Waste Management 135 (2021) 318–326

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Estimating the material stock in wooden residential houses in Finland

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ARTICLE INFO

Keywords:
Reuse and recycling
Cascading
Recovered wood
Material stock
Residential houses
Wood intensity

ABSTRACT

The aims of this study were to quantify the amount of wood in residential houses in Finland in 2017 that could be available for cascading, and to characterize the age distribution and gross floor area of the houses in the stock. Through a bottom-up material stock analysis, the mass of wood and the gross floor area of buildings in each building type and construction period were estimated. The study found that 10 million tons of wood are contained in the structures of residential houses built before 1969, equivalent to around 59% of the stock. Since much of this stock is nearing end of life, this material should soon become available for cascading so providing a significant potential resource. It was also found that, overall, the structural parts of residential houses embody 17.5 million tons of wood, of which around 9 million tons is, theoretically, reusable and recyclable. However, for effective reuse and recycling, further analysis of the quality, type and future availability of recovered wood is required. The current results could be used for material stock and flow analyses to help planning for the use of recovered wood. Further research is needed to fill in gaps in the time-series of the number and gross floor area of buildings constructed and their average gross floor area. Moreover, a material intensity analysis of Finnish buildings is needed to better quantify the wood used.

1. Introduction

Reuse and recycling is being actively promoted (European Commission, 2016; Husgafvel et al., 2018) since it could contribute substantially to increasing resource efficiency and climate change mitigation through cascading, that is, the sequential use of materials, to extract as much utility and value as possible from them (European Commission, 2014; Thonemann and Schumann, 2018). Improving resource efficiency in the construction industry presents a particular challenge since it accounts for about half of all materials consumed by humanity (European Commission, 2011; Ruuska and Häkkinen, 2014). In part, the need to improve resource efficiency in the sector arises from increasing waste generation from construction and demolition (C&D) practices (Bringezu et al., 2017; Müller, 2006; Villoria Sáez and Osmani, 2019). In Europe, C&D activities account for 820 million tons (Gálvez-Martos et al., 2018) of waste annually, equivalent to 46% of the total (Eurostat, 2018) and, whilst the composition of C&D waste varies between European countries, wood can represent a significant fraction. For this reason, there is increasing interest in the cascade use of wood, with studies suggesting that cascading might not only improve materials recovery, extend material life cycles and enhance overall resource efficiency (Höglmeier et al., 2013; Husgafvel et al., 2018), but may also reduce the environmental burden of construction (Niu et al., 2021). Depending on its quality, recovered wood could substitute virgin wood in the same application or in different applications, before eventual combustion for energy (Höglmeier et al., 2017; Sakaguchi et al., 2017, 2016).

The fraction of wood in C&D waste is particularly high in the Nordic countries where, in Finland, for instance, it accounted for 36%, by mass, in 2007 (Meinander et al., 2012). Currently, around 90% of wood recovered from C&D activities in Finland is chipped for energy (Meinander et al., 2012; OSF, 2019a, 2019b), with a consequent low degree of reuse and recycling in products (Sokka et al., 2015). In the absence of fungal decay or insect attack, however, the natural ageing of wood does not necessarily result in any significant loss in properties (Kránitz et al., 2016). Thus, the quality of wood that has not been damaged or contaminated in use, or during demolition, often makes reuse and recycling, rather than burning for energy, a viable alternative

Abbreviations: AADH, Attached and detached houses; C&D, Construction and demolition; GFA, Gross floor area; GCC, Gross cubic content; MS, Material stock; OSF, Official Statistics of Finland.

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https://doi.org/10.1016/j.wasman.2021.09.007
Received 27 May 2021; Received in revised form 12 August 2021; Accepted 8 September 2021
Available online 24 September 2021
0956-053X/

(Höglmeier et al., 2017; Sakaguchi et al., 2017).

Wood is, and has been, widely used in Finland as a construction material (Huuhka et al., 2018; Huuhka and Lahdensivu, 2016), suggesting that a considerable amount could become available for reuse and recycling. Despite this potential, several factors must be taken into consideration. For instance, how wood is used in buildings, as well as the demolition process, can lead to unwanted contamination, damage and reduced dimensions that will affect reuse and recycling options (Falk et al., 1999; Sakaguchi et al., 2017, 2016). Further, there is a lack of data about the anticipated amount and type of wood that will become available (Höglmeier et al., 2017; Icibaci, 2019). For these reasons, detailed knowledge about the quantity, type of wood product, future availability and the quality of recovered wood, as well as the age distribution of buildings in the building stock, is urgently needed (Höglmeier et al., 2017; Icibaci, 2019; Sakaguchi et al., 2017). As a first step, determining the quantity of wood within the building stock is necessary. Further, in order to make predictions about the future availability of wood, the age distribution of buildings in the building stock is required. This can then be combined with other parameters, such as the types of wood products used and their quality, to forecast the future availability of recoverable wood (Augiseau and Barles, 2017; Höglmeier et al., 2017; Kalcher et al., 2017).

Material stock (MS) analyses are the methodological approaches most frequently used to estimate the quantity of recovered wood and the age distribution of buildings in the building stock (Daxbeck et al., 2009; Deilmann, 2009; Fraanje, 1997; Höglmeier et al., 2017; Kalcher et al., 2017; Schiller, 2007). MS analyses lay the foundation for understanding stock dynamics (the future availability of recovered wood) and the potential to alter end-of-life practices by either reuse or recycling (Han and Xiang, 2013; Kleemann et al., 2017; Müller, 2006; Ortlepp et al., 2018, 2016; Tanikawa and Hashimoto, 2009; Wiedenhofer et al., 2015). To understand stock dynamics, MS analyses use the lifetime of buildings, or the products contained within them, as variables to estimate either the future quantity (Stephan and Athanassiadis, 2018) or the quantity and quality (Höglmeier et al., 2015) of recoverable material (so-called MS and flow analyses). Subsequently, these studies can also be used as a basis for proposing mechanisms to decrease waste generation (Kalcher et al., 2017) and associated environmental impacts.

Augiseau and Barles (2017), citing Birat et al. (2014) noted that there are two methodological approaches – top-down and bottom-up – to MS analysis, with the methodological details varying significantly, depending on data availability and the assumptions made. The top-down approach calculates yearly stock through the difference between inflows and outflows. The bottom-up approach uses the material intensity (Gontia et al., 2018) and the division of the stock into categories (e.g. building type, construction period) to obtain an estimate of the total material used (Augiseau and Barles, 2017). Several factors, such as age, the intended use of buildings, the number of floors and the year of construction all influence the MS analysis in each category (Augiseau and Barles, 2017; Sandberg et al., 2014). Significantly, the bottom-up approach enables both the quantity and quality of materials to be determined at different levels of detail, depending on the available data and its quality (Augiseau and Barles, 2017; Lichtensteiger and Baccini, 2008).

MS analyses in the context of wood material use in buildings have not been conducted in Finland, though Pingoud et al. (2003) undertook a carbon stock analysis of Finnish buildings in 2000, based on waste statistics about housing production and "decennial increase of wood materials in buildings". The analysis did not, however, provide the actual amount of wood materials in the buildings, nor the age distribution of the building stock.

The study reported herein focused on a MS analysis of building types that have typically been constructed in wood, since they potentially contain a large quantity of material that could be reused or recycled. In Finland, the majority of the building stock, particularly residential buildings, has been constructed since the 1970s (OSF, 2017a) from which time, yearly, more than 80% of attached and detached houses (AADH) have been built in wood (OSF, 2017b). Furthermore, AADH that represent 41.5% of the buildings stock and 67% of the residential building stock by gross floor area (GFA) (OSF, 2017a), have always been predominantly constructed from wood (Huuhka and Lahdensivu, 2016). Thus, the aims of the research reported in this article were to quantify the amount of wood in structural parts of residential houses in Finland that could become available for cascading, and to investigate its age distribution and GFA in the building stock.

2. Material and methods

The bottom-up MS analysis approach of Müller (2006), shown schematically in Fig. 1, was used to calculate the quantity of wood in structural parts and the GFA of buildings in AADH in the year 2017. The analysis was undertaken for each building type and construction period to show the age distribution of the stock of both attached and detached houses. The year 2017 was chosen as it was the most recent year for which detailed statistical data were available. The mass of the MS (S^W) is dependent on two variables – GFA (S^{WC}) and wood intensity (K^W), the latter being expressed as the mass of wood per square meter of GFA in a representative building (kg/m^2). The output, which is the future availability of recovered wood, was not included in the study.

2.1. System boundary

The MS analysis focused on AADH, excluding holiday dwellings (free-time residential houses) since they are not included in the building stock statistics published by the Official Statistics of Finland (OSF). In addition, due to the lack of data about all components within buildings, the MS analysis only considered wood elements used in the construction of roofs, external walls, dividing walls, windows, floors and basement ceilings (Gontia et al., 2018). Therefore, wood that was used for i) renovation, refurbishment and modernization measures, ii) finishes and surface materials (doors, stairs, floorings, etc.) and iii) formwork, packaging, and waste from wood processing on the construction site, was not included.

Nevertheless, if statistical data on these categories were available, the MS analysis would enable the assortments listed above to be included. In the current study, all data presented refers to the stock of houses in Finland in 2017, but the general approach to the MS analysis could be adapted to data available in other regions, years, and types of building.

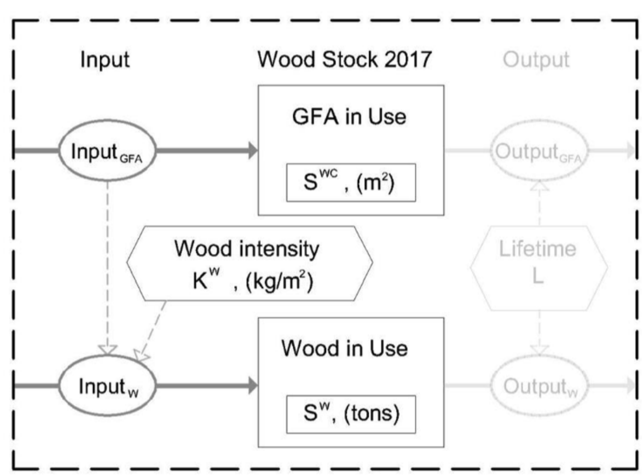

Fig. 1. MS model by Muller (2006) adopted to the Finnish building stock. On the left side: the input of timber and building stock; in the middle: the standing timber and building stock, on the right side: the output of timber which is not included in the current study.

2.2. Number of buildings

OSF (OSF, 2018) divides the number (N) of existing building types (a) into nine time periods (b) in the range P_1 to P_9, by year of construction or renovation, as follows: before 1920 (P_1), 1921–1939 (P_2), 1940–1959 (P_3), 1960–2009 (P_{4-8}) split into five decadal periods, and 2010–2017 (P_9). According to OSF, the year of renovation might have been recorded as the year of construction for buildings built prior to 1980, as their year of construction is missing. It is not clear from the statistics how many buildings fall into this category, however, is not likely to be very significant, since numerically the majority of Finnish residential buildings were constructed after 1970 (OSF, 2017a). It was thus assumed that all the recorded data related to the year of construction. These data were retrieved from OSF (2018), section 1.1 "Buildings by intended use and by year of completion or renovation, 2017".

2.3. GFA of wooden buildings

The total GFAs of attached and detached houses (both wooden and non-wooden) in 2017 (S^{All}) were around 35 million and 165 million square meters respectively (OSF, 2018). These data were retrieved from OSF (2018), section 1.2 "Buildings by intended use, GFA and type of heating on 31 December 2017".

To calculate the GFA of wooden buildings (S^{WC} in m^2) for each building type (a) and construction period (b), Eq. (1) was used:

$$S^{WC}(a,b) = N(a,b) \times AA_{GFA}(a,b) \times Sh^{WC}(a,b) \tag{1}$$

Where N is the number of wooden and non-wooden buildings in 2017 (OSF, 2018), AA_{GFA} is the average GFA of buildings in 2017 [m^2] and Sh^{WC} is the ratio of completed wooden buildings to all buildings [%].

To calculate the average GFA of AADH (AA_{GFA}), the building stock was divided into houses constructed prior to 1969 and after 1970. This division was necessary because statistical data on average net floor area of AADH were only available for AADH built after 1970 (P_{5-9}). Thus, average GFA was calculated differently for AADH built before 1969 and from 1970 onwards. For houses built after 1970, OSF provides the average net floor area per dwelling (OSF, 2017c), measured from the inner surfaces of its walls, including the floor areas of living spaces (OSF, 2009a). To calculate the average net floor area for attached houses, the average net floor area per dwelling was multiplied by 5. This is because the number of dwelling units, totaling 464,000 (OSF, 2017c), divided by the number of buildings, totaling 81,293 (OSF, 2018), means that on average each attached house comprises five dwellings. To calculate the average GFA (AA_{GFA} in m^2) from the net floor area for every building type (a) and construction period (b), Eq. (2) was used:

$$AA_{GFA}(a,b) = AA_{Net}(a,b) \times (1 + R(a,b)) \tag{2}$$

Where AA_{Net} is the average net floor area [m^2], R is the ratio of the floor area occupied by walls in relation to the net floor area [%].

R was calculated by determining the ratio between the area of the walls and the net floor area. The wall area was calculated by multiplying the length (m) of all external and dividing walls by their thicknesses. It was assumed that the thicknesses of the walls remained constant over time, and that external walls were 0.32 m thick and dividing walls were 0.18 m thick (Finnish Wood Research Oy, 2013). As shown in Table 1, R was calculated from data obtained from Gontia et al. (2018), for 18 representative detached and attached houses built in wood. Then, R applied to the average net floor area of houses built between 1970 and 2017.

For houses built prior to 1969, it was assumed that the average GFA of all AADH had been constant during the periods considered. This is because there was limited information about the average net floor area or average GFA of buildings built before 1920 (P_1) and built in the periods 1921–1939 (P_2), 1940–1959 (P_3), 1960–1969 (P_4) in the statistics. The statistics showed that the average size of attached and detached houses built every year were constant between 1952 and 1966, at around 350 square meters (OSF, 1968, 1961). A similar assumption is true for houses built before 1951 as their size distribution was similar for all periods, as shown in Appendix A (Oikotie.fi).

Eq. (3) was used to calculate the constant value of the average GFA of AADH constructed before 1969 (AA_{GFA} in m^2).

$$AA_{GFA}(a,b) = \left(S^{All} - \sum_{b=P_5}^{P_9} S(a,b) \right) \div \sum_{b=P_1}^{P_4} N(a,b) \tag{3}$$

Where S^{All} is the total GFA of all AADH in 2017 [m^2] obtained from OSF (2018), $\sum_{b=P_5}^{P_9} S(a,b)$ is the total GFA of each building type (a) constructed in the construction periods after 1970 [m^2] and $\sum_{b=P_1}^{P_4} N(a,b)$ is the total number of each building type (a), constructed in the construction periods before 1969 obtained from OSF (2018).

As can be seen from Eq. (1), the ratio of completed wooden buildings to all buildings (Sh^{WC}) is used. It was assumed that the ratio between the GFA of new wooden buildings and non-wooden buildings constructed in a certain year is still valid for the buildings remaining in 2017. It was necessary to make this assumption since no breakdown between the GFA of wooden and non-wooden buildings is available in the statistics and

Table 1
Building information of 18 AADH, used for understanding the relation between net floor area and GFA. f: floor. Retrieved from Gontia et al. (2018).

Building types	Construction period	Number of floors	GFA (m^2)	Building footprint size (m * m)	Footprint size (m * m)		R (%)
					external walls	dividing walls	
Detached	1890–1900	1.5f + basement	144	6 * 8	0.32 * 42	0.18 * 28	15.2
	1900–1910	1.5f + basement	198	7.5 * 8.8	0.32 * 48.9	0.18 * 20	11
	1910–1920	2f + basement	172	6.5 * 8.8	0.32 * 61.2	0.18 * 15	15.1
	1920–1930	1.5f + basement	252	8 * 10.5	0.32 * 55.5	0.18 * 40	11.4
	1930–1940	2f + basement	300	10 * 10	0.32 * 80	0.18 * 41	12.7
	1940–1950	2f + basement	243	7.5 * 10.8	0.32 * 73.2	0.18 * 34	14.2
	1950–1960	1f + basement	248	7.5 * 16.5	0.32 * 48	0.18 * 27	9.1
	1960–1970	1f + basement	298	9.8 * 15.2	0.32 * 50	0.18 * 40	8.8
	1970–1980	1.5f	236	8 * 14.8	0.32 * 68.4	0.18 * 37	14.2
	1980–1990	2f	144	8 * 9	0.32 * 68	0.18 * 26	23
	1990–2000	1.5f	289	8.5 * 18	0.32 * 79.5	0.18 * 39	12.6
	2000–2010	2f	220	10 * 11	0.32 * 84	0.18 * 42	11
Attached	1880–1900	2f	354	17 * 10.4	0.32 * 109.6	0.18 * 28	13
	1880–1900	2f	390	9.5 * 20.5	0.32 * 120	0.18 * 46	13.6
	1890–1910	2f	450	10 * 22.5	0.32 * 130	0.18 * 91	15
	1920–1930	2f + basement	528	11 *16	0.32 * 108	0.18 * 50	7.3
	1930–1950	2f + basement	300	8.5 * 11.8	0.32 * 81.2	0.18 * 33	15.2
	1990–2000	5f	1240	8 * 31	0.32 * 390	0.18 * 70	11

the demolition rate and lifetime of wooden and non-wooden building types, built in different construction periods, is unknown and difficult to estimate. It is, therefore, not possible to directly calculate the share of existing wooden buildings in 2017 from the statistics.

The ratio of completed wooden buildings to total buildings (Sh^{WC}) was acquired from the 'building production' statistics, published by the OSF (OSF, 2019b). These statistics have been published since 1995. For years prior to 1995, such data is not available in the statistics. The statistics divide the GFA of new buildings into years of construction and by building material. According to the OSF definition, the building material refers to the material from which the vertical supporting structures of the buildings are mainly made (OSF, 2009b). OSF divides the building material into six groups: concrete, steel, wood, brick, other, and unknown. Thus, buildings with wood as the building material are considered to be wooden buildings.

Eq. (4) was used to calculate the ratio of completed wooden buildings to total buildings (Sh^{WC} in percentage) for each building type (a) and construction period (b):

$$Sh^{WC}(a,b) = \left(\overline{A_{WC}(a,b') \div A_{All}(a,b')}\right) \times 100 \tag{4}$$

Where A_{WC} is the GFA of new wooden buildings built every year [m^2], b' is the construction year which is in the range of b and A_{All} is the GFA of new buildings built every year [m^2].

In the 'building production' statistics, the share of completed wooden buildings by building type (a) was not available for houses constructed before 1995 (P_{1-6}). Thus, it was assumed that these values were the same as in P_7. This is a reasonable assumption as the use of wood was very common in buildings before 1995 in Finland and it was almost the only construction material used until the early 1900s (Karjalainen and Koiso-Kanttila, 2005). Moreover, wood has always dominated the construction of the structural parts of attached houses and detached houses in Finland (Huuhka and Lahdensivu, 2016; Jeskanen, 2000).

2.4. Wood intensity of wooden buildings

To date, no analysis of the material intensity of the building stock in Finland has been conducted, so the Swedish material intensity database published by Gontia et al. (2018) was used. Gontia et al. (2018) calculated the intensity of all materials used in representative buildings for each decade or several decades. To calculate the wood intensity only, the volume of wood in wooden buildings (V_l^W in m^3) was determined from the database. Then, Eq. (5) was used to calculate the wood intensity (K^W in kg/m^2) of each building:

$$K^W = \left(\sum V_l^W \times D_l^W\right) \div GFA \tag{5}$$

Where $\sum V_l^W$ is the sum of the volume of wood in wooden buildings, l is the type of the wood (e.g., beam) within a representative building, GFA is the GFA of a representative building [m^2]. As in Gontia et al. (2018), the densities of materials (D_l^W in kg/m^3) were from a German online database (MASEA, 2016).

Swedish wood intensity values were used to calculate the MS in Finland since both countries have had similar wooden construction methods as well as a common history and culture (Cristescu et al., 2020). To validate this assumption, however, the standardized design drawings of several Finnish detached houses built between 1918 and 1964 were obtained from Metsätalousministeriö (n.d.). Data about the volume and type of wood was extracted from bills of quantity and design drawings. Then, the wood intensity of Finnish detached houses was calculated as explained above and detailed by Gontia et al. (2018).

2.5. Mass of wood in wooden buildings

After the GFA of wooden buildings (S^{WC} in m^2) and wood intensity (K^W in kg/m^2) were determined, Eq. (6) was used to calculate the mass of the MS (S^W in *tons*) in each building type (a) and construction period (b):

$$S^W(a, b) = S^{WC}(a, b) \times K^W(a, b) \times 0.001 \tag{6}$$

3. Result and discussion

3.1. The average GFA of buildings

In Table 2, the average GFA of houses built after 1970, their wall ratio and the conversion factor between net floor area and GFA are shown (bottom table). Table 2 also shows the wall ratio for houses constructed before 1969, used to estimate the correlation between the wall ratio of attached and detached houses (top table). The wall ratio of attached houses in P_1 (–1920) and P_2 (1921–1939) are 15.2% and 15.3% respectively, whereas for detached houses they are 13.8% and 12.5% for the corresponding periods. The ratios of attached houses are about 2% higher than detached houses, which can be explained by the greater number of rooms, and so the greater floor area occupied by the dividing walls, and that each dwelling in an attached house shares at least one wall with an adjacent dwelling. Thus, where the average GFA of representative buildings was not available for attached houses, the ratio for detached houses was increased by 2% (cells marked with an asterisk in Table 2).

In Table 2, the floor area occupied by walls in relation to net floor area is in the range 8%-25%, and this value clearly influences the magnitude of the GFA of houses built in different periods. Taking detached houses constructed in P_5 (1970–1979) as an example, the number of houses (OSF, 2018), their average net floor area (Table 2) and average GFA (Table 2) are respectively 152471, 66 m^2 and 75 m^2. From this it can be concluded that the total area of the walls in P_5 is around 1.43 million square meters, or, 12.4% of the total area of detached houses. So, the number and representativeness of attached and detached houses used to calculate the ratio of the floor area occupied by walls in relation to net floor area (R) can affect accuracy when converting net floor area to GFA. Metsätalousministeriö (n.d.) shows a collection of typical houses in different periods that are consistent with the attached and detached houses used in the present study to calculate the ratio of the floor area occupied by walls in relation to net floor area.

Prior to 1969, the average GFA of detached and attached houses constructed in different periods was assumed to be similar for all periods, equaling 198 m^2 and 508 m^2, respectively. For more reasonable estimations of the average GFA of these houses, studying building typologies and their evolution over time (similar to the study by Kaasalainen and Huuhka (2016)) or statistical data about the average GFA of houses in the time periods considered, is required.

3.2. Total GFA of buildings

Fig. 2 shows the age distribution and the primary construction material of AADH in Finland in 2017. The age distribution is required as it shows where materials are integrated into the building stock. Such information could then be combined with the lifetime of buildings to forecast the future availability of recovered wood. Fig. 2 also provides an easy comparison of the order of magnitude of construction materials employed. For instance, in P_3 (1940–59), a large GFA of wooden detached houses was added to the stock due to the ready availability of wood for construction as well as the publication of standardized design drawing for detached houses (Siikanen, 2007). In addition, Fig. 2 shows that the use of non-wooden construction materials increased from P_3 (1940–59) to P_6 (1980–89) due to the emergence of precast concrete elements and the standardization of prefabricated concrete buildings (Huuhka and Lahdensivu, 2016). Significantly, wooden houses

Table 2
Top table: Converting net floor area to GFA for representative houses, constructed before 1969 (used to estimate the correlation between wall ratio of attached and detached houses); Bottom table: Assumed average GFA, *R* for AADH, constructed after 1970. Cells with asterisk are increased by 2%.

Year of construction	Period	Building type	Average net floor area per dwelling (m^2)	Number of dwellings	***R*** (%)	Average GFA (m^2)
–1920	P_1	Detached	–	–	13.8	–
		Attached	–	–	15.2	–
1921–1939	P_2	Detached	–	–	12.5	–
		Attached	–	–	15.3	–
1940–1959	P_3	Detached	–	–	11.7	–
		Attached	–	–	–	–
1960–1969	P_4	Detached	–	–	8.8	–
		Attached	–	–	–	–

Year of construction	Period	Building type	Average net floor area per dwelling (m^2)	Number of dwellings	***R*** (%)	Average GFA (m^2)
1970–1979	P_5	Detached	66	1	14.2	75
		Attached	73	5	16.2*	424
1980–1989	P_6	Detached	91	1	23.0	112
		Attached	71	5	25.0*	445
1990–1999	P_7	Detached	85	1	12.6	96
		Attached	70	5	14.6*	402
2000–2009	P_8	Detached	105	1	11.0	117
		Attached	71	5	13.0*	398
2010–2017	P_9	Detached	110	1	11.0	122
		Attached	71	5	13.0*	403

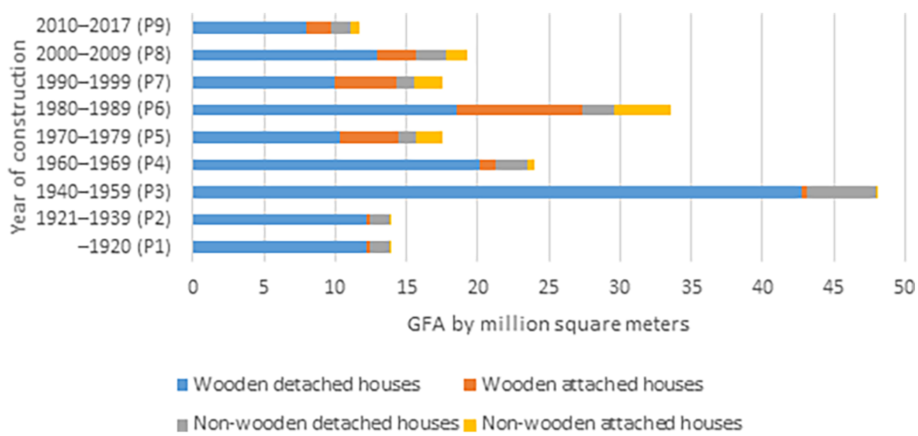

Fig. 2. The age distribution of AADH in Finland in 2017 by GFA and construction material.

represent 86% (74% detached houses, 12% attached houses) of AADH extant in 2017, confirming that wood dominated the construction of AADH in Finland for many years (Huuhka and Lahdensivu, 2016).

It is notable that the uncertainties associated with the distribution of houses by GFA in each period is higher prior to 1969 because average GFA is assumed to be similar for all periods. Periods after 1970 contain the most reliable data, with information about detached houses having greater accuracy in general. The greater accuracy of data about detached houses is because the number of dwellings has less variation in comparison to attached houses.

3.3. Wood intensity in the wooden buildings

The wood intensity of AADH in Sweden is summarized in Table 3 (Gontia et al. 2018). As shown, the wood intensity of detached houses decreases from P_1 to P_8 because wooden construction methods became more resource efficient (from log constructions to light frame structures and prefabricated techniques) over time (Gontia et al., 2018; Thelandersson et al., 2004).

As noted by Gontia et al. (2018), attached houses do not follow the same trend as their wood intensity has less variation (some attached houses were representative of several decades). Hence, the wood

Table 3
Assumed wood intensity values for wood AADH in Finland in kg/m^2 according to Gontia et al. (2018).

Wood intensity (kg/m^2)	–1920	1921–1939	1940–1959	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009	2010–2017
Period	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
Detached	193	117	103	53	58	54	50	47	47
Attached	280	187	187	187	187	187	187	187	187

intensity of attached houses in P_{2-3} was applied to P_{4-8}. Regarding buildings constructed in P_9, the wood intensity of the houses is absent, so it was assumed that the wood intensity in the buildings in P_9 is similar to P_8. This is a reasonable assumption since wooden construction methods have remained largely unchanged since 2000.

In Table 4, the calculated wood intensity of several Finnish detached houses is compared with the values derived from Gontia et al. (2018) for Swedish detached houses. The comparison reveals that the wood intensity of Finnish and Swedish detached houses is rather close. However, this might not be true for other building types and buildings built with other materials such as concrete or brick. Table 4 shows that the variation in wood intensity in the 1940s is probably due to the difference in the footprint of the houses. According to a sensitivity analysis performed by Gontia et al. (2018), for detached houses, a greater building footprint corresponds to around a 30% lower wood intensity. A similar relationship is true for Finland. For instance, amongst the Finnish houses built in the 1940s, the houses with large and small footprints have wood intensities of 114 kg/m^2 and 150 kg/m^2 respectively. This means that the wood intensity in a larger house is around 30% greater than a smaller one.

3.4. Mass of wood in the buildings

Fig. 3 shows the stock of wood in structural parts of houses in Finland in 2017 for each construction period by GFA and mass of wood. The overall mass of the MS in Finnish houses in 2017 is calculated to be 17.5 million tons, with detached houses accounting for 74% of this. According to Höglmeier et al. (2017), who conducted their study in Germany, 53% of recovered wood is suitable for reuse (26%) and other high value products (27%) and there is potential to increase this by re-evaluating regulations that currently limit cascading. If a similar potential was assumed for Finland, more than 9 million tons of wood could be suitable for cascading in future decades. Sakaguchi et al. (2017), who investigated the potential cascading of recovered wood through a case-study in Finland, also concluded that around 50% of wood is suitable for reuse or recycling.

Comparing houses built before 1969 and after 1970 shows that pre-1969 houses contain a greater mass of wood (around 10 million tons), than those constructed after 1970 (around 7 million tons). A study of buildings demolished in Finland between 2000 and 2010, showed that houses built before 1969 dominated the demolition of detached and

Table 4
Comparison of wood intensity of Finnish and Swedish detached houses. f: floor.

Building types	Year of construction	Location	Number of floors	Building footprint size (m * m)	Floor area (m^2)	Wood intensity (kg/m^2)
Detached	1930s	Sweden	2f + basement	10 * 10	100	117
		Finland	1.5f	7.8 * 5.8	45.24	121
		Finland	1.5f	7.8 * 5.8	45.24	120
	1940s	Sweden	2f + basement	7.5 * 10.8	81	103
		Finland	1.5 + basement	4.95 * 6.2	30.69	150
		Finland	1.5f + basement	8.7 * 6.2	53.94	114
	1950s	Sweden	1f + basement	7.5 * 16.5	123.75	43
		Finland	2f + basement	10 * 7.7	77	47
		Finland	2f + basement	8.7 * 7	60.9	58

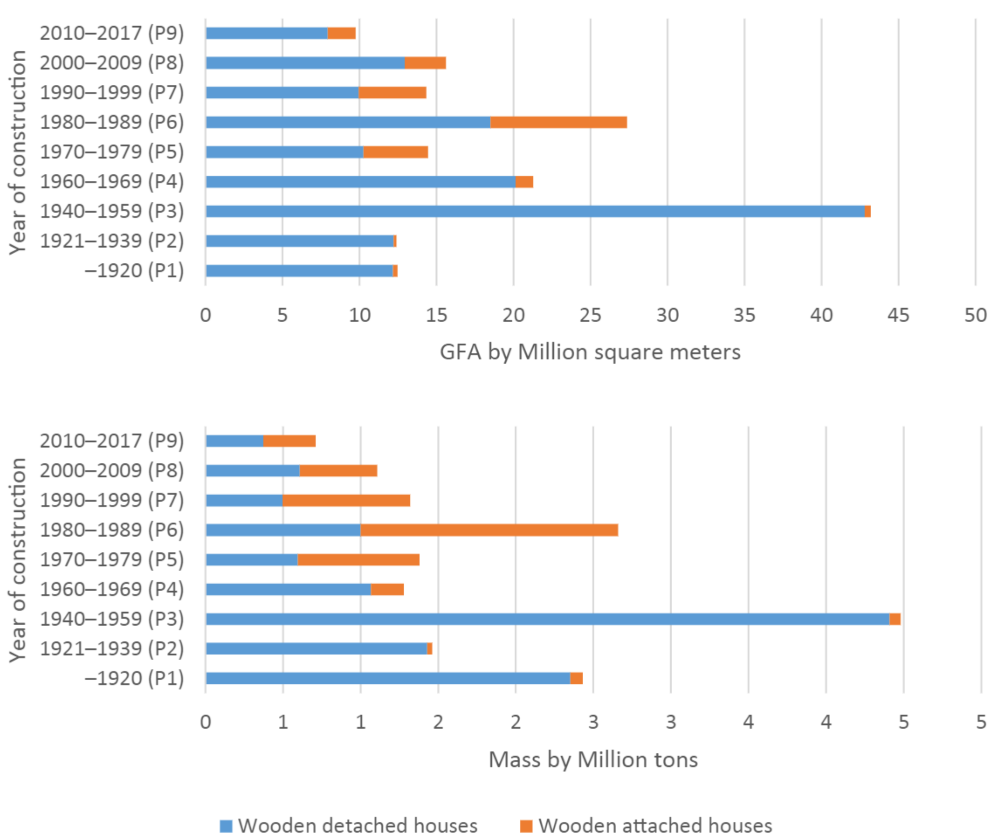

Fig. 3. Top: GFA of wood AADH in Finland in 2017; Bottom: Mass of embodied wood in AADH built in wood in 2017.

attached houses with around 87% and 50% of demolished floor area, respectively (Huuhka and Lahdensivu, 2016), so if demolition patterns remain stable, pre-1969 houses could provide a significant amount of wood for cascading.

Fig. 3 also shows that there is a significant amount of wood in detached houses constructed in the period 1940–1959, accounting for a GFA of around 43 million square meters and 4 million tons of wood. Remarkably, this amount is equal to the total mass of wood in attached houses and higher than the mass of wood in detached houses built in other periods. This represents a significant potentially resource, which without careful planning, will be used for energy though, depending on its quality, it could be reused or recycled into new products (Höglmeier et al., 2017; Sakaguchi et al., 2017). Thus, local authorthies in collaboration with enterprises should plan for the cascading of wood through actions such as replacing normal demolition methods with disassembly, advancing the sorting of wood waste, priortizing cascading over energy recovery and monitoring the flows of wood waste from C&D activities.

Table 5 shows a comparison of wood contained in the residential building stock in Finland, Austria and Bavaria, Germany. As shown, the volume of wood used in relation to the building volume, or gross cubic content[1] (GCC), varies siginifcantly. Finland, with around 80 cubic meters of wood per 10^3 cubic meters GCC contains 3 and 4 times more wood than Austria and Bavaria, respectively, though there is less variation in the volume of wood per building. Probable explanations for this are the different construction methods, since the present study focussed on buildings constucted from wood only, however, different methological approaches may also have played a part. The majority of wood contained in shell construction is mainly in roof structures, external walls and ceilings (Höglmeier et al., 2015, 2013), although wooden residential houses in Finland contained wood in dividing walls, window frames and floors as well.

3.5. Limitation, uncertainties, and future studies

Throughout the current study, research gaps and barriers to the development of MS analysis were noted. These issues and some recommendations for addressing them are summarized in the following paragraphs.

A full time-series of the number and GFA of buildings constructed in each period are only available from 1965 onwards in OSF, thus alternative approaches to creating time-series are needed if the "real" data are not available. This may include contact with statistical offices, or different approaches (e.g. estimation according to population and lifestyle conducted by Müller (2006)).

MS analysis articles are usually combined with the outflow of material using the lifetime of buildings. However, an analysis of the outflow of wood was not conducted in the current study due to the paucity of data on the lifetime of Finnish buildings. According to Huuhka and Lahdensivu (2016), relatively few studies have been conducted on this topic and clearly further research is needed. It is therefore recommended to conduct similar studies to that made by Huuhka and Lahdensivu (2016) since in Finland real data on demolished buildings are available, enabling a realistic estimate of the lifetime distribution of building to be made (Huuhka and Lahdensivu, 2016). The aforementioned study is a good starting point for analysing the age of buildings at the time of demolition. In the future, the lifetime distribution of buildings in relation to the period of construction, building type and demolition year, should be studied.

As described in Section 2.3, assumptions and estimations from different sources were used for the calculation of GFA. This causes some uncertainties about the quality of data not yet available in data sources and the literature. Regarding the reliability and availability of data, a study of typical building typologies in each decade in collaboration with experienced architects and engineers in the field of wooden buildings is recommended. The popularity of the building type, room height, construction method, room size, building materials, number of floors, and location should be analysed in this kind of study. Another solution is to have close contact with key data providers (e.g., statistical offices) as they might have a record of unpublished data, or they could provide solutions to acquire the missing data from other sources.

Currently, information about the material intensity in residential buildings in Finland is not available. The analysis detailed herein used Swedish material intensity for the calculation of MS due to the similarities identified in these two countries. Currently, a material intensity study is in progress for Finnish residential buildings by the authors. Not only should the overall use of wood be studied, but also the types of wood used in the buildings should be identified to provide a clear understanding of the actual dimensions, type, and quantity of wood in the buildings.

The current analysis only considers wood used in residential houses, while other building types, such as non-residential buildings have used wood for constructions as well. In general, there is little knowledge about the amount and inventory of wood in the non-residential building stock and MS analyses have been mainly conducted for residential buildings and for the mineral building stock (Ortlepp et al., 2016). This is because of the variety of non-residential buildings in terms of the types of construction, materials, and their structure (Ortlepp et al., 2016).

Wood used in non-structural applications, such as cladding, and interiors is not included in the current analysis, therefore, the actual amount of wood in the stock of houses will be higher than the amount estimated here. This aspect has not been included in this analysis due to a lack of data and the higher cascading potential of structural parts. To address this issue, collaborating with key data providers could again be fruitful. This is because the production of new data types can be planned for the purpose of conducting MS analyses enabling future strategies to be achieved. Data on wood used in non-structural applications would enable a MS analysis of all types of wood products to be carried out. Such analyses would create a full picture of future wood wastes that could be used in a material cascade. To provide the new data types, one recommendation is to update the construction project notification forms (RH1 and RH2 forms in Finland) and gather additional information about material used for dividing walls or horizontal structures, as well as construction method (e.g. log construction).

Renovation, reconstruction and extension measures use an appreciable share of wood in the building and construction industry in Finland (Huuhka and Lahdensivu, 2016). Yet, this has not been included in this analysis due to difficulties in tracking input materials into the building stock. The inclusion of wood from renovation, reconstruction and extension measures requires reliable data that is constantly updated and circulated, from the design phase to the use phase and the end-of-life of buildings. For new buildings, building information modelling using building information model tools (e.g., Revit) and connecting it with other data sources (e.g., Environmental Product Declaration) could provide a good understanding of the material quantity, type, quality, and size that enters and exits a building during its life cycle. Digitalizing the data of old buildings could also provide valuable data concerning potential future changes in the building. So far, MS and flow analysis which have calculated the flow of renovation, reconstruction and extension material, have used data on lifetime of building elements and micro economic data (Augiseau and Barles, 2017), or used data on renovation cycles (Sartori et al., 2016).

4. Conclusions

The current study applied a bottom-up MS analysis in which number of buildings multiplied by the GFA of buildings and their corresponding wood intensities, yielded the mass of wood and the GFA of building per building type in each construction period. Statistics, literature on

[1] GFA of a building multiplied by average height of floor (Kalcher et al., 2017).

Table 5
Mass and volume of wood in residential buildings – comparison of studies. Finland, Austria, and Germany. Gross cubic content (GCC), which is GFA multiplied by average floor height of floor For converting GCC to GFA and vice versa, the average height of the floor was assumed to be 2.8 m (Cells marked with asterisk) (Kalcher et al., 2017).

Reference	Location	Building types	Number of buildings	GFA(10^6 m^2)	GCC (10^6 m^3)	Volume of wood (10^9 m^3)	Volume of wood/ GCC ($m^3/10^3$ m^3)	Volume of wood per building (m^3/building)
Current study	Finland	Wooden residential houses	1,229,473	170.99	479*	38.44	80	31
Kalcher et al. (2017)	Austria	Residential buildings (shell construction)	1,973,979	612.95	1736	44.08	25	22
Höglmeier et al. (2017)	Bavaria, Germany	Residential buildings (shell construction)	2,954,850	1233.21*	3453	62.15	18	21

material intensity, and information about standardized Finnish houses were used as the main data sources unless they were not available. Where the data was not available justified assumption were made.

The study found that 17.5 million tons of wood is embodied in Finnish houses, of which around 50% could be suitable for cascading and will become available in the future, providing a potentially significant resource source. The study thus highlights the importance of studying the future availability, types, and quality of recovered wood products, since comprehensive knowledge is needed to establish a market for second life wood products, decreasing waste generation and the demand for virgin wood.

It was also estimated that the mass of wood embodied in AADH built before 1969 is higher than after 1970. Moreover, detached houses, especially detached house built in the period 1940–1959, contain a higher mass of wood compared to attached houses. Thus, the construction periods and building types that should be focused on to establish reuse and recycling strategies were identified. The aforementioned results provide a comprehensive understanding of the existing stock through MS analysis that is the basis for a MS and flow analysis. The combined results of the current study and the lifetime of buildings would provide valuable information concerning the flow of material. Such analyses would help decision makers and policy makers anticipate the future availability of recovered wood as a secondary resource. To illustrate further, demolition is connected to new construction in Finland (Huuhka and Lahdensivu, 2016), and the share of new wooden multistorey buildings is expected to triple by 2030 (FTP, 2012). Thus, there are a significant number of buildings that would need to be demolished by then and a large amount of wood from these demolitions will exit the building stock. Such information would help plan for the recovery of wood, so that it is used to its best effect to create benefits for a circular bioeconomy and to limit the excess production of wood products from virgin wood.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the EIT Climate-KIC project “ReWood II” [grant number: TC_2.1.5_190346_P279-1A]; the Forest Value ERA.net project “InfutUReWood”, which is financially supported by the Finnish Ministry of the Environment and others [grant number VN/4236/2018]; and the Finnish Foundation for Technology Promotion (Tekniikan Edistämissäätiö). Special thanks to Fredric Mosley for his support during data collection.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2021.09.007.

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