Supplementary information for:

A hierarchical building material intensity framework for circular economy potential modelling

Authors & affiliations

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Summary:

In this Supplementary Information SI2, Section 1 provides additional detail on deriving material intensities, Section 2 outlines the detailed methodology for material stock calculations and Section 3 presents the results on uncertainty analysis.

1 Datasets

The derived material intensities are provided as spreadsheets in Supplementary Information SI1. In Section 1.1 details on assigning age information to insulation specifications is provided.

1.1 Assigning age information for insulation specifications

For insulation specifications, the material history information were cross checked with insulation requirements provided in building regulations- Approved Documents L, Conservation of fuel and power(Department for Communities and Local Government, 2006, 2010, 2014; Department for Levelling Up, Housing and Communities, 2023; Department of the Environment and the Welsh Office, 1995; Office of the Deputy Prime Minister, 2002). After the check, only the specifications which complied with the regulations of age cohort were assigned a YES value.

2 Material stock modelling for residential properties in Wandsworth borough of London

The detailed methodology for the material stock calculation in the study area is presented in Figure 1. As explained in the main article the material stock estimation for the pilot study consists of four processes:

1. Distinguishing low rise houses and multistorey apartments;
2. Filtering feasible specifications using design information and age checks;

3. Assigning selection probability value;
4. Calculating material quantity.

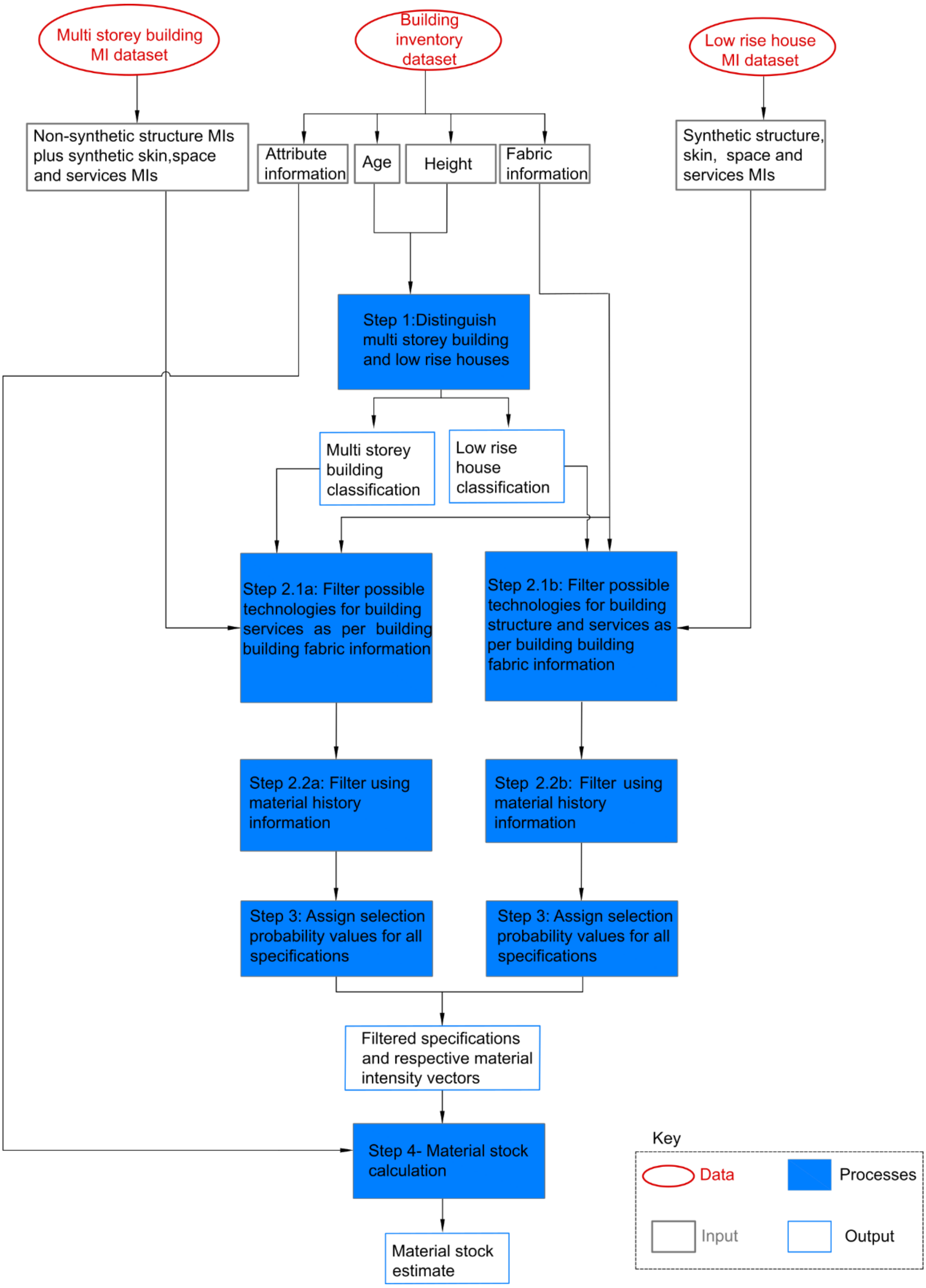


Figure 1. Methodology for stock estimation of Wandsworth, London.

2.1 Assumptions for material stock modelling

1. For low rise single family houses substructure isn't modelled due to high uncertainty regarding substructure details and limited reuse potential for low rise houses;
2. Skin options for roofs are assigned as per roof types. For pitched roof, finishes such as tiles and sheet metal is assigned while for flat roofs finishes such as screed and ballast are included;
3. Multistorey frame residential buildings are considered to be concrete framed buildings as concrete frames are dominant structure for multistorey residential buildings in the UK due to their strong acoustic, vibration and fire resistance features (Burridge, 2020; The Concrete Centre, 2018);
4. External walls for multistorey frame residential buildings are assumed to be brick cladding systems due to their increased popularity for mid-high rise buildings and benefits such as speed and efficiency, cost effectiveness and low weight (Brick Development Association, 2023; Calibayan, 2024);
5. Representative of typical UK houses it is assumed that all houses will have building services installed unless specified otherwise in the building inventory dataset;
6. For properties for which heat type is classified as "communal" or "no heating system" only radiators/heating pipes are assigned as part of heating services;
7. For this pilot study only properties under post 2010 age cohort will be assigned underfloor heating as heating emitters. This is supported by the limited adoption of underfloor heating systems in 2000s and significant growth in using underfloor heating systems since 2018 (Contract Flooring Journal, 2023).

2.2 Building stock calculation

As explained in the main paper if "j" index each HMI element then the material stock for the building "B" is calculated using the following equations:

$$M_{B,y} = \sum_j g_{B,j} m_{y,j} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (i)$$

$$m_{y,j} = \sum_k r_{y,k} p_{jk} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (ii)$$

$$g_{B,j} = c_j \, a_{Bj} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (iii)$$

Where,

$M_{By} =$ Total expected material stock of material "y" for building "B"

$m_{y,j}$ = Material intensity vector for element "j"

$r_{y,k}$ = Material intensity vector for material "y" in specification "k" of element "j"

p_{jk} = Selection probability value for selected specification "k" in element "j"

$g_{B,j}$ = Scaling factor for $m_{y,j}$

a_{Bj} = Selected building attribute of building "B" for element "j"

c_j = Conversion ratio calculated for element "j" from "n" number of buildings in the dataset developed in Dai *et al.*(Dai et al., 2025)

The details for scaling factor's and conversion ratio's are provided in Table 1,2 and 3. The nomenclature used for the calculations are as follows:

GFA	Gross floor area	w	Window count
h	Floor height assumed as 2.7 meters	D	External door count
l	Total inner wall length	d	Internal door count
t	Perimeter	r	Room count
f	Floor count		

Table 1. Conversion ratios used for scaling factors for Structure, Skin, Space

HMI Index (Layer-Function)	**Functional unit of Material intensity**	**Building attribute ($\boldsymbol{a_B}$)**	**Conversion ratio ($\boldsymbol{c}$)**
Structure-Floor, Skin-Floor, Space-Floor	$\frac{kg}{m^2\ of\ floor\ plan\ area}$	$a_B = GFA_B$	$c\ = 1$
Structure-Wall, Skin-Wall (External wall)	$\frac{kg}{m^2\ of\ wall\ elevation\ area}$	$a_B = GFA_B$	$c = \frac{\sum_{x=1}^{n}\{(t_x \times f_x \times h_x)/GFA_x\}}{n} = 1.56$
Space-Wall (Internal wall)	$\frac{kg}{m^2\ of\ wall\ elevation\ area}$	$a_B = GFA_B$	$c = \frac{\sum_{x=1}^{n}\{(l_x \times f_x \times h_x)/GFA_x\}}{n} = 0.78$
Structure-Roof, Skin-Roof, Space-Roof (For flat roofs)	$\frac{kg}{m^2\ of\ roof/floor\ plan\ area}$	$a_B = GFA_B$	$c\ = 1$
Structure-Roof, Skin-Roof, Space-Roof (For pitched roofs)	$\frac{kg}{m^2\ of\ pitched\ roof\ area}$	$a_B = GFA_B$	$c\ = 1.08$ $(Calculated\ assuming\ a\ pitch\ of\ 22.47\ degrees.)$
Structure for multistorey apartments	$\frac{kg}{m^2\ of\ floor\ area}$	$a_B = GFA_B$	$c\ = 1$

Table 2. Conversion ratios used for scaling factors for openings.

HMI Index (Layer-Function- Sub-function)	**Functional unit of Material intensity**	**Building attribute ($\boldsymbol{a_B}$)**	**Conversion ratio ($\boldsymbol{c}$)**
Space-Opening-Door (internal doors)	$\frac{kg}{unit}$	$a_B = GFA_B$	$c = \frac{\sum_{x=1}^{n}\{(d_x)/GFA_x\}}{n} = 0.073$

Skin-Opening-Door (external doors)	$\frac{kg}{unit}$	$a_B = GFA_B$	$c = \frac{\sum_{x=1}^{n}\{(D_x)/GFA_x\}}{n} = 0.025$
Skin-Opening-Window	$\frac{kg}{unit}$	$a_B = GFA_B$	$c = \frac{\sum_{x=1}^{n}\{(w_x)/GFA_x\}}{n} = 0.078$

Table 3. Conversion ratios used for scaling factors for openings.

HMI Index (Layer-Function-Sub-function)	**Functional unit of Material intensity**	**Building attribute (a_B)**	**Conversion ratio (c)**
Services-Plumbing, Services-Electrical (pipes and cables)	$\frac{kg}{m}$	$a_B = GFA_B$	$c = \frac{\sum_{x=1}^{n}\{(l_x)/GFA_x\}}{n} = 0.33$
Services-Heating-Emitter (radiators)	$\frac{kg}{unit}$	$a_B = GFA_B$	$c = \frac{\sum_{x=1}^{n}\{(r_x)/GFA_x\}}{n} = 0.098$
Services-Heating-Heat Source (boilers/heat pumps/Storage tanks)	$\frac{kg}{unit}$	$a_B = 1$ $(Assuming\ one\ heat\ source\ per\ property)$	$c = 1$
Services-Ventilation (Ventilator)	$\frac{kg}{unit}$	$a_B = 2(Assuming\ two\ per\ property$ $-one\ for\ kitchen\ and\ one\ for\ bathroom)$	$c = 1$

2.3 Feasible specification selection

To explain how specifications are filtered to calculate material stocks let's consider a sample building "A" whose details as described in the building inventory dataset is provided in Table 4. As per Table 4, the building falls under the age cohort of post 2010 buildings, has a gross floor area of 40 m^2 and is constructed with solid walls and a pitched roof.

To calculate the material quantity for the building, design rules are applied using construction subsystem rules to filter suitable technologies for the Structure layer of low rise houses and Service layer of both low rise and multistorey apartments. An example of construction subsystem rules are is provided in Table 5 and full details are provided as spreadsheets with Supplementary Information SI1. As explained in the main paper since the building height is less than 12 meters the building is classified as low rise load bearing masonry house and the quantities are calculated in the following steps:

1. As presented in Table 5, if the wall under the "wall_type" is described as a solid wall then possible technologies will be stone and brick, whereas for cavity walls the possible technologies will be brick, precast concrete block and precast concrete panel. So only stone and brick wall specifications are considered.
2. Then the specifications with feasible technologies are provided in Table 6 and age information is now checked. Since stone walls aren't prevalent for post 2010 building construction, the stone wall specifications have null values assigned for their material history information. This step of checking age information further filters out stone wall specifications.
3. For the remaining feasible specifications an equal probabilistic approach is adopted to assign selection probability values for each feasible specification under each "Layer- Function- Sub-Function" (HMI element) combination which represents a unique usecase. Here as shown in Table 6, the solid wall under the "Load bearing

structure" sub-function has three feasible specifications and has five feasible specifications under the "Internal finish" sub-function. Adopting an equal probabilistic approach a selection probability value (p_{jk}) of 0.33 (1/3) is provided for the specifications under the "Load bearing structure" sub-function and p_{jk} of 0.2 (1/5) is provided for the six specifications under the "Internal finish" sub-function. Following this, scaling factors are applied using a conversion ratio of 1.56 for external walls to scale HMIs for walls derived in functional unit of $kg/m^2$of wall elevation as per available building attribute information (a_B)-GFA to calculate material quantity using equations provided in Section 2.2.

4. In a similar manner, quantities for other building Functions such as roofs, floors and services are calculated.

Table 4. Example of building inventory dataset

Id	**GFA (m2)**	**wall_type**	**roof_type**	**Building height (m)**	**Building age**
A	40	Solid	Pitched	6.5	2011

Table 5. Example of construction subsystem rules

Dataset attribute	**Building fabric information**	**Construction Subsystem**	**Possible technologies**
"wall_type "	cavity	Wall-Cavity	Brick, Precast concrete block, Precast concrete panel
"wall_type "	Solid	Wall-Stone	Stone
"wall_type "	Solid	Wall-Solid brick	Brick

Table 6. Worked example for calculating the material quantity of solid external walls using the HMI framework

Layer	**Function**	**Sub-function**	**Technology**	**Specification**	**Material**	**Material history- Post 2010**	$r_{y,k}$ **(Kg/m2 of wall elevation)**	p_{jk}	$m_{y,j}$	a_{Bj} **(GFA)**	c_j	$g_{B,j}$	M **(kg)**
Structure	Wall	Load bearing structure	Stone	600 mm thick sandstone	sandstone	NULL	1380	NA	NA	NA	NA	NA	NA
Structure	Wall	Load bearing structure	Stone	600mm thick limestone	limestone	NULL	1320	NA	NA	NA	NA	NA	NA
Structure	Wall	Load bearing structure	Brick	220 mm thick brick	brick	YES	385	0.33	127.05	40	1.56	62.4	7927.92
Structure	Wall	Load bearing structure	Brick	105 mm thick brick	brick	YES	183.75	0.33	60.63	40	1.56	62.4	3783.78

Structure	Wall	Load bearing structure	Brick	215 mm thick brick	brick	YES	376.25	0.33	124.14	40	1.56	62.4	7747.74
Skin	Wall	Internal finish	Plaster	13 mm thick dense plaster	plaster	YES	16.9	0.2	3.38	40	1.56	62.4	210.91
Skin	Wall	Internal finish	Plaster	13 mm thick lightweight plaster	plaster	YES	7.8	0.2	1.56	40	1.56	62.4	97.34
Skin	Wall	Internal finish	Plasterboard	12.5 mm thick plasterboard	plasterboard	YES	8.75	0.2	1.75	40	1.56	62.4	109.02
Skin	Wall	Internal finish	Plasterboard	13 mm thick dense plasterboard	plasterboard	YES	11.7	0.2	2.34	40	1.56	62.4	146.02
Skin	Wall	Internal finish	Plasterboard	15 mm thick plasterboard	plasterboard	YES	10.5	0.2	2.1	40	1.56	62.4	131.04
Total													20153.95

3 Building level results and uncertainty modelling

Based on Monte Carlo samples the results in Figure 2 are presented as violin plots to showcase the range of uncertainty and compare stock results across the two building types (Pre 1920 and Post 2010 house). Figure 2a and 2b present the results as per the building shearing layers which highlight that the highest variability is observed within the structure for both the building types. The results can be further disaggregated as per other hierarchies to better understand the source of this uncertainty.

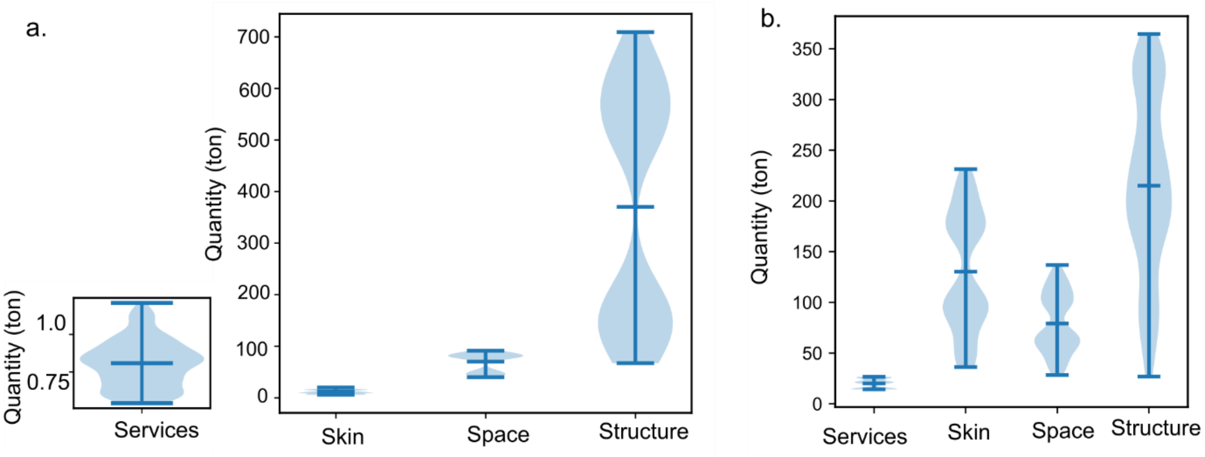
Figure 2c, 2d and 2e present results for building structures as per various building functions for both the building types which provide insights into areas of variability and how material stocks differ across the two building types.

Comparing stocks for wall structures in Figure 2c, the quantity of stocks within walls of pre 1920 house is significantly higher with a bimodal distribution due to the possibility of load bearing solid walls for a pre-1920 house either being solid stone walls, which are extremely heavy, or solid brick walls. In comparison, the distribution of wall specifications/combinations for a post 2010 house is relatively spread out which is the result of the multiple options in wall technologies and specifications such as precast blocks, precast panels and bricks.

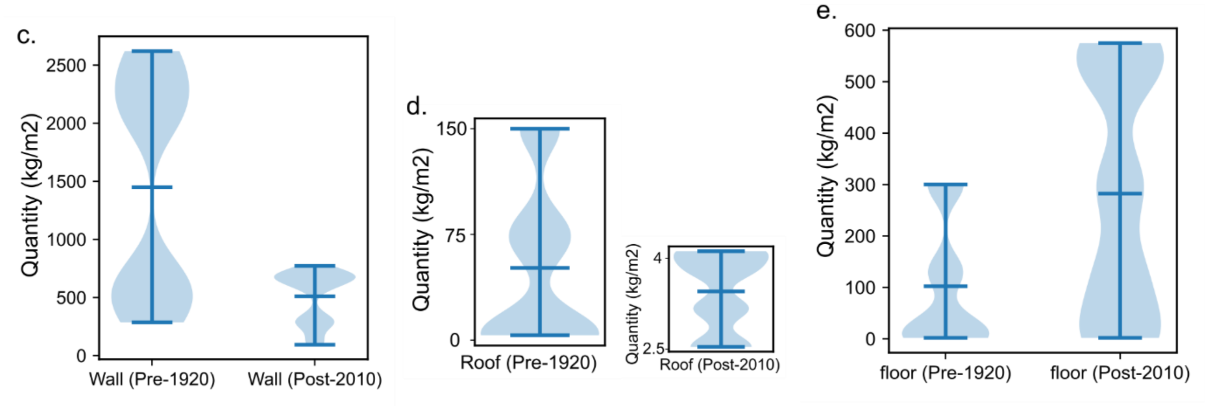
As presented in Figure 2d, the quantity of stocks in roofs is significantly higher for a pre-1920 house than a post 2010 house. This can be attributed to the difference in roof type. The pre 1920 house has a flat roof which can be built from lighter timber structures to denser concrete structures while the post 2010 house has a pitched roof which is constructed from lighter structures.

For floor structures the quantity for post 2010 houses is higher than pre 1920 houses. Similar to the wall and roof construction, the London Building Stock Model v2 (Greater London Authority, 2024) doesn't provide any information on floor construction. Reflecting how a wider variety of construction types became available with time, for a post 2010 house estimation is done using broader range of materials- from lighter timber to heavier concrete and precast elements which results in a higher estimation range.

To investigate areas with the highest variance it is useful to examine stock ranges at a Subfunction level. Sub-functions of building elements with the highest variance is presented in Table 7&8 for the two building types. As presented in Table 7&8, the highest variance for a pre-1920 and post 2010 low-rise house is within wall and floor structures respectively. This then enables comparison of level of variance between different technologies and selection of different specifications within a technology. In Figure 3 and 4 stock results are disaggregated by technologies and specifications to compare variance between technologies and specifications within technologies. From the tables and figures, it is clear that for both wall and floor structures in pre 1920 and post 2012 houses, majority of the variance (around 95%) is a result of selection of different technologies rather than different specifications within those technologies. In this manner, the framework allows exploration of uncertainties as per various building levels to understand reasons behind variance and pinpoint areas where more granular information is required to improve stock results.



a & b. Stock estimate ranges as per building shearing layer for a.) pre 1920 and b.) post 2010 low rise house



c,d & e. Stock estimate ranges for pre 1920 and post 2010 house as per c.) wall d.)roof e.) floor building Functions

Figure 2. Comparison of material stock ranges between a pre-1920 and post 2010 low rise house.

Table 7. Breakdown of variance for different subfunctions for a pre-1920 house.

Layer	**Function**	**Subfunction**	**Mean mass (ton)**	**Standard deviation (ton)**	**Total variance**	**Number of technologies**	**Variance between technologies**	**Variance within technologies**	**Number of samples**
Structure	Structure-Wall	Structure-Wall-Load bearing	334.88	215.16	46294.44	2.00	44347.80	1946.64	500
Structure	Structure-Floor	Structure-Floor-Load bearing	23.73	26.92	724.74	2.00	552.48	172.25	500
Space	Space-Wall	Space-Wall-Non-Load Bearing Structure	56.43	16.82	283.00	1.00	0.00	283.00	500
Structure	Structure-Roof	Structure-Roof-Load bearing	11.83	12.66	160.33	2.00	124.50	35.83	500
Space	Space-Floor	Space-Floor-Intermediate finish 1	4.98	3.91	15.32	2.00	13.85	1.47	500
Skin	Skin-Floor	Skin-Floor-Intermediate finish 1	4.99	3.90	15.23	2.00	13.75	1.49	500

Skin	Skin-Wall	Skin-Wall-Internal finish	4.50	1.64	2.69	1.00	0.00	2.69	500

Table 8. Breakdown of variance for different subfunctions for a post-2010 house.

Layer	**Function**	**Subfunction**	**Mean mass (ton)**	**Standard deviation (ton)**	**Total variance**	**Number of technologies**	**Variance between technologies**	**Variance within technologies**	**Number of samples**
Structure	Structure-Floor	Structure-Floor-Load bearing	76.31	60.97	3717.47	3.00	3512.60	204.87	500.00
Structure	Structure-Wall	Structure-Wall-Load bearing	137.94	58.97	3477.02	3.00	1171.71	2305.31	500.00
Skin	Skin-Wall	Skin-Wall-Non-Load Bearing Structure	113.67	57.31	3283.99	2.00	43.56	3240.43	500.00
Space	Space-Wall	Space-Wall-Non-Load Bearing Structure	56.11	28.61	818.58	2.00	7.66	810.92	500.00
Space	Space-Floor	Space-Floor-Intermediate finish 1	7.93	5.70	32.44	2.00	28.68	3.75	500.00

Skin	Skin-Floor	Skin-Floor-Intermediate finish 1	3.94	2.85	8.14	2.00	7.20	0.93	500.00
Skin	Skin-Roof	Skin-Roof-Finish 2	1.68	1.34	1.80	2.00	1.72	0.08	500.00
Skin	Skin-Wall	Skin-Wall-Internal finish	4.44	1.21	1.47	3.00	0.18	1.30	500.00

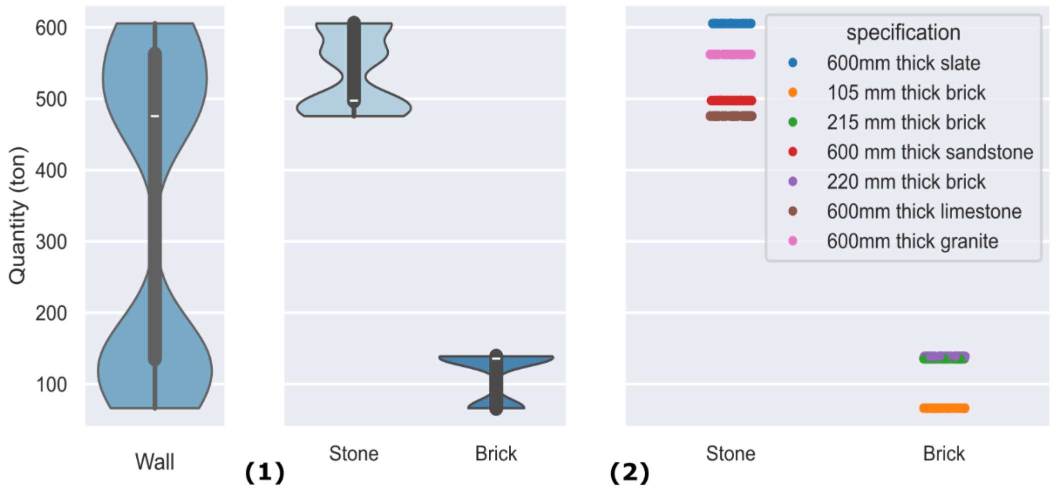


Figure 3. Stock estimate ranges for wall structures of a pre-1920 house as per (1) technologies and (2) specifications.

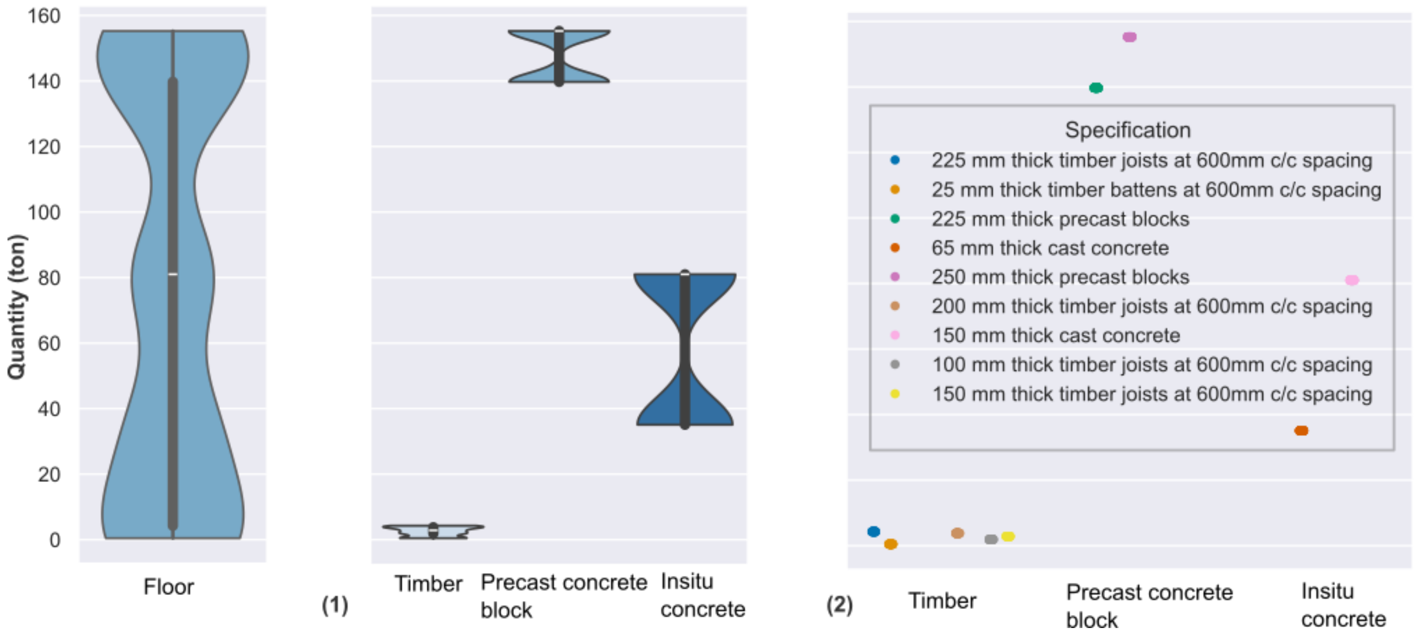


Figure 4. Stock estimate ranges for floor structures of a post 2010 house as per (1) technologies and (2) specifications.

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