose of transitioning NZ's building construction sector to a circular economy.

11 | Further Recommendations

Further work is required to complete the picture for material flow in the building construction sector. Further assessments of the material input and working with manufacturers and suppliers of building materials is suggested to improve the understanding of the mass of material entering the building construction sector. Furthermore, this work could help any understanding of the mass of reused or recycled material being used and highlight areas for improvement.

Estimations in the materials being used in construction should be expanded to cover commercial building envelopes, and other materials used in construction. This expansion could be undertaken with the same methodology as this project used for the residential sector or through more case studies that represent a variety of commercial structures. It is also likely that the ongoing research could influence these estimations, as projects such as the mandatory site waste management plans in some regions could help identify and categorise a number of building types in NZ. Further research into commercial structures, and all of the materials used in construction, would enable more accurate estimations of the proportions of materials that end up as waste from the commercial building construction sector, as well as a much more accurate representation of the proportions of waste from other areas of the building sector. This data could also identify parts of the sector that are more prone to producing waste and highlight trades or building products that contributing more to the waste issue.

The use of life cycle analysis (LCA) for the building sector could highlight the materials resulting in the greatest environmental impact (e.g. climate change, eutrophication, ecotoxicity, land use, resource extraction). The use of LCA has the potential to identify materials used in smaller quantities that cause more environmental damage, which is unseen in a material flow analysis. An LCA model of the NZ building construction sector would also supply a tool for evaluating the prospective environmental benefit of new potential building products and materials.

12 | Glossary

Anchor Pile: "A pile directly supporting a bearer, and used to resist horizontal as well as vertical loads. The pile is embedded in concrete to a depth of 900 mm below cleared ground." [24]

Bearer: "A beam supported on jack studs, foundation walls, piles, or piers and carrying joists, jack studs, or subfloor framing." [24]

Bottom Plate: "A plate other than a wall plate placed under the bottom ends of studs." [24]

Bracing Unit (BU): "A bracing unit is a measure of:

a) The horizontal force (bracing demand) on the building (1 kilo Newton is equal to 20 bracing units);

b) The resistance to horizontal force (bracing capacity) of building elements." [24]

Dwang (nog): "A short (usually horizontal) member fixed between framing timbers. Also known as nogging." [24]

Footing: "That portion of a foundation bearing on the ground and any adjoining portion that is reinforced so as to resist the bearing forces. A footing may be spread out to provide an increase in bearing area or an increase in stability." [24]

Joist: "A horizontal framing member to which is fixed floor decking, or ceiling linings, and which is identified accordingly as a floor joist or ceiling joist." [24]

Lintel: "A horizontal framing timber spanning an opening in a wall." [24]

Low Density Housing (LDH): "In New Zealand, LDH includes stand-alone dwellings, generally 1–2 storeys, on an individual section where the size is greater than 400 m^2".[55]

Medium Density Housing (MDH): "Multi-unit dwelling (up to 6 storeys)".[55] In this report, apartments, townhouses, duplexes, and retirement village units have been included as MDH. Apartments greater than 6-storeys would typically fall under high density housing (HDH). However, there is no distinction between the height of apartment blocks in the data available from Statistics NZ. Therefore, apartments were all assumed to fall under MDH.

Ordinary Pile: "A pile required to resist vertical loads only." [24]

Pile: "A block or column-like member used to transmit loads from the building and its contents to the ground." [24]

Purlin: "A horizontal member laid to span across rafters or trusses and to which the roof cladding is attached." [24]

Rondo: A light weight metal batten system for wall and ceilings.[56]

Stud: "A vertical framing timber."[24]

Soffit: "the underside of an architectural structure such as an arch, a balcony, or overhanging eaves."[57]

Top Plate: "A plate placed over the top ends of studs." [24]

Trimming Stud: "A stud located on the side of an opening." [24]

Truss: "A truss is a structural framework designed to bridge the space at the top of a room and to provide longitudinal support for a roof."

References

1. Statistics New Zealand. (2022). Data from: Building consents issued: December 2021.
2. Ministry of Business, Innovation and Employment. (2020). *Building work that does not require a building consent* (5th ed.). https://www.building.govt.nz/assets/Uploads/projects-and-consents/building-work-consent-not-required-guidance.pdf
3. Jianping L et al. (2014). Global environmental issues and human wellbeing. In L. Jianping, L. Minrong, W. Jinnan, L. Jianjian, S. Hongwen, H. Maoxing (Eds.), *Report on Global Environmental Competitiveness (2013)* (pp. 3-21). Springer. https://doi.org/10.1007/978-3-642-54678-5_1
4. Ellen Macarthur Foundation. (2019). *Completing the picture: How the circular economy tackles climate change.* https://emf.thirdlight.com/link/w750u7vysuy1-5a5i6n/@/preview/1?o
5. Nelson J. (2022). The viability of waste copper chromium and arsenic treated timber reinforced polypropylene as a sustainable building material. [Unpublished master's thesis]. University of Waikato.
6. Hossain MU, Ng ST. (2018). Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review. *Journal of Cleaner Production*, *205*, 763-780. https://doi.org/10.1016/j.jclepro.2018.09.120
7. BRANZ. (2022). *Minimising waste*. Level. https://www.level.org.nz/material-use/minimising-waste/
8. Ministry for Primary Industries. (2021). Data from: December 2021 Quarter Production.
9. Forest Industry Engineering Association. (2022). *Australia & New Zealand forest products industry map 2022* (5th ed.). https://fiea.org.nz/forest-products-map-2022/
10. Te Waihanga. (2021). *Infrastructure resources study.* https://www.tewaihanga.govt.nz/assets/Infrastructure-Resources-Study-11-Nov-21.pdf
11. Forest Owners Association. (2021). *Facts and figures. 2020/21*. https://www.nzfoa.org.nz/images/FGT_3704_Facts_and_Figures_202021_Web_FA1.pdf
12. Ministry for Primary Industries. (2021). Data from: December 2021 Quarter Production.
13. Ministry for Primary Industries. (2021). Data from: Forest Quarterly Trade Exports.
14. Ministry for Primary Industries. (2021). Data from: Forest Quarterly Trade Imports.
15. Ministry for Primary Industries. (2021). Data from: Production of veneer, plywood, laminated veneer, lumber, particleboard, and fibreboard, 1951 to most recent.
16. Statistics New Zealand. (2022). Data from: Ready mixed concrete by region (AST) (Annual-Dec).
17. Confidential. (2022). Zoom, emails, and phone calls with industry experts.
18. Portland Cement Association. (2019). *How concrete is made.* https://www.cement.org/cement-concrete/how-concrete-is-made#:~:text=Typically%2C%20a%20mix%20is%20about,another%205%20to%208%20percent.
19. Fletcher Steel. (2016). *New Zealand steel industry fact sheet.* https://fletcherbuilding.com/news/new-zealand-steel-industry-fact-sheet/
20. Deloitte. (2018). *Cost of residential housing development: A focus on building materials.* https://www2.deloitte.com/content/dam/Deloitte/nz/Documents/Economics/nz-en-DAE-Fletcher-cost-of-residential-housing-development.pdf
21. Commerce Commission New Zealand. (2014). *Investigation into Winstone Wallboards Limited.* https://comcom.govt.nz/__data/assets/pdf_file/0028/94393/Winstone-Wallboards-Limited-Investigation-closure-report-22-December-2014.pdf
22. GIB. (2022). *Plasterboard demand and supply update.* https://www.gib.co.nz/gib-news/gib-update/

plasterboard-demand-and-supply-update/

23. BRANZ. (2020). *Trends in materials used in new houses 2010–2019.* https://www.branz.co.nz/pubs/research-now/physical-characteristics/1-materials-houses/

24. Standards New Zealand. (2011). *NZS 3604:2011. Timber-framed buildings.* https://www.standards.govt.nz/shop/nzs-36042011/

25. Wiley Online Library. (n.d.). Appendix A: Weights of building materials. https://onlinelibrary.wiley.com/doi/pdf/10.1002/9780470697818.app1

26. Spanman. (2022). *Weights of building materials.* https://www.spanman.net/Members/Technical/Weight-Of-Building-Materials

27. Wu H et al. 2022. Analyzing the climate change potential of residential steel buildings in New Zealand and their alignment in meeting the 2050 Paris Agreement targets. *Buildings, 12*(3), 290. https://doi.org/10.3390/buildings12030290

28. National Association of Steel Framed Housing. (2019). *NASH Standard Part 2:2019 Light steel framed buildings.* https://codehub.building.govt.nz/resources/nash-standard-part-22019/#!#resource-detail

29. Ministry for the Environment. (2021). *New Zealand's greenhouse gas inventory 1990–2020*. https://environment.govt.nz/publications/new-zealands-greenhouse-gas-inventory-1990-2019/

30. Clay Brick & Paver Manufacturer's Association. (n.d.). *Brick Modules and Designing in Brick.* https://bricksnz.co.nz/designing-to-brick-modules/

31. PJ Fitzpatrick. (2022). *How to calculate roof area.* https://www.pjfitz.com/diy/roofing-installation/calculate-roof-area/

32. Percy C. (2018). *Appraisal No. 289 (2018) GIB Fire Rated Systems.* BRANZ. https://d39d3mj7qio96p.cloudfront.net/media/documents/289_2018a2.pdf

33. Building Performance. (n.d.). *House insulation requirements*. https://www.building.govt.nz/building-code-compliance/h-energy-efficiency/h1-energy-efficiency/building-code-requirements-for-house-insulation/house-insulation-requirements/

34. Percy C. (2022). *Appraisal No. 648 (2022) Knauf Glasswool Insulation.* BRANZ. https://d39d3mj7qio96p.cloudfront.net/media/documents/648_2022.pdf

35. Burghout P. (2012). *Appraisal No. 289 (2012) GIB Fire Rated Systems*. BRANZ. https://www.gib.co.nz/assets/Uploads/BRANZ-Appraisal-289-GIB-Fire-Rated-Systems-2012.pdf

36. Preston C. (2008). *Appraisal No. 301 (2008) Bradford Insulation*. BRANZ. https://www.eboss.co.nz/assets/literature/25/18559/301.pdf

37. Tiger Shield. (2020). *Aluminium foil insulation sheet.* http://www.bubbleinsulations.com/Aluminum-Foil-Insulation-Sheet

38. Campion R. Technical Manager, Window and Glass Association NZ ed2022.

39. Build. (2022). *Choosing the right window size.* https://build.com.au/choosing-right-window-size

40. Statistics New Zealand. (2019). Data from: 2018 Census population and dwelling counts – amended 5-3-2020.

41. Page IC, Fung JF. (2009). *Housing life cycle and sustainability Part One No.214.* BRANZ. https://d39d3mj7qio96p.cloudfront.net/media/documents/SR214_Housing_life_cycle_and_sustainability_-_part_1.pdf

42. Scott F, True North Consulting. (2013). *Treated timber waste minimisation project. Milestone 1: Industry Overview*. *Environment Canterbury Report No. R13/31.* Environment Canterbury. https://www.ecan.govt.nz/document/download?uri=1815993

43. Eunomia Research and Consulting Ltd; Waste Not Consulting Ltd. (2015). *New Zealand waste data framework*. https://eunomia.co.nz/wp-content/uploads/2017/06/National-Waste-Data-Framework-Combined-Protocols-27-Aug-FINAL.pdf

44. Ministry for the Environment. (2021). Infrastructure and Services Stocktake Report. Confidential. Construction and Demolition Material Stream Analysis.

45. Auckland Council. Data from: Summary Waste Data with C&D Breakdown.

47. BRANZ. (2016). Data from: Construction Site Waste Generation Rates by Material.

48. Regeneration T. (2022). Repurposing Tāmaki Houses House Deconstruction 2020-2021 Report 2.

49. Hernandez G et al. 2022. Quantifying and managing plastic waste generated from building construction in Auckland, New Zealand. *Waste Management & Research: The Journal for a Sustainable Circular Economy*. https://doi.org/10.1177/0734242X221105425

50. Berry T-A, Wallis SL, Kestle L, Day A, Hernandez G. (2022). Determining the Feasibility of a Circular Economy for Plastic Waste from the Construction Sector in New Zealand.

51. Soo VK et al. (2021). *Steel recycling report. HERA Report No R5-89vs: 2021.* HERA. https://www.hera.org.nz/wp-content/uploads/R5-89-Steel-Recycling-Report-v2.pdf

52. PRIMEPAC. (2022). *Timber & building films.* https://www.primepac.co.nz/products/plastic-packaging/timber-building-films/

53. BRANZ. (2022). *Convert waste volume to weight.* https://www.branz.co.nz/sustainable-building/reducing-building-waste/assessing-waste/volume-weight/

54. New Plymouth District Council. (2022). *Construction waste reduction plan: A guide.* https://www.npdc.govt.nz/media/bziontdn/npdc-construction-waste-reduction-guide.pdf

55. BRANZ. (n.d.). *MDH definitions.* https://www.mdh.org.nz/what-is-mdh/mdh-definitions/

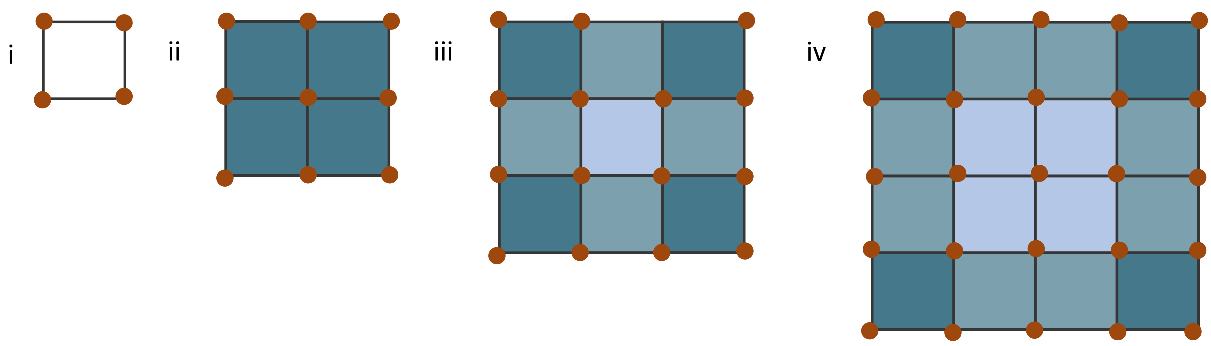
56. Rondo. (n.d.). *Products.* https://www.rondo.co.nz/products/

57. Oxford Reference. (2022). *Soffit.* https://www.oxfordreference.com/view/10.1093/oi/authority.20110803100516159#:~:text=1%20Ceiling.,or%20any%20exposed%20architectural%20element

13 | Appendices

13.1 Appendix I - Equation Derivation

An area-based unit defined was produced based on having piles at the corner of a 1.65 x 2.00 m rectangle as shown below for floor areas made of i) 1 unit, ii) 4 units, iii) 9 units, and iii) 16 units.



An equation for the number of piles was then derived based on the amount of units in the floor area defined as . The units in each floor are split into different categories based on the number of piles that a unit shares and with how many other unit it shares the pile. Therefore, piles that are not shared can be equal to 1 pile, piles shared with one other square can be equal to 0.5 piles, and piles shared between 4 units were considered equal to 0.25 piles for each unit. Thus, the following equations were derived.

For $A = 1$

$$No.\ of\ piles = 4$$

For $\sqrt{A} > 1$

Corner Units: There are four corner units each of which can be regarded as having 2.25 piles, thus,

$$No.\ of\ piles = 4 * 2.25 = 9$$

For $\sqrt{A} > 2$

Side Units: The side units can be regarded as having 2 piles that are shared with 2 units, and 2 piles shared between 4 units, thus having 1.5 piles per unit. The number of side units increases as function of A thus the number of piles for the side units can be derived as,

$$No.\ of\ side\ units = (\sqrt{A} - 2) * 4$$

$$\therefore No.\ of\ piles = 1.5(\sqrt{A} - 2) * 4 = 6(\sqrt{A} - 2)$$

Interior Units: For the units on the inside of the floor, all of the piles are shared between 4 units, thus there is a total of one pile per unit. The number of interior units also increases as a function of A, thus the number of piles can be derived as,

$$No.\ interior\ units = (\sqrt{A} - 2)^2 = A - 4\sqrt{A} + 4$$

$$No.\ piles = A - 4\sqrt{A} + 4$$

Total: Thus, adding all of the equations together gives:

For $\sqrt{A} > 2$ or $A > 4$

$$No.\ of\ piles = 9 + 6(\sqrt{A} - 2) + A - 4\sqrt{A} + 4$$

$$\therefore No.\ of\ piles = A + 2\sqrt{A} + 1$$

Note: the equation only works based on the assumption that the floor area is the same ratio of length to width as the units (i.e. 1.65 : 2.00), and for floor areas greater than 4 (i.e. greater than 12.8 m^2).

13.2 Appendix II - Waste Survey Used to Collect the Data on Residential Waste

The following survey is to be used to collect data on the estimated quantities of construction waste associated with the following stages of construction for a residential building.

1. Concrete foundation / sub-floor
2. Frame & Truss
3. Roofing
4. Cladding
5. Joinery
6. Insulation
7. Internal lining- plasterboard

Please fill out the following questions by estimating the volumes of waste disposed of using **one** of your most typical buildings as the example.

1. **Circle what type of building this survey is being filled out for and enter the m2 floor area.**
   a. Standalone ____ m2
   b. Terraced townhouse ___m2
   c. Three Storey walk up ___m2
2. **What is the subfloor constructed with?**
   a. Concrete
   b. Timber
3. **Timber Questions:**
   a. Out of the timber that comes onto site for construction, estimate the m3 volume that ends up as waste
      i. < 0.5m3
      ii. 0.5m3 – 1.0m3
      iii. 0.5m3 – 1.0m3
      iv. 1.0m3 – 1.5m3
      v. 1.5m3 – 2.0m3
      vi. 2.0m3 – 2.5m3
      vii. 2.5m3 – 3.0m3
      viii. > 3m3 – provide estimated volume ____

b. From your estimated volume of timber waste from the previous question, what percentage would be
   i. Untreated ___
   ii. H 1.2 treated ___
   iii. H 3.2 treated ___
   iv. H 4 treated ___
   v. H 5 treated ___
c. What parts of the building contribute the most timber waste?
d. What is done with the timber waste? (e.g. sent to landfill, reused, recycled, etc.)

4. **Steel Questions:**
   a. Out of the steel that comes onto site for construction, estimate the m3 volume that ends up as waste;
      i. < 0.25 m3
      ii. 0.25m3- 0.5m3
      iii. 0.5m3 – 0.75m3
      iv. > 1m3- provide estimated volume _____
   b. What parts of the building contribute the most to steel waste?
   c. What is done with the steel waste? (e.g. sent to landfill, reused, recycled, etc.)
5. **Plasterboard Questions:**
   a. For the plasterboard that comes onto the site for construction, estimate the m2 volume that ends up as waste?
   b. What is done with the plasterboard waste (e.g. sent to landfill, reused, recycled, etc.)
6. **Insulation Questions:**
   a. Out of the fibre glass insulation that comes onto site for construction, estimate the m3 volume that ends up as waste;
      i. < 0.25 m3
      ii. 0.25m3- 0.5m3
      iii. 0.5m3 – 0.75m3
      iv. > 1m3- provide estimated volume _____
   b. Out of the polystyrene that comes onto site for construction, estimate the m3 volume that ends up as waste;
      i. < 0.25 m3
      ii. 0.25m3- 0.5m3
      iii. 0.5m3 – 0.75m3
      iv. > 1m3- provide estimated volume _____
   c. What is done with the insulation waste? (e.g. sent to landfill, reused, recycled, etc.)
7. **Packaging Questions:**
   a. What type of packaging is used for the materials associated with the following stages of construction

and estimated mass or volume that ends up as waste

i. Concrete foundation

1. Plastic — Estimated volume________m3
2. Paper bags & Carboard — Estimated volume________m3
3. Wood — Estimated volume________m3
4. Metal — Estimated volume________m3
5. Other ________ — Estimated volume________m3

ii. Frame & Truss (Include sub-floor if not concrete slab)

1. Plastic — Estimated volume________m3
2. Paper bags & Carboard — Estimated volume________m3
3. Wood — Estimated volume________m3
4. Metal — Estimated volume________m3
5. Other ________ — Estimated volume________m3

iii. Roofing

1. Plastic — Estimated volume________m3
2. Paper bags & Carboard — Estimated volume________m3
3. Wood — Estimated volume________m3
4. Metal — Estimated volume________m3
5. Other ________ — Estimated volume________m3

iv. Cladding

1. Plastic — Estimated volume________m3
2. Paper bags & Carboard — Estimated volume________m3
3. Wood — Estimated volume________m3
4. Metal — Estimated volume________m3
5. Other ________ — Estimated volume________m3

v. Joinery

1. Plastic — Estimated volume________m3
2. Paper bags & Carboard — Estimated volume________m3
3. Wood — Estimated volume________m3
4. Metal — Estimated volume________m3
5. Other ________ — Estimated volume________m3

vi. Insulation

1. Plastic — Estimated volume________m3
2. Paper bags & Carboard — Estimated volume________m3
3. Wood — Estimated volume________m3

4. Metal — Estimated volume________m3
5. Other ________ — Estimated volume________m3

vii. Internal lining- plasterboard

1. Plastic — Estimated volume________m3
2. Paper bags & Carboard — Estimated volume________m3
3. Wood — Estimated volume________m3
4. Metal — Estimated volume________m3
5. Other ________ — Estimated volume________m3

b. What is done with the waste from the following packaging materials (e.g. sent to landfill, reused, recycled, etc.)?

1. Plastic
2. Paper bags & Carboard
3. Wood
4. Metal
5. Other ________

c. Are there any other sources of plastic waste on site (e.g. building wrap for construction)? (Please include sources in the answer). If yes, what is the estimated mass (or volume) of plastic waste from these sources?

Āmiomio Aotearoa
C/- School of Engineering
The University of Waikato
Private Bag 3105
Hamilton
https://www.waikato.ac.nz/research-enterprise/research-with-waikato/amiomio-aotearoa