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PII: S2590-289X(19)30024-6

DOI: https://doi.org/10.1016/j.rcrx.2019.100027

Reference: RCRX 100027

To appear in: *Resources, Conservation & Recycling: X*

Received Date: 23 May 2019

Revised Date: 5 November 2019

Accepted Date: 25 November 2019

Please cite this article as: de Tudela ARP, Rose CM, Stegemann JA, Quantification of Material Stocks in Existing Buildings Using Secondary Data- A Case Study for Timber in a London Borough, *Resources, Conservation and amp; Recycling: X* (2019), doi: https://doi.org/10.1016/j.rcrx.2019.100027

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Quantification of Material Stocks in Existing Buildings Using Secondary Data- A Case Study for Timber in a London Borough

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Highlights

- Material stocks in buildings were estimated with national statistics and local maintenance data.
- Timber in Tower Hamlets (London) homes is estimated at nearly 1 tonne/dwelling.
- Timber is more concentrated in floors and roofs, and in older buildings.
- Our methods and results can inform planning and policy towards sustainable material reuse.

Abstract

The existing building stock represents a huge accumulation of physical resources: a material 'reserve' that could be mined in the future to improve resource efficiency. However, in the absence of systematically collected information about materials deposited in the built environment, the ability to manage and exploit them is limited. An approach to quantification of material stocks based on the use of secondary data from external research bodies, national statistics and a housing stock management database is used to estimate the timber stock in residential buildings constructed in the London Borough of Tower Hamlets before 1992. Results show a total timber accumulation of almost 67,000 tonnes across 68,000 dwellings, with a material intensity for timber between 20-34 kg/m^2 of building floorspace (6.8-11.2 kg/m^3 of gross building volume) for terraced houses and 5.4-11 kg/m^2 (1.8-3.6 kg/m^3) for flats and maisonettes. Generally, there is more timber in floors and roofs, and in older buildings. This method appears to be robust, as it results in comparable timber intensities to those determined using other methods in previous studies. It can be used for other materials and may be useful in other contexts where data is available (i.e., other scales, building types and

materials), and capable of contributing to the growing understand of existing buildings as material banks.

Keywords: wood, lumber, urban mining, circular economy, material flow analysis (MFA), material intensity coefficient (MIC)

1 Introduction

Construction and demolition waste (C&DW) accounts for about a third of total generation of waste in the UK (DEFRA, 2016) and also Europe (Eurostat, 2016). In 2011, the European Commission identified C&DW as 'a priority stream' due to the large amounts being generated and the high potential for reuse, recycling and recovery of these waste materials (Mudgal *et al.*, 2011). As a consequence, the target for diversion of non-hazardous C&DW from landfill was set at 70 mass % by 2020 in the Waste Framework Directive (European Commission, 2008). The UK has been comfortably meeting this target with close to 90% diversion of C&DW from landfill since 2010 (DEFRA, 2016). However, UK and EU legislation does not distinguish targets for the different levels of the waste hierarchy. In fact, the main path for waste streams diverted from landfill is often at the lower levels, with most of the C&DW diverted from landfill either backfilled, burned, or recycled in a way that squanders its embodied environmental impacts, rather than reused (DEFRA, 2017). Developing knowledge to support reuse of materials from C&DW could retain a higher proportion of embodied impacts, and avoid use of processing energy for recycling (Gill and Manchanda, 2006) or production of new materials, as well as the exploitation of natural materials resources (Vieira and Pereira, 2015; Iacovidou and Purnell, 2016; Oezdemir, Krause and Hafner, 2017). This issue is highly relevant in urban contexts, where a dense built environment contains huge amounts of materials (Stephan and Crawford, 2017) with the potential for urban mining (Cheng *et al.*, 2018; Mesta, Kahhat and Santa-Cruz, 2019).

As part of an effort to manage the impact of urban C&DW, much research since the late 1990s has focused on the estimation of types and quantities of materials in the urban building stock, focusing on a variety of spatial and time scales, built work and materials (Augiseau and Barles, 2016; Condeixa, Haddad and Boer, 2017; Gontia et al., 2018; Heeren and Fishman, 2019). In light of this, an EU-funded project, Buildings as Material Banks (BAMB, 2015),

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brought together a network of researchers, designers and developers, to try to make this concept operational, e.g., by developing 'material passports', to provide building information including material composition and potential for maintenance, reuse and remanufacturing. The BAMB project, however, has focused on the design of new buildings. An extension of this idea termed E-BAMB (Existing Buildings as Material Banks; Rose and Stegemann, 2018) proposes organised collection of open access knowledge about materials stocks in existing buildings; this could form part of the National Materials Datahub to which the recently released Resources and Waste Strategy for England aspires (DEFRA, 2018). Other European urban mining initiatives include MINEA (MINEA, 2019) and ProSUM (ProSUM, 2019).

Some countries, including Japan, Austria, Germany and Switzerland, have already published academic literature relevant to urban mining, that uses digitised building information at local and national level (e.g.,Tanikawa *et al.*, 2015; Kleemann, Lederer, Rechberger, *et al.*, 2016; Schebek *et al.*, 2016; Heeren and Hellweg, 2018). Many other countries are now also developing similar approaches; for example, the UK Government announced in 2011 that all centrally procured projects will use Level 2 Building Information Modelling (BIM), with collection of building data in a collaborative 3D environment, by 2016 (IPA, 2016). This new practice should help eradicate much of the risk and uncertainty associated with sharing information in a virtual construction environment (NBS, 2017), and create a digital record of materials added to stocks, but again will only apply to new buildings. However, a major challenge is that such standardised individual building data in an open, accessible format has not previously been collected for existing buildings (O'Brien, 2015; Condeixa, Haddad and Boer, 2017; Mesta, Kahhat and Santa-Cruz, 2019). At present, the only option is to apply available information about the composition of the building stock from other sources to understand the potential for reclamation and reuse (Oezdemir, Krause and Hafner, 2017; Arora *et al.*, 2019; Bergsagel and Lynch, 2019).

The present study discusses a general approach to gathering such secondary data about materials for mining upon building demolition, for contexts in which no systematic geospatial data exists for this purpose. The specific objectives of the study are to:

1) find available sources of information for the categorisation of buildings based on age and type in a UK case study area,

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2) develop a method for the estimation of material intensities (i.e., in kg/m^2 of building floorspace and kg/m^3 of gross building volume) from the available information, and

3) demonstrate this method by calculating the timber accumulation associated with the housing stock in the case study area.

2 Previous Research

Previous studies have attempted to estimate quantities and qualities of C&DW from the building stock as a 'future anthropogenic resource deposit for secondary raw materials' (Kleemann, Lederer, Rechberger, *et al.*, 2016) with a focus on different building materials, different scales (municipal, national) and the use of different types of data (national statistics, geographical information system [GIS] data). Material flows (e.g., mass over time) and accumulations (mass per unit of assessment) may be estimated based on macro-economic statistics, or by extrapolating material intensities (in mass per building floorspace or volume) to larger building stocks, based on combination of disaggregated data about the material composition of buildings from a variety of sources. The information generated in these studies can be used for a variety of purposes, such as forecasting and comparing future input and output flows (Condeixa, Haddad and Boer, 2017; Mesta, Kahhat and Santa-Cruz, 2019), studying the influence of different parameters and variables on future flows, studying urban metabolism (Arora *et al.*, 2019; Miatto *et al.*, 2019) and analysing the interactions between flows and stock (Cheng *et al.*, 2018; Stephan and Athanassiadis, 2018). Findings from previous research have enabled construction of models to anticipate and improve knowledge of stock accumulation (Han and Xiang, 2013; Tanikawa *et al.*, 2015).

Although the purpose and scope of studies of material stocks in existing buildings vary, they generally use information such as GIS datasets (for different spatial scales and times) and various other, less systematic, data about specific buildings. The most common sources of data are:

- Government sources, which often provide vast and relatively uniform and reliable data and statistics on housing and population. This type of stock data may be found from national data, e.g., collected for management of regional economies, to local level data collected for planning, building control, and heritage/conservation purposes.

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- On-site investigation and 'as-built' information collected by architects, developers, building owners, etc.
- Waste management reports, which provide information on the quantities and types of material collected from demolition of specific buildings (Rose and Stegemann, 2018).
- Data published by other universities/authors or private research institutions.

Approaches based on macro-economic data are bedevilled by aggregation of data, such that information may be insufficiently detailed to aid in material mining, e.g., neglecting quality of the reported flows, or combining data based on characteristics unrelated to materials' potential uses (e.g., European Waste Catalogue or Nomenclature of Economic Activities (NACE) codes, which relate to industrial origin rather than material use) (Rose and Stegemann, 2018). Whereas it seems that bottom-up accumulation of data about the material composition of buildings can provide more detailed information, systemic inaccuracies can arise (Mastrucci *et al.*, 2016; Gontia *et al.*, 2018), e.g., by neglecting or underestimating building renovations or upgrades during the use phase of a building (Kleemann, Lederer, Aschenbrenner, *et al.*, 2016). Estimates of materials stocks based on materials collection statistics from demolition of buildings are often incomplete and underestimated (Kleemann, Lehner, Szczypińska, *et al.*, 2016).

Examples of studies based on the use of macro-economic statistics include those executed in Switzerland (Lichtensteiger and Baccini, 2008), France (Barles, 2009, 2014), the United States and Japan (Fishman *et al.*, 2014). Bottom-up approaches have been carried out in Norway (Bergsdal et al. 2007; Sartori et al. 2008), Germany (Ortlepp, Gruhler and Schiller, 2016a, Schebek et al. 2016), Austria (Kleemann, Lederer, Rechberger, *et al.*, 2016), Sweden (Gontia *et al.*, 2018) and Australia (Stephan and Athanassiadis, 2018). Secondary data used in previous research includes historical cadastral maps and manuals on building material composition (Miatto *et al.*, 2019), building catalogues developed for other purposes (e.g., energy consumption) (Schebek *et al.*, 2016; Oezdemir, Krause and Hafner, 2017), specialized architectural data (Gontia *et al.*, 2018) or visual surveys of typical building typologies for a specific area (Arora *et al.*, 2019; Mesta, Kahhat and Santa-Cruz, 2019). The academic community has increasingly recognised the potential and importance of the explicit map representation of anthropogenic resources (Miatto *et al.*, 2019). 4D-GIS (Tanikawa and Hashimoto, 2009) has been used to map and

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analyse the material composition of the building stock in Japan (Tanikawa *et al.*, 2015), Vienna (Kleemann, Lederer, Rechberger, *et al.*, 2016), Padua (Miatto *et al.*, 2019), Taipei (Cheng *et al.*, 2018), Chiclayo (Mesta, Kahhat and Santa-Cruz, 2019), Grenada (Symmes *et al.*, 2019) and Melbourne (Stephan and Athanassiadis, 2018). The only identified previous study of material stocks in buildings that concerns the UK is a GIS-based case study for an 8 km^2 urban area in Salford, Manchester, included for comparison with a Japanese case study by Tanikawa and Hashimoto (2009).

3 Approach

3.1 General Method

A general approach with the following steps was conceived:

1. Identification of scope and boundary of study, i.e., characterisation of the study location, selection of the building and material types of interest.
2. Development of a general model for the calculation of material quantities in buildings.
3. Elaboration of a strategy to discover sources of information and data for application in the model:
   a) Characterization of buildings: i.e., purpose, size, age and type of construction of buildings.
   b) Characterization of building components: i.e., characteristics and quantities of building elements and materials.
4. Application of the data search strategy (3.) in the study area.
5. Customisation of the model (2.) for the study area and calculation of material quantities for building and material types of interest.
6. Aggregation of mass and volume figures of all building elements per material against spatial (floor area, building volume) information to estimate a material intensity for the study area, represented as mass per building floorspace (kg/m^2) or volume (kg/m^3).

This approach was applied for bottom-up quantification of timber stocks in existing residential buildings, using the London Borough of Tower Hamlets (henceforth “Tower Hamlets”) in East London as a case study.

3.2 Case Study Scope and Boundary

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Tower Hamlets has a population of 306,000 people across an area of 19.44 km^2 (LBTH, 2017). Since 2016, it has had the most rapidly growing housing stock amongst all London Boroughs (LBTH, 2016). The governance, planning and organisational structure of Tower Hamlets is typical of that for most municipalities in the UK; it was particularly useful as a representative focus area because of the prevalence of two of the most common types of dwellings in the UK: terraced houses and flats/maisonettes (DCLG, 2015; LBTH, 2016). However, there is a large proportion of social housing in Tower Hamlets; this dropped from 86% of 61,000 dwellings in 1981 to 36% of 121,000 dwellings in 2014 (LBTH, 2016), while the proportion of social housing in England as a whole has dropped from a post-World-War-II high of 26.5% of 4.5 million dwellings to 17.2% of 23.5 million dwellings in 2014 (Ministry of Housing, 2015).

3.3 Datasets

3.3.1 Data sources

A combination of different types of data sources (as introduced in 2) was used to develop a bottom-up model of timber in Tower Hamlets housing stock, including:

- Valuation Office Agency (VOA) data on ‘dwelling ages’ and ‘types of dwelling’ for the whole of England and Wales, to support taxation and benefits (VOA, 2017);
- a stock management database originally developed by Tower Hamlets for maintenance of their housing stock (Ward, 2017);
- specific building information gathered through on-site investigation of terraced houses and flats/maisonettes in Tower Hamlets, to estimate average number and dimensions for building components.

Findings for timber stocks based on these sources were validated by comparison with data from similar bottom-up studies in kg/m^2 of building floorspace (Tanikawa and Hashimoto, 2009; Hu, van der Voet, and Huppes, 2010; Han and Xiang, 2013; Huang *et al.*, 2013; Surahman, Higashi and Kubota, 2015; Condeixa, Haddad and Boer, 2017; Cheng *et al.*, 2018; Gontia *et al.*, 2018; Mesta, Kahhat and Santa-Cruz, 2019; Miatto *et al.*, 2019; Symmes *et al.*, 2019) and kg/m^3 of building volume (Kleemann, Lehner, Szczypińska, *et al.*, 2016; Ortlepp, Gruhler and Schiller, 2016a; Gontia *et al.*, 2018; Miatto *et al.*, 2019).

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Data collected by the Tower Hamlets Planning Department (LBTH, 2019) were also considered. Although much of this is now available on-line, the data were found to be often incomplete, without a systematic way to search and retrieve specific information about the associated buildings, such as ages, types, or materials. The task of accumulating data gathered for individual buildings for the entire housing stock of the case study area was therefore deemed impractical. Examination of a subset of waste management reports for a Tower Hamlets regeneration project (provided on a confidential basis) suggested that this data is also generally incomplete or inaccurate and it was decided not to pursue this as a data source.

3.3.2 Valuation Office Agency data

The VOA 'dwelling age' dataset published in 2015 provides information on the number of houses at 'Lower layer Super Output Area' (LSOA) level in ten-year intervals, creating twelve periods of construction from pre-1900 to 2015. LSOA are a geographic hierarchy put in place to improve the reporting of small area statistics in England and Wales. They have been automatically aggregated to be as consistent in population size as possible, with a minimum population of 1000, and mean of 1500 (ONS, 2019). Data on 'dwelling type' includes a London-wide breakdown at borough level into categories (terraced house, flat/maisonette, semi-detached house, detached house, bungalow other and unknown), and by the number of bedrooms, and is also given at LSOA level. This data is accurate to the nearest ten dwellings (Mayor of London, 2015), which accumulates to an error of less than 0.1% over a century. This study focused on terraced houses and flats/maisonettes, as semi-detached houses, detached houses, bungalows and 'unknown/other' represent a negligible percentage (2.3%) of the total dwelling stock in Tower Hamlets. Terraced houses and flats/maisonettes may to some extent be comparable with the categories "single-family" (SF) and "multi-family" homes (MF) used in other studies (Wiedenhofer *et al.*, 2015; Mastrucci *et al.*, 2016; Ortlepp, Gruhler and Schiller, 2016b; Gontia *et al.*, 2018). In these, single-family homes are separate dwellings inhabited by one or two families; multi-family houses contain more than two dwellings in the building (Nemry *et al.*, 2010).

To further assess the accuracy of this information, and the representativeness of Tower Hamlets of the UK, the VOA data for Tower Hamlets were compared with the categorisation of buildings by type and age in the English Housing Survey (Ministry of Housing, 2015), which offers information about the stock

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profile of housing for the whole of England. A comparison of the proportions of dwellings per construction period from both these sources of data (Table S.1) showed that the construction of English dwelling stock is much more evenly distributed through time than that in Tower Hamlets, where 40% is post-1990.

3.3.3 Tower Hamlets Homes stock management database

A stock management database was created and maintained by Tower Hamlets prior to the transfer of 2.3 million homes from local authorities to registered social landlords under the Housing Act of 1988 (Pawson and Fancie, 2003). Stock management databases are probably common in the UK and elsewhere, as it would be difficult to own, maintain and manage large housing stocks without them. The borough database was transferred to Tower Hamlets Homes (THH), an independent management organisation, which has used it to record changes in ownership and maintenance of their housing stock since 2001 (Ward, 2017).

The THH stock management database contains information needed to plan maintenance of their housing stock, including original year of construction, materials, number and condition of buildings elements, such as windows, doors, sills, etc., and dates of installation, replacement and maintenance, per dwelling, and for the overall building. Data have been collected for 776 terraced houses and 11,267 flats/maisonettes, and a small proportion (~1% of dwellings) of semi-detached and detached houses, and bungalows, that were neglected in this study (3.3.2). In the UK, terraced houses are commonly of brick construction with traditional cut roofs (this will change depending on period of construction) (Figure 1(a)), while flats/maisonettes are subdivided terraced houses, or in multi-storey reinforced concrete buildings with either flat or prefabricated roof trusses (Figure 1(b)) (NHBC, 2015).

(a) (b)

Figure 1. Typical (a) terraced houses (OnTheMarket,com, 2019), and (b) flats (Chilton, 2014) in Tower Hamlets

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As it is continuously up-dated, the THH stock management database reflects the current state of the building stock, following demolition and maintenance, rather than the state at the time of construction. Because the Tower Hamlets council ceased any form of house-building in the early 1990s until 2015, the database does not contain any information for buildings built after 1992. This analysis was therefore limited to housing constructed before 1992, which represents about 60% of the total stock in Tower Hamlets.

For this research, the housing stock was grouped into five periods of construction: pre-1919, 1919-1939, 1945-1964, 1965-1983 and 1984-1992. Before 1919, housing was built using traditional construction techniques. Between the wars, most new homes had cavity walls, simplified timber hinged casements and concrete strip foundations. Post-war construction used a greater variety of techniques, so, for the purpose of this research, post-1945 periods have been grouped based on major changes in UK building regulations in 1965 and 1984 (DCLG, 2015).

3.3.4 Sample Survey

Since the THH stock management database did not include information on the dimensions of some specific building elements, the research included measurement of 58 windows and partition walls from three different dwellings to establish average dimensions for timber elements in windows and partition walls in terraced houses and flats/maisonettes in Tower Hamlets (see final column of Table 4).

3.4 Material Stock Estimation Method

Data regarding the number and percentage of dwellings constructed in Tower Hamlets, aggregated for the chosen periods of construction from pre-1919 to 1992 (Table 1), and types of dwelling (Table 2) were extracted from the VOA database. Under the assumption that, on average over the 8 to >20 year timeframe of each period of construction, the same dwelling types were constructed, the percentages from Table 1 were multiplied by the number of houses in

Table 2, to estimate the number of terraced houses and flats/maisonettes that were built in each period of construction (Table 3).

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Table 1: Valuation Office Agency (2015) data on dwelling ages for the London Borough of Tower Hamlets

	Pre-1919		1919-1939*		1945-1964		1965-1983		1984-1992	Post-1992	Total**
Period of construction	Pre-1900	1900-1918	1919-1929	1930-1939	1945-1954	1955-1964	1965-1972	1973-1983	1984-1992	Post-1992	
Number of dwellings	15,130	1,590	2,040	4,060	7,220	11,140	10,020	9,650	8,690	45,020	114,560
% of total dwellings	14.3		5.2		15.7		16.9		7.5	40.3	100

*Records indicate that no properties were built from 1940-1944
**There were also 2,150 dwellings (1.9%) of unknown age

Table 2: Valuation Office Agency (2015) data on dwelling types for the London Borough of Tower Hamlets

	Bungalow	Flat/ Maisonette	Terraced House	Semi Detached House	Detached House	Total*
Number of dwellings	140	100,460	13,510	470	160	114,740

*There were also 1,960 dwellings (1.7%) of other or unknown type

Table 3: Numbers of terraced houses and flats/maisonettes calculated for each period of construction in the London Borough of Tower Hamlets

	% of all dwellings	Terraced Houses	Flats/Maisonettes	Total
Pre-1919	14.3%	1,936	14,394	16,330
1919-1939	5.2%	706	5,252	5,958
1945-1964	15.7%	2,126	15,806	17,932
1965-1983	16.9%	2,277	16,934	19,211
1984-1992	7.4%	1,006	7,481	8,487
Total	59.5%	8,051	59,868	67,919

Data on the categorisation of buildings by dwelling type and age (Table 3) were then combined with information from the THH stock management database about the building materials associated with specific building elements (e.g., doors, windows) in terraced houses and flats/maisonettes, in the chosen periods of construction, to calculate material intensities for timber.

3.5 Calculations for timber elements

3.5.1 Number of timber elements per dwelling

Numbers of timber windows (including sills), doors (including frames), stairs, roof structures, floors boards, floor joists and internal walls were determined by searching the THH stock management database for elements described as hardwood, softwood or timber in the terraced houses, flats, and maisonettes, including also communal external doors and roof structures, for each period of construction. Together, these elements contain most of the timber embedded in a dwelling. The numbers of these elements were each divided by the total number of terraced houses and flats/maisonettes in the database for each

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period of construction (Table 3), to obtain the average numbers per dwelling (N_e).

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Table 4: Information used for the calculation of timber building element volumes in terraced houses (TerH) and flats/maisonettes (F/M)

Category	Data Sources[1]	Description	Assumptions	Dimensions (mm)	
				TerH	F/M
Windows + Sills	OSS BCH SMD	Double-hung sliding/ single glazed (TerH) and pivot and single-glazed (F/M) Softwood or hardwood	Average number = 7.09-9.22 (TerH) and 6.06-7.01 (F/M) 4 glazing bars/window	894x1513 Cross-sections from BCH Sill 144x45x894	1147x1217 Cross-sections from BCH Sill144x45x1147
Internal Doors + Frames	BCH SMD	Non-glazed softwood panelled doors	Average number = average number of bedrooms + 3	1981x35x762 83x57[a]	1981x35x762 83x57[a]
Entrance Doors + Frames	BCH SMD	Panelled hardwood and softwood with a single glass panel	Average number = 1	1981x35x762 83x57[a] -(900x600)[b] 838x121x44[c]	1981x35x762 83x57[a] -(900x600)[b] 838x121x44[c]
External Doors + Frames	BCH SMD	Non-flush hardwood and softwood with a single glass panel	Average number =1 (TerH) and 0.34-1.21 (F/M)	1981x35x762 83x57[a] 900x600[b] 838x121x44[c]	1981x35x762 83x57[a] (900x600[b] (838x121x44[c]
External Communal Doors + frames	BCH SMD	Part-glazed hardwood	Average number = 2.38-3.9 (F/M only)	-	1981x35x762 900x600[b] 838x121x44[c]
Staircases	BCH SMD	Straight staircase with balustrade; Softwood	Floor to floor height = 2600 mm; pitched angle of 42 degrees; width = 865 mm. spindle spacing = 111 mm centre-to-centre	200x32x833[d] 222x32x833[d] 240x32x269[d] 38x20x860[d] 100x100x1100[d] 75x50x2691[d]	200x32x833[d] 222x32x833[d] 240x32x2691[d] 38x20x860[d] 100x100x1100[d] 75x50x2691[d]
Fascia/Soffit/Barge	BCH SMD	Softwood	Scenarios considered include: timber fascia board only, timber soffit board only, and timber fascia board and soffit board. Average number of roof linear meters was calculated for each type of dwelling and period of construction.	19x135[e] 16x175[e]	19x135[e] 16x175[e]
Floorboards	BCH SMD	Softwood	Average floor area = 100 (TerH), 79 (F/M) m^2 Gaps between floorboards neglected	20 [f]	20 [f]
Floor Joists	BCH SMD	Softwood	Based on same floor areas as floorboards; 27 joists (TerH); 35 joists (F); 21 joists (M) Floor joist spacing = 400 mm centre-to-centre.	4800x225x50	4000x200x38
Roof Structure	BCH SMD	Softwood	Pitch of gabled roofs = 20 degrees (unbraced) and 40 degrees (braced); rafter, brace and ceiling joist spacing = 400 mm centre-to-centre; average roof area = 50 (TerH) and 450 (building with multiple F/M) m^2 54 rafters, 16 braces, 27 joists (TerH); 226 rafters, 60 braces, 113 joists (F/M)_	3112x100x50[g] 2592x100x50[h] 1575x100x50[i] 4800x150x50[i] 10400x100x50[i]	3112x100x50[g] 2592x100x50[h] 1575x100x50[i] 4800x150x50[i] 10400x100x50[i]
Internal Walls	OSS	Softwood studs	9 m of timber, including 2 head plates, 48 studs and 47 noggins (TerH); 7.5 m, including 2 head plates, 40 studs and 39 noggins (F); 5 m, including 2 head plates, 28 studs and 27 noggins (M); stud spacing = 400 mm centre-to-centre;	95x45	95x45

[1]OSS= On-site Sampling / BCH= Building Construction Handbook / SMD= Tower Hamlets Homes Stock Management Database; [a]Cross-section of softwood jamb and head; [b]Glass panel was subtracted from door; [c]Hardwood sill; [d]Dimensions introduced in the following order: riser, going, stringer, baluster, landing posts and handrail; [e]Dimensions introduced in the following order: fascia boards, soffit boards; [f]Softwood timber floorboard thickness; [g]Rafters for braced roof [h]Rafters for unbraced roof [i]Dimensions introduced in the following order: braces, joists and ridge/ wall plates.

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3.5.2 Volumes of timber building elements

Table 4 shows the dimensions used to calculate the volume of each type of building element (V_e in 3.5.2). For windows and doors, the most common types were identified by looking at THH data, and the dimensions for those types were then assumed for all dwellings. Unless otherwise stated, sectional dimensions of standard building elements were taken from the 'Building Construction Handbook' (Chudley and Greeno, 2016). Whenever dimensional information could not be found in the Building Construction Handbook or the THH stock database, average dimensions were ascertained by survey (3.3.4).

3.5.3 Building floorspace and volume

For terraced houses, the average building footprint for each period of construction was estimated based on the average roof area indicated in the THH stock management database, assuming pitches of 20 and 40 degrees for braced and non-braced roofs, respectively. For flats/maisonettes, the average building footprint was estimated as the average building area indicated in the THH stock management database. The average building footprints were multiplied by the average number of floors to calculate the building floorspace. Assuming a nominal height per floor of 3m (which can be compared with a range of floor-to-ceiling heights of 2.4-2.9m, and subfloor thickness of 0.1-0.4m in Chudley and Greeno, 2016), the gross building volume (GV) was three times the average building footprint.

3.6 **Material intensities**

For each type of building element (denoted by subscript e in Equation 1), the quantity of timber (in tonnes) for each dwelling type (terraced houses and flats/maisonettes) in each period of construction was calculated as:

$$Q_e = N_e \times V_e \times \rho \times D \qquad \text{Equation 1}$$

with:

N_e = Number of timber building element type per dwelling (for terraced houses and flat/maisonettes, per period of construction, as determined in 3.5.1)

V_e = Volume of timber building element type (m^3, based on data from Table 4; 3.5.2)

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ρ = Bulk density = 0.48 for softwood and 0.72 for hardwood (t/m^3) (Chudley and Greeno, 2016)

D = Total number of terraced houses or flats/maisonettes per period of construction (Table 1)

The calculated timber quantities can be summed to provide desired estimates across the element types, dwelling types, and periods of construction (e.g., **Error! Reference source not found.**). The overall total quantity of timber divided by average building floorspace or gross building volume (3.5.2) yielded the material intensity for timber in kg/m^2 or kg/m^3, respectively.

3.7 Sources of error

One of the advantages of this study was the access to the THH stock management database, which includes data on the replacement of building elements, making it possible to overcome the inaccuracies due to missing refurbishment data noted by previous studies (in Section 2) to a certain extent. This is especially relevant for the quantification of timber stocks, as timber building elements such as windows or floorboards can have shorter maintenance cycles and are often more replaceable than building elements such as structures or facades.

Table 5: Summary of sources of error and estimates of their magnitudes, with level of confidence in these estimates

Source of error	Magnitude of error	Confidence
VOA data		
Number of houses	<0.1%-5%	High
Missing age categories	2%	High
Neglect of semi-detached, detached and other houses	2.3%	High
THH stock management database		
Only includes buildings built before 1992	High	Low
Neglect of communal elements other than roofs and doors	Moderate	Moderate
On-site survey		
Based on small sample	Moderate	Moderate
Calculations		
Combination VOA numbers with THH stock management database quantities	Moderate	Moderate
Assumption of standard element sections	Moderate	Moderate
Assumption of standard roof pitches	<20%	High
Assumption of standard floor height	10-20%	High

A summary of the sources of error in our study is shown in Table 5. Quantitative estimates of the magnitudes of the associated errors are shown in Column 2,

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with the level of confidence in these estimates in Column 3. Like other studies on the subject, this study depended very much on the availability and nature of the available building information data. The most significant source of error was probably that the data was limited to buildings constructed before 1992 (3.3.3), which was a condition peculiar to Tower Hamlets Social Housing that probably did not apply more widely across the borough, or country. Also, the distribution of dwelling types by age could only be assumed, although the error associated with the number of dwellings over time provided by the VOA appeared to be less than 2% (3.3.2; 3.4). However, other information from Tower Hamlets reported 121,000 dwellings (3.2), as compared with the 115,000 in the VOA (3.3.2), suggesting an error of up to 5% in the building numbers. Use of mean floor areas, and assumed roof pitches and heights of floors/buildings across periods of construction, in calculating gross building volumes are further sources of error. Other studies use very accurate GIS data for such calculations (Kleemann, Lederer, Rechberger, *et al.* 2016; Mastrucci *et al.*, 2016; Tanikawa and Hashimoto, 2009; Evans, Liddiard and Steadman, 2017). Standardising dimensions of building elements for calculation of timber volumes was also a source of error, especially as some of these dimensions were based on a relatively small survey. In this regard, the study benefits from the use of a relatively small case study area, as opposed to studies using similar approaches at a city or national level (Schebek et al. 2016; Kleemann, Lederer, Rechberger, et al. 2016; Ortlepp, Gruhler and Schiller, 2016a; Gontia et al. 2018). There is a smaller level of inaccuracy in the harmonization of building types at a smaller scale, as construction and material composition of buildings in a local area are more likely to be similar.

4 Results and Discussion

4.1 Timber stocks

Based on this model, the timber quantity embedded in the almost 60% of the residential building stock in Tower Hamlets built until 1992, accounting for a total of 8,000 terraced houses and 60,000 flat/maisonettes, was calculated. Detailed mass and volume data for timber building elements in terraced houses and flats/maisonettes are shown in **Error! Reference source not found.** to

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Error! Reference source not found.. Figure 2 illustrates an increase in the rate of accumulation of timber during the last century to 1992 (net of demolition and refurbishment to 2016), with more than half of the net accumulation of 67,000 t since World War II. This may be explained by the dramatic increase in the construction of residential high-rise buildings (e.g., Figure 1(b)) in post-war Britain due to political factors and the on-going housing shortage of the time (Hanley, 2012; NHBC, 2015), as well as higher demolition rates for older building stock. This trend in growth is typical of that for other building materials across Europe (Kleemann, Lederer, Rechberger, *et al.*, 2016; Džubur and Laner, 2018) and globally (Krausmann *et al.*, 2017).

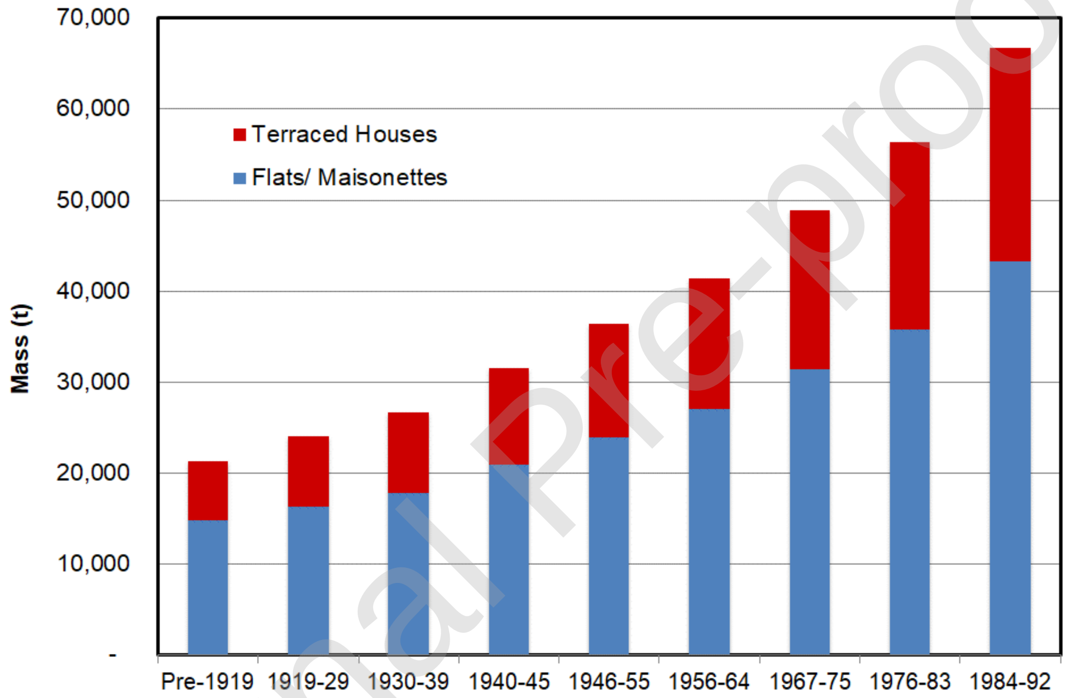

Figure 2. Timber stock in the London Borough of Tower Hamlets in 2016 for terraced houses and flats/maisonettes constructed before 1993, divided by construction cohort

Dividing the total timber mass by the total number of dwellings yields an average of 0.98 tonnes of timber per dwelling. In 2016, the housing stock in England accounted for a total of 23.7 million dwellings (MHCLG, 2018). Making the rough estimate that 0.5% of the total housing stock is demolished per year, around 116,000 tonnes of waste timber arise from housing demolition alone. Although this number falls short of the 484,000 tonnes of non-hazardous waste wood reported for England's C&D activities in 2016 (DEFRA, 2019), the remainder may be due to additional arisings from construction, which represent

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about half of C&DW in the UK (Rose and Stegemann, 2018), as well as from non-domestic buildings. Also, the results of this study are probably very much tied to the building typology of Tower Hamlets. Whilst flats and maisonettes make up the vast majority of the residential housing in Tower Hamlets, they only represent 21% of all housing in the UK, with terraced houses comprising 28%, and semi-detached and detached properties constituting 25% and 17%, respectively (MHCLG, 2018). Therefore, timber stock analysis is likely to be different in other parts of the country, and correcting the present model to allow for a more typical balance of housing types across the UK would yield a larger quantity of timber waste. However, the method demonstrated here should be applicable elsewhere, as long as other housing associations have access to data sources such as those used in this research.

4.2 **Material intensity**

Material intensity for timber, expressed as average mass per building floorspace, is shown in Figure 3, in comparison with values from the literature. Two exceptionally high values from a Taiwanese and a Brazilian study (480 and 869 kg/m^2, reported by Cheng *et al.*, 2018 and Condeixa, Haddad and Boer, 2017, respectively) were omitted to avoid distortion of the scale. The ranges of 20-34 kg/m^2 for terraced houses, and 5.4-11 kg/m^2 for flats/maisonettes, corresponding, respectively, to 6.8 to 11 kg/m^3 and 1.8 to 3.6 kg/m^3 of building volume, are broadly consistent with the literature, though timber intensities for flats/maisonettes in Tower Hamlets are notably low.

Unsurprisingly, terraced houses (i.e., single family homes; 3.3.2) generally have a higher timber intensity than flats/maisonettes (i.e., multi-family homes), due to their different geometry and style of construction, both in our data and the global literature. In the UK, terraced houses are generally constructed in masonry and characterized by a higher content of timber in floor and roof structures, whereas flats/maisonettes are more likely to be found in large post-war concrete framed buildings. More detailed data on timber intensity values for terraced houses and flats/maisonettes in Tower Hamlets are shown in **Error! Reference source not found.**.

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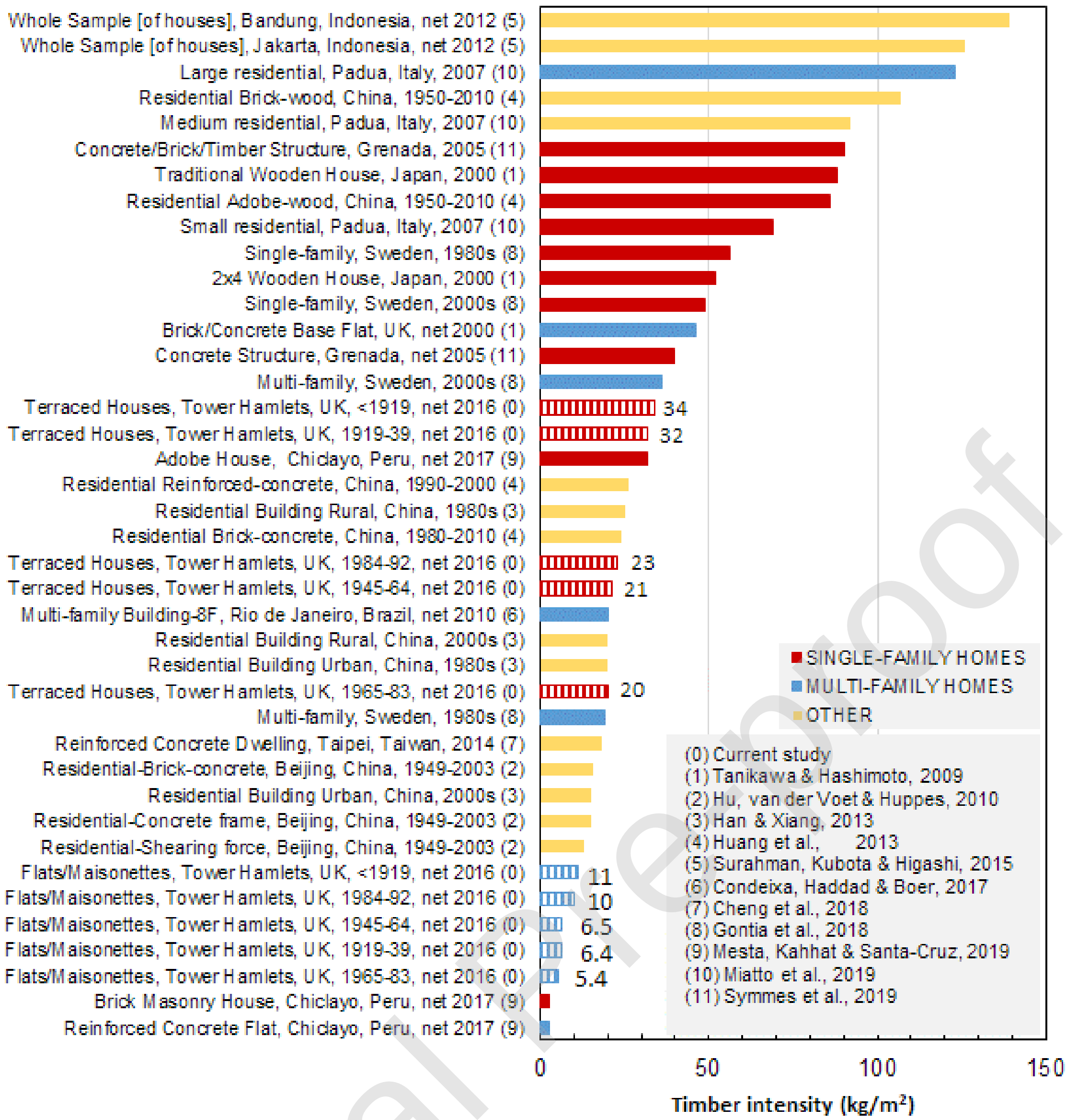

Figure 3.: Material intensity (kg/m^2 building floorspace) for timber in terraced houses and flats/maisonettes in the London Borough of Tower Hamlets (labelled striped bars) for different periods of construction, in comparison with findings from the literature for other areas (see legend for sources)

The change in timber intensity (in kg/m^3 of building volume) for Tower Hamlets over time was compared to trends for residential buildings in Germany, Vienna (Kleemann, Lehner, Szczypińska, *et al.*, 2016), Padua (Miatto *et al.*, 2019), and Sweden (Gontia *et al.*, 2018) in Figure 4. The German and Viennese studies also assess current stock from similar construction periods and observe similar characteristics of the building stock, with a progressive shift from traditional masonry walls and timber floor construction to concrete framed residential buildings. The Swedish and Italian studies assess similar construction periods but use architectural design data and historical maps, respectively.

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Consequently, they are not net as of the present, i.e., they include timber masses that have since been removed from the stock by demolition or refurbishment. The German and Viennese results for buildings constructed more than a hundred years ago are therefore much closer to those found in the present study for Tower Hamlets. As might be expected, the results from all five studies become more similar closer to the present time.

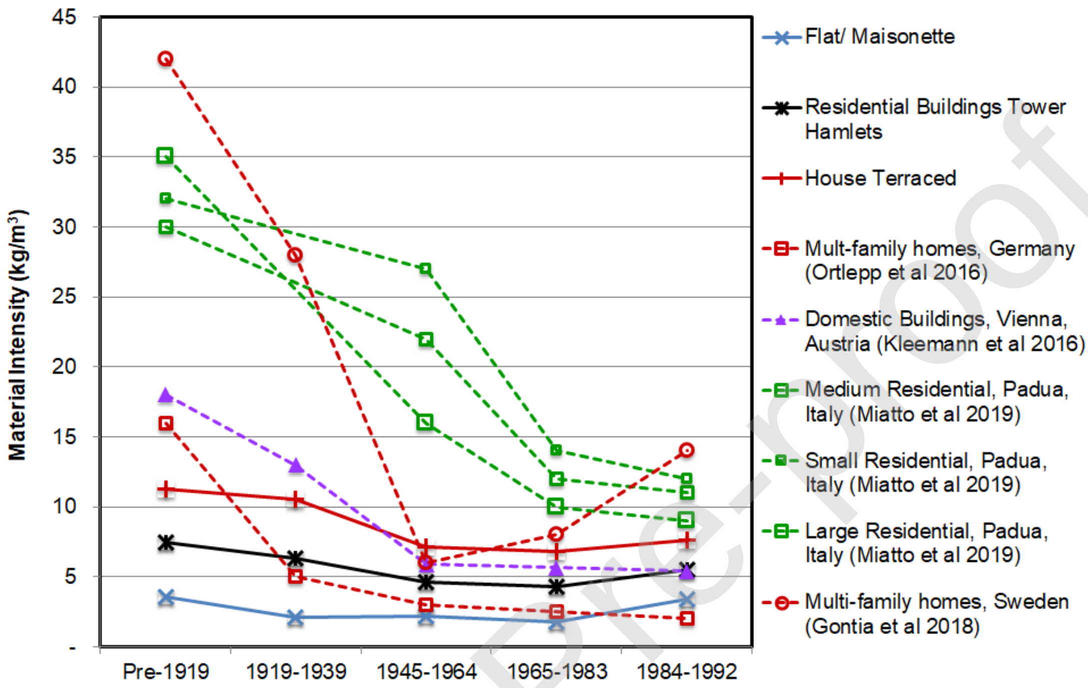

Figure 4: Comparison of material intensity for timber in kg/m³ of building volume in this study vs other studies (lines are shown added to aid observation of trends and do not represent a physical reality)

For all but the Italian study, the timber mass intensity drops significantly until the end of the World War II. Timber intensity increases again after 1984 (Table S.3). It is difficult to discern the exact reasons for the trends shown in the results, as these may be due to a variety of reasons such as: prevalent construction methods of the time; the replacement of common timber building elements (i.e. windows, flooring) by non-timber materials in social housing due to the Decent Homes Standard programme (Dowson *et al.*, 2012); losses during World War II; the adoption of prefabrication in 1945 as an approach to house building; or the lack of access to forests and timber following World War II (Forestry Commission 2017; NHBC 2015), with more stringent building standards and better availability of timber later in the period of study.

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Timber per gross building volume values for earlier constructions are considerably lower in this study of Tower Hamlets than in the others. This may be because we made use of a stock management database, which records elements that may have been replaced with alternatives to the original timber, particularly since cheaper materials would have been attractive to social landlords. The timber intensity values shown for Vienna and Germany are representative of technical and social developments within the residential sector in those areas, and may not necessarily be representative of similar developments in the UK housing sector. It is also worth noting that neither of the studies used for comparison focused on social housing, which may be less generous with materials, and they did not distinguish between types of residential building.

4.3 Location of timber in residential buildings

Besides the quantification of timber in residential buildings, these results also enable examination of the spatial distribution of the stock within the building. Figure 5 shows the location of timber mass in terraced houses and flats/maisonettes over time. This information can be useful in planning the recovery of timber prior to demolition (soft-stripping). Providing such information has a two-fold benefit; it offers valuable information for the identification of the volume and type of material to be demolished, which is encouraged by waste prevention policies in the UK (DEFRA, 2007), and it can contribute to earning Building Research Establishment Environmental Assessment Method (BREEAM) credits for the development of a pre-demolition audit (BREEAM, 2016). It is apparent that most of the timber mass (64-75%) is embedded in the floors and roof, for all periods of construction.

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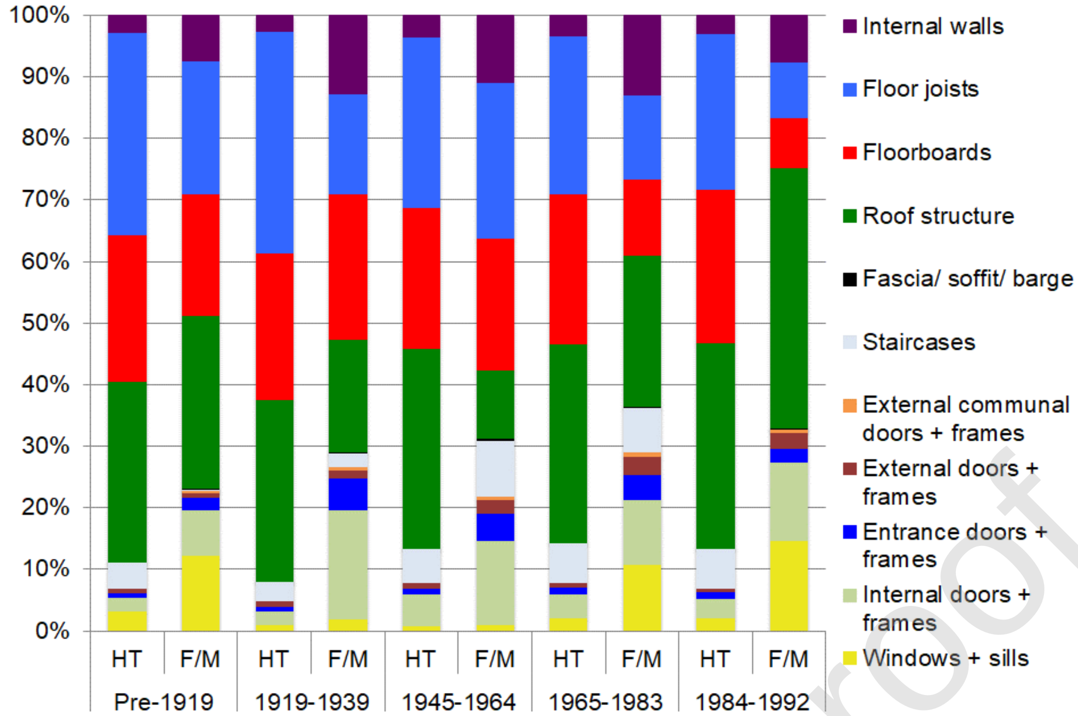

Figure 5. **Mass distribution (%) of building elements for terraced houses (TerH) and flats/maisonettes (F/M) for each period of construction**

4.4 Implications for material mining

At present, timber arising from demolition is usually discarded in a waste collection skip container without care for maintaining its quality, followed by chipping and recycling or energy recovery (Rose and Stegemann, 2018). Demolition and waste management processes thus tend to dictate a limited waste wood market. Most timber from C&DW has the potential to be salvaged and prepared for reuse, but there must be a market in which it can generate economic value. For example, it may be possible for secondary timber to be used as feedstock in the production of engineered timber products such as cross-laminated timber, thus maintaining a high-value use of the material in building structures (Rose et al., 2018). Information that can be used to identify reusable components (of any material) in advance may help to facilitate such new repurposing and upcycling opportunities, rather than only downcycling. The small case study area and close focus of the type of study demonstrated here can provide better information on the potential to recover specific elements from demolition, as it provides a more granular description of the different types of components. Distinguishing between a timber door and a floorboard opens

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up the potential to reuse components, rather than assessing only volumes of forthcoming waste to be managed

However, the reuse of timber, and other building materials, depends very much on careful deconstruction practices and pre-treatment before reuse, which is labour intensive and, generally not perceived as cost-effective. A possible solution to this is to involve waste separation companies earlier in the waste chain by creating the necessary step of separating large and reusable pieces before they arrive at waste transfer stations (Goverse *et al.*, 2001). Organisations like Community Wood Recycling (CWR, 2018) in the UK do this by offering an alternative to the general waste collection skip container for removal of timber. Finding recycling concepts for waste wood containing nails, remnants of concrete, paints and other contaminants is nevertheless a big challenge. New links and networks between contractors, demolition contractors, waste management companies and designers should be created to explore all the potential reuse options of timber.

5 Conclusions and Recommendations

A method using secondary data collected for other purposes to calculate material quantities in building stocks was demonstrated to estimate timber quantities and intensities for Tower Hamlets that are consistent with those reported in the literature based on other approaches. Results show a total timber accumulation of almost 67,000 tonnes across 68,000 dwellings, with a material intensity for timber between 20-34 kg/m^2 of building floorspace (6.8-11.2 kg/m^3 of gross building volume) for terraced houses and 5.4-11 kg/m^2 (1.8-3.6 kg/m^3) for flats and maisonettes. Generally, timber is concentrated in floors and roofs. The material intensity of timber in more recent buildings is less than in older buildings, but still significant. Timber can therefore be expected to remain a significant fraction of C&DW and new buildings in the future. Since timber represents a relatively small fraction of total stocks in buildings, the method described here could be applied to other construction materials.

The detailed characterization of the built environment in the form of material stocks and flows is a necessary leap forward in the strategic planning of management of demolition waste as a resource. The method presented in this

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paper and tested for timber can help to predict quantities of material stocks, including others in addition to timber, in the built environment and combined with demolition rates to predict flows to be expected from demolition; other presentations of the same data could be used to predict the material quality that could be achieved with building disassembly, and this could be represented in GIS format. These approaches could contribute considerably to the understanding of E-BAMB and allow proactive planning of material mining, reuse, repurposing, and upcycling by academics, designers and entrepreneurs. This in turn would give contractors and demolition contractors new means to divert materials away from wasteful downcycling processes, incineration and landfill.

Declaration of interests

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.

Acknowledgments

This research was partly supported by EPSRC through the UCL Centre for Urban Sustainability and Resilience (Grant Reference: EP/G037698/1). We would especially like to thank Nick Martin from Poplar HARCA and Geoffrey Ward from THH for their time and support, as well as Community Wood Recycling, Bywaters and Hadfields Wood Recyclers, and Dr Helena Titheridge, UCL CEGE, for helpful suggestions. We would also like to thank the reviewers for exceptionally constructive comments.

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