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A material stock and flow analysis for Australian detached residential houses: Insights and challenges

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ABSTRACT

Material use within construction dominates resource consumption worldwide. Correspondingly, construction is associated with high rates of waste. Transitioning to a circular economy relies heavily on domestic markets, efficient supply chains, and a clear understanding of current and predicted material flows. Material flow analyses have been used extensively globally to generate insights into materials in use, changes over time and future waste generation. However, existing databases do not hold the necessary information to conduct such an analysis for the Australian residential construction industry. This paper uses a novel qualitative bottom-up approach to complement data gaps in existing databases to establish a material stock and flow analysis of the Australian residential construction industry. This approach has highlighted the dominance and continued growth of concrete by the sector, and has shown the importance of addressing data gaps in the industry as well as employing a location-based approach to move towards the circular economy.

1. Introduction

Globally, governments are marshalling efforts towards the establishment of Circular Economies (CE) due to the fact that many raw materials are finite resources (Ellen MacArthur Foundation, 2013; European Commission, 2020). Principles of the CE include the elimination of waste and pollution, circulating products and materials at their highest value, and regenerating nature. These guiding principles allow governments to enhance circularity through the implementation of policy (Meglin, Kytzia and Habert, 2022). Internationally, material flows have increased from 7.6 to 95.2 Gt/year between 1900 and 2014 (Wiedenhofer et al., 2019) with a total 'in-use stocks' of manufactured capital estimated at 928 Gt in 2014. Australia has one of the highest per-capita material footprints of all developed nations, and arguably the construction industry has one of the greatest needs to improve material efficiency and move towards a CE (Wiedmann et al., 2015, Australian Government, 2018). Indeed, the substantial growth in manufactured capital has been attributed to the infrastructure and building requirements that accompany growing economies (Krausmann, Wiedenhofer and Lauk, 2017).

In the construction industry, a large and growing amount of resources are used to construct buildings, both in their initial construction phase as well as ongoing maintenance and refurbishment during occupation. Construction is estimated to be responsible for almost 50 % of the worldwide annual resource consumption (OECD, 2019), as well as contributing 25 % of all CO_2 emissions (Becqué et al., 2019). Focusing on Australia, the construction sector as a whole was estimated to be responsible for 18.1 % of Australia's carbon footprint (Yu et al., 2017) with residential buildings accounting for a 23.7 % share of the construction embodied carbon emissions (equivalent to 21.5 Mt CO_2-eq). Material consumption also contributes to the embodied carbon in buildings. Currently, it is estimated that embodied carbon emissions from building materials is responsible for a 16 % share of the whole-of-life carbon emissions of the building globally (GBCA and thinkstep-anz, 2021), with operational carbon emissions responsible for the remainder. However, as energy efficiency of buildings improve and the electricity grid decarbonises with increased use of renewables, the share of embodied carbon emissions from materials in buildings is estimated to grow to 85 % by 2050 (GBCA and thinkstep-anz, 2021). This trend highlights the importance of considering the materials used in construction, including the carbon emissions from these. In addition, the construction industry is responsible for a large amount of waste, both through the processing of raw materials to generate construction materials and through demolition and construction processes (Osmani, 2011). Focusing on weight, this category is dominated by materials such

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Nomenclature

ABS	Australian Bureau of Statistics
ACT	Australian Capital Territory
CSIRO	Commonwealth Scientific and Industrial Research Organisation
NatHERS	Nationwide House Energy Rating Scheme
CE	Circular Economy
C&D	Construction and Demolition
MFA	Material Flow Analysis
NSW	New South Wales
NT	Northern Territory
QLD	Queensland
SA	South Australia
Vic	Victoria
WA	Western Australia

as brick and concrete but also includes a variety of other materials such as wood, glass, metals, and plastic. Worldwide it is suggested that the Construction and Demolition (C&D) waste accounts for over a third of all waste generated (Holland Circular Hotspot, 2022). In Australia, the figure is similar with 29 million metric tonnes (Mt) of construction waste per annum generated, accounting for approximately 38 % of all waste generated, with approximately 6.45 Mt going into landfills and 22.52 Mt being recycled – mostly into road base or infrastructure requirements (Pickin et al., 2023).

Transitioning to a CE offers a framework through which to simultaneously reduce the material consumption and waste generation from the construction industry. Reviews of the challenges and barriers facing the implementation of CE in the construction industry highlight the need for improved regulation and policies to enhance material efficiency and to ensure the C&D waste is seen as a valuable resource (Shooshtarian et al., 2022; Gasparri et al., 2023). Also, guidelines have been developed for buildings to consider circularity through design (Zaman et al., 2023). Policies in Australia however, such as the National Waste Policy Action Plan (Australian Government, 2019) provide aggregated and overall targets of resource recovering and increased use of recycled content in materials. Considering the construction industry is the third largest industry in Australia (on a gross domestic product basis), and leading consumer of extracted resources (Ai Group, 2016; Böhme et al., 2018), policies specifically targeting this industry are needed. However, the challenge to ensure that the materials are kept at their highest value is often not realised. Currently C&D waste is mainly being down-graded for recycling or, in the case of organic material such as wood, used for energy generation (Pickin et al., 2023).

Developing policies to manage resource consumption and waste management requires thorough understanding of the material flows, stocks available and future trends. Material flow analysis (MFA) has been established as a tested method to determine stock and flow modelling for specific materials or industries, in particular construction and building (for instance Huang et al., 2013; Tanikawa et al., 2015; Condeixa, Haddad and Boer, 2017; Lederer et al., 2021). An overview of MFA studies for construction and methods used has been provided by Tanikawa et al. (2015). The authors classify approaches to MFA studies into four categories: bottom-up (utilising material flow coefficients and inventory), top-down (using material statistic data), demand-driven (using socioeconomic indicators) and remote sensing (geo-location data). The first two of these rely on available statistical data – with the bottom-up employing material flow coefficients with inventory statistical data, whereas the top-down approach looks at material inflow statistical data over a period of time. The demand-driven approach also considers a period of time but relies on socioeconomic indicators to model the demand, whereas the final grouping – remote sensing - uses geographical location data to estimate stock spatial distribution at a singular point in time. A mixture of approaches, often determined by the data available or the focus of the study, is used across the literature. MFA studies often target individual materials (such as Schiller et al. 2017) or specific areas of interest (for instance Stephan and Athanassiadis, 2017; Huuhka and Kolkwitz, 2021). MFA has shown promising results when quantifying the impacts of decarbonisation strategies on the construction industry; in particular when it is integrated with energy modelling and life cycle assessment (such as Yang et al., 2022, Arehart et al., 2022).

In Australia, the use of MFA has been limited. Schandl et al. (2008) used a top-down approach to estimate total resource extraction and consumption across the country. In this study they estimated that total material consumption in Australia in 2002 was 32.11 tonnes per capita, of which 9.69 tonnes (30.2 %) was construction materials. Pilot MFAs have been undertaken for certain materials (glass, metals, paper/cardboard, plastics and tyres) as part of the National Waste Report 2020 (Pickin et al., 2021). A larger scale MFA for construction was also estimated to understand the impact of embodied carbon in buildings (GBCA and thinkstep-anz, 2021). Stephan and Athanassiadis (2017) conducted a bottom-up MFA using land use data to identify archetypes and estimate the embodied energy and GHG emissions for the stock of a geographical location in the city of Melbourne. However, a material stock and flow analysis of the Australian residential construction industry has not been identified in the public domain.

The aim of this paper is to provide a data-driven overview of the material stock and flow of the Australian residential construction industry. Understanding the material stocks from historical and current consumption patterns will improve the awareness of the future waste streams from the industry to enable the transition towards a CE. This paper forms part of a larger body of work investigating building materials in a CE (Dalton et al., 2023). Specifically, this analysis aims to delve into the complexities of construction types to examine at an individual level the materials required for construction and how this has changed over time. Due to the number and complexity of construction typologies available, the scope of this study was constrained to residential detached houses, however it is hoped that this methodology could be adapted and extended in future work.

2. Methodology

2.1. Modelling process

MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time. It connects the sources, the pathways, and the intermediate and final sinks of a material. Because of the law of the conservation of matter, the results of an MFA can be controlled by a simple material balance comparing all inputs and outputs of processes, and thereby the build-up of stocks occurring over time. It is this distinct characteristic of the MFA that makes it attractive as a decision-support tool in resource management, waste management, and environmental management (Brunner and Rechberger, 2016).

The basic components of an MFA are system boundaries, processes, stocks, and flows (OECD, 2008). First, system boundaries, including (i) the material for which the system is quantified, (ii) the time interval, and (iii) the geographical scope of the study, are identified. Next, the system variables, namely processes, stocks, and flows are determined. A process is defined where material is transformed, stored, or distributed. Stocks, within each process, show the amount of material or products measured at a given point in time. Finally, flows, indicating the transport of material, between processes, or coming from outside, or going to outside of the system boundaries, are specified.

A mixed-method approach was applied for modelling the MFA of residential housing stock, with a bottom-up approach used to drive the calculation. Mixed-method approaches to MFA have been successfully adopted in the past (e.g. Hashimoto, Tanikawa and Moriguchi, 2007; Lederer et al., 2021; Yang et al., 2022). In their review of approaches to

MFA studies, Lanau et al. (2019) highlighted that the bottom up approach is deemed more accurate as it is incorporating available information from reliable sources/ databases. However, due to the complexities of calculating the scale of a bottom-up approach, MFA will often need to be limited. In this study, industry databases with relevant information were identified where available. In addition to these, seven probing interviews were conducted with the objective to clarify and verify specific quantitative data points. These expert interviews with senior managers were necessary to verify identified data gaps such as construction waste volume and clarify datapoints to determine relevant timelines for the introduction of new construction techniques such as waffle pod slabs. The expert interviews directly informed the quantitative stock and flow analysis. Probing interviews of relevant quantitative data further strengthens research rigour (Love et al., 2002). A list of interviewees is provided in Table B.1 in Appendix B.

The overall stock of material in the residential construction sector (S_t) is determined based on the difference between flow of material into the system (FI_t) and flow of material out of the system (FO_t) - that is construction waste), as detailed in Eq. 1. This is depicted in Fig. 1, along with the relevant data sources in Table 1.

$$S_t = \sum_{\tau=t_0}^{t} \sum_{m} (FI_{m,\tau} - FO_{m,\tau}) \tag{1}$$

Where,

S_t: Total (cumulative) stock of material in residential detached construction sector at time (t)
$FI_{m,t}$: Material flow into residential construction for each material (m) and year (t) (tonnes per year)
$FO_{m,t}$: Material flow out of residential construction in form of waste (tonnes per year)

On the upstream side, material flow into the residential detached construction sector is determined by the total quantity of housing constructed multiplied by the materal requirements, as described in Eq. 2. Due to the diversity of housing constructions, multiple typologies were considered, with the approximate share of each housing type in the state used in the calculation to determine requirements of individual materials. On the downstream side, as depicted in Eq. 3, the flow out of the industry is calculated from the known construction waste quantities apportioned by the share of market occupied by residential detached construction. Data sources for each of the individual components are listed in Table 1, and are explored in depth in the following section.

Table 1
Data sources used in MFA calculation.

Variable	Name	Description	Data source
H_i	Housing	Number and size of houses constructed by state/territory and sector	NHFIC, 2020; ABS, 2022
$C_{i,j}$	Construction	Breakdown of construction types for location, based on a national database detailing housing construction materials for recent years combined with various industry reports and historical based assumptions	CSIRO, 2022 Australian Construction Insights, 2018; Houghton, 2021
M_j	Materials	Existing databases provided broad overviews of the material quantities. Detailed quantities for constructions developed by quantity surveyor	IBISWorld, 2022a, 2022b, 2022c, 2022d, 2022e Interviews with experienced quantity surveyor
W_i	C&D waste	C&D waste extracted from the National Waste Report, combined with assumptions on the industry market shares to apportion waste accordingly	Pickin et al., 2021 Crowther, 2000; ABS, 2022

$$FI_{m,t} = \sum_{i}\sum_{j} M_j .\ H_i .\ C_{i,j} \tag{2}$$

M_j: Material intensity of housing typology (j) (tonnes per m^2 of construction)
H_i: Total floor area constructed per state (i) year (m^2 per year)
$C_{i,j}$: = Share of housing typology in construction per state (i) (fraction per year)

$$FO_{m,t} = \sum_{i} W_i . R_i \tag{3}$$

Where,

W_i: Waste from construction & demolition per state (i)

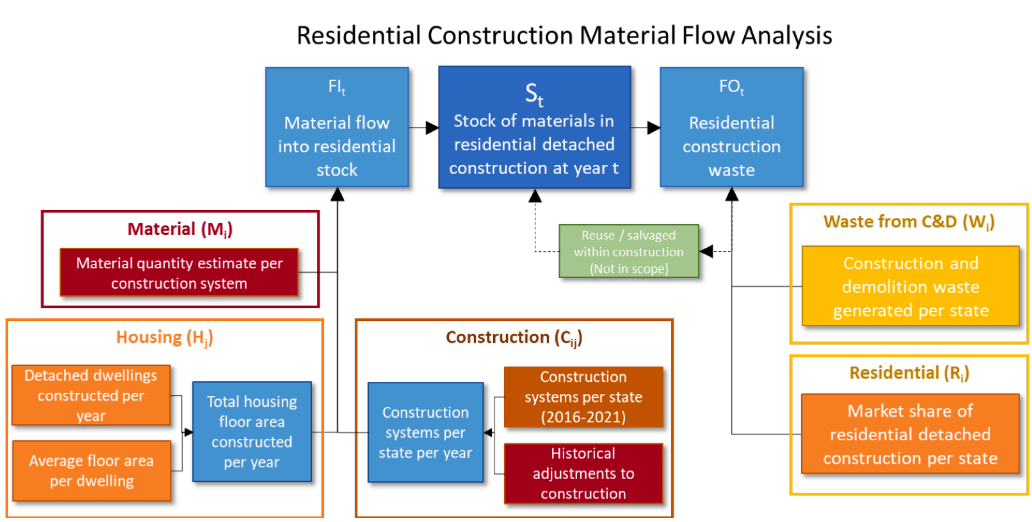

Fig. 1. Overview of MFA approach used in analysis.

R_i : Share of residentital detached construction of all construction in state (i)

Certain limitations and exclusions were placed on the study to ensure that results were achieved in the timeframe required. These limitations are areas where the MFA could be further extended to improve the outcomes of the study, and include:

- Renovations/extensions are not considered – although these contribute a sizeable component to the construction market (>30 %), there is, however, very little data available, and it often relates to the non-structural materials of the house (as discussed by Stephan and Athanassiadis, 2018).
- Only main structural elements of the house (walls, floor structure, roof and windows) were considered. Furnishings, fitout (bathrooms/kitchens), wall and floor coverings and landscaping requirements are all excluded from this study. This approach of limiting materials under consideration is commonly adopted in MFA studies (such as Huang et al., (2018,) who limited their study to nine main materials, and Lederer *et al.*, 2021 who limited their study to eight materials). Those that do consider all materials acknowledge that these elements contribute less than 1 % of the elements in the building (Condeixa, Haddad and Boer, 2017).

2.2. Housing data (H_i)

Housing data extracted from the ABS included the number of detached house dwelling completions per year and the average dwelling size (floor area) over this time (refer to Fig. A.1). The dwelling size is defined by the ABS (2023) to be the usable space in the building, delineated by the external perimeter of the external walls of the buildings, excluding areas such as carports, unenclosed verandas etc which are attached outside the external walls. The overall number of detached dwellings constructed in Australia has not changed dramatically over the 50-year period from 1970–2020, although there is periodic variation across the years. However, there has been variation in the size of houses being constructed, with the data available from 1980 highlighting an increase in dwelling size from 1980 until around 2005 at which point differences between the states are seen. Prior to 2005, a breakdown of floor size by state was not available, therefore variation between states was interpolated based on the average value and the differences in 2005. After 2005, the average dwelling size exhibited less variation, however the disparity between the states persisted.

2.3. Construction data ($C_{i,j}$)

Data on housing construction types has historically not been recorded. In recent years, the national research organisation CSIRO has sought to establish a national record of construction type through the CSIRO Housing Data Portal (CSIRO, 2022), based on submitted NatHERs certificate data. This portal provides a breakdown of construction materials for major components of housing, including variation across states. Results, shown in Fig. 2, highlight the geographical spread of housing constructions. Whilst some of these differences can be attributed to designing for different climates (such as increased use of double glazed windows in the cooler climates of Tasmania and the Australian Capital Territory), other differences are simply geographical anomalies, such as the almost exclusive use of cavity brick construction in Western Australia. Whilst this source of information is useful, it is far from comprehensive. A number of limitations have been identified in this dataset including:

- insufficient information recorded – omissions include frame material type and number of stories in house.
- uncertainty regarding the information presented – material/construction type has been recorded as free text input and is interpreted by CSIRO. This leads to a large proportion of 'unknown' and may have resulted in inaccurate representation.
- data sets are not exhaustive – whilst they cover a large number of houses construction, it does not cover all dwellings.

The CSIRO Housing Portal data provides a clear picture of recent construction trends; however, to estimate the material stocks in use at present, it is necessary to know historical construction approaches as well. However, no historical data has been recorded in Australia. Hence, the research team used a qualitative approach to determine anecdotal changes to the construction industry over the last 50–70 years (Table 2). This qualitative data has been incorporated retrospectively into the MFA to estimate material constructions over the past 50 years.

2.4. Material data (M_j)

In order to estimate material flows based on construction data it is

Fig. 2. Housing typology analysis from CSIRO Housing Portal, based on data sourced from CSIRO (2022). Please refer to nomenclature for explanation of the acronyms used for the states. In figure a) TF refers to timber frame and SF refers to steel frame.

Table 2
Major historical changes to construction in Australia (please refer to the link in Appendix A for the supplementary file for further details on the calculated assumptions of historical changes).

	Pre-1950's	1970's	1975	1985	2000 Now
Walls	*Predominantly full brick in good areas, brick veneer in outer areas and fibro clad in rural areas.*	*Mostly brick veneer and some fibro.*	*Change from asbestos cement clad to fibre cement clad. Introduction of radiata pine framing.*	*Development of zincalume coating also resulted in lightweight steel framing developments. Introduction of double-glazed windows. Increase in number of double storey homes.*	
Floors	*Exclusive use of suspended timber floor.*	*Concrete slab on ground introduced, market grew quickly.*		*Introduction of waffle pod slabs, with a sharp increase in the market over the next 10 years.*	
Roof	*Previously terracotta tiles or corrugated metal sheeting. Cement tiles introduced from 1950s.*			*Introduction of metal sheet (Colorbond) roofing.*	*Increased use of metal sheet roof in market to modern day dominance.*

necessary to know material intensities of the standard construction typologies. Attempts have been made to develop material intensity coefficients for housing designs in various countries (Gontia et al., 2018, Huang et al., 2013), with an international database established by Heeren and Fishman (2019) to collate this data. However it has been recognised that these coefficients need to be geographically based to account for regional differences in construction methodologies. Here, typical materials for external and internal walls, floors, windows and roof/ceiling assemblies were identified with material compositions estimated by a highly experienced quantity surveyor – with over 40 years experience across various regions within Australia. Details are depicted in Fig. 3 (further details are provided in Table A.1 in Appendix A). Estimates are based upon values per square metre of housing construction. Typical conversions between floor area and perimeter were used in conjunction with estimated window to wall ratios to estimate quantities for external walls and windows based on the dwelling floor area. Additionally, assumptions on the split of double storey dwellings compared to single storey dwellings were made at state level, with historical assumptions applied retrospectively (Houghton, 2021). By using material coefficients for typical construction components, it allows for greater flexibility of overall designs total, with combinations of housing components as suited to the regional construction uses. In the data collected here, the total material intensity coefficient varies from 0.1 to 0.9 t/m^2. This is in line with other detailed studies, such as Gontia et al. (2018) who found studied material intensity coefficients for buildings in Sweden in detail, with results ranging from 0.4–0.9 t/m^2. Additionally, in their study from buildings in China, Yang et al. (2020) found total material intensity coefficients of residential buildings ranged from 0.1–2 tonnes/m^2 construction. Therefore, although the values estimated for Australian buildings would be considered lighter weight than some other studies, this is a reflection of the light weight construction methods employed.

2.5. *Construction and demolition waste* (W_i)

Historically, data on Australian construction waste is scarce. However, in recent years, state-based data has been collected as part of the National Waste Action Plan. Data collected by each of the states is brought together in the national report (Pickin et al., 2023), although at times this data is supplemented, manipulated or replaced by national industry data or estimates. Collection of the national waste data started in 2006/2007. However, national data was not collected in the years 2007/08, 2011/12 and 2012/13. To assist in the MFA calculations, estimates were made based on the trends of surrounding years. The construction waste data available is highly aggregated, with no split available between the sectors, origin of waste (residential, commercial or infrastructure) or the source of the waste itself (construction or demolition). One study has provided a singular split of the data, suggesting that demolition is responsible for a far greater proportion of the waste than construction and estimating a rough even split between residential and commercial (Crowther, 2000). However, the study by Crowther (2000) is outdated. Therefore, for the purpose of this analysis, data from the ABS for the market proportion of residential construction vs commercial construction (ABS, 2022) is used to estimate the proportion of construction waste data assigned to the residential detached sector.

Quantities for C&D waste generation for the collection period have been adjusted for the residential detached sector only, as well as the adjusted flows by material and state for a single year (2018), with details provided in Fig. A.2 in Appendix A. Waste flows are dominated by heavyweight materials (masonry), which includes asphalt, brick, concrete and rubble. These materials are largely recycled; however, this is often in the form of crushed rubble used as aggregate in roads and infrastructure development (Rahman, Mohajerani and Giustozzi, 2020). As they are mostly disposed of together, there is little data available on the split between these materials for most states.

The analysis of the Australian residential housing, construction, material and construction & demolition waste data allows for an MFA to be conducted.

3. Results

3.1. *Material flow in residential detached construction*

The MFA of the residential construction industry aims to visualise patterns in the consumption of materials across the sector based on historical data. Aggregated data combined with assumptions described

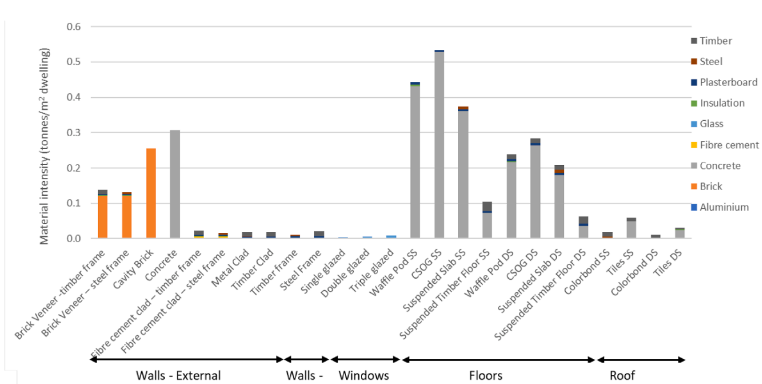

Fig. 3. Material intensity of various construction types, expressed as tonnes of material per m^2 of dwelling.

in the previous section are used to determine the overall flow of material into the construction sector and waste quantities out of the sector over time. Material flows over the time period of 1970–2020 are provided in Fig. 4a, where it can be seen that concrete and brick are the dominant material flows, combined accounting for over 90 % of the weight of construction materials after 1980. The variance in annual figures can be attributed to variance in the annual number of dwellings constructed, whereas the overall increase in material consumption, particularly between 1970 and 1990, can be attributed to the combination of increase in dwelling size and changes in construction methodology – in particular, the increased uptake of concrete slab flooring.

When the material input flows from the residential construction sector are combined with the waste output flows attributed to the sector, an overall stock and flow analysis can be determined. As seen in Fig. 4b, this analysis highlights the increase in materials currently in use in the construction industry and is particularly beneficial for the industry due to the long lifespan construction materials experience (typically >50years). Results are only presented for the years when C&D waste is available (2007–2018) to visualise the balance between flow in and out. To determine housing stocks in use, only houses built after 1970 are considered in the analysis. Therefore, the initial stock at year 2007 consists of all the materials used in housing from 1970–2007. This is a vast simplification of existing stock and will likely be an underestimation, however it provides sufficient context for the study scope.

It can be seen in Fig. 4b that the material stocks in use in the residential construction sector are continually increasing, with the quantity of new/virgin materials used annually more than double the flow of waste out, contributing to rapidly growing stocks of in use materials. The growth rate of the stock overall is around 2 %, which is higher than that in Vienna as determined by Lederer et al. (2021) at 0.6 %. This could be due to a larger existing baseline stock as well as a higher construction growth rate.

Stock and flow analyses for the four major states in Australia are shown in Fig. 5, displaying a similar trend of increasing material stocks for NSW, VIC, QLD, and WA. The only noticeable difference between the states is NSW, which exhibits a much smaller gap between the material flows and C&D waste than the other states. When compared to Victoria, NSW displays similar volumes of waste, however the material flow into Victoria is substantially higher than NSW.

3.2. Material consumption and waste generation per state

On further investigation, the waste generated in NSW per m^2 of new construction (0.41 t/m^2) was almost double that of Victoria (0.23 t/m^2). Differences in material and waste intensities, expressed as tonnes of material/waste per m^2 of new construction, are shown in Fig. 6. Variation can be seen between the states, with NT and WA displaying higher material consumption per m^2 of construction, due to higher levels of concrete and brick construction used in these states. Waste generation, when normalised based on the m^2 of construction, also exhibits variation, with lower rates in Victoria, Tasmania and ACT, and higher rates in SA and NT. These differences may be due to inconsistencies in reporting, differences in the amount of greenfield construction compared to sites involving demolition, or it could be due to movement of waste across state boundaries, which is known to happen due to location and availability of waste management facilities, as well as differences in landfill levies (Wu et al., 2020). The lack of further data available and the uncertainty surrounding the data that is available makes it difficult to adequately assess the quantities of waste being generated in each state.

The flow of construction and waste material in and out of each state for a single year can also be visualised using a Sankey diagram, as seen in Fig. 7. This diagram provides a visually quantitative comparison between flows, including the end market for each of the waste materials (recycling, disposal or energy recovery).

4. Discussion

Understanding the material and waste flows specific to the residential detached construction industry is a crucial component in working towards a CE. This investigation into the material and waste flow of the Australian residential construction industry is a first of its kind, although it follows from similar works internationally. There are significant limitations in this study, notably restricting the scope considered in the study to only detached residential houses. It would be useful to extend this to consider all residential construction to allow for per capita comparisons to be made (such as was undertaken by Yang et al. (2022)). It would also be beneficial to extend the study beyond just new construction materials to also consider renovations (for example Condeixa et al., 2017, Stephan and Athanassiadis 2018).

The study identified significant data gaps across the entire industry which restricts the accuracy of the modelling. Data gaps range from lack of data capture on housing constructions, to aggregated material data, differences in waste recording and sectors of missing data such as the reuse of materials. Each of these data gaps are explained in detail below.

4.1. Aggregated industry data

Construction material sales details are available for certain materials at an aggregate level, however there is little transparency provided in terms of the application of that material and the predominant use – in particular, the sector of the construction industry where the material was used (commercial, residential etc). The timber industry, for example, has overall volume data but would not be able to determine how much of that material is being supplied into framing for residential housing compared to other markets. There is also no data on regional supply of materials or the movement of materials, such as timber harvested in Victoria that is supplied to NSW. Many CE initiatives are regionally based and hence aggregated state/nation-wide data is less meaningful when informing circularity.

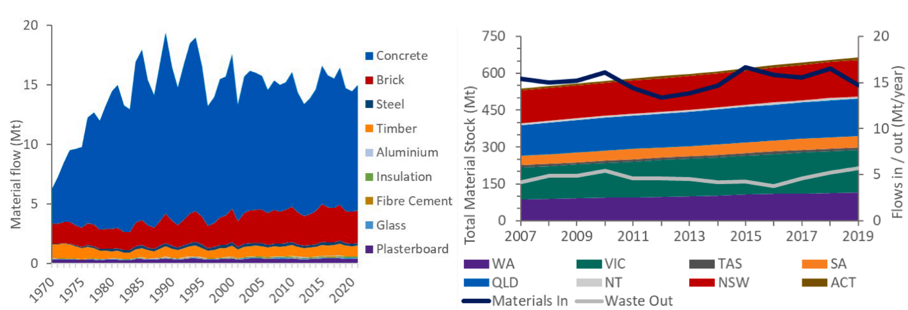

Fig. 4. (a) Annual estimate of material flow into residential detached construction from MFA model and (b) Overall stocks and flows for residential construction 2007–2019.

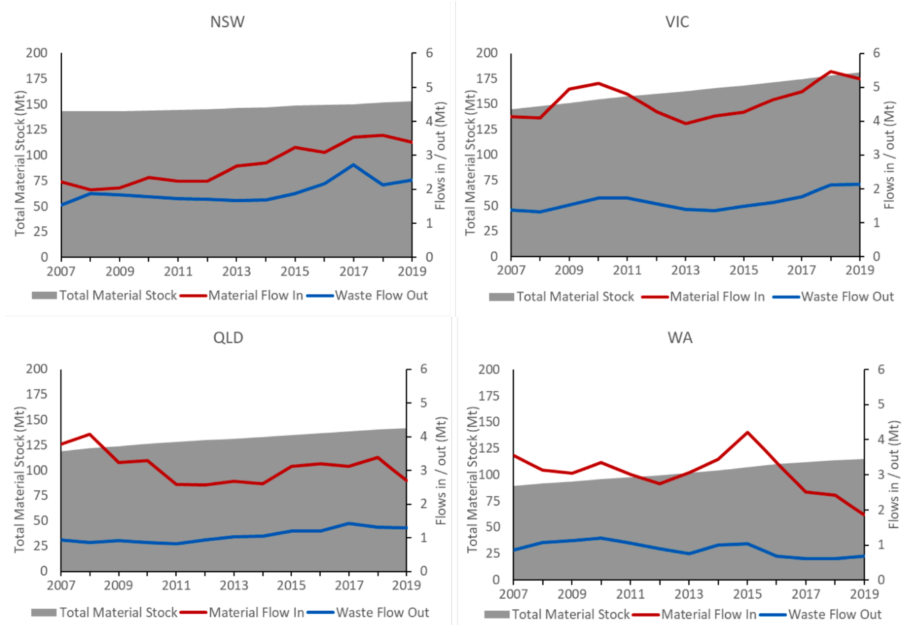

Fig. 5. State based stocks and flows for residential construction 2007–2019 for the four major states (NSW, Vic, QLD and WA). Please refer to nomenclature for explanation of the acronyms used for the states.

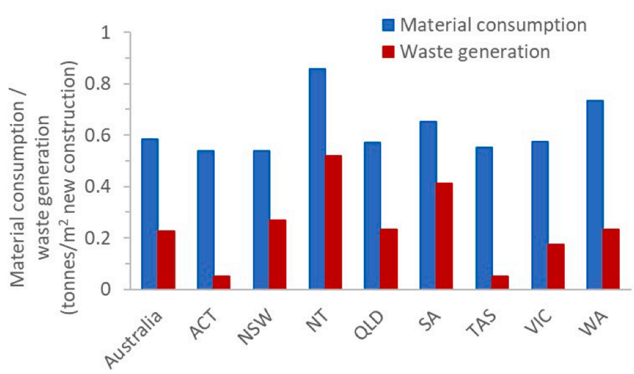

Fig. 6. Material consumption and waste generation in tonnes per m^2 of residential detached construction by state for 2019. Please refer to nomenclature for explanation of the acronyms used for the states.

4.2. Incomplete and inaccurate construction data capture

Historically, there has been little to no data available on the types of construction materials used in housing. This is not a problem unique to Australia (Hashimoto et al., 2007, Huang *et al.* 2013). In recent years, builders have been reporting to the Australian Housing Data portal, as part of the requirement for NatHERS certificate energy efficiency ratings. Although this data is insightful from an MFA perspective; it is also incomplete and potentially inaccurate. The data sheets provided by the construction industry are limited in the information they supply, with text manually handwritten by the builder, which can make it difficult to interpret or categorise. Some data that would be required for an accurate MFA, such as the number of stories in a house or framing materials used, are not recorded in the current system. In addition to this, limitations on the data inputs available means that only a single wall type can be recorded, so the information recorded in not always fully reflective of the actual build. For example, a double story house with brick veneer façade on the ground floor and a fibre cement façade on the first floor would be captured as a brick veneer home, which would lead to an overestimation of the quantity of bricks used in construction.

4.3. Inconsistent construction data

Construction material data recorded by industry bodies such as IBISWorld is often presented financially, such as the value of the market in $million, which does not easily translate to a mass or volume of product, as would be needed for an MFA. Material quantities reported in projects are also not often reported purely by mass quantity. For example, wall quantities reported in a bill of materials will typically be expressed in terms of the lineal metres of wall, which does provide information about the material used, height of the wall in question or square metreage of insulation used. Window sizing is often reported as the window to wall ratio rather than absolute value of window quantities. Data points such as these are crucial to develop an accurate MFA, but, since they do not serve the construction industry in any other way, they are typically not reported.

4.4. Incomplete and inaccurate construction waste data

Construction waste data available in Australia is highly aggregated and not available on a more regional (council) level. It has only been collected for the last 14 years and was not collected every year. There are also inconsistencies in how states report data figures, and breakdown of categories into sub-types of materials is not always available. Available data sources are also not able to distinguish between the source of the waste (construction, demolition or manufacturing), the industry sector (commercial, residential or infrastructure), or even which state the waste has come from – which is important when considering the cross-jurisdictional movement of waste. This information would enable more detailed analysis of where improvements can be made and where a drive towards more circular outcomes would be most beneficial. For example, Lederer et al. (2021) found in their study that avoiding demolishing old buildings and focusing instead on renovations can result in both a reduction in waste as well as in primary raw material consumption. Further analysis of the end markets for the waste is also crucial – construction waste is dominated by masonry materials, with this type of waste currently being down-cycled and used as a supplement for regional infrastructure projects (e.g. roads, railways). Due to the low value nature of this material, a global economy for this type of waste, similar to what we see in the scrap metal sector, is unlikely to occur.

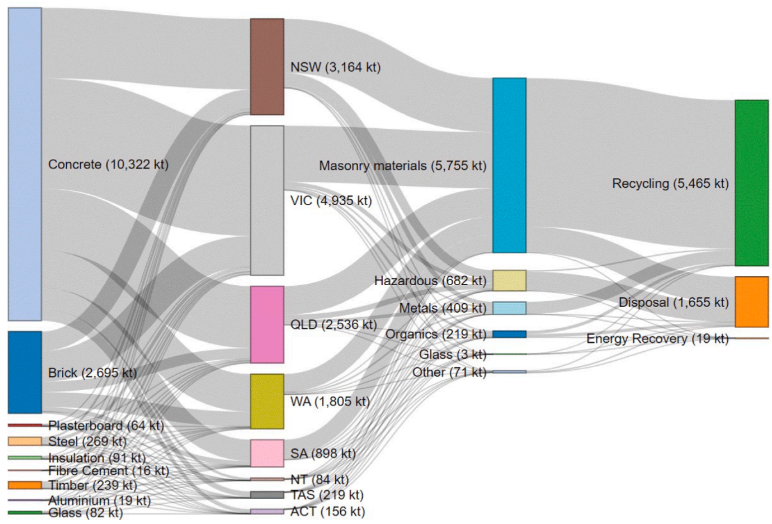

Fig. 7. Sankey diagram depicting the material flow into the residential construction industry and the waste flows out of the industry for 2019. Please refer to nomenclature for explanation of the acronyms used for the states.

Hence, any moves towards greater circularity will need to be centred on the local/regional level, with a focus on maintaining the value in materials through maximisation of reuse and salvage.

4.5. Lack of data on salvaged or reused materials

The salvaged construction material market is growing, particular in salvaged bricks and hardwood in areas where a growing awareness of environmental issues has led to increasing demand for products and demand outstripping supply in some cases. However, there is currently no records on the volumes of materials redirected from disposal/recycling as they are often not processed at waste management facilities. Even though this may only be a small niche of the industry, it is highly important from a circular perspective as it represents one of the major opportunities in a CE – retaining the value in existing materials. Information gained in this area would support the measurement of circularity in the industry and help to drive the growth of the CE.

5. Conclusion

This study presents the result from a first of its kind MFA of the residential detached house construction industry in Australia. Despite limitations in the data available, a novel bottom-up approach has been applied that was capable to give some early insights into material and waste flow in the Australian residential construction sector. This methodological approach has the potential to guide other researchers in their attempt to conduct MFA's when data sources are limited.

It was found that material flows into the residential detached construction industry are largely dominated by brick and concrete, with a steady increase in the material stocks being experienced in Australia. Differences in dominant construction styles between some states (e.g. double brick in WA compared to brick veneer in NSW) can result in variations in the material intensity (tonnes of material required per 100m^2 of housing construction built) – with WA having an estimated material intensity 36 % higher than NSW. Differences were also seen in the waste intensity of construction, however there is insufficient information to identify the underlying causes of differences between the waste intensity of states or the contribution of cross-jurisdictional movement of waste between states to these differences. This study has been limited by focusing only on residential detached construction and it is recommended that further work extend this to consider all residential construction. This would allow for comparison to be made between states on a per capita basis which would further deepen the understanding of differences between states.

A major finding of this study is in the identification of prominent data gaps, regarding both construction materials and C&D waste, which provide challenges for determining the material flows and stock in use within the construction industry in Australia. Closing the data gaps identified, connecting the existing databases and making data available for regional decision makers is critical when enabling a CE. Firstly, a database which captures the composition of buildings is required in order to optimise the information flow across the supply chain and to better coordinate supply and demand of various construction material. Also, the capture of information around reused or salvaged material would enable quantification of current circularity practices and any developments in this area. In the long-term, mandatory digitalisation of the residential construction industry, such as the introduction of material passports, would allow for accurate representation of stock in-use and tracking of construction materials over the life-span of the house. This would also enable more advanced descriptive, predictive, and prescriptive analytics capabilities for various stakeholders in the construction sector.

CRediT authorship contribution statement

Leela Kempton: Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Tillmann Boehme:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Mehrdad Amirghasemi:** Methodology, Writing – original draft, Writing – review & editing, Visualization.

Declaration of Competing Interest

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

Leela Kempton reports financial support was provided by Australian Housing and Urban Research Institute.

Data availability

The data that has been used is confidential.

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Appendix A

Data for the following charts is available upon request.

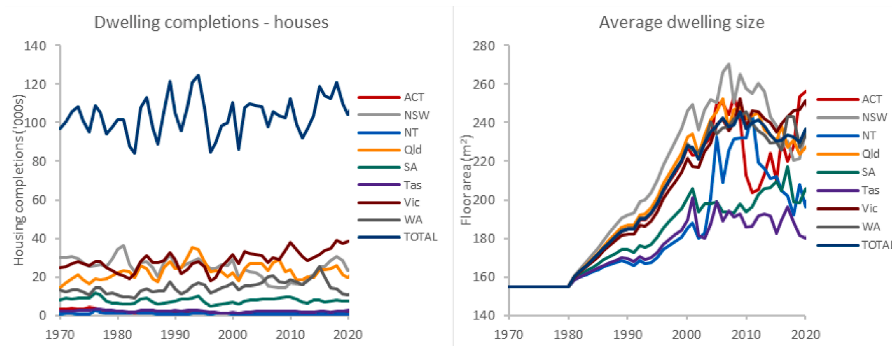

Fig. A.1. Dwelling completions and average floor area for all states Based on data sourced from ABS, 2021, 8752.0 Building Activity: Table 39 'Number of Dwelling Unit Completions by Sector, States and Territories: Original'; ABS, 2021, 8752.0 Building Activity: Average Floor Area; NHFIC (2020), State of the Nation's Housing 2020.

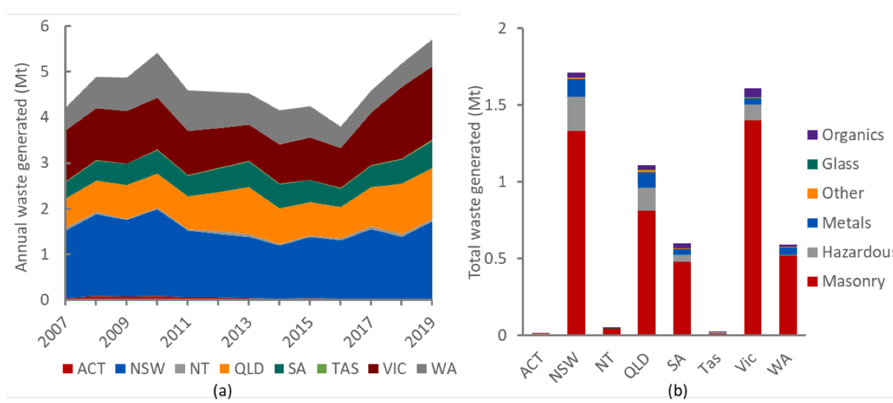

Fig. A.2. (a) C&D waste generated annual by state for the time period 2007–2019, and (b) breakdown of materials in C&D waste for 2019 (Based on data from Pickin et al. (2021) and ABS (X. 2022) 8752.0 Building Activity, Australia, Number of Dwelling Unit Completions by Sector, States and Territories: Original).

Table A.1
Material intensities of standard construction types (tonnes per m^2 of dwelling floor area).

Construction			Aluminium	Brick	Concrete	Fibre cement	Glass	Insulation	Plasterboard	Steel	Timber	Total
Walls - External	Brick Veneer -timber frame			0.122				0.001	0.004		0.011	0.137
	Brick Veneer – steel frame			0.122				0.001	0.004	0.004		0.130
	Cavity Brick			0.256								0.256
	Concrete				0.308							0.308
	Fibre cement clad – timber frame					0.006		0.001	0.004		0.011	0.021
	Fibre cement clad – steel frame					0.006		0.001	0.004	0.004		0.014
	Metal Clad							0.001	0.004	0.003	0.011	0.018
	Timber Clad							0.001	0.004		0.014	0.019
Walls - Internal	Timber frame								0.007	0.004		0.012
	Steel frame								0.007		0.013	0.020
Windows	Single glazed		0.001				0.003					0.003
	Double glazed		0.001				0.005					0.006
	Triple glazed		0.001				0.008					0.009
Floor	Single storey	Waffle Pod			0.432			0.005	0.006			0.443
		Concrete Slab on Ground			0.528				0.006			0.534
		Suspended Slab			0.360				0.006	0.009		0.374
		Suspended Timber Floor		0.000	0.072				0.006		0.027	0.105

(continued on next page)

Table A.1 (*continued*)

Construction			Aluminium	Brick	Concrete	Fibre cement	Glass	Insulation	Plasterboard	Steel	Timber	Total
	Double storey	Waffle Pod			0.216			0.003	0.006		0.014	0.239
		Concrete Slab on Ground			0.264				0.006		0.014	0.284
		Suspended Slab			0.180				0.006	0.009	0.014	0.208
		Suspended Timber Floor		0.000	0.036				0.006		0.021	0.063
Roof	Single storey	Sheet metal						0.001		0.004	0.014	0.019
		Tiles			0.049			0.001			0.010	0.060
	Double storey	Sheet metal						0.001		0.002	0.007	0.010
		Tiles			0.024			0.001			0.005	0.030

Appendix B

Table B.1
List of interviewees and their relevant industry.

Reference	Industry
1	Quantity Surveyor
2	Steel Research
3	Timber Institute
4	Research Institute
5	Landfill
6	Steel
7	Brick Recyclers

References

ABS, 2022. 8752.0 Building Activity, Australia. Available at: https://www.abs.gov.au/statistics/industry/building-and-construction/building-activity-australia/latest-release (Accessed: 20 April 2023).

ABS, 2023. *Average Floor Area of New Residential Dwellings, Australian Bureau of Statistics: Building Activity, Australia*. Available at: https://www.abs.gov.au/articles/average-floor-area-new-residential-dwellings.

Ai Group, 2016. Australia's Construction Industry: Profile and Outlook. Available at: https://cdn.aigroup.com.au/Economic_Indicators/Construction_Survey/2015/Construction_industry_profile_and_Outlook.pdf (Accessed: 20 April 2023).

Arehart, J.H., et al., 2022. Structural material demand and associated embodied carbon emissions of the United States building stock: 2020–2100. Resour. Conserv. Recycl. 186, 106583 https://doi.org/10.1016/J.RESCONREC.2022.106583. Available at.

Australian Construction Insights, 2018. Faming Material use in Residential Construction.

Australian Government, 2018. National Waste Policy 2018: Less waste, More Resources.

Australian Government, 2019. 'National Waste Policy Action Plan 2019'.

Becqué, R., et al., 2019. Accelerating Building Decarbonization: Eight Attainable Policy Pathways to Net Zero Carbon Buildings For All. Washington, DC.

Böhme, T., et al., 2018. Causes and mitigation for declining productivity in the Australian mid-rise residential construction sector. Built Environ. Project Asset Manage. 8 (3), 253–266. https://doi.org/10.1108/BEPAM-10-2017-0097. Available at.

Brunner, P.H., Rechberger, H., 2016. Handbook of Material Flow Analysis : For Environmental, Resource, and Waste Engineers, Second Edition. https://doi.org/10.1201/9781315313450. Available at:

Condeixa, K., Haddad, A., Boer, D, 2017. Material flow analysis of the residential building stock at the city of Rio de Janeiro. J. Clean. Prod. 149, 1249–1267. https://doi.org/10.1016/J.JCLEPRO.2017.02.080. Available at:

Crowther, P., 2000. Building Deconstruction in Australia. Overview of Deconstruction in Selected Countries. CIB Report No. 252.

CSIRO, 2022. Australian Housing Data. Available at: https://ahd.csiro.au/ (Accessed: 20 April 2023).

Dalton, T., et al., 2023. Building Materials in a Circular Economy. https://doi.org/10.18408/ahuri5328401. Available at:

Ellen MacArthur Foundation, 2013. Towards the Circular Economy Vol 1: Economic and Business Rationale For an Accelerated Transition. https://doi.org/10.1596/37331. Available at:

European Commission, 2020. Circular Economy Action Plan. Available at: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en (Accessed: 20 April 2023).

Gasparri, E., et al., 2023. Circular economy in construction: A systematic review of knowledge gaps towards a novel research framework. Front.Built Environ. https://doi.org/10.3389/fbuil.2023.1239757 [Preprint]. Available at:

GBCA and thinkstep-anz, 2021. Embodied Carbon and Embodied Energy in Australia's Buildings. Sydney.

Gontia, P., et al., 2018. Material-intensity database of residential buildings: A case-study of Sweden in the international context. Resour. Conserv. Recycl. 130, 228–239. https://doi.org/10.1016/J.RESCONREC.2017.11.022. Available at:

Hashimoto, S., Tanikawa, H., Moriguchi, Y., 2007. Where will large amounts of materials accumulated within the economy go? – A material flow analysis of construction minerals for Japan. Waste Manage. 27, 1725–1738. https://doi.org/10.1016/j.wasman.2006.10.009. Available at:

Heeren, N., Fishman, T., 2019. A database seed for a community-driven material intensity research platform. Sci. Data 6. https://doi.org/10.1038/s41597-019-0021-x. Available at:

Holland Circular Hotspot, 2022. Circular Buildings: Constructing a Sustainable Future. Available at: https://hollandcircularhotspot.nl/wp-content/uploads/2022/10/Circular-Buildings-constructing-a-sustainable-future.pdf (Accessed: 20 April 2023).

Houghton, J., 2021. Timber Usage in Residential Construction 2017-18 dataset: Report on Methodology and Results. Available at: https://fwpa.com.au/timber-usage-in-residential-construction-2017-18-dataset-report-on-methodology-and-results/ (Accessed: 20 April 2023).

Huang, T., et al., 2013. Materials demand and environmental impact of buildings construction and demolition in China based on dynamic material flow analysis. Resour. Conserv. Recycl. 72, 91–101. https://doi.org/10.1016/J.RESCONREC.2012.12.013. Available at:

Huuhka, S., Kolkwitz, M., 2021. Stocks and flows of buildings: Analysis of existing, demolished, and constructed buildings in Tampere, Finland, 2000–2018. J. Ind. Ecol. 25 (4), 948–960. https://doi.org/10.1111/JIEC.13107. Available at:

IBISWorld, 2022a. Industry Report C1492: Wooden Structural Component Manufacturing in Australia.

IBISWorld, 2022b. Industry Report C2021: Clay Brick Manufacturing in Australia.

IBISWorld, 2022c. Industry Report C2031: Cement and Lime Manufacturing in Australia.

IBISWorld, 2022d. Industry Report C2033: Ready-Mixed Concrete Manufacturing in Australia.

IBISWorld, 2022e. Industry Report E3223: Roofing Services in Australia.

Krausmann, F., Wiedenhofer, D., Lauk, C., 2017. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. Proc. Natl Acad. Sci. U.S.A. 114 (8), 1880–1885. https://doi.org/10.1073/pnas.1613773114. Available at:

Lanau, M., et al., 2019. Taking stock of built environment stock studies: progress and prospects. Environ. Sci. Technol. 53 (15) https://doi.org/10.1021/acs.est.8b06652. Available at:

Lederer, J., et al., 2021. Raw materials consumption and demolition waste generation of the urban building sector 2016–2050: A scenario-based material flow analysis of Vienna. J. Clean. Prod. 288 https://doi.org/10.1016/j.jclepro.2020.125566. Available at:

Meglin, R., Kytzia, S., Habert, G., 2022. Regional circular economy of building materials: Environmental and economic assessment combining Material Flow Analysis, Input-Output Analyses, and Life Cycle Assessment. J. Ind. Ecol. 26 (2), 562–576. https://doi.org/10.1111/JIEC.13205. Available at:

NHFIC, 2020. State of the Nation's Housing 2020 National Housing Finance and Investment Corporation. National Housing Finance and Investment Corporation.

Available at: https://www.nhfic.gov.au/sites/default/files/2022-10/nhfic_state-of-the-nations-housing-report_accessible-updated.pdf (Accessed: 20 April 2023).
OECD, 2008. Measuring Material Flows and Resource Productivity Volume 1. Available at: https://www.oecd.org/environment/indicators-modelling-outlooks/MFA-Guide.pdf (Accessed: 20 April 2023).
OECD, 2019. *Global Material Resources Outlook to 2060, Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences*. OECD, Paris. https://doi.org/10.1787/9789264307452-EN. Available at:
Osmani, M., 2011. Construction Waste. Waste 207–218. https://doi.org/10.1016/B978-0-12-381475-3.10015-4. Available at:
Pickin, J., et al., 2021. National Waste Report 2020.
Pickin, J., et al., 2023. National Waste Report 2022. Available at: https://www.dcceew.gov.au/sites/default/files/documents/national-waste-report-2022.pdf (Accessed: 27 February 2023).
Rahman, M.T., Mohajerani, A., Giustozzi, F., 2020. Recycling of waste materials for asphalt concrete and bitumen: a review. Materials (Basel) 13 (7), 1495. https://doi.org/10.3390/ma13071495. Available at:
Schandl, H., et al., 2008. Australia's Resource Use Trajectories. J. Ind. Ecol. 12 (5–6), 629–819. https://doi.org/10.1111/j.1530-9290.2008.00075.x. Available at:
Schiller, G., Gruhler, K., Ortlepp, R., 2017. Continuous material flow analysis approach for bulk nonmetallic mineral building materials applied to the German building sector. J. Ind. Ecol. 21 (3), 673–688. https://doi.org/10.1111/jiec.12595. Available at:
Shooshtarian, S., et al., 2022. Transformation towards a circular economy in the Australian construction and demolition waste management system. Sustain. Prod. Consump. 30, 89–106. https://doi.org/10.1016/j.spc.2021.11.032. Available at:
Stephan, A., Athanassiadis, A., 2017. Quantifying and mapping embodied environmental requirements of urban building stocks. Build. Environ. 114, 187–202. https://doi.org/10.1016/J.BUILDENV.2016.11.043. Available at:
Stephan, A., Athanassiadis, A., 2018. Towards a more circular construction sector: Estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks. Resour. Conserv. Recycl. 129, 248–262. https://doi.org/10.1016/j.resconrec.2017.09.022. Available at:
Tanikawa, H., et al., 2015. The weight of society over time and space a comprehensive account of the construction material stock. J. Ind. Ecol. 19 (5) https://doi.org/10.1111/jiec.12284. Available at:
Wiedenhofer, D., et al., 2019. Integrating Material stock dynamics into economy-wide material flow accounting: concepts, modelling, and global application for 1900–2050. Ecol. Econ. 156, 121–133. https://doi.org/10.1016/J.ECOLECON.2018.09.010. Available at:
Wiedmann, T.O., et al., 2015. The material footprint of nations. Proc. Natl Acad. Sci. U.S.A. 112 (20), 6271–6276. https://doi.org/10.1073/PNAS.1220362110. Available at:
Wu, H., et al., 2020. Cross-regional mobility of construction and demolition waste in Australia: an exploratory study. Resour. Conserv. Recycl. 156 https://doi.org/10.1016/J.RESCONREC.2020.104710. Available at:
Yang, D., et al., 2020. Urban buildings material intensity in China from 1949 to 2015. Resour. Conserv. Recycl. 159 https://doi.org/10.1016/J.RESCONREC.2020.104824, p. 104824. Available at:
Yang, D., et al., 2022a. Spatial–temporal dynamics of the built environment toward sustainability: a material stock and flow analysis in Chinese new and old urban areas. J. Ind. Ecol.2 27, 84–95. https://doi.org/10.1111/jiec.13335. Available at:
Yang, X., et al., 2022b. Key strategies for decarbonizing the residential building stock: Results from a spatiotemporal model for Leiden, the Netherlands. Resour. Conserv. Recycl.Resour. Conserv. Recycl. 184, 106388 https://doi.org/10.1016/J.RESCONREC.2022.106388. Available at:
Yu, M., et al., 2017. The carbon footprint of Australia's construction sector. Proc. Eng. 180, 211–220. https://doi.org/10.1016/J.PROENG.2017.04.180. Available at:
Zaman, A., et al., 2023. Development of the circular economy design guidelines for the Australian built environment sector. Sustainability 2023 15 (3), 2500. https://doi.org/10.3390/SU15032500. *Vol. 15, Page 2500*Available at: