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Estimating the material intensity of wooden residential houses in Finland

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ABSTRACT

Improving resource efficiency in the building sector is a significant challenge, largely due to a lack of knowledge about material usage in buildings. Material intensity (MI) quantifies materials used in buildings, normalized by floor area or volume. MIs serve as indices for material stock and flow models and as an inventory approach for assessing the environmental impact of the built environment. Therefore, this study aimed to determine MIs of Finnish wooden residential houses built between 1940 and 2010 due to the dominance of them in residential building stock and their demolition rates. Factors influencing MI and cross-country comparisons were also explored because they had not been explored enough in the literature. Results showed construction method, time cohort, floor area, design choices and footprint shape impacted MI. Accounting for variability of MI was recommended, particularly when using it for material stock and flow analysis. Data and method disparities restrict cross-country comparison of MI.

1. Introduction

Improving resource efficiency in the building sector is one of the biggest challenges facing society today. Globally, the manufacture of building products is responsible for the emission of 3.6 $GtCO_2$ every year (UNEP, 2022), whilst in Europe, a third of the total volume of waste generated annually is accounted for by construction and demolition activities (EC, 2018). Current construction practices using conventional materials like concrete and steel result in substantial CO_2 emissions (Mishra et al., 2022). Wood is therefore emerging as an increasingly important material, potentially helping buildings become a carbon sink (Arehart et al., 2021; Pomponi et al., 2020) and replacing non-renewable materials (Amiri et al., 2020). However, there are limits to how much forest can be harvested sustainably for wood products, so to reduce the demand for primary wood, the design of durable wood products and effective strategies for lifetime extension, through reuse and recycling, are essential (Churkina et al., 2020; Mishra et al., 2022). Whilst such strategies can ultimately help mitigate climate change and enhance resource efficiency (EC, 2020; Husgafvel et al., 2018; Niu et al., 2021), significant efforts are still required to implement effective reuse and recycling in practice (Kabirifar et al., 2020). One of the barriers to this is the paucity of data about the quantity and quality of wood products that can be recovered from building demolitions and other sources, for reuse and recycling in the future (Falk et al., 1999; Höglmeier et al., 2017; Icibaci, 2019; Nasiri et al., 2021; Sakaguchi et al., 2016, 2017).

In general, a vital step in predicting the future quantity of recoverable materials arising from building demolitions is to create material stock and flow models that account for damage and the loss of quality that invariably occur in the use phase and during demolition. One approach to modelling the inflow of materials is to determine the amount of material initially used in a building, normalized by the floor area, typically gross floor area (GFA), or the internal volume of the building (expressed as e.g. kg m^{-2} or kg m^{-3}) that is specific, for example, to each building type, construction period, and the intended use of the building (Gontia et al., 2018; Heeren and Fishman, 2019). This measure, known as material intensity (MI), can then incorporate other parameters such as the inflow of buildings to the stock, the lifetime of buildings, and the quality of materials following demolition, enabling an estimation of materials versus recoverable materials and their flows over space and time to be made (Gontia et al., 2020; Heeren and Fishman, 2019; Heeren and Hellweg, 2019; Höglmeier et al., 2017; Kalcher et al., 2017; Kleemann et al., 2016; Pia et al., 2022; Wiedenhofer et al., 2015). MIs can also serve as an inventory method in the life cycle assessment of the built environment. This method utilizes the spatial characteristics of the built environment, MI, and the embodied greenhouse gas emission of materials, to evaluate the environmental impacts and embodied energy associated with material stock and flows (Schandl et al., 2020).

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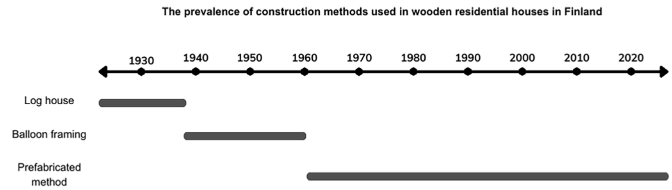


Fig. 1. A summary of the prevalence of construction methods used in wooden residential houses. More detailed information can be found in appendix.

According to Kleemann et al. (2016), two main methodological approaches have been implemented across all MI studies. The first analyses the materials used in construction, analysing the building in its original state (Aldrick et al., 2021; Gontia et al., 2018; Kleemann et al., 2016; Ortlepp et al., 2018), whilst the second analyses the waste material after demolition. Renovation and material replacement due to maintenance are usually disregarded in the first approach, and included in the second (Kleemann et al., 2016). This is because the technical documentation of buildings and building information models (if applicable) are not usually updated after the design phase unless major renovation occurs. This is less significant for the structural parts of a building which remain more-or-less intact during its lifetime (Kalcher et al., 2017). Data about non-structural parts can be updated through on-site surveys. A benefit of the first method is that depending on the source of the data, it can provide not just an overall value for the volume of the materials available in buildings, but provide this at the level of individual products, such as wood, and their dimensions (Nasiri and Hughes, 2022). Such data can then be combined with data about the damage and contamination of a material after demolition or disassembly to determine the share of recoverable material (Falk et al., 1999; Höglmeier et al., 2017; Icibaci, 2019; Nasiri et al., 2021; Sakaguchi et al., 2016, 2017). The same cannot be guaranteed by the second method, since materials recovered from demolition are recorded according to waste streams with heterogenous compositions (Kleemann et al., 2016; Lichtensteiger and Baccini, 2008). Currently, however, the gross weight and volume of heterogenous materials in designated containers are the only parameters that are typically measured and collected (Alakangas et al., 2015; Harte et al., 2020).

More than thirty MI studies have been conducted around the world of which about two thirds have been conducted in Europe (Heeren and Fishman, 2019). The results from such research are not, however, transferable to other geographical locations (Gontia et al., 2018) unless there are similarities in the climate, geological activity (e.g. earthquakes), building materials, architectural trends, and construction methods in different time cohorts (Kalcher et al., 2017). MI research has not hitherto been conducted in Finland, although there is clearly a need for it (Heeren and Fishman, 2019; Nasiri et al., 2021). Nasiri et al. (2021) analysed wooden residential buildings in Finland to estimate the material stock for the year 2017, though highlighting that having an accurate estimate of MI for Finland is essential. The study found that approximately 17.5 million tons of wood are used in the structural elements of wooden residential houses in Finland, of which around 9 million tons could be recycled and reused (Nasiri et al., 2021). Due to the lack of information about the MI of Finnish houses, the study by Nasiri et al. (2021) relied on Swedish research published by Gontia et al. (2018) to estimate the amount of wood. Despite apparent similarities in building practices between the two countries, there may also be differences that could affect MI and consequently the estimated material stock of wood in the buildings. Therefore, the aim of this study was to establish the MI of wooden residential houses in Finland, including not only wood, but also concrete and brick.

To reach the goals of this study, the prevalence of construction methods used in wooden residential houses in Finland was reviewed to create time cohorts for representative buildings (Appendix). This is because MI is influenced by many external factors including architectural trends, historic and economic development, and resource availability (Gontia et al., 2018). Wooden residential houses in Finland were categorized into three time cohorts as shown in Fig. 1. An analysis of the results, limitations, and variables (e.g., GFA, construction method, footprint shape and number of storeys) of the MI was also conducted, mainly because these aspects had not yet been explored well enough in the literature. Specifically, a detailed comparison was made between Finland and Sweden, due to similarities in building construction, to investigate any cross-border differences.

2. Material and methods

2.1. System boundary

The MI in the current study focused only on wooden single-family houses built in Finland between 1940 and 2009. This choice was motivated by two main factors; firstly, all single-family and two-family houses (data for these is combined in most Finnish housing statistics) account for approximately 88% of the number and 53% of the GFA of the residential building stock in 2021 (Statistics Finland, 2022); secondly, of the single-family and two-family houses demolished between 2000 and 2010, 65% were built after 1940 (Huuhka and Lahdensivu, 2016).

Further, due to the dearth of information about the building-elements in the selected building types, and the importance of cascading for structural applications (Niu et al., 2021), the MI only included structural elements used in the construction of roofs, external walls, dividing walls, floors, basements, and foundations. Of all building materials used only brick, concrete, and wood were included. Fig. 2 illustrates the elements and materials included in the present work.

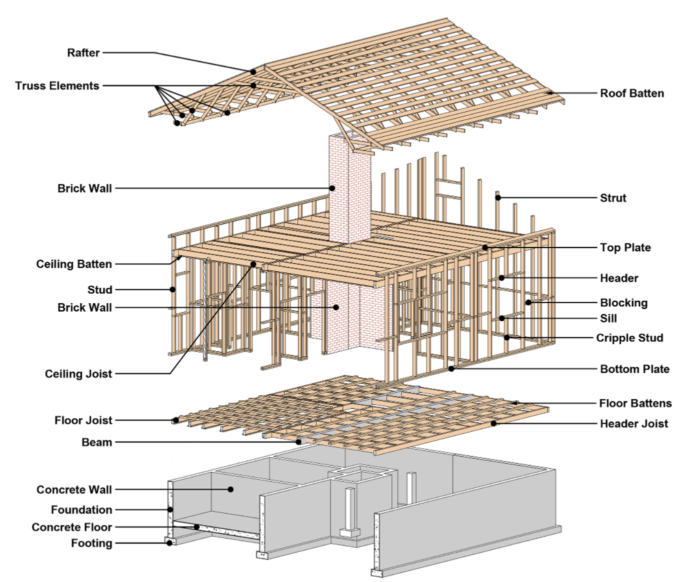


Fig. 2. Building materials and building-elements included in MIs for balloon framing and prefabricated houses.

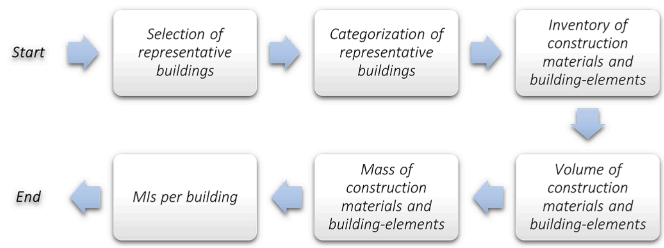


Fig. 3. Process of creating MI for Finnish buildings.

2.2. Method steps

MI was determined by calculating the mass of each building material contained in representative buildings in each time cohort and building-element. Fig. 3 outlines the steps involved.

2.2.1. Selection of representative buildings

For the selection process, an Excel spreadsheet was obtained from the municipal building register of Vantaa, the second largest city in Finland. The spreadsheet contained, amongst other things, background information about existing buildings in Vantaa in the year 2018: unique permanent building id that is the same in all official local and national databases, building type (e.g., single-family houses), construction year, frame material, façade material, gross and total floor area, and number of storeys. Corresponding information for all of Finland was not available. Based on the total number of buildings and GFAs, single-family and two-family houses have greater average GFA in Vantaa than in the country as a whole – approximately 12% during the time period 1940–1959 and 10% from 1960 onwards, with the difference decreasing towards the 2000s (Statistics Finland, 2022). Since data for the whole country combines single-family and two-family houses, the difference might also reflect different shares between the two.

The selection process began by dividing Vantaa's existing wooden single-family houses (5586 houses in total) into decadal construction periods. Next, the median GFA was determined from the register for each decade, and this was used to select representative buildings for each decade. Since MIs are calculated in relation to (typically gross) floor area, this minimizes error when applying them to a stock where actual building size varies.

Using the permanent building id to distinguish buildings, technical documents (construction permit documents, i.e., architectural drawings and engineering drawings such as truss details) of the representative buildings were then purchased from Lupapiste Kauppa.[1] When examining the material available for purchase, it was often found that a representative building did not have the requisite technical documents or were unusable for another reasons (e.g., the house was primarily made of a material other than wood), in which case the next best representative building was chosen.

2.2.2. Categorization of representative buildings

Based on the prevalence of wooden residential houses in Finland (described in Fig. 1), the selected buildings were divided into two time cohorts: 1940–1959 and 1960–. Next, the buildings in each group were categorized based on their construction method, construction decade and number of storeys (Table 1). This division was necessary to enable a more accurate evaluation of MI. Building type and construction decade were used to code the buildings (e.g., SF-1940: single-family house, built in the 1940s).

[1] A Finnish digital archive that stores technical documents of buildings submitted during the building permit application process.

2.2.3. Inventory of building materials and building-elements

Each of the buildings summarized in Table 1 were modelled in Revit Architecture with AGACAD[2] tools according to their technical documents. To create the inventory data sheet, all the structural components detailed in Section 2.1 were modelled. The inventory data contained information about dimensions, and framing member of wooden elements. Elements made from brick and concrete contained information about their area and volume. For all building materials, the framing member and the storey where it was located were also noted. The building technical documents contained information about architectural and engineering drawings. Where information was lacking, estimates were made based on similar buildings built in the same decade (Section 2.3).

2.2.4. Quantifying building materials and building-elements

To calculate the amount of each material (*m*: wood, concrete, brick) in every building (*j*) by building-element (*i*) Eqs. (1), 2, and 3 were applied. Eqs. (1) and 2 were used to calculate the volumes of wood and concrete (*m*: wood, concrete) ($V_{m,\ i,j}$ in m^3). Eq. (3) determines the number of bricks (*m*: brick) ($Count_{\ Brick,i,j}$):

$$V_{Wood,\ i,j} = \sum L_{Wood,\ i,j} \times D_{Wood,i,\ j} \tag{1}$$

Where $L_{Wood,i,j}$ is the length of the wooden framing members (e.g., stud) in the wooden element *i* (e.g., exterior walls of the first floor) and building *j*, and $D_{Wood,i,j}$ is the cross-sectional area of the wooden framing members in wooden element *i* and building *j*.

$$V_{Concrete,i,j} = V_{i,j} - \left[\left(R_i / \rho_{Steel}\right) \times V_{i,j}\right] \tag{2}$$

Where $V_{Concrete,i,j}$ is the volume of concrete element *i* (e.g., first floor) and building *j*. R_i is the mass of steel required in 1 cubic metre of concrete (kg/m^3-concrete). ρ_{Steel} is the density of steel, 7850 kg/m^3 (SFS, 2009). R_i/ρ_{Steel} was applied to estimate proportion of steel required for different concrete elements. As a rule of thumb and based on expert knowledge, R_i in footings and slabs is around 80 kg/m^3-concrete, while in columns and beams it is about 160 and 110 kg/m^3-concrete, respectively (Ugochukwu et al., 2020).

$$Count_{Brick,i,j} = A_{i,j} \times CONS_{Brick,i} \tag{3}$$

Where $A_{i,j}$ is the area of building-element *i* in building *j*, excluding openings (if applicable). $CONS_{Brick,i}$ is brick consumption per square metre of that building-element (excluding mortar), retrieved from an environmental product declaration (EPD) of red clay brick (Rakennustietosäätiö, 2020).

2.2.5. Mass by building material and building-element

In every building, the stock of each building material by building-element ($S_{m,i,j}$ in *kg*) was calculated using Eqs. (4) and 5:

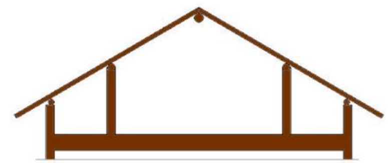
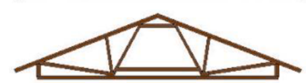
$$S_{m,i,j} = V_{m,i,j} \times \rho_m \tag{4}$$

$$S_{m,i,j} = Count_{Brick,i,j} \times M_{1\_Brick} \tag{5}$$

Where ρ_m is the density of building materials. The density of materials was taken either from the EPD of products or a Finnish database called "Emissions database for construction". M_{1_Brick} is the mass of one brick, retrieved from an EPD of red clay brick (Rakennustietosäätiö, 2020), and equals 2.8 kg per brick. Table 2 summarises the density values for each building material.

[2] AGACAD is an add-on for Revit that allows for the detailed modelling of wood structures (including balloon framing and heavy-timber framing), encompassing all levels of detail such as wall structures and connections. Available at: https://agacad.com/

Table 1
Categorization of building typologies according to their year of construction. f: floor/storey; b: basement, LVL: laminated veneer lumber, GFA: gross floor area.

Time cohort	Construction method	Number of storeys	Building material	Building Code	Construction decade	Roof technique	Roof technique figure	GFA (m^2)	Height of floors (m)	Length of interior walls (m)
1940–1959	Log house[1]	*1.5f + b*	Log, timber, brick, concrete	SF-1940	1940s	Purlin roof		77	2.5 (1st floor) + 2.2 (Attic)	5
1940–1959	Balloon framing[2]	*1f + b*	Timber, brick, concrete	SF-1950	1950s	Swedish truss		127	2.5 (1st floor)	25
1960–	Prefabricated method[3]	*1f + b*	Timber, brick, concrete	SF-1960	1960s	Triple fink truss		208	2.5 (1st floor)	35
		1f	Timber, concrete	SF-1970	1970s	Fan truss		92	2.4 (1st floor)	24
			Timber, brick, concrete	SF-1980	1980s	Attic truss		153	2.48 (1st floor)	48
			Timber, brick, concrete	SF-1990	1990s	Double fink truss		189	2.5 (1st floor)	42
			Timber, brick, concrete, LVL	SF-2000	2000s	Attic truss with inclined bars		156	2.48 (1st floor)	46

[1] This construction system utilizes horizontal logs that are stacked directly on top of each other. The load-bearing walls serve a dual purpose as both structure and enclosure, with exposed joints that express the construction method.
[2] The balloon frame technique consists of full-height wall framing elements which usually use light sawn timbers, assembled with nails.
[3] This technique is similar to the balloon frame technique, but to minimize construction time on-site, the structural frames can be modularized into planar structural elements like walls and floor units or volumes.

Table 2
Summary of density of building materials.

Building material	Density (ρ in kg/m^3)	Reference
Concrete	2400	(SYKE, 2022)
Sawn timber	479	(Rakennustietosäätiö, 2021)
LVL	475	(Puutuoteteollisuus, 2019)
Log	475	(Rakennustietosäätiö, 2022)

2.2.6. Aggregation of MI

The aggregated MI by building material *m* and building-element *i* in building *j* ($MI_{m,i,j}$ in kg/m^2) was calculated using Eq. (6):

$$MI_{m,i,j} = \frac{S_{m,i,j}}{GFA_j} \tag{6}$$

Where GFA_j is the area enclosed by the outer surface of the external walls of every storey (including the basement but excluding the attic unless the building is 1.5 storeys) of building *j*.

2.3. Limitations and assumptions

Limitations and assumptions made in relation to building materials are listed below:

- The technical documents of some buildings did not specify stud and batten spacing. In these cases, wall elements as well as floor and roof battens were modelled assuming that spacing is between 45 and 60 cm. The assumption was made based on the spacing between the framing members of similar buildings.
- Some of the detailed designs did not specify the dimensions of timbers used for the construction of roofs. In such cases, measurements were made from the drawings.
- There were some building-elements for which detailed designs were not available. The dimensions of timber within those building-elements were determined based on the detailed designs of similar buildings.
- The technical documents of buildings did not specify the type of brick. Thus, it was assumed that they were built of red clay brick.
- Information regarding bearing piles was completely missing from the architectural data, so they were not included in the analysis.

2.4. Influence of building parameters on MI

In addition to the buildings listed in Table 1, further Finnish buildings, commonly constructed in the 1940s and 1950s using balloon framing, were examined to investigate how GFA, footprint shape and the number of storeys influence MI. Buildings constructed in these two decades were chosen since, according to Nasiri et al., (2021), they account for around 23% of the total estimate, or around 4 million tons of wood in 2017. The MI of these buildings was calculated according to the same method explained above.

3. Results and discussion

3.1. Building MI

In the buildings that were analysed, the chimneys and their surrounding walls were always built with brick, except for SF-1970 which was common not to have a chimney. In all buildings, the basement slab, the lower part of the external walls on the first floor, and the external walls underground were constructed from concrete. The rest of the building-elements were mainly of wood.

Fig. 4 shows MI, in units of mass [kg] per square metre of GFA, for each of the aggregated building materials – brick, concrete, logs and timber. From the data presented in Fig. 4, the average MI of the buildings studied is 641 kg/m^2. MIs decline from the 1940s until the 1970s and then increase again, reaching 563 kg/m^2 in the 2000s. This increase is largely due to the greater MI of concrete, which rose from 244 kg/m^2 in SF-1970 to 467 kg/m^2 in SF-2000 (excluding SF-1990), as a result of the adaptation of a new foundation technique and the increased height of the concrete base in external walls. As a result of switching from log walls and purlin roofs to wooden frame construction and truss roofs, MIs drop from 952 kg/m^2 in SF-1940 to 868 kg/m^2 in SF-1950. In general, the MI of concrete is the main factor influencing total MI, averaging around 88% and ranging from 244 to 840 kg/m^2. In contrast to concrete, the other materials have little variation in their MIs when considering absolute amounts. For timber, they range from 23 to 53 kg/m^2 and for bricks, they are below 45 kg/m^2.

Fig. 5 shows, for each decade, the MI of brick and concrete separated by building-element (note the different MI scales in Fig. 5). According to the data shown in Fig. 5, on average the 'foundation' and 'external wall, basement' represent the largest share of the total MI, being 138 kg/m^2 and 477 kg/m^2 respectively. This is consistent with the findings of a study by Aldrick et al. (2021) which analysed 37 wooden single-family houses in Toronto, Canada and the study by Gontia et al. (2018). The MI of 'external wall, basement' decreases from 618 kg/m^2 in SF-1940 to 258 kg/m^2 in SF-1960 and increases from 23 kg/m^2 to 123 kg/m^2 for basement slabs. The MI of the basement slab increased primarily because of the larger GFA of SF-1950 compared with SF-1940 and the larger GFA of SF-1960 compared with SF-1950. Additionally, the surface area of the basement slabs as well as their thickness have an impact on the MI. In buildings built after 1970 (buildings without basement), the foundation and first floor represent the largest portion of the MI, which respectively range from 79 to 227 kg/m^2 and 36 to 239 kg/m^2. From 1970 onwards, an increasing trend in the MI of the first floor was observed, resulting from the increase in the surface area of concrete floors. Additionally, buildings with first floors made entirely, or even partially, of concrete have higher MIs.

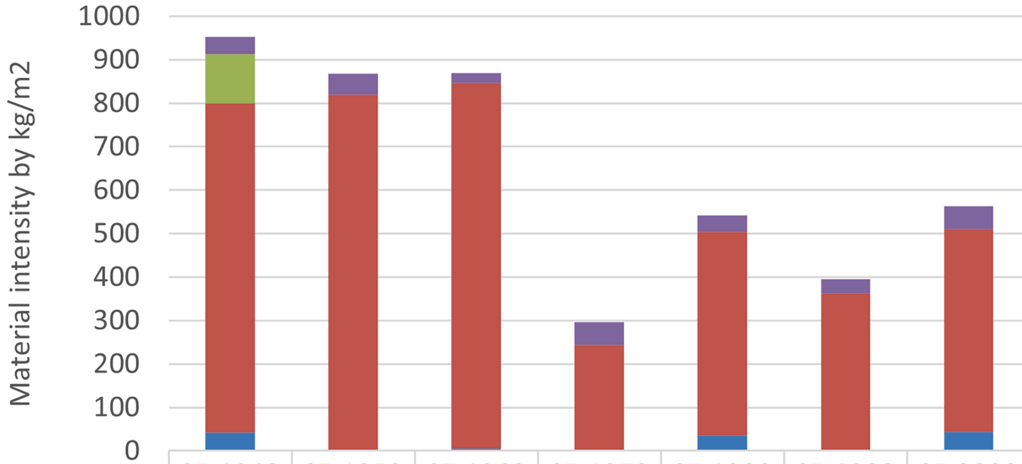
Fig. 6 shows the decadal MI of logs and timber separated by building-element. In Fig. 6, the external and interior walls contain on average 46% of all the wood in a building, except for SF-1940. For SF-1940, the MI of external walls and interior walls is around twice as high as the other buildings, as they are of log construction. In first floors, the wood MI for SF-1940, SF-1950, SF-1960, and SF-1970 is around 8, 9, 4, and 15 kg/m^2, respectively. SF-1970 has the highest MI due to the use of sleepers[3] and blockings[4] in the construction of the floors. Because of the lack of evidence for the inclusion of floor blockings and sleepers, the material consumption of first floors in SF-1960 is lowest. For SF-1960, only joists and floor battens are included.

To provide a thorough comparison of MI both aboveground and underground, the MI of underground elements was merged with the concrete base and compared with that of the above ground elements. Approximately 60% of the MI for SF-2000 is accumulated above ground due to the large amount of concrete used in first floors (thicker floor in comparison to others). The situation is not the same in the other buildings, where the above ground building-elements account for an average of 28% of the MI. The MI of the roof and attic decrease from the 1940s to the 1960s and increase again from the 1960s to the 2000s, due to the change in roof construction techniques (e.g., purlin roof, Swedish truss).

Fig. 7 shows the average MI of Finnish single storey houses built with prefabricated methods after the year 1970. Even though the buildings analysed are wooden, wood products (timber, and occasionally LVL) make up on average only 9% of the MI. The remainder consists of brick and concrete, of which only 6% is brick. As can be seen from Figs. 4 and 5, the building-elements vary in their MIs in the previously mentioned

[3] Horizontal load-bearing timbers are typically installed on a concrete slab and serve as a support for the floorboards.

[4] Short pieces of dimensional lumber in wood-framed construction to stabilize longer members or as a support for fixtures.



	SF-1940	SF-1950	SF-1960	SF-1970	SF-1980	SF-1990	SF-2000
Timber	39	48	23	53	38	33	53
Log	112	0	0	0	0	0	0
Concrete	758	818	840	244	468	361	467
Brick	43	1	6	0	35	1	44

Fig. 4. MI for seven typical Finnish buildings: Aggregated by material category. The codes of the buildings are shown in Table 1.

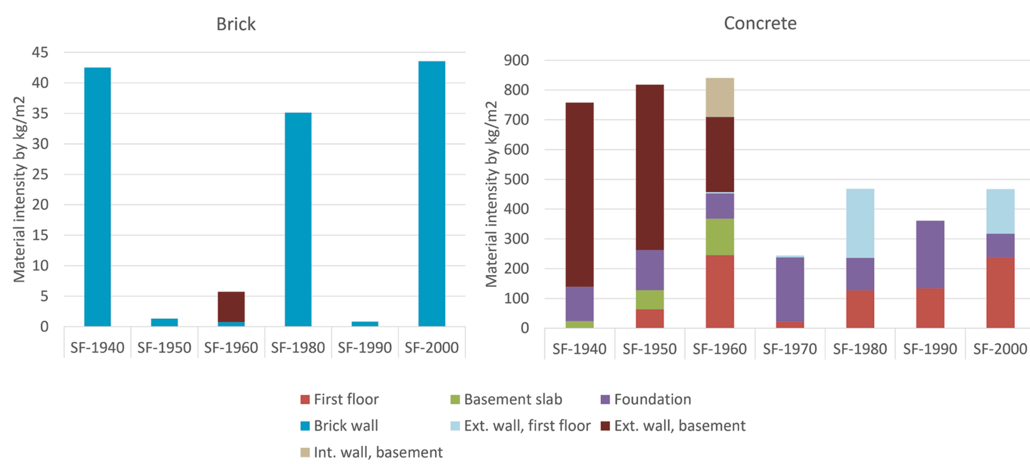


Fig. 5. MI for seven typical Finnish buildings: Aggregated by material category (brick and concrete) and building-element. The codes of the buildings are shown in Table 1. Ext. wall: External wall; Int. wall: Interior wall. Note the different MI scales in figures.

buildings, even though their construction method and number of storeys are the same. Variations are due to differences in the buildings' structural components. The average MIs shown in Fig. 7 may disregard the design decisions (e.g., thickness of floor, the height of concrete base) although it may not have a big impact on material stock and material flow analyses since parameters like number and average GFA of buildings per decade are decisive as well. To increase the accuracy of MI results for individual buildings, it is suggested that the MI of more buildings is assessed with respect to the buildings analysed in the current study. For this as a first step, the random building should first be compared to the most appropriate reference in terms of construction methods, construction technique and design choices in floors, walls, roofs, and foundations. The MI of the reference elements can then be applied to the same elements in a random building to estimate its mass.

3.2. Influence of building parameters on MI

In Table 3, two different types of footprint shapes[5] are shown: two consist of overlapping rectangles with a height of one storey, plus a basement (GFA=101 and 127); and three are adjacent rectangles with a height of 1.5 storeys plus a basement (GFA=117, 128, and 177). The smaller rectangular shape serves as the main entrance in both types and may be connected to a storage space in the first type. The buildings listed in Table 3 were constructed in the 1950s using similar construction methods, but their GFA, footprint shape, roof technique, and number of stories varied.

The influence of the MI to GFA was determined by analysing buildings with similar footprint shape, number of storeys, and construction method. Analysis indicates that the larger the GFA, the lower the MI, which agrees with the findings of the study by Gontia et al. (2018). The

[5] The shape of building's area at ground level, as defined by its external walls.

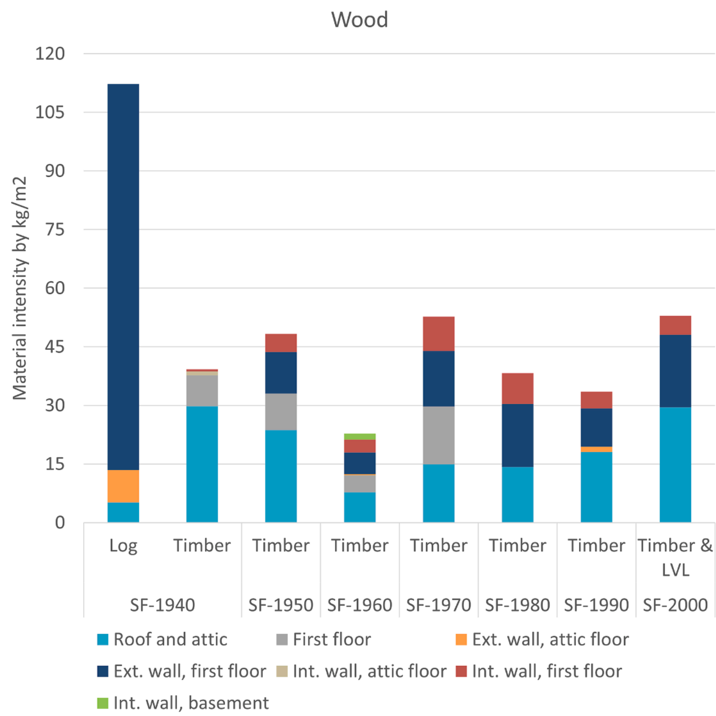


Fig. 6. MI for seven typical Finnish buildings: Aggregated by material category, wood, and building-element. The codes of the buildings are shown in Table 1. Ext. wall: External wall; Int. wall: Interior wall.

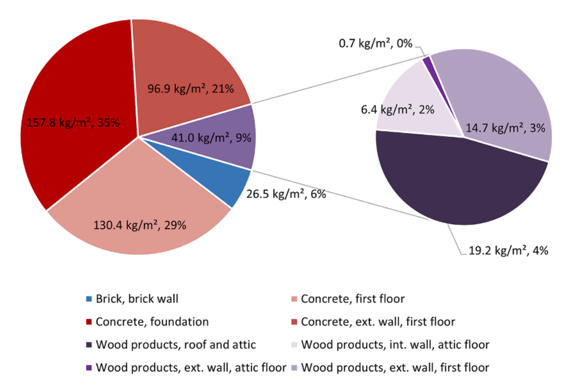


Fig. 7. Average MI. Finnish single-story houses built using prefabricated methods after 1970 (SF-1970, SF-1980, SF-1990, SF-2000). Aggregated by material category and building-element. The codes of the buildings are shown in Table 1. ext. wall: external wall; int. wall: interior wall.

MI of GFA=117 is approximately 10% higher than GFA=128 and 16% higher than GFA=177 (Fig. 8a). MI of GFA=101 is also approximately 9% larger when compared to GFA=127 (Fig. 8b). The overall MI increases in the analysed buildings as a result of an increase in the MIs of concrete and brick, but the MI of wood remains relatively unchanged which is in line with the findings of a study by Aldrick et al. (2021). Our observations also reveal that the change in Ml is smaller in larger buildings compared to smaller buildings, and the change in MI is generally smaller for single storey buildings.

As may be seen from Fig. 8c, and even the comparison between 8a and 8b, the footprint shape also influences MI as was also concluded by Gontia et al. (2018). In Fig. 8c, overlapping rectangular shapes (GFA=127) have a higher MI than adjacent rectangles (GFA=128). However, in the two buildings analysed, the number of storeys did not significantly influence the MI, which contradicts the findings of Gontia et al. (2018). They concluded that single-family houses with 1.5 storeys had up to 50% lower MI values than two-storey houses. Nevertheless, in the current study GFA=128 with 1.5 storeys has around 20% lower MI than GFA=127 with 1 storey height indicating that the number of storeys in buildings with 1–1.5 storeys may not significantly impact MI. Notably the 20% difference arises from both number of storeys and footprint shape, making the impact of number of storeys even less significant. Buildings with more than two storeys might show a different pattern to those with 1–1.5 storeys (Gontia et al., 2018).

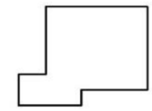
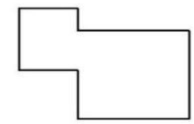
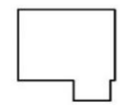
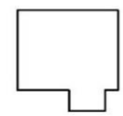
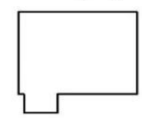
3.3. *Cross-border comparison of MI*

This section compares the MIs of the current study with a Swedish study (Gontia et al., 2018). Due to dearth of information on the MI of houses in Finland, the study conducted by Nasiri et al. (2021) relied on MIs for Sweden to estimate the mass of wood in Finnish residential houses in 2017. The study justified this decision based on perceived similarities in building practices and climatic conditions between the two countries. However, it is important to acknowledge that despite these similarities, there may be differences arising from e.g., historical and economic trajectories that could impact the MI and, consequently, the estimated wood in the Finnish building stock. Therefore, this comparison was necessary to examine the variation in MI between Sweden and Finland and to identify the requirements for cross-country comparison of MI.

Because brick structures were not included in the Swedish study, the MIs of concrete and wood are compared herein (Table 4). The total MIs (MIs of concrete and wood only) in the current study are 1.3–2.6 times higher than those reported in the Swedish study in all construction periods. Of the two materials, concrete has the greatest impact on the overall MI. The MIs of concrete represent on average 90% of the total MIs in the current study, whereas they represent on average 81% of the total MIs in the Swedish study. The average MI of wood in the current Finnish study was found to be almost identical to that of the previous Swedish study, with values of 57 kg/m^2 and 58 kg/m^2, respectively.

As shown in Table 4, MIs, classified according to construction periods in the current study and in the Swedish study by Gontia et al. (2018), show a decrease in total MIs from the 1950s to the 1970s, an

Table 3
Buildings built in 1950s with variation in GFA and footprint shape and number of storeys; f: floor/storey; b: basement; GFA: gross floor area. GFA=127 is the baseline result.

Construction decade	Construction method	Number of storeys	Roof technique	GFA (m^2)	Footprint shape
1950s	Balloon framing	*1f + b*	Swedish truss	101	
				127	
		1.5f + b	Attic truss	117	
				128	
				177	

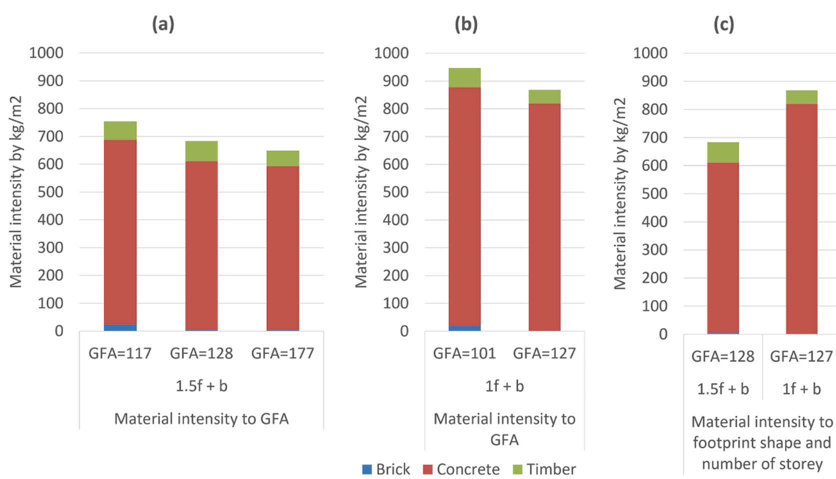


Fig. 8. MI results in relation to changes in a) GFA of buildings with 1.5 storey; b) GFA of buildings with 1 storey; c) footprint shape and number of storeys. In the figure, buildings are shown according to their GFA and number of storeys. GFA=127 indicates the baseline result (SF-1950). The rest indicate the results of the additional buildings analysed for influence of building parameters on MI; f: floor/storey, b: basement; GFA: gross floor area.

Table 4
Comparison of MIs from the current study and the Swedish study by Gontia et al. (2018). The materials included were adjusted to make the MIs comparable.

Source	Location	Building type	Construction decade	Number of storeys	GFA (m^2)	MI (kg/m^2)		
						Concrete	Wood	Total
Gontia et al. (2018)	Sweden	Single-family houses	1940s	*2f + b*	243	250	103	353
			1950s	*1f + b*	248	499	43	542
			1960s	*1f + b*	298	369	53	422
			1970s	1.5f	236	178	58	236
			1980s	2f	144	294	54	348
			1990s	1.5f	289	183	50	233
			2000s	2f	220	176	47	223
Current study	Finland	Single-family houses	1940s	*1.5f + b*	77	758	152	910
			1950s	*1f + b*	127	818	48	866
			1960s	*1f + b*	208	840	23	863
			1970s	1f	92	244	53	297
			1980s	1f	153	468	38	506
			1990s	1f	189	361	33	394
			2000s	1f	156	467	53	520

increase in the 1980s, and a subsequent decrease in the 1990s. The MIs of concrete exhibit a similar trend, but wood does not. From the 1950s onwards, the MIs of wood in both studies are less than 60 kg/m^2, whilst in the 1940s, they were 152 kg/m^2 in Finland and 103 kg/m^2 in Sweden. In general, the current study shows some instances where larger differences in MIs of wood were observed (construction periods: 1940s, 1950s and 2000s).

Therefore, despite the similarities between building practices in the countries, significant disparities in total MIs can exists. The variations primarily stem from the MIs of concrete. Conversely, the differences in MIs for wood were observed to be smaller and may be attributed to the choice of the buildings analysed in the two countries. Thus, although the material stock analysis conducted by Nasiri et al. (2021) is not incorrect, it would yield slightly different results if the MI of Finland were utilized in their calculations.

Discrepancies observed between the current study and the Swedish study in terms of MIs, may be attributed to variation in the characteristics of the buildings analysed in the two studies. The Swedish study had buildings that were up to two storeys in height and had larger GFAs than in the current study, which is known to influence the total MIs as discussed in Section 3.2 and noted by Gontia et al. (2018). To effectively compare MIs across different countries, it becomes crucial to identify representative buildings, their characteristics (e.g., number of storeys, footprint shape, GFA), and the impact of altering characteristics on MI. Additionally, the uncertainties that may arise from altering characteristics, can be reduced by analysing multiple buildings of similar type, construction method, and time cohort, but that differ in the number of storeys, footprint shape, and GFA. Ultimately, this would enable the calculation of average MIs that are representative of the entire building stock.

3.4. Assumption, limitation, and impact on MI

The primary limitation of the current study is that the data are from one type of building (wooden single-family houses) and are based on buildings commonly constructed between 1940 and 2009. A broader range of building types and regional-specific buildings might yield more variability in the MI. Consequently, this paper likely provides a conservative estimate of the overall MI variability in residential buildings.

Furthermore, due to constraints in acquiring the requisite technical documents, certain assumptions were made, and certain building-elements were excluded. These assumptions have a negligible impact on the MI variability since they were based on measurements from original drawings or drawings of similar buildings. Wooden buildings in Finland typically adhere to guidelines and regulations outlined by the national building code of Finland and others, thus reducing the above-mentioned uncertainties.

Another assumption was made about brick walls, assuming they were constructed from red clay brick. This assumption does not significantly affect the MI because red clay brick was commonly used for constructing chimneys and their surrounding walls in the houses analysed. Furthermore, the small MI of brick in the analysed buildings is not primarily due to the limited number of buildings analysed but rather reflects the specific building type and construction methods under consideration. From Fig. 8, the analysis of the MI of five wooden residential houses built in the 1950s revealed a similarly low brick MI.

It should be noted that the analysis does not include MI calculations for non-structural parts such as cladding and interiors. Consequently, the actual MI is expected to be higher than the MI estimated in the current study. In this case, the decision to exclude non-structural parts from the study was driven by both the limited data availability and the higher likelihood that structural components will be cascaded. This choice was made to maintain the integrity and reliability of the findings by focusing on the available data and minimizing potential inaccuracies or speculative conclusions.

4. Conclusions

This study describes an analysis of the MIs of wooden residential houses in Finland built after 1940 using seven representative typologies. To ensure that MIs provide an accurate estimate of materials in the building stock and its flow, the study discusses variables and limitations of MI, and conducts a cross country comparison of MI.

This study found that concrete accounted for a substantial mass in the buildings despite wood being ostensibly the main building material. This highlights the limitations of relying solely on MI as a comprehensive measure for evaluating the resource efficiency, circular economy, and sustainability of buildings. MI overlooks crucial factors such as the materials' durability, strength, embodied energy, carbon emissions, and the building's design and construction techniques. Therefore, it is recommended that MI be supplemented by the above indicators to obtain a more comprehensive evaluation.

Furthermore, the MI was found to be influenced by construction methods, design choices (e.g., thickening floors), GFA, and footprint shape. Therefore, studies that rely on extrapolating the MI of a single building or average MI of a few buildings to represent the entire building typology may not accurately estimate the materials in those typologies. This issue becomes especially important when MI is used as an indicator to material stock and flow analysis or a life cycle assessment of the built environment. More MI studies are required to develop accurate models for estimating material stock and flow of material, and waste generation, which are critical for assessing the environmental impacts of the built environment and developing effective resource management strategies.

Both similarities and differences were found between the current study and the Swedish study by Gontia et al. (2018), highlighting challenges for making a fair comparison between MIs of the two countries. Cross-country comparisons of MI studies can offer valuable insights into resource use and efficiency across different regions, informing policies and practices that promote sustainable resource use and help mitigate environmental impacts. Future studies should define clear system boundaries, account for the variability in MI within each building typology, and carefully consider the comparability of data and methods used to address these challenges.

CRediT authorship contribution statement

Bahareh Nasiri: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Tapio Kaasalainen:** Investigation, Resources, Data curation, Writing – review & editing. **Mark Hughes:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

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

Bahareh Nasiri reports financial support was provided by the Finnish Ministry of the Environement and others, and the Kone Foundation for Technology Promotion.

Data availability

Data will be made available on request.

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Appendix

The prevalence of wooden construction method used in residential houses

In general, wooden residential houses in Finland were categorized into three time cohorts as can be seen below:

–1939 Log construction was the most common construction method in Finland from the seventeenth century until the mid-twentieth century (Norri, 1996). Before the mid-eighteenth century, most log houses were single-storey; from then on, they increasingly became two-storey (Karjalainen and KoisoKanttila, 2005). From the eighteenth century, the floors of log houses began to employ wooden framing, as durability and thermal properties became more important (Heikkilä, 2005a, 2015b). An updated form of log construction emerged in the nineteenth century, with a high stone base, a double floor insulated with moss or sawdust, and smooth-hewn log walls (Norri, 1996).

1940–1959 Balloon framing largely replaced log construction for houses by the end of the 1930s (Siikanen, 2007), as it was less wood intensive than log houses, used sawdust for insulation and used cut-to-size timber (Norri, 1996). In the 1940s and 1950s, affordable housing was made possible through standardized housing (Schauerte, 2010). Most of the standardized houses used balloon framing with gable roof framing and a stone-structured cellar. They were 1.5 stories in height, used external board cladding for the façade, and were built with prefabricated elements (Heikkilä, 2005a).

1960– The advances made in Finnish industrial house manufacturing during and after the second world war resulted in the production of prefabricated wall units (Ruotsalainen, 2011). In the following decades, prefabricated methods developed from prefabricated planar units to prefabricated volumes. The prefabricated method uses platform framing, which is like balloon framing, except that the vertical studs are not extended from foundation to the roof. In the 1960s and 1970s, there were radical design changes (e.g. omitting cellars, gentle roof slope), leading to moisture damage and indoor air quality problems (Heikkilä, 2005b). In the 1980s, inclined ridge roofs became more popular and almost all flat roofs were converted to ridge roofs in later renovations (Heikkilä, 2005b).

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