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Timber modern methods of construction: a comparative study

(Volume II)

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6 Study on the thermal performance of the building envelope

6.1 Chapter overview

This chapter presents the experimental work carried out in the outdoor environment to test the thermal response of three wall samples to naturally-varying weather conditions during summertime.

SECTION 6.2 illustrates the scope and aims of the experiments and the thermo-physical properties of the wall samples tested.

SECTION 6.3 documents the method followed, the configuration of the testing apparatus and the main criteria whereby the large dataset obtained from the field observations has been statistically analysed.

SECTION 6.4 presents the results of the experiments. In particular, SECTION 6.4.1 discusses the values of the main thermal-inertia parameters of the walling systems tested (*i.e.,* time lag and decrement factor) and thus answers research question ④. SECTION 6.4.2, instead, answers research question ⑤, by exploring the correlation between the inertia parameters and some climatological and constructional variables. This correlation analysis permits a deeper insight into the thermal mechanisms that lead three wall systems to respond differently to the same thermal inputs.

Finally, **SECTION 6.5** offers a brief summary of the findings detailed in SECTION 6.4.

6.2 Scope, aim and objectives of the investigation

Thermal tests have been undertaken on wall samples constructed with different techniques, towards the optimisation of the building envelope.

The main aims of the tests are:

- to assess the thermal behaviour of the different wall panels, in terms of the instantaneous and time-dependent response during summertime. The study focuses on time lag and decrement factor, which define the influence of thermal mass on thermal behaviour;
- to identify the best-performing wall solution for the Scottish climate;
- to identify the aspects of the Scottish climate and of the construction methods and materials employed that most affect the time lag and decrement factor;
- to provide designers, researchers and construction companies with recommendations for the selection and use of the most appropriate methods of construction from a thermal point of view.

Wall systems under study

The thermal tests have been conducted on three different types of walls:

- wall **`B1`**, a closed-panel timber frame wall. This has heavy-weight cladding (concrete blocks). On the internal side of the wall is a service void.
- wall **`D1`**, a cross-laminated-timber wall. Internally, a service void is attached to the CLT panel, while the insulation layer is fixed on the external side of the panel itself. Acrylic render is the external finish and is supported by gypsum board.
- wall **`F`**, a masonry wall. This is a double-leaf lay-up. The internal leaf has a structural role, whereas the external leaf has a cladding function.

See SECTION 6.3 for further information and APPENDIX F for detailed drawings.

The colour of the external, acrylic render was light grey, corresponding to RAL colour code 7035, and with solar absorptivity *circa* 0.35.

The wall samples had the same theoretical, overall thermal transmittance (or "U-value"), which is below the maximum value allowed by Scottish Building Regulations for external walls in domestic buildings. The U-value was set at 0.21 ± 0.005 W/(m^2·K).

Due to the different lay-up of the walls, each of them has different thermal properties (other than the U-value). Total thermal mass is one of the varying parameters. The highest thermal mass is contained in wall **F** (load-bearing masonry). Both the total thermal mass and the "effective" thermal mass (*i.e.,* the thermal mass of the layers within 100 mm of the internal surface of the walls) have been evaluated.

The different distribution of various intensive properties across the thickness of each wall is shown in FIGURES 6.2 – 6.4.

TABLE 6.1 Thermo-physical properties of the building materials employed for the construction of the three walls under investigation.

Materials		Fundamental intensive properties			Derived intensive properties		Use in walls		
category	**material type**	**thermal conductivity (W/(K·m))**	**density (kg/m^3)**	**mass-specific heat capacity (J/(kg·K))**	**volume-specific heat capacity (J/(m^3·K))**	**thermal diffusivity (m^2/s)**	**B1**	**D1**	**F**
minerals	gypsum plasterboard	0.25	927	1000	927000	2.70E-07	✓	✓	✓
	MD concrete blocks	0.45	1450	1050	1522500	2.96E-07	✓		✓
	HD concrete blocks	1.15	**1950**	**1200**	2340000	4.91E-07			✓
	gypsum render carrier	0.26	**955**	**1030**	983650	2.64E-07		✓	
	mineral wool	0.04	45	1030	46350	7.55E-07	✓		
wood-based	softwood	0.10	390	1700	663000	1.51E-07	✓	✓	
	OSB	0.13	650	1700	1105000	1.18E-07	✓		
	CLT	0.13	390	1600	624000	2.08E-07		✓	
plastics	PUR	0.02	31	800	24800	7.26E-07		✓	✓
	acrylic render	0.20	800	1000	800000	2.50E-07	✓	✓	✓
air cavities	vented cavity (50mm)	0.27	1	1008	1008	2.68E-04	✓		✓
	ventilated cavity	0.40	1	1008	1008	3.97E-04		✓	
	unventilated cavity (25mm)	0.14	1	1008	1008	1.38E-04	✓	✓	

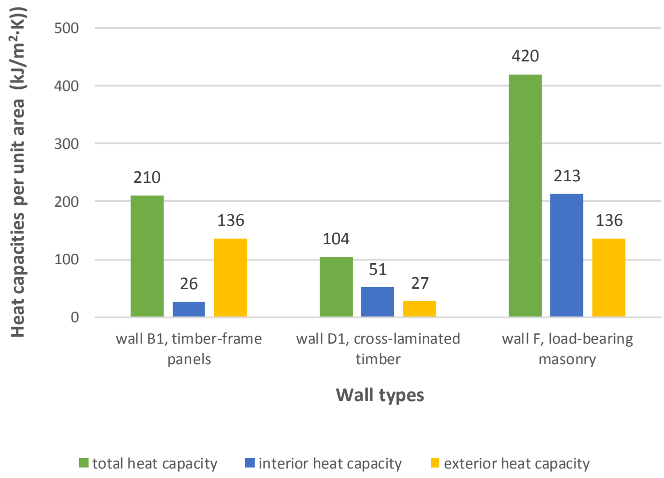

FIGURE 6.1 Total, exterior and interior heat capacities (per unit area) of each wall tested.

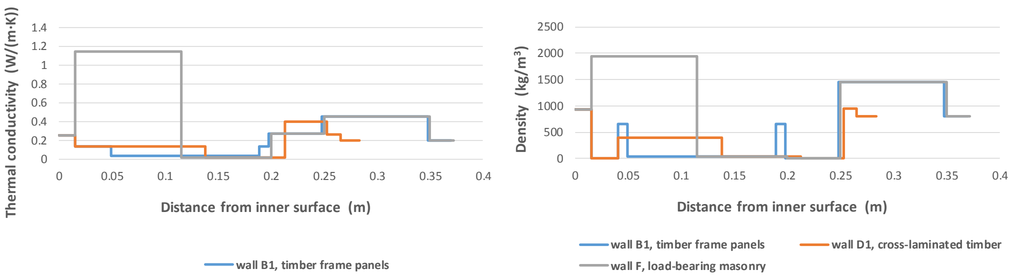

FIGURE 6.2 Distribution of thermal conductivity (left) and density (right) across the thickness of each wall.

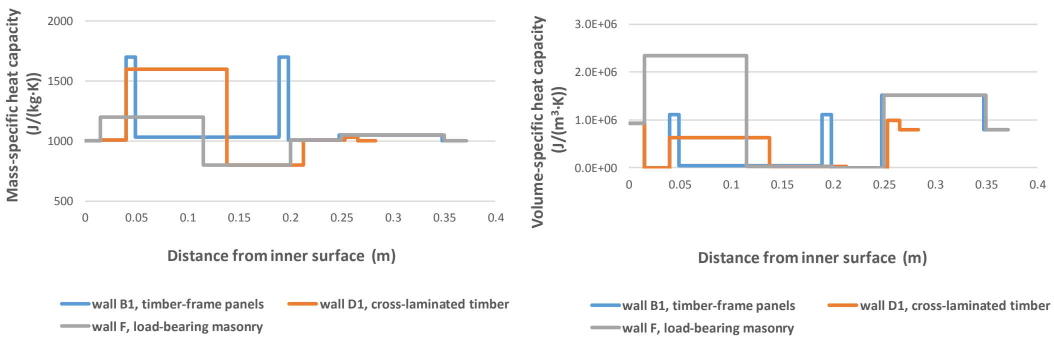

FIGURE 6.3 Distribution of mass-specific heat capacity (left) and volume-specific heat capacity (right) across the thickness of each wall.

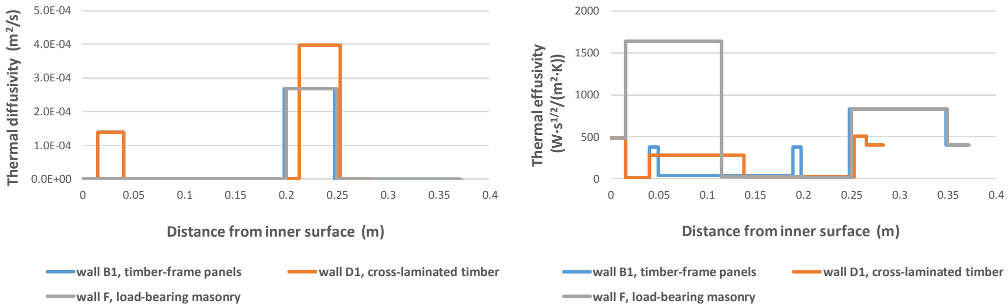

FIGURE 6.4 Distribution of thermal diffusivity (left) and thermal effusivity (right) across the thickness of each wall.

6.3 Experiment methodology

The experiments were conducted following the same procedure as that of similar tests described in the literature and using an analogous apparatus (in particular, the field experiments by Ng (2011), Kaška *et al.* (2009) and Buratti and Moretti (2005)).

The tests were carried out in the summer of 2015, for four consecutive months: June to September.

6.3.1 Experimental apparatus

The tests were conducted in the outdoor environment, in the open space of a testing facility[1] located in Edinburgh.

The three wall samples were inserted in an *ad-hoc* enclosure, specifically-built for this purpose, which was divided into three cells. The envelope of the enclosure and the internal walls separating the cells were highly thermally insulated (*i.e.,* walls, roof and floor offered a surface-to-surface thermal resistance of 4.41 $m^2 \cdot K/W$, equivalent to an overall surface-to-surface thermal transmittance of 0.23 $W/(m^2 \cdot K)$). The whole enclosure was water- and air-tight.

The samples to be tested were constructed as small portions of full-scale walls, with real thicknesses, and with elevational area equal to *circa* 2.2 m^2, all East-facing. There were no obstructions or objects in front of the wall samples or any other side of the enclosure, so this was fully exposed to the local weather conditions and solar radiation (*i.e.,* no shade). The enclosure was elevated from the ground floor by approximately 400 mm, in order to protect the wall samples and the floor construction from any rainwater run-off on the ground surface.

Each cell was accessible by means of doors having the same thermal insulation as the enclosure walls and good air-tightness. Each door contained an adjustable ventilator, which could be completely closed and, if needed, also insulated on the inside. The

[1] Unit 10, Baileyfield Industrial Estate, Baileyfield Crescent, Portobello area, Edinburgh, EH15 1YU.

ventilators were protected externally with small overhangs, to prevent wind-driven rainwater penetration.

FIGURES 6.5-6.10 show the configuration of the apparatus.

Wall samples **B1** and **D1** were partially prefabricated in a Glasgow-based factory and completed on the testing site (with the addition of internal and external linings), according to the specifications provided to the construction company. The present author supervised the correct assembly of the samples on site and checked that the components utilised (their materials, sizes and positions) corresponded to the given specifications. Workmanship, both offsite and onsite, was of a good standard.

Wall **F** was completely built on site.

The cell housing wall sample **D1** was delimited by the South-facing wall of the enclosure (see FIGURE 6.10). In order to prevent lateral heat gains for wall **D1** through the Southern side of the apparatus, this side was protected by means of a synthetic-fabric sun-blind, detached from the outer surface of the wall itself, so as to avoid direct exposure of this wall to solar radiation.[1] This precautionary measure was taken in order to ensure that wall sample **D1** (and its cell) would operate under the same conditions as the other two walls (and respective cells).

The apparatus was thermally monitored by means of several sensors. Thermocouples (TCs) were installed in appropriate locations to measure:

- the interior- and exterior-surface temperature of the wall samples;
- the interior-surface temperature of the other walls of the enclosure;
- the air temperature outside (in the shade);
- the air temperature inside each cell.

The TCs installed inside the enclosure cells were also fixed in their position with adhesive tape (at a height of approximately 1.4 m from the finished floor of the enclosure).

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[1] This configuration did not affect the U-value of the Southern wall; it just provided the desired level of protection from sunlight.

The 16 TCs were connected to a datalogger placed on a table inside the middle cell. The central position of the datalogger allowed a symmetrical configuration and helped minimise the length of the TC wires connected to it. The datalogger was connected to the mains power supply, but also had a long-lasting battery, which would automatically be used in case of black-out, thus guaranteeing continuous electricity supply and uninterrupted monitoring and recording of the temperatures. The datalogger produced very little heat and therefore should not be regarded as an internal heat source for the middle cell.

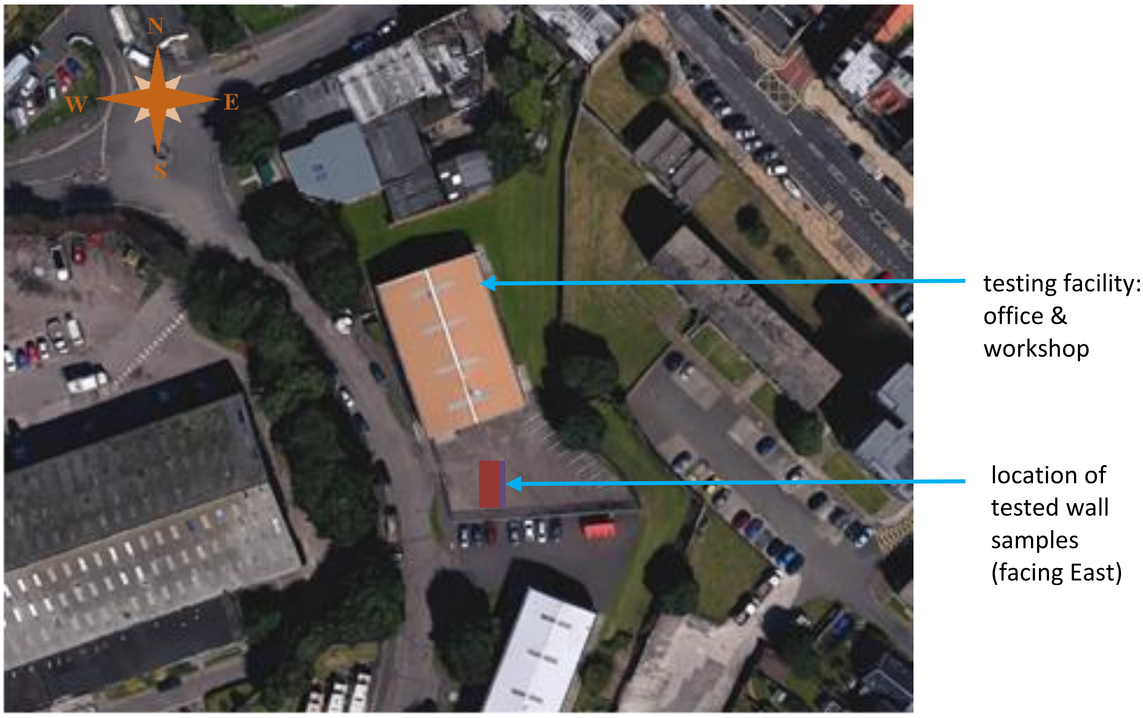

FIGURE 6.5 Aerial view of the site where the tests have been conducted. Image source: Google Maps, ca.2017.

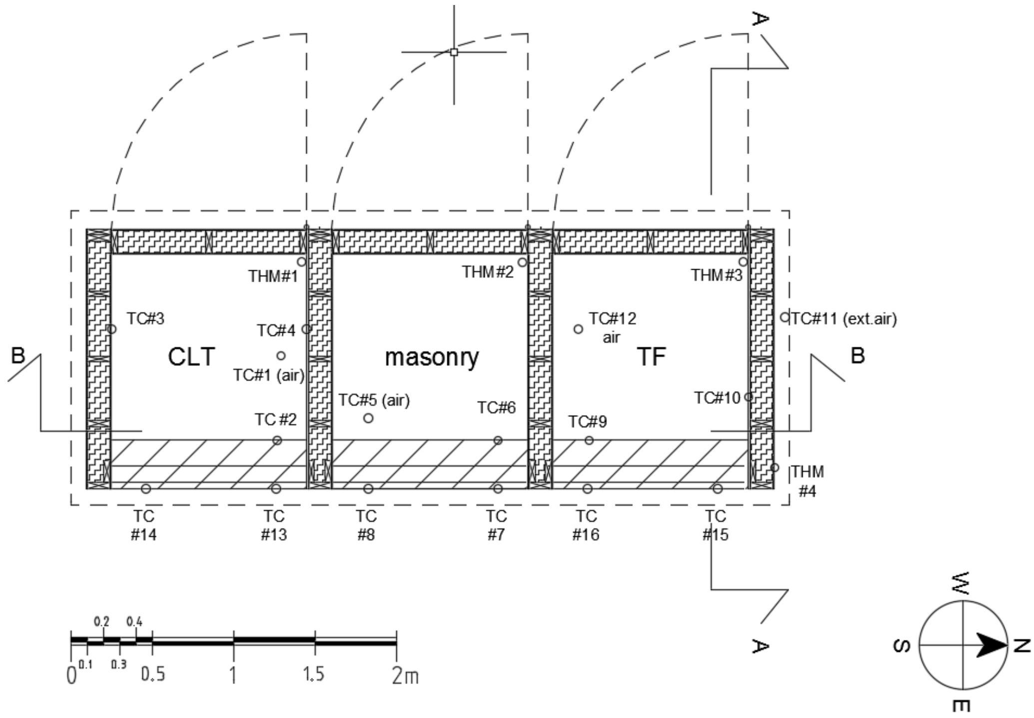

FIGURE 6.6 Plan view of apparatus showing location of thermal sensors. (TC: thermocouple; THM: thermohygrometer).

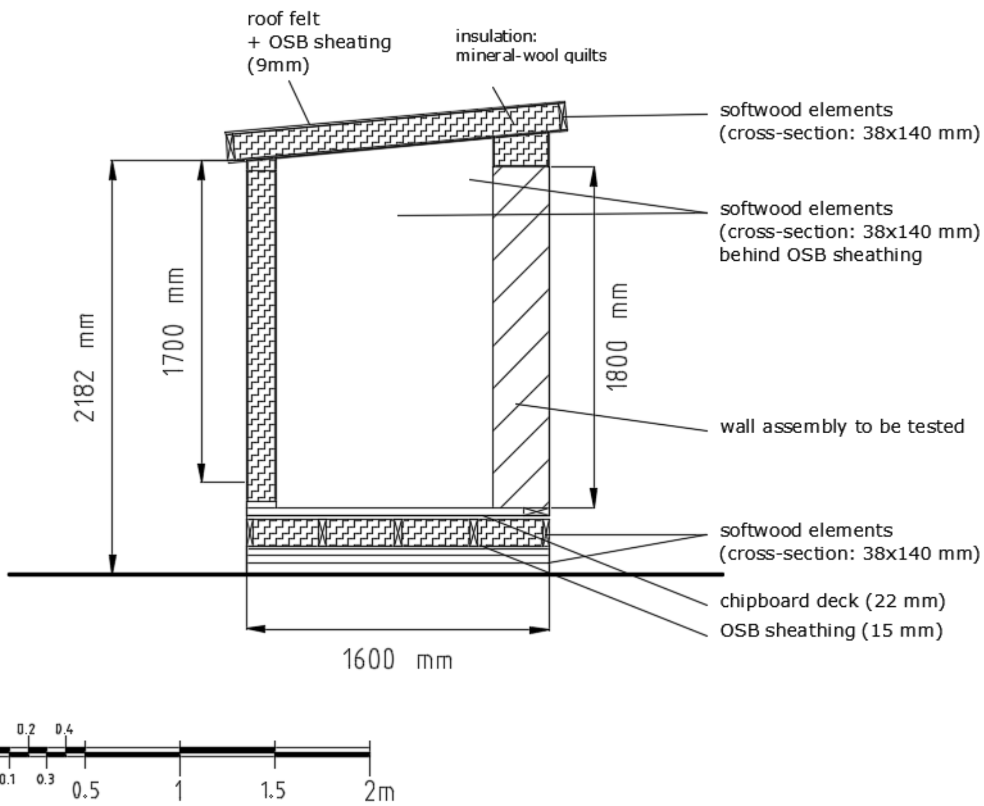

FIGURE 6.7 Cross-section (A-A) of the apparatus.

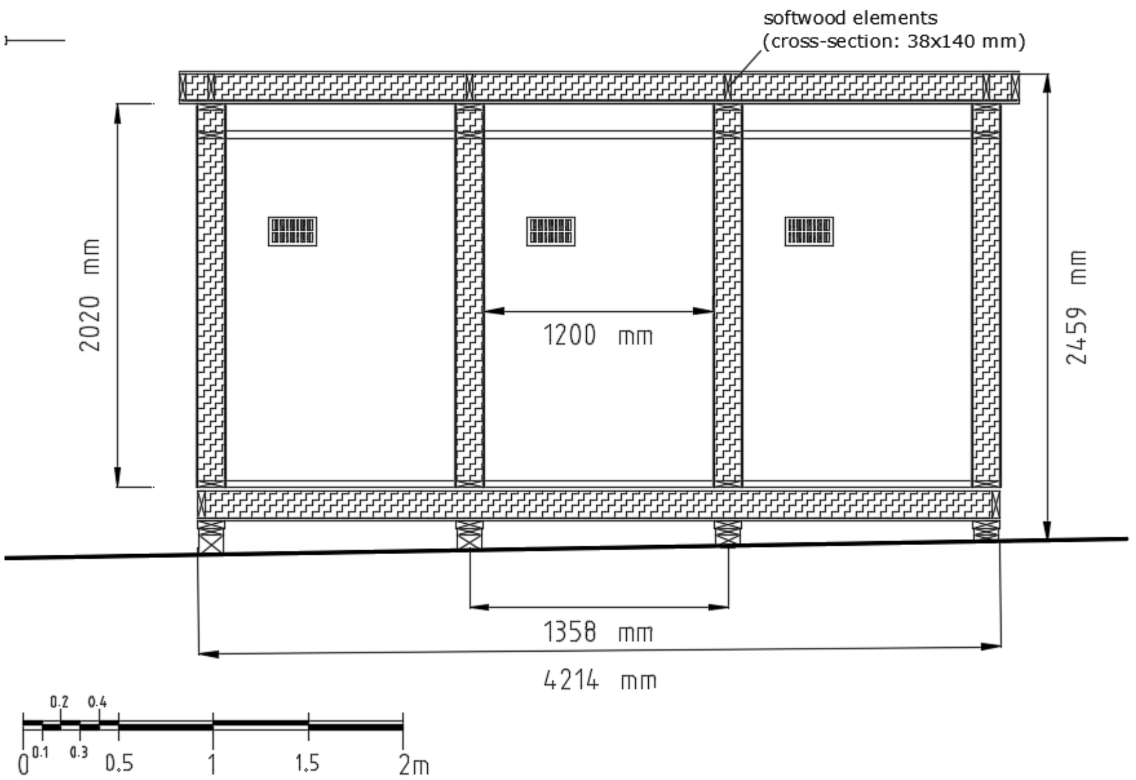

FIGURE 6.8 Longitudinal section of the apparatus (B-B).

FIGURE 6.9 Photographic views of the apparatus: East-facing side with sample walls (a & c), rear (b) and internal cells (d).

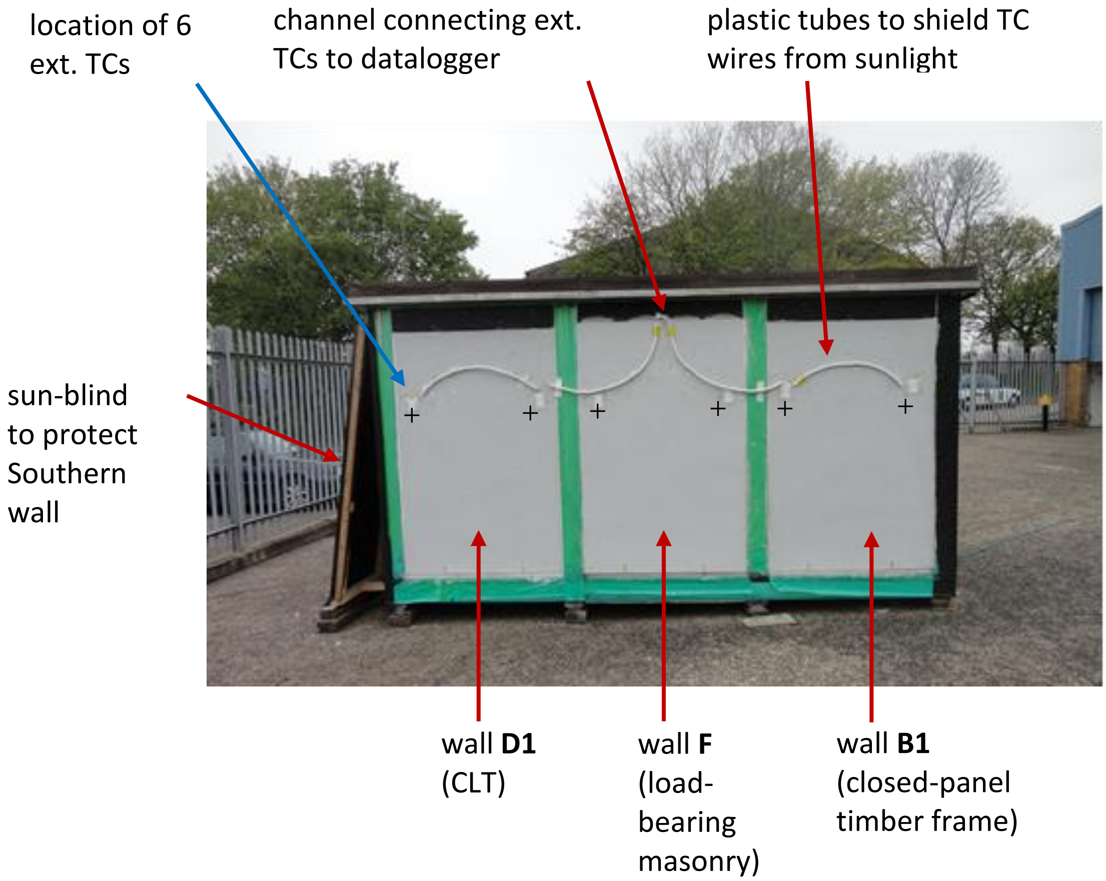

FIGURE 6.10 Front view of the apparatus, showing the location of the thermocouples (TCs) placed on the outside of the wall samples.

6.3.2 Specification and calibration of testing equipment

TABLE 6.2 offers a description of the instruments used for these experiments.

TABLE 6.2 Inventory of the instruments used for the thermal tests.

Quan-tity	Device type	Product name	Manufacturer's details	Technical properties
2	datalogger	"Squirrel 2020-1F8"	Grant Instruments (Cambridge) Ltd 29 Station Rd Shepreth Cambridgeshire SG8 6GB, UK	16 sensor channels; logging speed: 20 readings / sec on 1 channel only int. memory: 128Mb (up to 14 million readings) USB 1.1 & 2.0 compatible working environm.: -30 to 65°C, RH up to 95% (non-condensing) dimensions: 235 mm x 175 mm x 55 mm weight: 1.2 kg enclosure material: ABS resolution: to 6 significant digits
16	thermo-couples	K-type thermo-couples	Grant Instruments (Cambridge) Ltd (same address as above)	one wire made of nickel-manganese-aluminium alloy one wire made of nickel-chromium alloy
1	datalogging software	"Squirrelview"	Amber Instruments Ltd Dunston House, Dunston Rd Chesterfield, Derbyshire, S41 9QD, UK	displays up to 16 channels in real time data downloader application customisable data export for Excel™, Lotus™ or other applications logger diagnostic
4	thermo-hygrometers	"EasyLog" series, "EL-USB-2" model	Lascar Electronics Ltd Module House Salisbury Wiltshire SP5 2SJ, UK	temperature: measurement range: -35°C to 80°C (-31°F to 176°F) internal resolution: 0.5°C (1°F) accuracy (overall error): 0.55°C (1.04°F) typical (5 to 60°C) long term stability: <0.02°C (0.04°F) / year relative humidity: measurement range 0 to 100% RH internal resolution: 0.5% RH accuracy (overall error): 2.25% RH typical (20 to 80%RH) long term stability: <0.25% RH / year logging rate: 10 seconds to 12 hours

6.3.2.1 Thermocouples

Thermocouples consist of two thin, metal wires of different chemical composition, which are joined at the ends (or "junctions"). Due to the *Seebeck effect* (occurring when two different metals are joined), an electromotive force is generated within a TC, whose magnitude depends upon the temperature gradient between its ends (Long, 1999). By virtue of this phenomenon, TCs do not need external supply of electricity.

The TCs utilised were of type "K", that is, one of the wires was made of a nickel-chromium alloy[2] and the other of a nickel-manganese-aluminium[3] alloy.

The TCs had been individually tested and calibrated in one of the University's laboratories before the apparatus was set up, for a temperature range[4] between 0°C and +60°C. The calibration process led to the determination of a corrective coefficient for each TC, which allowed correct translation of the electrical outputs recorded into physical temperatures.

The calibration was conducted by submerging the TCs into a basin of distilled water of known temperature (thanks to the use of a reference, calibrated thermometer). This operation was repeated multiple times, so as to avoid systematic errors. During each iteration, the temperature of the water containing the reference thermometer was measured and the voltage readings from the TCs were recorded.

For each TC, a linear, parametric voltage-temperature equation was studied, which defined the mathematical relationship between the voltage measured by the TC itself and the known temperature. Thus, the corrective parameter could be identified for each TC, through a least-squares fit of voltage *versus* temperature. Finally, all of these corrective coefficients were uploaded onto, and saved in, the datalogger, ensuring a correct conversion from each voltage output to its corresponding temperature.

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[2] This alloy is referred to as "chromel" (a registered trademark of Concept Alloys Inc.); its composition is approximately 90% nickel and 10% chromium.

[3] Alloy known as "alumel" (another registered trademark of Concept Alloys Inc.); its composition is *circa* 95% nickel, 2% manganese, 2% aluminium and 1% silicon.

[4] Temperatures outside this interval would be very unlikely to occur during these experiments.

The linear temperature-voltage relationship mentioned above is expressed by the following equation:

$$T_{hot} = a \cdot VOL$$

where T_{hot} is the temperature of the "hot junction"[5] of the TC (°C), "*a*" is the corrective coefficient (°C/V) found from calibration and *VOL* is the voltage output (V).

Since the temperature interval for which the calibration was conducted was relative small, a linear relationship between voltage and temperature proved to be of sufficient accuracy and a higher-order relationship (*e.g.,* a quadratic polynomial) was unnecessary.

Two TCs were installed on the outer surface of each wall sample, due to their exposure to the elements and susceptibility to being removed by strong winds. These TCs were inserted into shallow holes (5mm deep, *circa* 1.5mm in diameter) drilled into the render finish of the wall. This measure allowed protecting the metal ends from direct solar radiation (which could have altered the recordings) and keeping them in place more safely. Weather-resistant adhesive tape, suitable for outdoor conditions, was used to fix the TCs to the render surface.

The external parts of the TC wires were inserted into flexible, corrugated conduits made of plastic, in order to avoid direct contact with sun radiation and consequent susceptibility to "lateral" thermal heating.

6.3.2.2 Datalogger

A datalogger with 16 channels was used (one channel for each thermocouple), supplied by Grant Instruments Ltd.

[5] The so-called "hot junction" of a TC is the end that measures the desired temperature.

FIGURE 6.11 "Squirrel F-18" datalogger, by Grant Instruments Ltd. Image source: Grant Instruments, ca.2017.

6.3.2.3 Thermohygrometers

Thermohygrometers (THGs) were also installed inside each cell and outside the enclosure (in the shade), to provide a further means of monitoring. The internal THGs were located at the same height as the TCs.

The TCs were set to record temperatures every 5 minutes (*i.e.,* 12 times per hour, 288 times per day), as this was deemed to be the necessary level of accuracy for the purposes of the experiments.

The THGs were set to record temperatures every 10 minutes (*i.e.,* 6 times per hour, 144 times per day).

FIGURE 6.12 "EL-USB-2" thermohygrometer, by Lascar Electronics Ltd. Image source: Lascar Electronics, ca.2017.

6.3.3 Assessment of errors and uncertainties

6.3.3.1 Measurement errors

For the duration of the tests, the experimental apparatus was attentively monitored through frequent inspections and maintenance work (where needed), so as to ensure that it was functional and operating as intended.

TABLE 6.3 Description of the error types relevant to these tests.

Error definition	**Error characteristics**				**Gravity**	**Uncer-tainty**	**Com-ments**
	Randomness		**Source**				
	Random	**Systema-tic**	**Instrumenta-tion**	**Procedure**			
inaccuracy of datalogger		✓	✓		low	± 0.1°C	
inaccuracy of TCs		✓	✓		low	± 0.5°C	
miscalibration of TCs		✓		✓	low		
decalibration of TCs		✓	✓		n/a	0	decalibration is unlikely at the operational temperatures occurred during these tests
displacement of TCs (by wind)	✓			✓	high	0	observations when TCs had been displaced are excluded from analysis
misplacement / wrong embedding of TCs	✓			✓	medium		
data readings	✓			✓	n/a	0	

Abbreviations

TC(s)	thermocouple(s)

Due to occasional, very strong winds, some days' worth of testing was lost, since the external TCs were removed from the outer surface of the wall samples. However, the days lost were just a small proportion of the overall duration of the tests. The recordings from these days were excluded from the statistical analysis of the observation dataset.

The intensity of solar radiation was not measured during the tests (since it was not strictly necessary for the experiments). However, for completeness, this parameter was sourced from the Met Office's database (*i.e.,* measurements taken from its nearest observation site, located in Edinburgh Gogarbank).

Measurement errors can fall within two main categories: errors arising from the inherent properties of the instruments deployed and errors arising from operational mistakes: both types are dealt with in the following sections.

Equipment-related errors

During the calibration process, the uncertainty in TC measurement was determined to be ±0.5°C of reading values. An additional uncertainty of ±0.1°C of reading values was considered, to account for errors in datalogger conversion (due to its resolution).

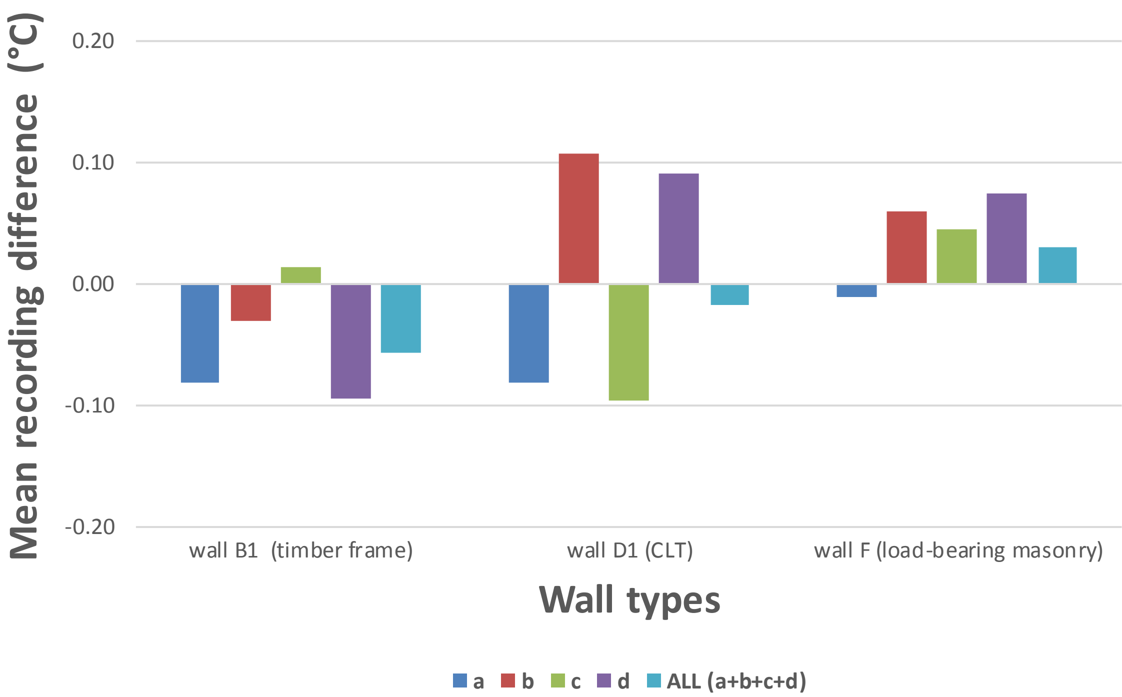

FIGURE 6.13 Mean recording differences between pairs of TCs on the exterior side of each wall, by climatic category.

Operation-related errors

All equipment pieces were installed and used by rigorously following the manufacturer's instructions and the recommendation found in the literature, from similar experimental studies.

In particular, great care was taken towards the correct positioning and embedding of the TCs:

- in the external TCs:
    - the ends were located inside *ad-hoc* holes in the wall finish, to avoid direct exposure to solar radiation;
    - the ends were only in contact with the wall render and were detached from the tape and silicone used to fix the wires to the walls;
    - the external portions of the wires were protected by flexible, plastic tubes (to prevent exposure to sunlight);
    - the drilled holes accommodating the TC metal ends were kept dry (*i.e.,* no dew or water droplets) and clean from dust or dirt;
- for the internal TCs, an appropriate type of plastic adhesive tape was used;
- for all TCs (internal and external), the central position of the datalogger (*i.e.,* inside the middle cell) allowed the avoidance of long wires (for both internal and external TCs). Short wires are indeed preferred, as they contribute towards more reliable and accurate measurements.

6.3.3.2 Uncertainties arising from the test set-up

As regards the use of the datalogger:

- measured data was downloaded frequently, in order to prevent the logger from stopping new recordings or overriding previous ones;
- it was often checked that its internal batteries were fully charged, so that they would be able to supply electricity in case of mains failure.

In order for the three cells to operate in the most similar conditions as possible:

- the walls separating the middle cell from the lateral ones were highly insulated;
- the Southern wall of the enclosure (belonging to cell **D1**) was sheltered by means of an *ad-hoc* sunblind, to avoid cell **D1** from being exposed to extra solar radiation in comparison with the two other cells;
- measurements of the internal-surface temperatures of all cells (except for the ones on the inside of the tested wall samples) were attentively monitored, so as to guarantee consistency and comparability of testing conditions across the three cells. All such differences in temperature were minimal and thus considered negligible for the purposes of these tests. In other words, the different orientation of the cells did not affect their interior conditions and the sun-blind located on the Southern side of the enclosure was successful in protecting the cell of wall **D1** (CLT) from overheating.

6.3.4 Structure of data analysis

The data measured was statistically analysed. Due to the variability of the Scottish weather, widely differing weather conditions occurred throughout the duration of the tests. Cold, rainy days (more typical of spring weather and not very representative of typical summertime conditions) were discarded from the analysis. Days that were considered typical of summertime, instead, were grouped into four different categories, named “a” to “d”, defined in terms of solar energy received by the walls in the morning (until 12:30 PM), E_{AM}.

The climatic categories are as follows:

- category "a", $E_{AM} \geq 8$ MJ/m^2;
- category "b", 6 MJ/m^2 $\leq E_{AM} <$ 8 MJ/m^2;
- category "c", 4 MJ/m^2 $\leq E_{AM} <$ 6 MJ/m^2;
- category "d", $E_{AM} <$ 4 MJ/m^2.

Daily cycles were measured from 07:00 (AM) each day to 06:55 (AM) of the following day. The times at which the outer and inner surfaces of the wall samples reached their maximum and minimum daily temperatures were used to calculate the time lag (TL):

$$TL = t_{T.int,max} - t_{T.ext,max} \qquad (hours)$$

EQUATION 6.1

where $t_{T.ext,\ max}$ and $t_{T.int,max}$ are the times at which the maximum temperatures occurred on the wall's exterior surface and interior surface, respectively.

The maximum and minimum temperatures recorded both on the internal and external wall surfaces were used to determine the decrement factor (DF), which is dimensionless:

$$DF = \frac{A_{int}}{A_{ext}} = \frac{T_{int,max} - T_{int,min}}{T_{ext,max} - T_{ext,min}} \qquad (/)$$

EQUATION 6.2

where A_{int} and A_{ext} are the amplitudes of the daily temperature oscillations on the interior and exterior surfaces of the wall, respectively; $T_{int,max}$ and $T_{int,min}$ are the maximum and minimum temperatures, respectively, on the interior side of the wall; and $T_{ext,max}$ and $T_{ext,min}$ are the maximum and minimum temperatures, respectively, on the exterior surface.

6.4 Results and discussion

6.4.1 Quantification of inertia parameters

For each of the climatic categories, the TL and DF values have been determined and then statistically analysed and averaged. The results can be seen in graphic form in FIGURES 6.14 and 6.15.

Among the climatic categories defined above, "a" is particularly significant for this study, because it includes a wide number of observations and represents the weather conditions during which the risk of overheating inside a dwelling is highest. Thus, in the following sections, category "a" is considered with particular attention.

6.4.1.1 Climatic category "a"

In category "a", **wall B1 (timber frame)** exhibits a TL of 9.14 hours: this means that the highest temperature on the interior side of this wall occurs 9.14 hours after the peak temperature has been reached on its outer surface, due to the external inputs (convective heat transfer with the surrounding air and, especially, radiative heat transfer due to sunlight). This TL-value also means that, if the maximum temperature on the outside of the envelope is reached on average at around 09:30 hours on a summer day, the interior peak occurs at about 18:30, when the outdoor conditions are about to become milder (with the sun being about to set and temperature about to decrease). The mean decrement factor of this wall, still within category "a", is 0.25, which means that the amplitude of temperature oscillation on the inner surface is one quarter of the amplitude on the outer surface.

Wall D1 (CLT) shows an average TL of 8.30 hours, meaning that it takes this length of time for the temperature wave to pass from the outside to the inside of this construction. Wall **D1**'s decrement factor is 0.15: this indicates that the temperature oscillation on the interior finish of the wall is 15% of the oscillation measured on the rendered surface outside.

Wall F (load-bearing masonry) exhibits a mean time lag of 8.00 hours and a decrement factor of 0.11. The latter parameter means that (within the outdoor conditions of category “a”) the temperature swing on the inside corresponds to the outer swing reduced by as much as 90% *circa*. This occurs thanks to the wall’s high thermal mass, concentrated in the outer leaf (medium-density concrete blocks) and especially the inner leaf (high-density concrete blocks, which possess not just increased density, but also increased heat capacity in comparison with the medium-density equivalents).

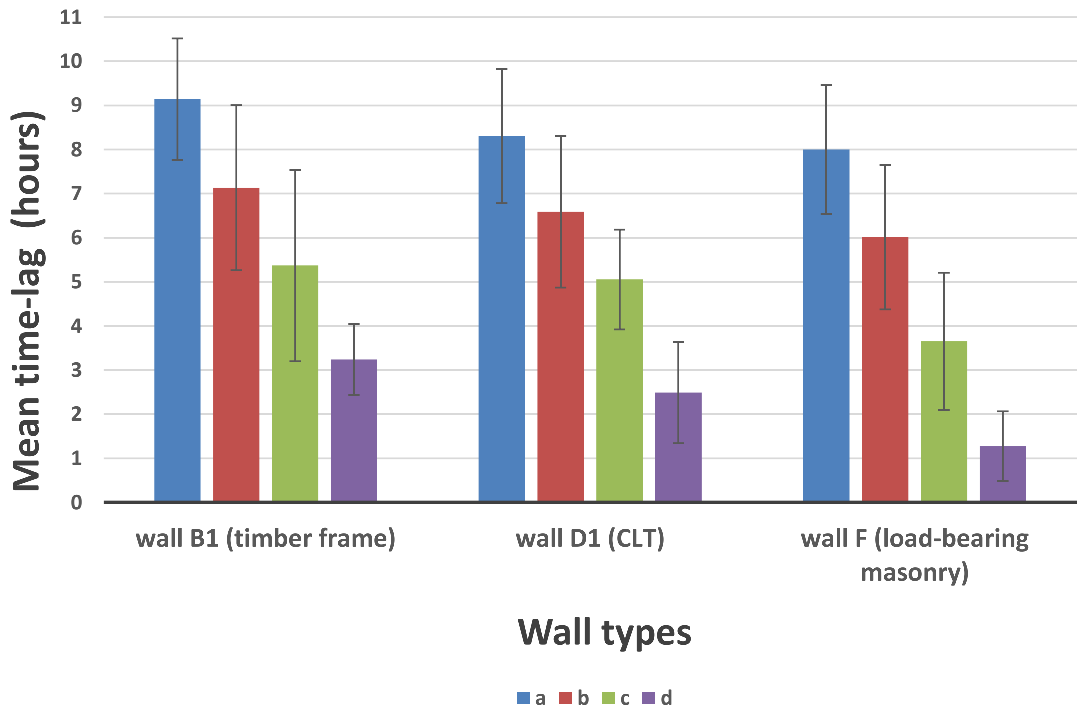

FIGURE 6.14 Mean time-lags for each wall and climatic category. Error bars show ± 1σ (i.e., ± one standard deviation) around the mean.

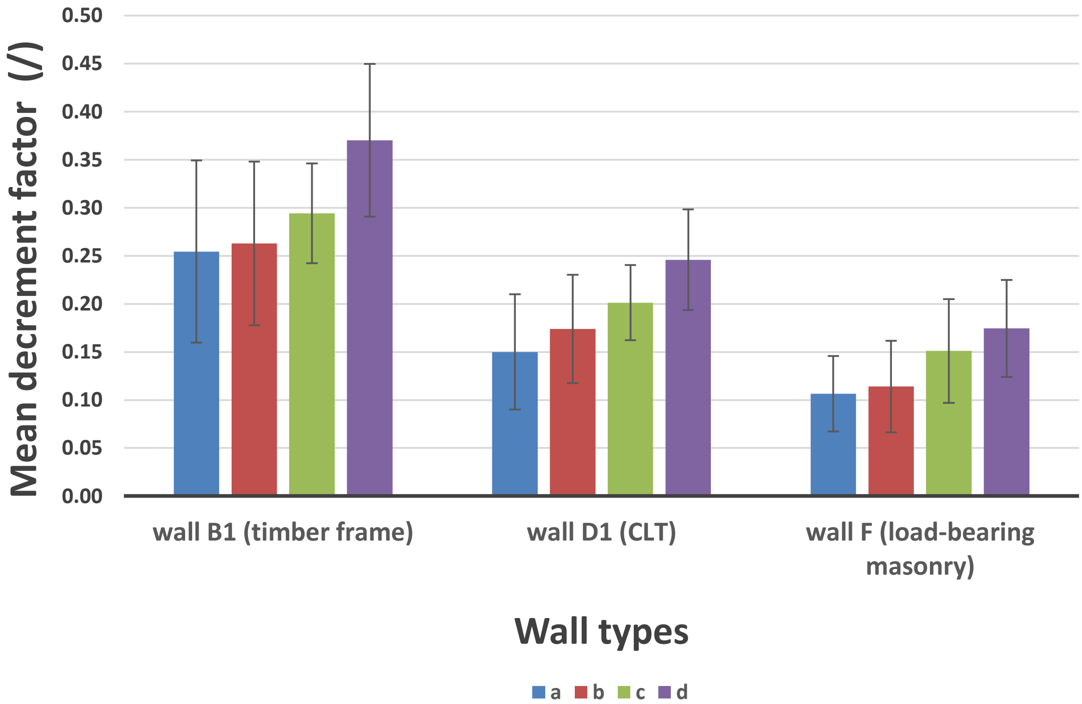

FIGURE 6.15 Mean decrement factors for each wall and climatic category. Error bars show ± 1σ (i.e., ± one standard deviation) around the mean.

In category "a", all three walls show a TL ranging between 8.00 and 9.14 hours (see FIGURE 6.14): a rather narrow interval. However, if the TLs of the two timber walls are compared with that of the masonry alternative, it can be seen that, surprisingly, the TL is shorter in the latter. While wall **D1** (CLT) only shows a marginal change[6] of +4% in TL (equivalent to +0.31 hours) relative to wall **F**; wall **B1** (timber frame) exhibits a more substantial increase of +14% (corresponding to +1.14 hours) with respect to **F**. This is particularly interesting, considering that **B1** and **F** share roughly the outer half[7] of their build-ups: both of them, indeed, have medium-weight cladding (*i.e.,* rendered blockwork). This means that the inner part of the wall composition is the decisive parameter leading to the mentioned difference in TL: in other words, the timber-frame panel, combined with the interior service void, has greater capacity to slow down the

[6] Relative differences in TL, between **B1** and **F**, are calculated as $(TL_{B1}-TL_F)/TL_F$ and expressed in percentage terms. Relative differences in DF are calculated as $(DF_{B1}-DF_F)/DF_F$. Analogous formulas have been applied for relative differences between **D1** and **F**.

[7] Walls **B1** and **F** also share the innermost layer: 15mm-thick plasterboard.

propagation of the heat wave than the combination of rigid insulation and heavy-weight blocks on the inside of wall **F**.

When the decrement factors are compared, the situation seems to reverse. In regard to this parameter, indeed, the best-performing wall is, by far, wall **F** (masonry) with a decrement factor as low as 0.11. The two timber walls offer less reduction in temperature-swing amplitude: wall **B1**'s decrement factor is +139% greater than that of wall **F** (a change corresponding to +0.15), whereas wall **D1** shows a change of +41% (equivalent to +0.04) relative to wall **F**.

Therefore, as far as the DF is concerned, CLT compares much more favourably with the masonry alternative than does timber frame, even though timber frame and masonry have a more similar wall build-up and, as discussed above, the comparison of TLs showed a better result for timber frame than it did for CLT.

The reason for this type of behaviour might lie in the fact that wall **D1**, in comparison with **B1**, has a very different mutual position of components with high thermal mass and components with high thermal resistance. In wall **D1**, indeed, the insulating layer is much closer to the outer surface than is thermal mass (the latter being provided by the solid-timber panels). In the timber-frame wall, instead, the temperature wave finds the thermal-mass layer first (blockwork) and then the thermal-resistance layer (mineral wool in between the studs). This difference in lay-up between **B1** and **D1** seems to have such important repercussions on the ability of the walls to reduce the magnitude of the temperature swings on their inner surfaces.

These results also seem to agree with those obtained in previous theoretical and/or experimental studies (such as Zhou *et al.*, 2008 and Ozel and Pihtili, 2007). These researchers have indeed concluded that placing most of the insulation on (or near) the outside of the envelope results in a decrease in DF. However, as was discussed in SECTION 3.3, there is no scientific consensus on this matter, to the extent that other authors (*e.g.,* Al Sanea and Zedan, 2001; Al Sanea *et al.*, 2012), have reached opposite conclusions and argue that placing the insulation layer on the inside of external walls yields lower, thus preferable, DFs.

It is also worth noticing that the innermost layers of both **B1** and **D1** are exactly the same: a service void finished with plasterboard, while wall **F** has no such void (since domestic services can easily be run inside *ad-hoc* chases created within the thickness of the concrete blocks).

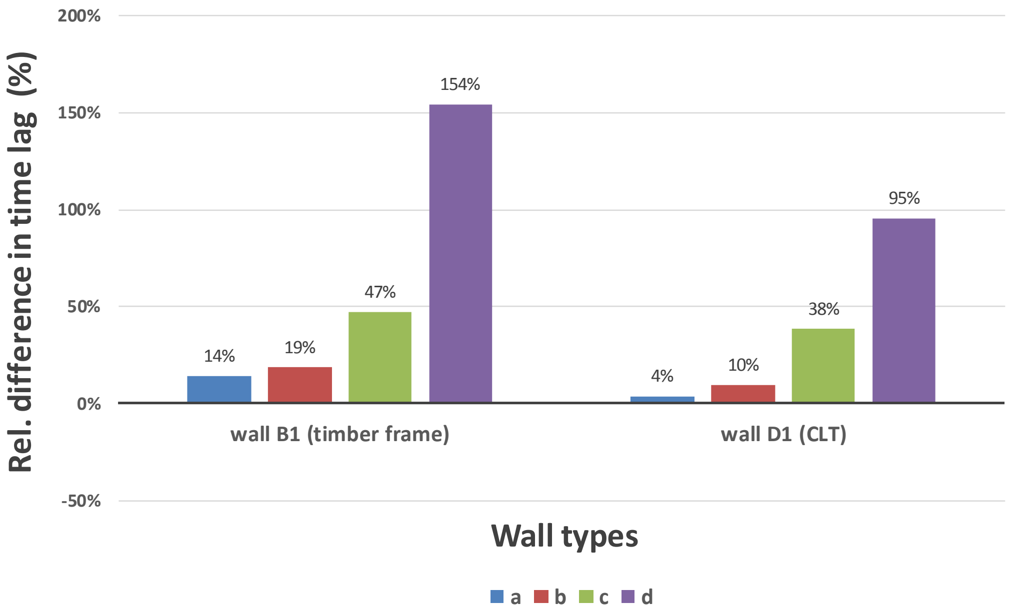

FIGURE 6.16 Comparison of walls B1 and D1 with reference wall F, in terms of time lag (percentage relative differences), for climatic categories "a" to "d".

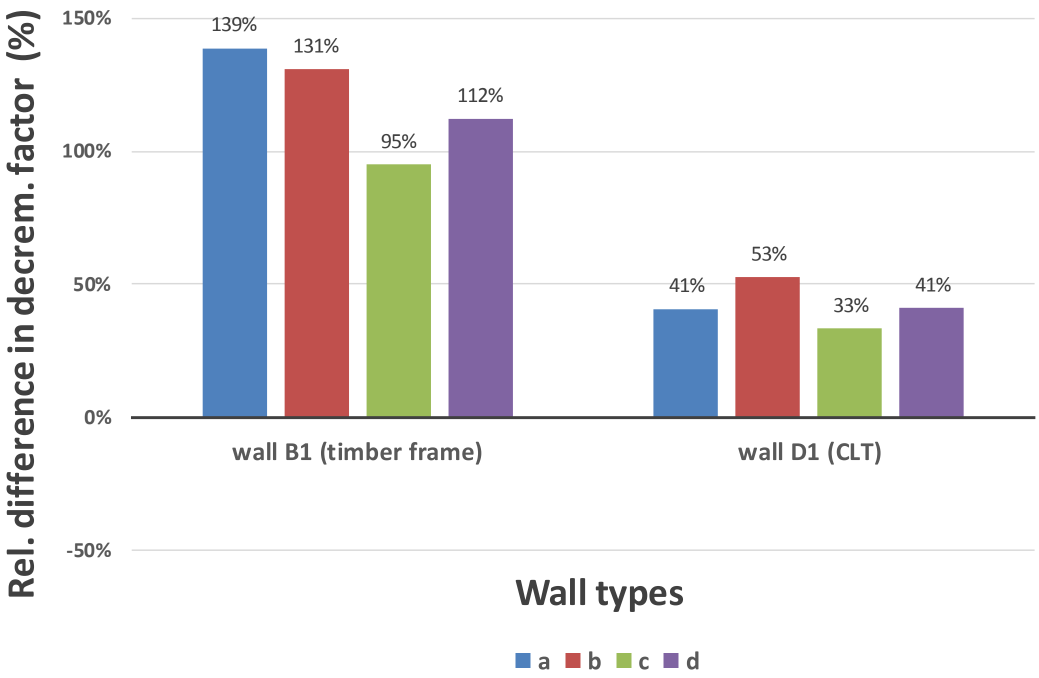

FIGURE 6.17 Comparison of walls B1 and D1 with reference wall F, in terms of decrement factor (percentage relative differences), for climatic categories "a" to "d".

6.4.1.2 Climatic categories "b", "c" and "d"

If both the TL and DF results of each wall are compared across climatic categories, it becomes evident that moving from category "a" to "d" entails a gradual reduction in time lag and an increase in decrement factor. This is because the dynamic response of the walls varies as a function of the climatic conditions to which they are exposed. This aspect will be discussed in more detail in SECTION 6.4.2.

With regard to **wall** **B1** and categories "b", "c" and "d", the TL assumes decreasing values of 7.13, 5.37 and 3.24 hours, respectively; whereas the DF takes values of 0.26, 0.29 and 0.37, respectively.

A very similar trend can be observed for **wall** **D1**, whose TL varies from 8.30 to 2.49 hours corresponding to categories "a" and "d" respectively; while its DF varies from 0.15 ("a") to 0.25 ("d").

Finally, the parameters of **wall** **F** assume TL values ranging between 8.00 and 1.27 hours and DF values between 0.11 and 0.17, from "a" to "d", respectively.

If the TL range intervals (from category "a" to "d") of the different walls are compared, it can be noted that walls **B1** and **D1** exhibit a similar range width[8] (*ca.* 6.0 hours), whereas wall **F** shows a wider TL interval (almost 7.0 hours). As regards DF intervals, these are again similar for walls **B1** and **D1**, but shorter for wall **F**. Thus, wall **F** exhibits greater variance for TL and smaller variance for DF – across the climatic categories – than the other two walls.

By comparing the results obtained under different climatic conditions, it can then be concluded that the DF is much less sensitive to changes in such conditions than is the TL. This also indicates that the magnitude of the DF is mostly a function of the inherent properties of the envelope's construction: changes in outdoor conditions can affect this parameter but not as much as observed for the TL. These conclusions are confirmed by the more accurate correlation analysis carried out in SECTION 6.4.2 and are in agreement

[8] Even though the upper and lower limits of these intervals differ, especially for the DF.

with the findings of other authors, such as Sun *et al.* (2013), Ozel (2013) and Kaşka *et al.* (2009).

6.4.1.3 Optimisation of time lag and decrement factor

The data analysis reported in the previous two sections suggests that the dynamic interaction between layers with very good thermal resistance and others with very high thermal mass leads to a situation in which the TL and the DF are not optimised simultaneously within the same construction method. This evidence supports the findings from previous studies[9] according to which a wall that offers the best TL does not necessarily offer the best DF too (as is often believed in the construction industry, when transient heat conduction is overly simplified and schematised).

However, since the wall samples tested in these experiments show only modest variation in TL and more marked disparity in DF, it can be said that, in this specific instance, the parameter that better expresses the differences in the inertia-related response is the DF.

6.4.2 Correlation between inertia parameters and other variables

This section aims at answering **research question ⑤** by presenting the analysis that has been carried out to understand the variables and the thermal mechanism that, for the walls tested, have led to the results shown in SECTION 6.4.1.

Specifically, the analysis aims at understanding:

- which layers/materials inside the build-ups could be changed or specified differently to improve the thermal response of the walls;
- which climatological values, in the Scottish climate, are particularly significant and should be factored in when predicting the thermal behaviour of walls related to their thermal inertia.

[9] Kontoleon *et al.*, 2013; Kontoleon and Bikas, 2007; Al Sanea and Zedan, 2001; Al Sanea *et al.*, 2012.

The correlation has been assessed between TL and DF values and other parameters, namely:

- correlation with amount of global solar energy received per unit area, E_{AM};
- correlation with thermal capacity of the walls, and, in particular:
    - correlation with total thermal capacity of the walls (*i.e.,* including the whole build-ups of the walls);
    - correlation with so-called "effective" thermal capacity of the walls (*i.e.,* relating to the components within 100 mm of the inner surface)
    - correlation with external thermal capacity of the walls (*i.e.,* relating to the components within 100 mm of the outer surface).

6.4.2.1 Correlation with solar energy

Correlation between TL and solar energy

The functional relationship between TL and solar energy has been investigated by performing regression analysis through the least-squares method. This involved defining a linear regression model for each wall, and checking its "goodness of fit".

The model equation has been tested by various means:

- checking the correlation coefficient, r;
- checking the coefficient of determination, r^2;
- checking the adjusted coefficient of determination, r^2_{adj};
- checking the standard error of the estimated values;
- graphic methods, examining various types of plots of the values obtained through regression:
    - plots of the residuals (or errors) against the independent variable, E_{AM};
    - plots of the residuals against the estimated TL-values.

APPENDIX Q provides the definitions and formulas used for the statistical and regression analyses conducted for this thermal study, while APPENDIX R offers a summary (in tabulated form) of the statistics of each regression analysis.

The regression analyses show that, for all three walls, the correlation coefficients are positive, as was expected, and are closer to 1 than they are to 0, which is an indication of strong linear relationships between TLs and solar energy.

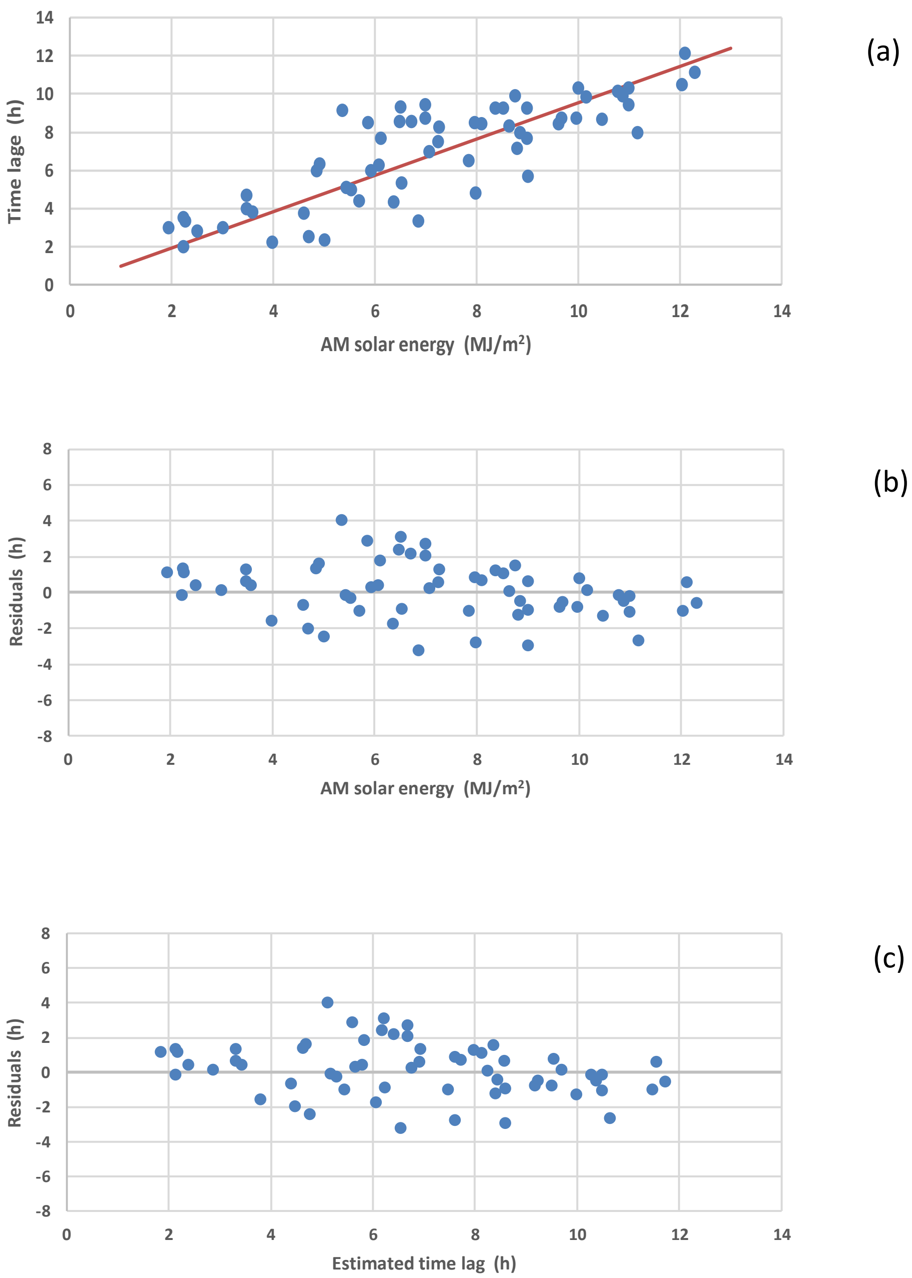

FIGURE 6.18 Regression-analysis plots for the time lag of wall B1: TL versus solar energy with regression line (a), residuals versus solar energy (b) and residuals versus estimated TL (c).

The regression-analysis plots for wall **B1** are shown in FIGURE 6.18, those for walls **D1** and **F** are provided in APPENDIX S.

The coefficients of determination are very high (about 0.95 for all walls). However, it has to be kept in mind that a high r^2-value indicates a robust correlation, but not necessarily a very good fit of the model (Madsen *et al.*, 2011, p. 114). Indeed, in the plots of TL *versus* E_{AM} (*e.g.,* FIGURE 6.18a for wall **B1**), it can be seen that not all points are extremely close to the regression lines.

By analysis of the residual-*versus*-E_{AM} plots for each wall (FIGURE 6.18b for **B1**), it can be appreciated that there is no particular pattern in the point distribution: the values are randomly scattered around the horizontal line y=0. Thus, the good functional relationship between TL and E_{AM} is confirmed.

Analysis of the other plots (*i.e.,* residuals against estimated TL-values) for the three walls leads to similar considerations (FIGURE 6.18c for **B1**); hence, it can be concluded that these graphic verification confirms the strength of the correlation between TL and E_{AM}.

EQUATIONS 6.3, 6.4 and 6.5 represent the regression models for **B1**, **D1** and **F**, respectively:

$$TL_{B1} = 0.95 \cdot E_{AM}$$

EQUATION 6.3

$$TL_{D1} = 0.87 \cdot E_{AM}$$

EQUATION 6.4

$$TL_{F} = 0.80 \cdot E_{AM}$$

EQUATION 6.5

Correlation between DF and solar energy

An analogous procedure to the one described above was followed to investigate the relationship between DF and E_{AM}.

EQUATIONS 6.6, 6.7 and 6.8 express the regression models for **B1**, **D1** and **F**, respectively:

$$DF_{B1} = -0.012 \cdot E_{AM} + 0.37$$

EQUATION 6.6

$$DF_{D1} = -0.012 \cdot E_{AM} + 0.27$$

EQUATION 6.7

$$DF_{F} = -0.008 \cdot E_{AM} + 0.19$$

EQUATION 6.8

The equations for **B1** and **D1** are very similar, whereas the equation for **F** signals the fact that the regression line for this wall is more horizontal.

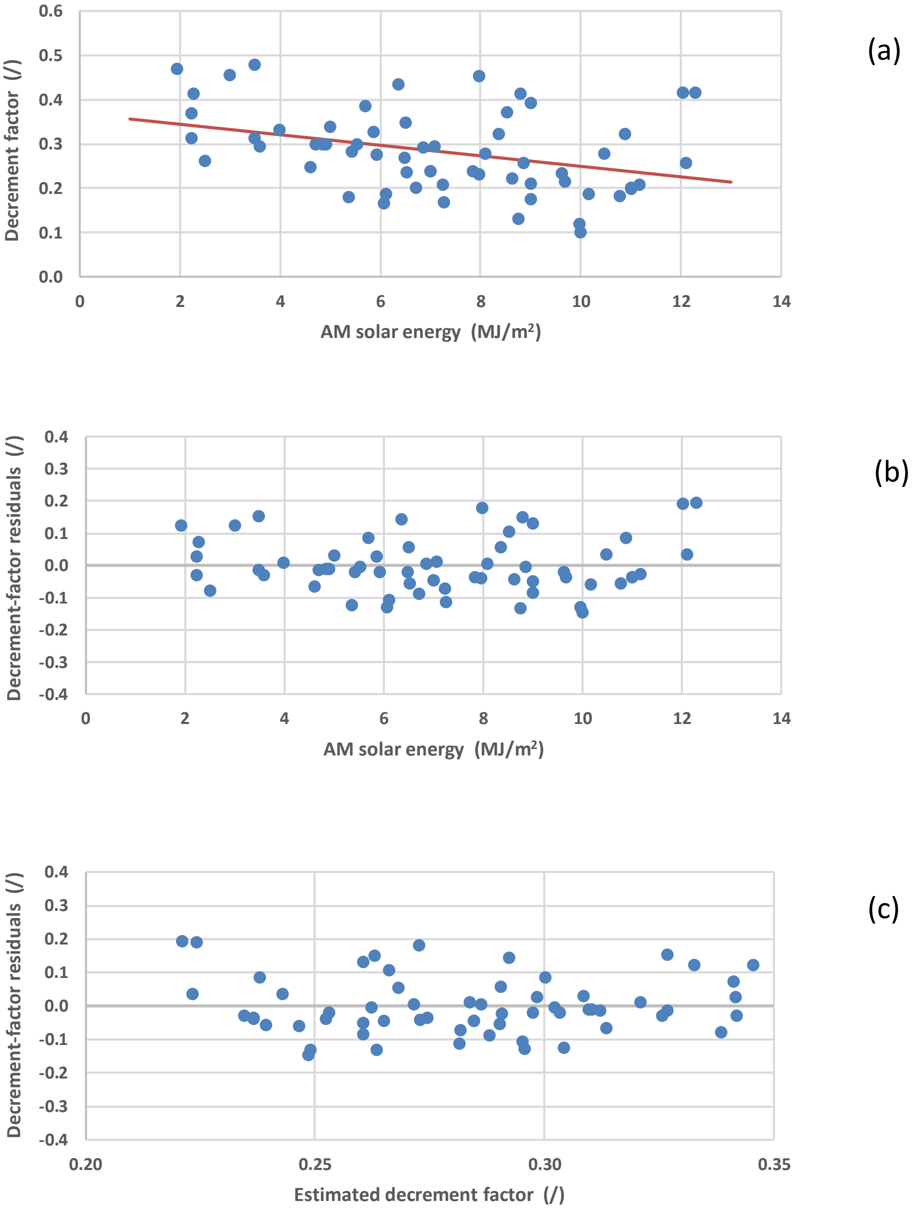

FIGURE 6.19 Regression-analysis plots for the decrement factor of wall B1: DF versus solar energy with regression line (a), residuals versus solar energy (b) and residuals versus estimated DF (c).

FIGURE 6.19 shows plots of the DF-values against solar energy and the regression line for wall **B1**; for buildings **D1** and **F**, see analogous graphs in APPENDIX S.

The quality and significance of the models obtained for the DF has been assessed by using the same analytical and graphic diagnostic tools as for the TL.

For the DF, the strength of the functional correlation with solar energy is weaker in all walls than it is for the TL.

The correlation coefficients for the three walls take values around -0.5, thus showing a negative correlation that is not very strong. Accordingly, the coefficients of determination are rather low for all walls. The plots of the data from the regression procedure, however, are good and do not reveal any significant problem with the fitted model (FIGURES 6.19b and 6.19c for wall **B1**): the plotted points, indeed, do not follow any particular pattern and are randomly distributed about the *x*-axis.

It can be thus concluded that there is a functional relationship between solar energy (E_{AM}) and both the TL and DF, but this reaches a higher level of statistical significance for the TL. These conclusions seem to confirm some findings from previous research (especially the work conducted by Sun *et al.* (2013), Ozel (2013) and Kaşka *et al.* (2009)), as also mentioned above.

It is worth keeping in mind that solar energy was not measured at the experiment site, but at the closest weather station; therefore, there is some "noise" in the values used for this study. It seems then reasonable to assume that, if the actual values of solar-energy received at the testing facility had been available, they would have probably shown a stronger relationship with the TL and DF in these regression analyses.

6.4.2.2 Correlation with thermal capacity

The correlation between the **overall thermal capacities** of the three walls with the inertia parameters appears very weak for both TL and DF. The same can be said of the correlation with the **thermal capacity of the outermost layers** (100 mm).

The strongest correlation identified is, by far, that between TL/DF and the **thermal capacity of the interior layers of the walls**: the walls with higher concentration of thermal mass on the inside exhibit a greater capability to attenuate the amplitude of the heat wave crossing them. FIGURE 6.20 illustrates this finding.

The comparison between walls **B1** and **D1** becomes particularly significant and illustrative of how thermal mass works. Wall **D1** has approx. half the *total* thermal capacity of **B1**,[10] but exhibits much better decrement factors. This is the result of a

[10] The total heat capacities (per unit area) are 210 and 104 kJ/(m²·K) for **B1** and **D1**, respectively. See FIGURE 6.1 in SECTION 6.2.

concentration of thermally-heavy materials towards the inside of **D1**'s build-up, which leads to about double interior thermal capacity[11] (FIGURE 6.20). In other words, although **D1** is a light-weight wall, with much lower *overall* heat capacity than **B1**, its (modest) thermal mass is concentrated where it is most effective to achieve a better reduction in temperature swing on the inside; thus, **D1** outperforms heavier **B1**, in terms of DF.

However, it was shown that – despite the differences in the distribution of thermo-physical properties across walls thicknesses – wall **B1** achieves a better time lag than **D1**, though by a small margin. If **B1** and **D1** did not have an equally-detailed service void on the inside, their *interior* heat capacities would differ more widely;[12] therefore, it seems reasonable to envisage that **D1** would achieve an even-better DF than **B1**.

When **D1** and **F** are compared, one can see that their interior heat capacities differ drastically: there is a 4:1 ratio between the capacities of **F** and **D1**. However, this is not fully reflected in the DF results, where the differential is much narrower (with *ca.* a 2:3 ratio between the values of **F** and **D1**).

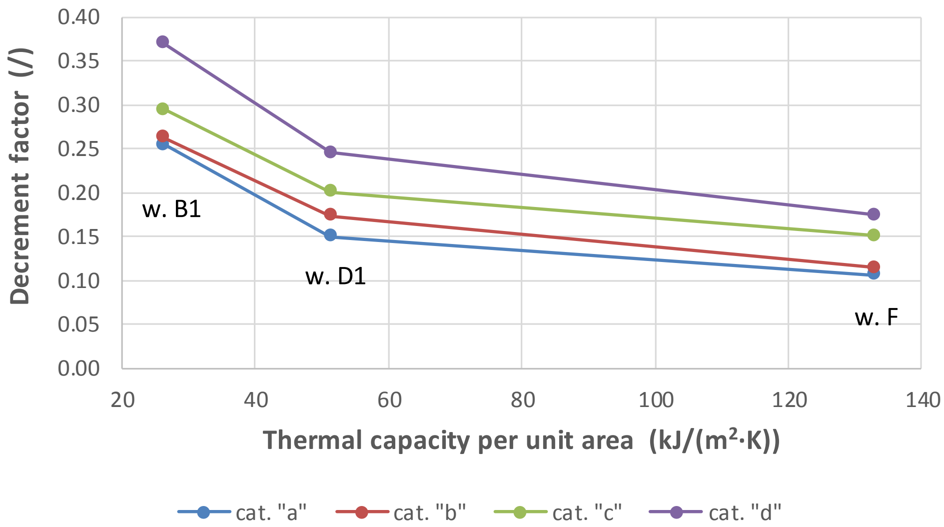

FIGURE 6.20 Average DF-values of each wall, plotted against the heat capacity (per unit area) of its inner layers (i.e., innermost 100 mm).

[11] The interior heat capacities (per unit area) are 25 and 51 kJ/(m^2·K) for **B1** and **D1**, respectively.

[12] **D1** would have an even-greater inner thermal capacity than **B1**, thanks to its massive wood panel.

6.4.2.3 Correlation between TL and DF

For all the walls, the values of TL and DF calculated for each observation (*i.e.,* for the same daily cycle) have been plotted against each other: see FIGURES 6.21 to 6.23. These plots show the presence of several outliers, but also confirm that TL and DF have a negative correlation, such that, when one increases, the other decreases.

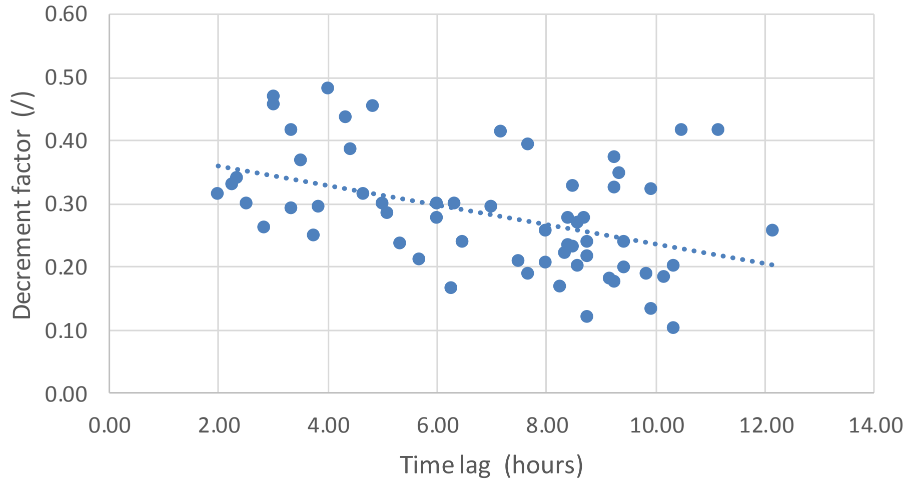

FIGURE 6.21 Plot of DF-values against TL-values of wall B1, for each observation of the experiments, with trend line.

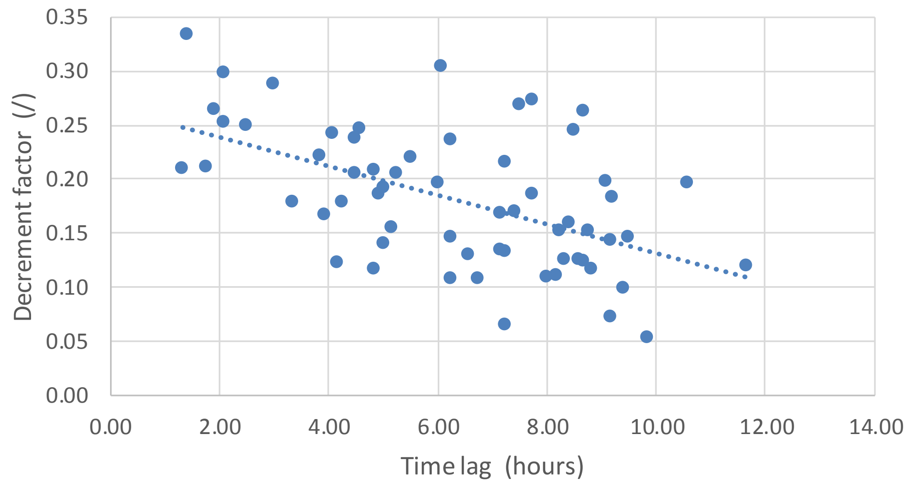

FIGURE 6.22 Plot of DF-values against TL-values of wall D1, for each observation of the experiments, with trend line.

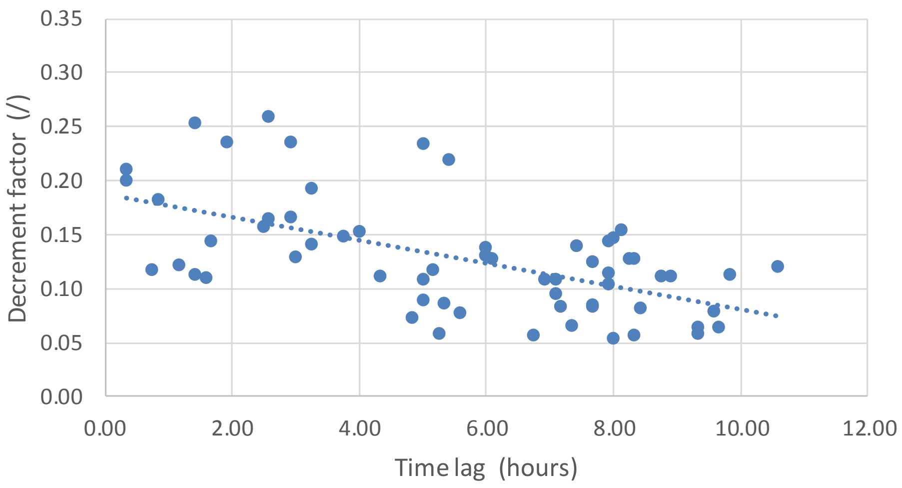

FIGURE 6.23 Plot of DF-values against TL-values of wall F, for each observation of the experiments, with trend line.

6.4.3 Further reflections on findings and thermal optimisation of timber walls

In SECTION 2.2, it was mentioned that the general public in Scotland – as well as in the rest of the UK – has a marked preference for heavy-weight types of exterior wall cladding. These can be easily achieved through blockwork, as in the case of the samples tested, or brickwork. Such a preference leads to the frequent construction of walls that have a higher overall thermal capacity than their light-weight counterparts, but these experiments have shown that the amount of thermal mass located on the outside of the walls does not significantly affect the magnitude of the inertia parameters (either time lag or decrement factor). Thus, such an increase in weight of the construction does not lead to enhanced thermal performance (at least within the aspects embraced in this study) or increased adaptability of domestic buildings to climate change and the overheating risk associated with it.

This aspect of construction becomes problematic from a thermal viewpoint, in that a very close thermal performance would still be obtained with less consumption of building materials.

Furthermore, it could be argued that, if the materials providing thermal capacity were placed in a different location within the wall's build-up, they could bring added value in terms of response to climate change. It is possible, indeed, to construct timber-frame walls in which the types and quantities of materials employed are very similar to those of **B1**, but the inner leaf and outer leaf are in a reverse position. In other words, the timber-frame panels maintain their load-bearing function, but are placed on the outside of the wall; whilst the masonry leaf is placed on the inside, where its elevated thermal-storage capacity offers benefits in terms of thermal inertia and consequent attenuation of outdoor temperature fluctuations. Such a novel type of construction[13] has been studied by Page *et al.* (2011), who have characterised it thermally under Australian weather conditions, in summertime. The experimental campaign conducted by these authors has demonstrated the effectiveness, in terms of thermal behaviour, of this unconventional method of construction, thanks to the presence of internal thermal mass. It would then be useful to test the benefits of such a walling system in the British climate.

It has to be said that this building technique, as a variation of timber-frame construction, would probably be more complex in terms of physical realisation, due to practicalities such as the foreseeable difficulty of the heavy leaf being on the inside of the envelope and the need for building operatives with adequate training.

In consideration of the LCA burdens[14] generated by the use of plastic membranes (to protect the wood-based inner leaf and insulation layer, where applicable, so as to avoid interstitial condensation from the water vapour produced inside a dwelling), the inversion of the two wall skins would probably be beneficial in this respect, too. The presence of a masonry layer on the inside of external walls, would indeed remove the need for any vapour-control layers. This could, in turn, lower the impacts of the walls in terms of acidification, eutrophication and photochemical creation of ozone.

At a more general level, it is noteworthy that the presence of a masonry layer (be it on the outside or inside of the wall) coupled with a timber-frame panel inevitably reduces the overall level of offsite construction that can be achieved (at least with mainstream equipment or building capacity). This results in loosing some of the benefits from offsite

[13] In the cited study, this wall system is referred to as "insulated reverse brick-veneer wall". It consits of (from the outside in): acrylic render, fibro-cement board, timber frame, brick skin, render. It is not described as one of Australia's standard construction systems.

[14] See discussion in SECTION 5.6.3.

methods, due to transportation of heavy materials, resorting to “wet” techniques and wet trades, longer duration of onsite operations, potential losses in the quality of the working environment for the operatives, in the quality of the build, and so forth.

6.5 Summary of findings

Three walling systems (closed-panel timber frame, **B1**; cross-laminated-timber panels, **D1**; and load-bearing masonry, **F**) have been thermally monitored during summertime, in Edinburgh. Statistical analysis of the data collected during the experiments has led to the following findings and considerations:

a) when the outdoor weather conditions are more exacting (and cause higher risk of overheating of the interior spaces), the **time lags** of the three walls are all rather good (that is, high) and while they do differ from one another, they do so within a relatively narrow range (*i.e.,* 1.14 hours maximum difference);

b) the **best-performing construction in terms of TL** is closed-panel timber frame (wall **B1**), with a time shift of 9.14 hours. This means that the temperature wave propagates from the outer to the inner surface in slightly over 9 hours, which is a satisfying result for an East-facing wall, since the peak temperature on the interior side of the wall occurs when the thermal conditions outdoors start to become milder, as the evening approaches;

c) the **best-performing build-up in terms of DF** is that of wall **F** (load-bearing masonry), thanks to its high thermal mass, both on the inside and outside of its configuration (due to the double block skins, with a central cavity). The DF of wall **F** is 0.11, meaning that the amplitude of the temperature swing on the interior surface of this wall is 11% of the amplitude on the outer surface;

d) the **differences in DF** between the three walls are much more pronounced than the differences in TL (within the same climatic categories);

e) in the comparison between different walling systems, **TL and DF might not achieve their best value simultaneously**, that is, for the same wall. This is contrary to the simplifying assumption, frequently made by professionals in the construction industry, that the two inertia parameters are necessarily (or easily) optimised within the same system included in the comparative judgement. This concept is in accordance with findings from other researchers (Kontoleon *et al.*, 2013; Kontoleon and Bikas, 2007; Al Sanea and Zedan, 2001; and Al Sanea *et al.*, 2012).

f) the **positioning of thermal mass** on the inside and thermal insulation on the outside of a wall's make-up tends to improve the DF (as is the case, within this study, for CLT in comparison with timber frame). Thus, the present study seems to confirm the thesis presented by other authors (Zhou *et al.*, 2008; and Ozel and Pihtili, 2007) that, when a single layer of insulation is incorporated in a wall (as opposed to multiple layers), the best performance is achieved if the insulation is placed on the outside (for a similar amount of thermal insulation and thermal mass, as in walls **B1** and **D1** in this study). However, in other investigations (Al Sanea and Zedan, 2001, and Al Sanea *et al.*, 2012), opposite conclusions have been drawn.

g) the DF appears to depend less on **climatological conditions** than the TL, as also argued by some other researchers (Sun *et al.*, 2013; Ozel, 2013 and Kaşka *et al.*, 2009). The DF, indeed, seems to depend more on the physical properties of the envelope's build-up than on the climatological profile of the site.

h) there is a rather strong, linear positive **correlation between the TL of a wall and the thermal input** that it receives (especially solar energy). Therefore, in transient conditions, the dynamic response of a wall is commensurate with the energy input it has received in the previous hours.

i) the DF of a wall shows a robust correlation with the amount of thermal mass positioned in its inner layers (**interior thermal capacity**). The thermal capacity of the whole thickness of a wall and the capacity of its outer layers seem to have a limited effect on the time lag and decrement factor.

Points a) to e) answer research question ④ (formulated in CHAPTER 1); points f) to i), research question ⑤.

7 Conclusions and future work

7.1 Chapter overview

This chapter provides final considerations on the findings of this research and their implications[1] for the housing and timber-construction sectors. In particular, **Section 7.2** identifies important linkages between the key findings relating to mitigation of climate change and adaptation to it, which derive from the two strands of work on LCA and thermal characterisation, respectively.

Section 7.3 reflects on how the framework, methodology and methods of this investigation have allowed answering the research questions and tackling the methodological problems and criticalities identified through the literature[2] review. Such criticalities include, *inter alia*, issues of potential comparison of the findings of this research with past or future studies by other authors and the adequacy of their generalisation to other building types. The advantages of carrying out a multi-impact LCA are also discussed, as opposed to studies that solely focus on one or two impacts (*e.g.,* "carbon footprints").

Section 7.4 embraces the wider context of this research, by discussing the implications of the findings for various aspects and actors of the construction industry: from the manufacturing of timber-based constructional systems, to housing-design practice and the legislative framework at the level of building control.

Finally, **Section 7.5** outlines some research pathways that could be followed to take this investigation forward, overcome some of its intrinsic limitations, and augment its contribution to knowledge by building upon its findings and continuing to use, where appropriate, the research framework illustrated in this thesis. Such suggestions aim at

[1] See Section 5.8 for a complete summary of the findings that answer the research questions on LCA, *i.e.*, ①, ② and ③ as articulated in Chapter 1, and Section 6.5 for the findings that answer the research questions relating to thermal inertia, *i.e.*, ④ and ⑤.

[2] See Section 3.2.

capitalising on the experience of this research project and on the efforts and resources that were put into it.

7.2 Response to climate change: mitigation and adaptation

The fact that, within this research, both an LCA and thermal experiments have been carried out on three external walls (**B1**, **D1** and **F**) has allowed evaluating them from two complementary points of view: their contributions to mitigation of, and adaptation to, climate change.

In terms of mitigation to climate change (measured in $GWP_{excl.seq.}$) in the cradle-to-gate stage, it has been seen[3] that the best-performing system is the timber-frame wall (**B1**), thanks to its lowest carbon emissions, followed by the masonry wall (**F**). When it comes to adaptation to climate change, instead, the situation is almost reversed: the three wall systems have shown relatively-similar time lags, but much greater variation in decrement factors. Thus, it is deemed sensible, in this specific context, to consider the results obtained in terms of decrement factors as those that best represent the difference in overall thermal response of the walls.

Therefore, it can be inferred that the masonry wall contributes more strongly than the other two walls to adaptation to a warming climate (followed by the CLT wall, **D1**), by virtue of its capacity to buffer the oscillation of internal temperatures and thus provide thermal comfort to occupants.

In addition, it should be noticed that a wall technique that allows *direct* benefits towards adaptation to increasingly-warmer summers also offers *indirect* beneficial effects towards mitigation. Indeed, by providing inhabitants with increased thermal comfort, a masonry wall such as **F** reduces the probability that they will resort to air-conditioning systems during the summer. Less reliance on mechanical systems, in turn, will entail significant energy savings and reduction in the carbon emissions arising from the

[3] See SECTION 5.6.2.

production of electricity. Ultimately, these savings in carbon would constitute further mitigation of climate change.

In other words, an effective passive cooling system for the building envelope with elevated thermal mass and inertia can, in summertime, contribute directly to adaptation to climate change and, indirectly, to its mitigation.

In addition, the avoided use of an air-conditioning system reduces reliance upon the electricity mix and, consequently, dependence on monetary fluctuations and foreign countries.

The considerations above also point out the complementarity and the multiple linkages that can be revealed by carrying out LCAs and thermal evaluations of the building envelope simultaneously and indicate that the research framework devised for this study enables to capture, at least partially, the complexity of the interaction between climate change and housing.

Furthermore, since the environmental impacts during the occupation phases of a building are mostly related to space heating and/or cooling, it becomes vital to have an experimental component in such studies. LCAs that solely rely on numerical simulations, with no comparison with, or validation against, measured data, are prone to under- or over-estimation of the building envelope's performance. Such an error would inevitably compromise the calculation of consumed electric energy and associated polluting emissions. The experimental component of this investigation aims at responding to the issue – repeatedly raised by researchers – of frequent, wide gaps between *design* performance and *measured* performance of buildings' thermal envelopes.

The experimental evidence gathered through this study could potentially lay the foundations for a future study on cooling-related energy use in housing (see SECTION 7.5 on future work), that is, an LCA of the operational phase of the building. This would allow an expansion of the boundaries of the work conducted so far.

7.3 Reflections on the methodology used

7.3.1 Implications of using a multi-impact LCA methodology

The consideration of a wide range of environmental aspects has allowed identifying some trade-offs (or "shifts") of environmental burdens which are often overlooked in the existing literature. For instance, the fact that in timber buildings the wooden components must be carefully protected from moisture (both in the form of water and vapour) entails a need for a larger amount of plastic than is generally the case in a masonry building. Therefore, timber techniques are more inclined to cause higher burdens associated with the manufacturing of plastic products, such as acidification, eutrophication and photochemical creation of ozone. This type of findings and insight into the environmental repercussions of timber techniques would not have been achieved if the CML methodology[4] recommended by the European standards had not been adopted and a much more common approach had been taken instead, with focus on just one or two impact categories (*e.g.,* energy consumption and/or carbon emissions). In other words, a single- or double-impact assessment would have probably allowed reaching clear-cut conclusions and making bold statements on the environmental pre-eminence of one technique over the others, but within a very partial and misleading approach.

The above-mentioned trade-off problems arising from plastic consumption might be partially alleviated by employing modified-wood products, such as acetylated timber, which are less susceptible to insect attack and fungal decay and also provide timber with increased dimensional stability. Since acetylated timber tends to be brittle, its suitability for structural members, within, for instance, open- or closed-panel systems, would be a worthy area of enquiry.

The set of contribution analyses[5] devised for this research and systematically performed throughout it has played an important role in the study of burden trade-offs, because

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[4] On the CML methodology, see SECTION 2.6.4 and the glossary in APPENDIX B.

[5] Three contribution analyses: by structural role (structural/non-structural components), by location inside or outside the envelope (envelope/non-envelope) and by material type.

they have allowed identifying the major contributors to the impacts studied and thus revealing the reasons behind the trade-offs themselves.

7.3.2 LCA results and advancements in building-material production

The findings of this research have shown that unexpected impact results might be obtained when comparing light-weight and heavy-weight cladding systems. Indeed, a light-weight system might not provide as high an environmental benefit as one might initially expect, especially if it makes use of cement-based render-carrier boards, which have elevated embodied impacts. In a case like this, then, the advantage of having smaller foundations is negated by the burden from the materials used for the light-weight cladding. These findings are noteworthy, because they show that both researchers and designers should be more cautious in their assumptions regarding light-weight and heavy-weight systems, since the former are not necessarily "greener" than the latter, as is often assumed *a priori.*

It can also be concluded from this study that designers and stakeholders should have no prejudice towards wall solutions such as blockwork, since improvements in the manufacturing of mineral-based products make them more sustainable than one might think. Therefore, comparison between timber-based and masonry-based buildings requires a high level of caution and attention to detail.

For the reasons above, when masonry techniques are considered for the design of a building, it is key to appreciate the differences between the environmental burdens arising from blockwork and those arising from brickwork, since the latter are likely to be much more substantial.

In consideration of all the recent industry advancements in building-product manufacturing, it becomes imperative for LCA practitioners to use up-to-date input data, which truly reflects the environmental loads currently associated with the cradle-to-gate phases.

The breadth of scope of this investigation (with numerous timber techniques analysed within the same comparative framework) has permitted achieving unanticipated findings, which could hardly have been predicted from analysis of the extant literature.

For instance, this comparative study has shown that many impact results obtained for the timber-frame variations (*i.e.*, houses **A**, **B1** and **B2**) do not apply to massive timber techniques (**D1**, **D2**, **E1** and **E2**) and not even to the more similar SIPs buildings (**C1** and **C2**). There is indeed high variation among the impacts of timber-based buildings, and this is sometimes greater than the variation between some timber-based solutions and the masonry system.

7.3.3 Result comparability with other LCAs in housing

It is noteworthy that this investigation lends itself to comparison with similar studies that might be conducted in future on housing. The evaluation of the thermal response of the envelope is independent of building type and size, and is thus intrinsically generalizable. The results of the LCA carried out have been normalised per unit floor area, in order to facilitate potential comparisons with future research by other authors and also to be more easily, and meaningfully, transferred or applied to other building types. The chosen layout of the semi-detached house, indeed, could be considered as an intermediate solution between the two other main types of houses: detached and terraced. Thus, it can be expected that the impact results (per unit floor area) for the house used in this study would be, quantitatively speaking, of the same order of magnitude as those of a detached or terraced dwelling with two or three floors above ground.

Besides facilitating comparisons, the framework devised for this LCA could also be applied to, and become the starting point for, future LCAs, if similar research questions were to be answered with regard to other low-rise dwellings. Then, the scope of this project could be extended so as to generate new contributions[6] to knowledge.

7.3.4 Data sources and reliability of results

The quality of input data and the consequent reliability of this LCA's results have been studied through an uncertainty analysis. Thanks to this, it has been possible to tackle input-data variability, which is a recurrent, inherent problem of the LCA discipline and

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[6] See also SECTION 1.5.

constitutes one of its main methodological limitations. The uncertainty analysis has shown that the vast majority of absolute and comparative environmental results presented in this study are reliable and possess a high probability of being accurate. This is because adequate input sources (*i.e.*, relevant and recent EPDs) have been found and used for most of the inputs needed to study the ten notional buildings. Where less good sources had to be used, instead, these had negligible influence over the impact results. Having chosen an *analytical* method (as opposed to a *stochastic* one) to carry out the uncertainty evaluation has proved beneficial, in that it has allowed "tracking" how the uncertainty of the inputs propagated to the uncertainty of the outputs.

Moreover, the framework used in this research would easily permit updating this study (and its outputs) when necessary, by keeping the results and the input data current and relevant, following the evolution of the manufacturing processes for building materials and the developments of construction methods. In this way, the framework devised can help overcome the limitations arising from input data.

7.3.5 Understanding and characterising thermal inertia

The thermal study undertaken indicates that great caution should be taken when making assumptions on the thermal inertia of masonry buildings and especially when comparing them with timber systems (with either light- or heavy-weight cladding, and either deploying framed or massive panels).

The experiments have indeed shown that when timber and masonry walls with the same level of thermal resistance are compared, the two main inertia parameters (*i.e.*, time lag and decrement factor) do not necessarily reach their best values in the same build-up.

Thus, due to the complex interaction between the materials offering thermal resistance and those providing heat capacity, the wall with the greatest ability to delay inward propagation of heat waves from the outside might not be the best at decreasing the amplitude of such waves. This aspect should be taken into account when making informed decisions about the build-ups of external walls, along with factors such as the climatic conditions in which the walls will be operating; the type of room enclosed by the walls (*e.g.*, bedroom or living area); the orientation of the walls and the possibility to cross-ventilate interior spaces, particularly at night, so as to cool them during summertime.

These experiments have demonstrated that timber walls employing framed or solid panellised systems can exhibit slightly-longer time lags than their masonry counterpart; but the latter shows a much-improved (*i.e.*, lower) decrement factor.

7.4 Implications and recommendations for the construction industry

7.4.1 Offsite manufacturing of panelised systems

The constructional process whereby timber elements (such as walls or roofs) are manufactured and erected plays a fundamental role in the magnitude of the environmental burdens associated with them. When the zero-wastage scenario (which only considers the quantities of materials incorporated in the completed building) is compared with a low-wastage and a high-wastage scenario (characterised by a high level and a low level, respectively, of offsite construction), all impacts tend to show an increase. More specifically, the majority of impacts rise by *circa* 5-7% from the baseline in the low-wastage scenario, and by 8-10% in the high-wastage scenario.

In particular, the study has shown that the way in which openings for doors, windows and rooflights are realised within wall or roof panels has noticeable repercussions on the overall quantity of materials used and their associated environmental costs. An additional complication lies in the fact that the portions of massive panels that have been removed to create openings are generally difficult to re-purpose. This leads to the conclusion that, in offsite timber techniques, a significant proportion of environmental impacts could be avoided by improving the operations inside the factory, while focus is often placed on the final operations carried out onsite, when the prefabricated panels are assembled and completed with their finishes. It is also worth mentioning that, since companies that produce timber-based panels generally capitalise on the ecological benefits associated with their products, improvements in the manufacturing processes would further enhance their environmental credentials.

For the reasons above, in terms of LCA practice, this study has highlighted the importance of accounting for the characteristics and dynamics of the manufacturing process when compiling the bill of quantities that constitutes the base for an LCA at the *building* level (as opposed to the level of an individual *material* or *component*). SECTION 7.3 includes some suggestions for future work relating to these aspects.

7.4.2 Prediction of thermal performance at the design stage

Evidence obtained from the tests performed supports the concept that both time-lag and decrement factor vary as a function of weather conditions, especially the thermal radiation received by the walls during daytime. In particular, the time lag appears to be more strongly correlated with solar radiation than the decrement factor. Such findings are remarkable in this area of research, since scholars have not reached a consensus on these issues and have drawn diverging conclusions from their investigations.

This has repercussions on building-design practice and construction quality, as it is important that designers gain awareness that a wall will perform differently under different weather conditions, in order that they can specify materials and produce constructional details that can effectively provide end-users with thermal comfort inside a dwelling.

On the one hand, designers tend to interpret and predict the thermal behaviour of roofs and external walls by making various simplifying assumptions; on the other, they often utilise thermal-simulation software that also employs simplified algorithms, which are unable to factor in all the key parameters at play. Besides, today's simulation programs have become apparently straightforward[7] and within everybody's grasp, and are often adopted by designers who, lacking specialist knowledge, are unable to operate them in a critical fashion and to exert sufficient control over the calculation methods used and the results obtained. These circumstances together are likely to result in erroneous modelling of complex thermal phenomena and, ultimately, in flawed prediction of the

[7] Thanks to their "user-friendly" interfaces.

building envelope's thermal performance that will not match the real performance of the erected building.

As an example, commercial software Cymap,[8] which is used among architects and other designers, determines values for thermal lags and decrement factors of walls as a mere function of the build-up indicated by the user, but irrespective of important factors such as the colour of the exterior finish (and correlated thermal absorptivity) and the solar-energy intensity that the wall will typically receive (depending on orientation, climatic profile of the location, *etc.*)

7.4.3 Building control in Scotland

The substantial variations in thermal response of different walls identified through the tests and the influence of the climatic profile upon it seem to suggest that some changes should be made to the current regulatory framework in Scotland. At present, indeed, the Scottish Building regulations (last updated in 2016) do not take the effects of thermal-energy storage into consideration and do not set any requirements for the thermal mass incorporated in the building envelope. Thus, control of thermal performance is, by far, dominated by the level of insulation, expressed in terms of maximum overall thermal transmittance allowed (*i.e.*, U-values). This problem is exacerbated by the fact that – as this research has shown – the differences in thermal response across wall systems that arise from thermal-mass levels become larger when weather conditions are more adverse (*i.e.*, hotter days in summer). This also means that, in the context of a warming climate, such variance in thermal-inertia parameters across wall build-ups is destined to become greater in the future, as Scottish summers gradually become warmer.

Thus, it can be said that Scottish building regulations are strongly keeping their focus on mitigation of climate change through elevated levels of insulation and air-tightness, which permit conservation of energy in winter and consequent savings in carbon emissions from the burning of fuel. It would be beneficial for the regulations to take a different approach and devote more attention to problems such as performance in

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[8] Developed by Cadline Limited, version observed: 2015.

summertime, overheating risk and adaptation to a warming climate. Besides, one should keep in mind that thermal mass is also expected to offer advantages in thermal performance during winter. For these reasons, the regulations should probably include some form of prescription of minimal levels of thermal capacity[9] within external walls, for the purposes of environmental protection and quality in housing.

7.5 Suggestions for future work

The study presented in this thesis could be developed in many directions to overcome its current limitations relating both to its scope and to methodological aspects.

As regards the life-cycle assessment of constructional techniques, it would be useful to widen the system boundaries so as to include life-cycle stages beyond the cradle-to-gate phases. This strand of work would initially include the "construction" phase of the notional buildings (as defined by the international standards[10]), which comprises transportation of the building materials from the factory gate to the construction site (module A4) and erection of the building[11] (module A5). In order to do this, a geographical area should be chosen for the building site. Within these broader boundaries, it would be very useful to assess the effect of producing timber components in Scotland (or in other regions of the UK), thus reducing the need for importation of processed timber materials. This would be particularly relevant in the light of the new manufacturing facilities for cross-laminated-timber systems that have opened in the last few years or are expected to open in the near future, as a result of large investments, both in Scotland and England. The opening of new manufacturing plants is also associated with the rising interest in using UK-grown resource for engineered timber.

[9] Steps in this direction were recently taken, for instance, in England. In the English building regulations, a requirement for the thermal-mass parameter (TMP) has been introduced to regulate the minimum content of thermal mass to be contained in a building (Approved Document L1A, *Conservation of energy and fuel in new dwellings*, §5.4; 2013 edition with 2016 amendments). The TMP is defined qualitatively and quantitatively on p. 7 and p. 196, respectively, of the *Government's Standard Assessment Procedure for Energy Rating of Dwellings*, 2012 edition ("SAP 2012").

[10] Standard EN 15804 (BSI, 2014a), whose content has been discussed in SECTION 2.6.6.

[11] See FIGURE 2.24.

Another route for future work would be to carry out further sensitivity analysis, so as to understand how changing some modelling assumptions (such as choice of building materials) would affect the absolute and comparative impact results already obtained and presented in this thesis.

In addition, the modelling of building-material wastage could be refined and developed further. This might include an update of the wastage rates used in the current model once new literature has been published on the subject and rates that are more precise are provided by other researchers. As an alternative, a more in-depth research could be directly carried out into the issue of wastage, in order to use new, primary data as input parameters when re-assessing scenarios 2 and 3.

With regard to the study on thermal performance of the envelope, the work done so far could be advanced by estimating the response of the other notional external walls (not included in the experiment) by means of *ad-hoc* mathematical models, potentially based on the finite-difference method. Such parametric models could be – at least partially, or indirectly – validated by creating a model for each of the three walls which have already been assessed experimentally (*i.e.*, **B1**, **D1** and **F**). This procedure would allow verifying how accurately the model could replicate the data obtained experimentally.

In a subsequent stage, the simulation study could be further developed, in order to estimate the operational energy that would be needed for space heating and cooling in the notional semi-detached house, to guarantee interior hygro-thermal comfort throughout the year. This could be achieved by implementing a dynamic thermal model of the houses and modelling the external walls according to the build-ups of the three walls tested in the current research. Such a study would lead to a better understanding of how the measured thermal-inertia properties of the envelope correlate with the in-use energy requirements for Scottish (or more in general, British) housing, either in the current climate or in future climate scenarios (based upon the projections available in the literature). Once energy demand is determined, the environmental impacts associated with it could also be predicted through an LCA approach. The findings of this research, in turn, would cast more light into the relationship between passive systems based on thermal mass and their environmental credentials, including their effectiveness as a measure of climate-change adaptation and mitigation.

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Appendices

A List of publications by the author

The list of the author’s publications related to the thesis is as follows:

Sanna, F., Hairstans, R., Leitch, K., Crawford, D., Menéndez, J. and Turnbull, D. (2012) 'Structural optimisation of timber offsite modern methods of construction', in Quenneville, P. (ed.), *World Conference on Timber Engineering – WTCE 2012*. Red Hook, NY: Curran Associates, pp. 368-377.

ISBN: 9781622763054

Smith, S., Hairstans, R., MacDonald, R. and **Sanna, F**. (2013) *Strategic review of the offsite construction sector in Scotland.* Edinburgh: Scottish Government.

ISBN: 9781782561712

Smith, S., Hairstans, R., MacDonald, R. and **Sanna, F**. (2013) *A strategic review of the offsite construction sector in Scotland. Summary report.* Edinburgh: Scottish Government.

ISBN: 9781782563945

Hairstans, R. and **Sanna, F.** (2017) 'A Scottish perspective on timber offsite construction', in Smith, R.E. and Quale, J.D. (eds.), *Offsite architecture: constructing a post-industrial future.* Abingdon: Routledge, ch. 15.

ISBN: 9781138821392

B Glossary of life-cycle assessment

Commonly-used terms relating to LCA studies are presented in this appendix.

Acidification: "deposition of airborne acids on lakes, (bare) soil, trees (leaves, roots, etc.) and other vegetation" (Klöpffer and Grahl, 2014, p. 73).

Allocation: "partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" (BSI, 2006a, § 3.17).

Attributional LCA: "attributional modelling depicts the system as it can be observed/measured, linking the single processes within the technosphere along the flow of matter, energy, and services" (JRC and IES, 2010, p. 158).

Burden shift: see **Trade-off.**

Carbon sequestration: natural process whereby wood-based products are considered to contain a storage of CO_2.

Characterisation: "the calculation of indicator results", which "involves the conversion of LCI results to common units and the aggregation of the converted results within the same impact category" (BSI, 2006b, § 4.4.2.4).

Characterisation factor: "factor derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator" (BSI, 2006a, § 3.37).

Classification: "assignment of LCI results to the selected impact categories" (BSI, 2006b, § 4.4.2.3).

Climate change: "climate change is defined here as the impact of human emissions on the radiative forcing (*i.e.,* heat radiation absorption) of the atmosphere" (Guinée, 2002, p. 59)

CML method: impact assessment tool from the University of Leiden's Institute of Environmental Science (Centrum voor Milieuwetenschappen or CML). This is the preferred method for EPDs.

Consequential LCA: "the 'consequential' LCI modelling framework aims at identifying the consequences of a decision in the foreground system on other processes and systems of the economy and builds the to-be-analysed system around these consequences" (JRC and IES, 2010, p. 164).

Cradle-to-gate EPD: EPD that only covers the product stage (information modules A1-A3), until a product is ready to leave a factory (BSI, 2014a).

Cradle-to-site EPD: EPD that covers the product and the transport to the construction site (information modules A1-A4), (BSI, 2014a).

Cradle-to-grave EPD: "EPD covering all life-cycle stages" (BSI, 2014a, § 6.2.1).

Declared unit: "quantity of a construction product for use as a reference unit in an EPD for an environmental declaration based on one or more information modules" (BSI, 2014a, § 3.8).

Endpoint impact category: "attribute or aspect of natural environment, human health, or resources, identifying an environmental issue giving cause for concern" (BSI, 2006a, § 3.36).

Eutrophication: "excessively-high environmental levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P)" (Guinée, 2002, p. 66).

Eutrophication potential (EP): "eutrophying emission to air, water and soil (in kg PO_4 equivalents/kg emission)" (Guinée, 2002, p. 66).

Global-warming potential (GWP), see also Climate change: "global-warming potential for a 100-year time horizon (GWP_{100}) for each greenhouse gas emission to the air (in kg carbon dioxide equivalent/kg emission" (Guinée, 2002, p. 60).

Goal: "the goal of an LCA states the intended application, the reasons for carrying out the study, the intended audience, *i.e.,* to whom the results of the study are intended to be communicated, and whether the results are intended to be used in comparative assertions intended to be disclosed to the public" (BSI, 2006a, § 5.2.1.1).

Grouping: "assignment of impact categories into one or more sets as predefined in the goal and scope definition", which "may involve sorting and/or ranking" (BSI, 2006b, § 4.4.3.3).

Environmental product declaration (EPD), *also known as* **type-III environmental declaration:** "environmental declaration providing quantified environmental data using predetermined parameters and, where relevant, additional environmental information" (BSI, 2014a, § 3.32).

Functional unit: "quantified performance of a product system for use as a reference unit" (BSI, 2006a, § 3.20).

Impact category: "class representing environmental issues of concern to which life cycle inventory analysis results may be assigned" (BSI, 2006a, § 3.39).

Information module: "compilation of data to be used as a basis for a Type-III environmental declaration covering a unit process or a combination of unit processes that are part of the life cycle of a product" (BSI, 2014a, § 3.8).

Interpretation: "phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations" (BSI, 2006a, § 3.5).

Life-cycle assessment (LCA): "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (BSI, 2006a, § 3.2).

Life-cycle impact assessment (LCIA): "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (BSI, 2006a, § 3.4).

Life-cycle inventory (LCI): “phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle” (BSI, 2006a, § 3.3).

Normalization: “the calculation of the magnitude of the category indicator results relative to some reference information” (BSI, 2006b, § 4.4.3.2.1).

Ozone depletion: “thinning of the stratospheric ozone layer as a result of anthropogenic emissions” (Guinée, 2002, p. 60).

Ozone-depletion potential (ODP): “ozone depletion potential in the steady state (ODP steady state) for each emission to the air (in kg CFC-11 equivalent/kg emission)” (Guinée, 2002, p. 60).

Photochemical ozone creation: “formation of reactive chemical compounds such as ozone by the action of sunlight on certain primary air pollutants” (Guinée, 2002, p. 65).

Photochemical-ozone-creation potential (POCP): potential of photochemical creation of ozone in the troposphere, “for each emission of VOC or CO to the air (in kg ethylene equivalents/kg emission” (Guinée, 2002, p. 66).

Product system: “collection of unit processes with elementary and product flows, performing one or more defined functions”, “which models the life cycle of a product” (BSI, 2006a, § 3.28).

Product category rules (PCR): “set of specific rules, requirements and guidelines for developing Type-III environmental declarations for one or more product categories” (BSI, 2014a, § 3.20).

Programme operator: “body or bodies that conduct a Type-III environmental declaration programme” (BSI, 2014a, § 3.22).

Scope: aspect of an LCA that “includes the following items: the product system to be studied; the functions of the product system or, in the case of comparative studies, the systems; the functional unit; the system boundary; allocation procedures; impact categories selected and methodology of impact assessment, and subsequent interpretation to be used; data requirements; assumptions; limitations; initial data quality requirements; type of critical review, if any; type and format of the report required for the study" (BSI, 2006a, § 5.2.1.2).

Sensitivity analysis: "systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study" (BSI, 2006a, § 3.31).

System boundary: "set of criteria specifying which unit processes are part of a product system" (BSI, 2006a, § 3.32).

Time horizon: "period of validity of the calculation [of emissions]" (Klöpffer and Grahl, 2014, p. 236).

Trade-off: situation in which the results of an LCA suggest that the product system analysed offers disadvantages in terms of contribution to an environmental impact that are offset by some benefits (*e.g.,* in terms of other environmental aspects).

Type-III environmental label: *see* **Environmental product declaration (EPD).**

Uncertainty analysis: "systematic procedure to quantify the uncertainty introduced in the results of a life-cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty and data variability" (BSI, 2006a, § 3.33).

Weighting: "the process of converting indicator results of different impact categories by using numerical factors based on value-choices" (BSI, 2006b, § 4.4.3.4.1).

C Environmental improvements for concrete- and timber-based building products

The following figures give a schematic representation of new developments and strategies to improve the environmental performance of concrete and timber-based materials. These improvements are discussed in CHAPTER 3.

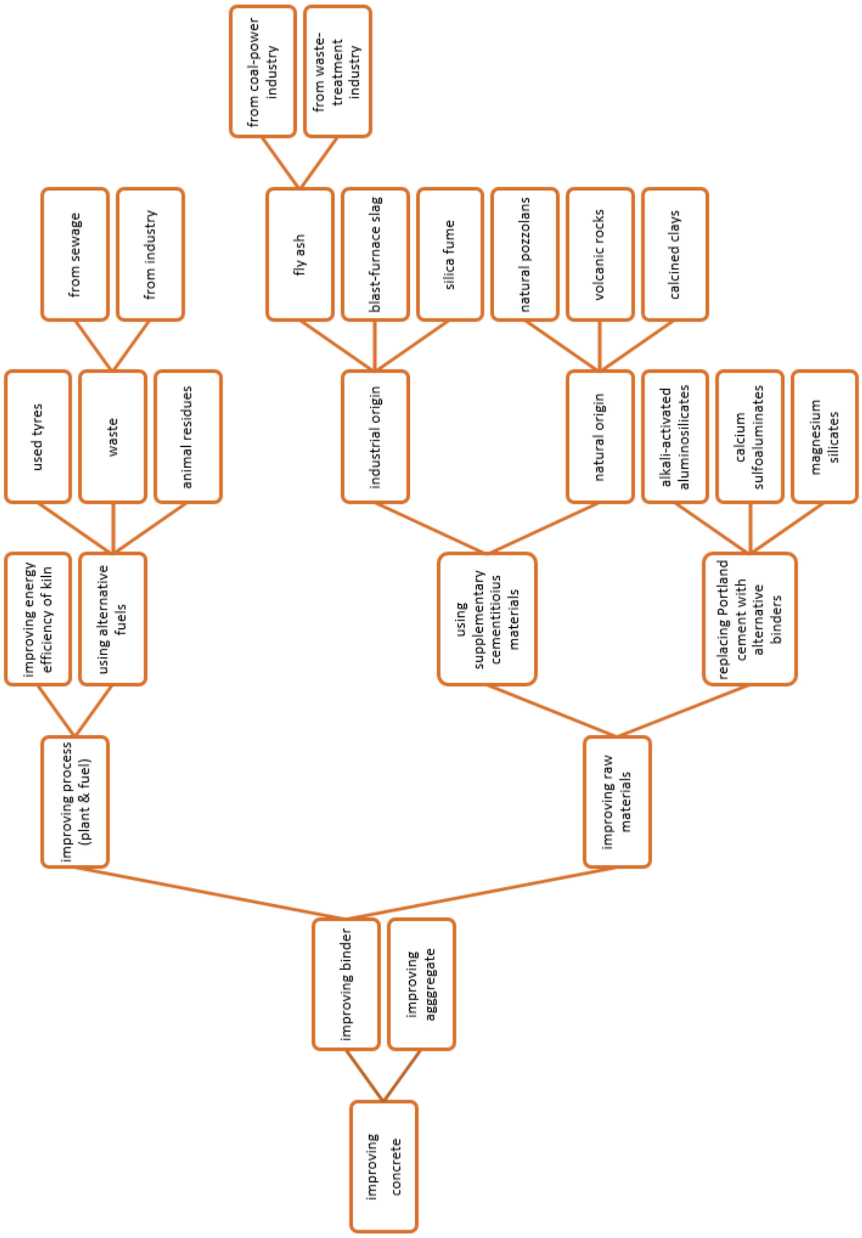


Figure C.1 Strategies that can be adopted to improve the environmental impacts associated with the manufacture of concrete products.

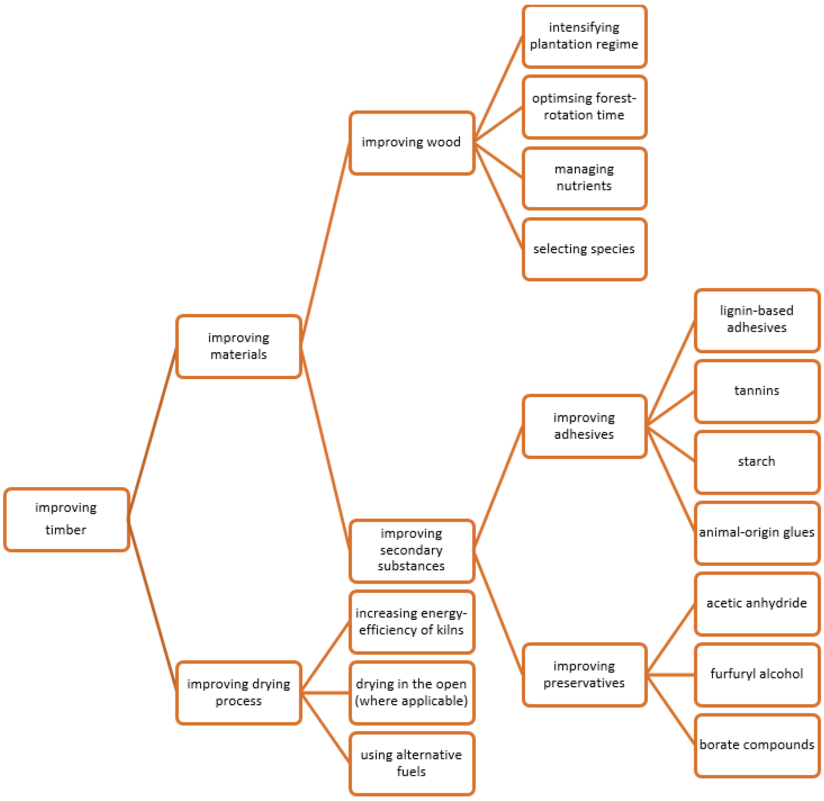


FIGURE C.2 Strategies that can be adopted to improve the environmental impacts associated with the manufacture of timber products.

D Maximum U-values allowed (Scottish Building Regulations)

The following tables offer a summary of Scottish Building Regulations in relation to U-values. These regulations have informed the design of the notional buildings, as discussed in CHAPTER 4.

TABLE D.1 Maximum U-values allowed by the Scottish Building Regulations 2013. Source: Table 6.3 of the Technical Handbook – Domestic, version 2013.

Type of element	(a) Area-weighted average U-value (W/m^{2}K) for all elements of the same type	(b) Individual element U-value (W/m^{2}K)
Wall [1]	0.25	0.70
Floor [1]	0.20	0.70
Roof	0.18	0.35
Windows, doors and rooflights	1.8	3.3

Additional information

1. Excluding separating walls and separating floors between heated areas where thermal transmittance need not be assessed, provided measures to limit heat loss arising from air movement within the cavity separating wall (see below).

TABLE D.2 Maximum U-values allowed by the Scottish Building Regulations 2016. Source: Table 6.3 of the Technical Handbook – Domestic, version 2016.

Type of element	(a) Area-weighted average U-value (W/m^{2}K) for all elements of the same type	(b) Individual element U-value (W/m^{2}K)
Wall [1]	0.22	0.70
Floor [1]	0.18	0.70
Roof	0.15	0.35
Windows, doors and rooflights	1.6	3.3
Cavity separating wall	0.2	

Notes:

1. Excluding separating walls and separating floors between heated areas where thermal transmittance need not be assessed, beyond measures to limit heat loss arising from air movement within any cavity separating wall.

E Pre-sizing of foundations (notional buildings)

Example of a table used to pre-size the foundations of the notional buildings, in order to estimate the quantity of the concrete constituents to be considered in the LCA.

TABLE E.1 Determination of the uniformly-distributed load (UDL) acting on Building A's foundation footing.

LOAD VARIATION IN TIME	LOAD CLASSIFICATION	LOAD TYPE	LOAD MAGNITUDE	UNIT	WIDTH/LENGTH of INFLUENCE AREA (m)	COMMENTS	RESULTING LOAD	UNIT
permanent	construction works	roof weight	0.69	kN/m^2	2.23		1.54	kN/m
permanent	construction works	interm. floor weight	0.33	kN/m^2	1.43		0.47	kN/m
permanent	construction works	ext. wall weight	12.73	kN/m	*n.a.*		12.73	kN/m
permanent	construction works	ground floor weight	0.35	kN/m^2	1.43		0.50	kN/m
permanent	construction works	foundation wall	5.55	kN/m	*n.a.*		5.55	kN/m
variable	imposed loads	load on ground floor	2.00	kN/m^2	1.43		2.85	kN/m
variable	imposed loads	load on iterm. floor	2.00	kN/m^2	1.43		2.85	kN/m
variable	imposed loads	load on roof	1.00	kN/m^2	1.43		1.43	kN/m
variable	snow load	snow load on roof	0.50	kN/m^2	1.43	neglected (not combined with load on roof)	0.00	kN/m
total load on footing							**27.91**	kN/m

F Constructional details (notional buildings)

Constructional details of the buildings analysed under the LCA study (the description of the notional buildings can be found in CHAPTER 4 and the results of the LCA study can be found in CHAPTER 5).

F.1 Foundations

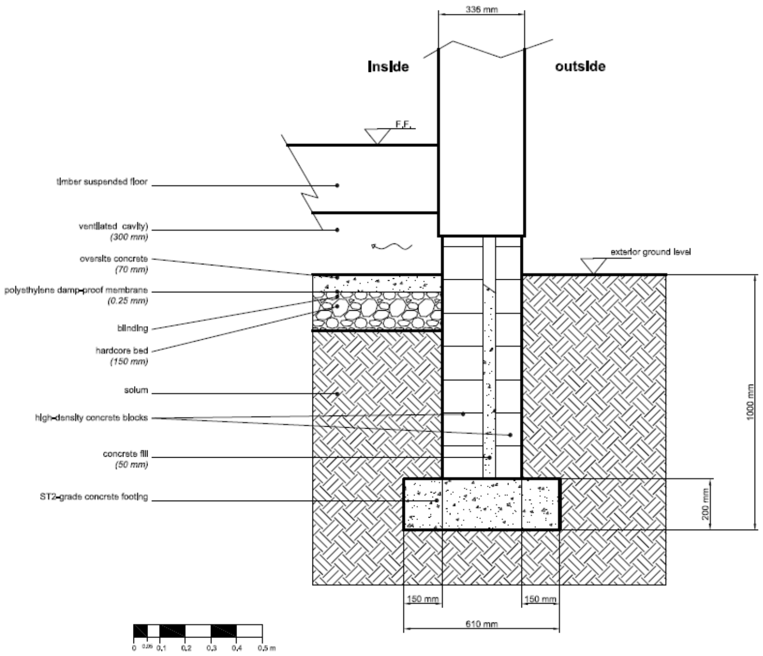


FIGURE F.1 Foundation A (heavy-weight external cladding), vertical section.

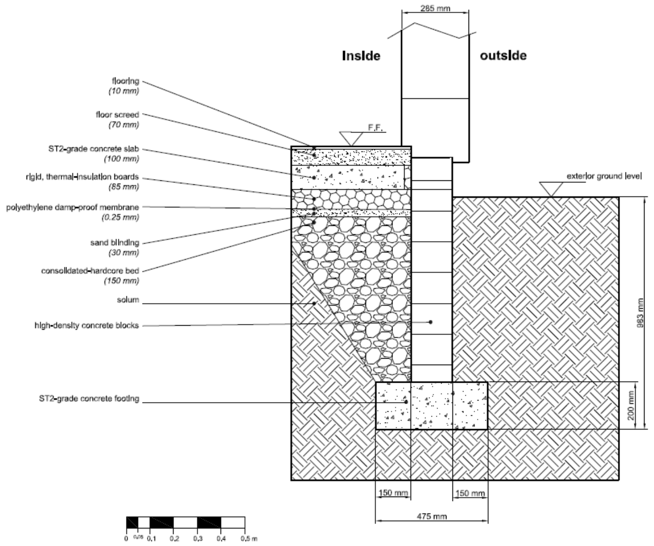


FIGURE F.2 Foundation D1 (strip foundations and ground-supported floor), vertical section.

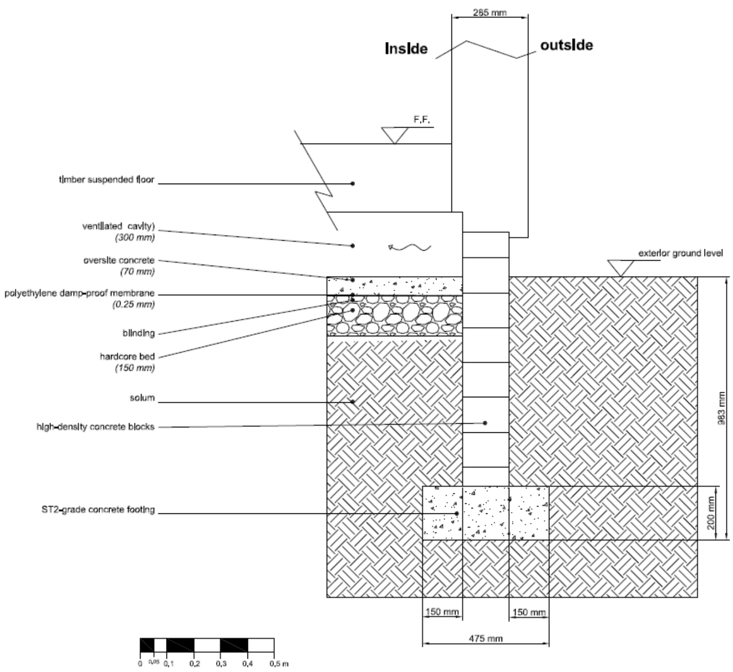


FIGURE F.3 Foundation D2 (strip foundations and suspended floor), vertical section.

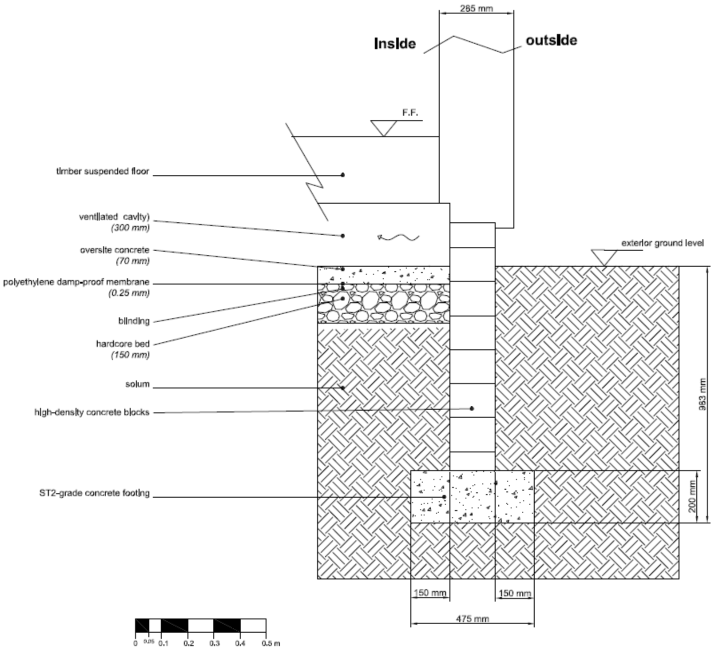


FIGURE F.4 Foundation E (strip foundations and suspended floor), vertical section.

F.2 Walls

F.2.1 External walls

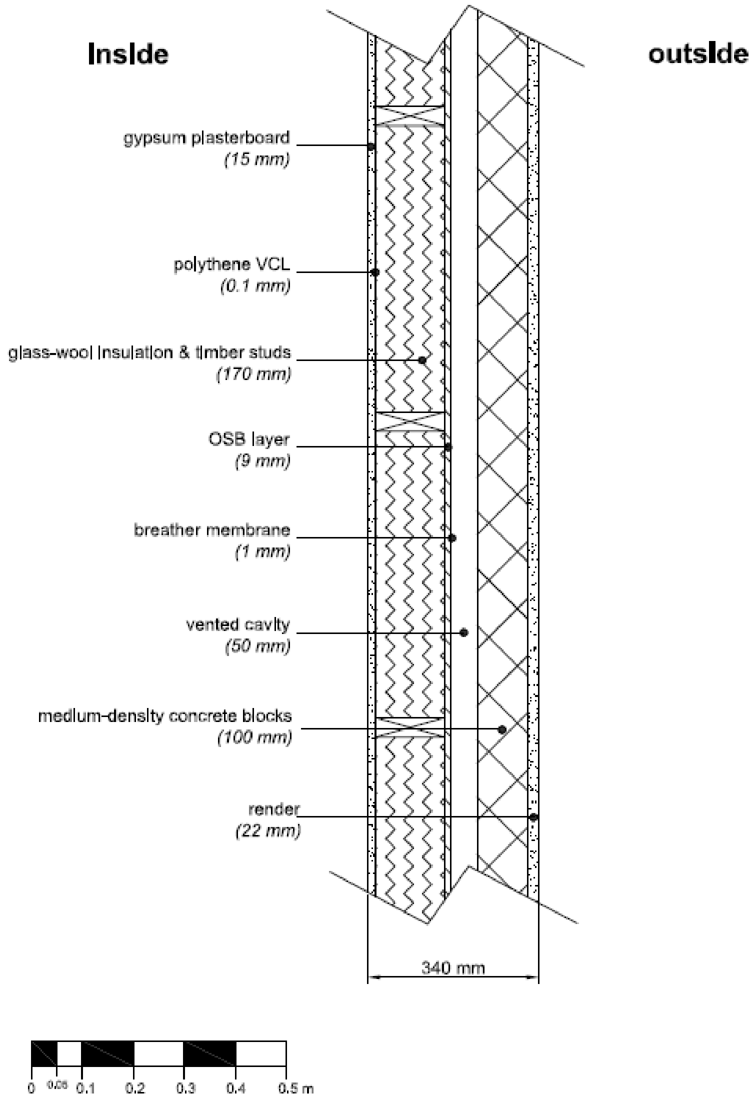


FIGURE F.5 Wall A (traditional, open-panel timber frame), horizontal section.

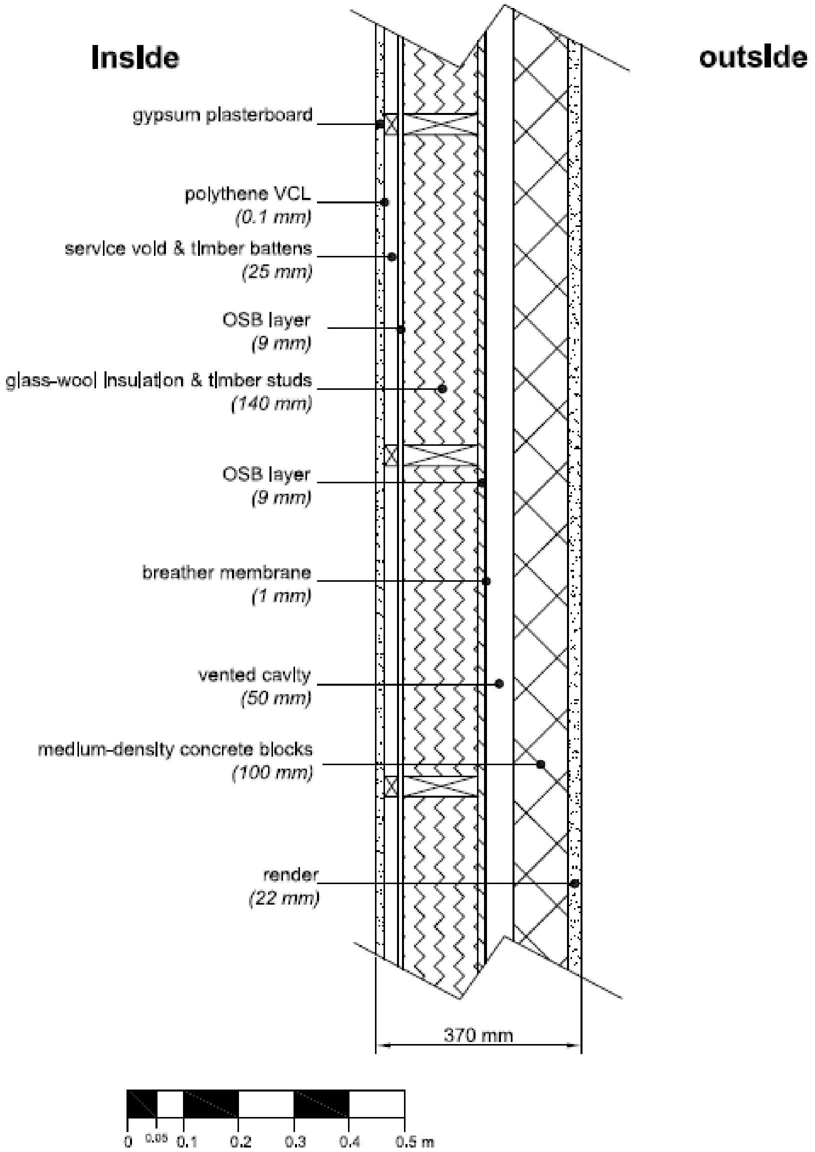


FIGURE F.6 Wall B1 (closed-panel timber frame, external solution: render on blockwork), horizontal section.

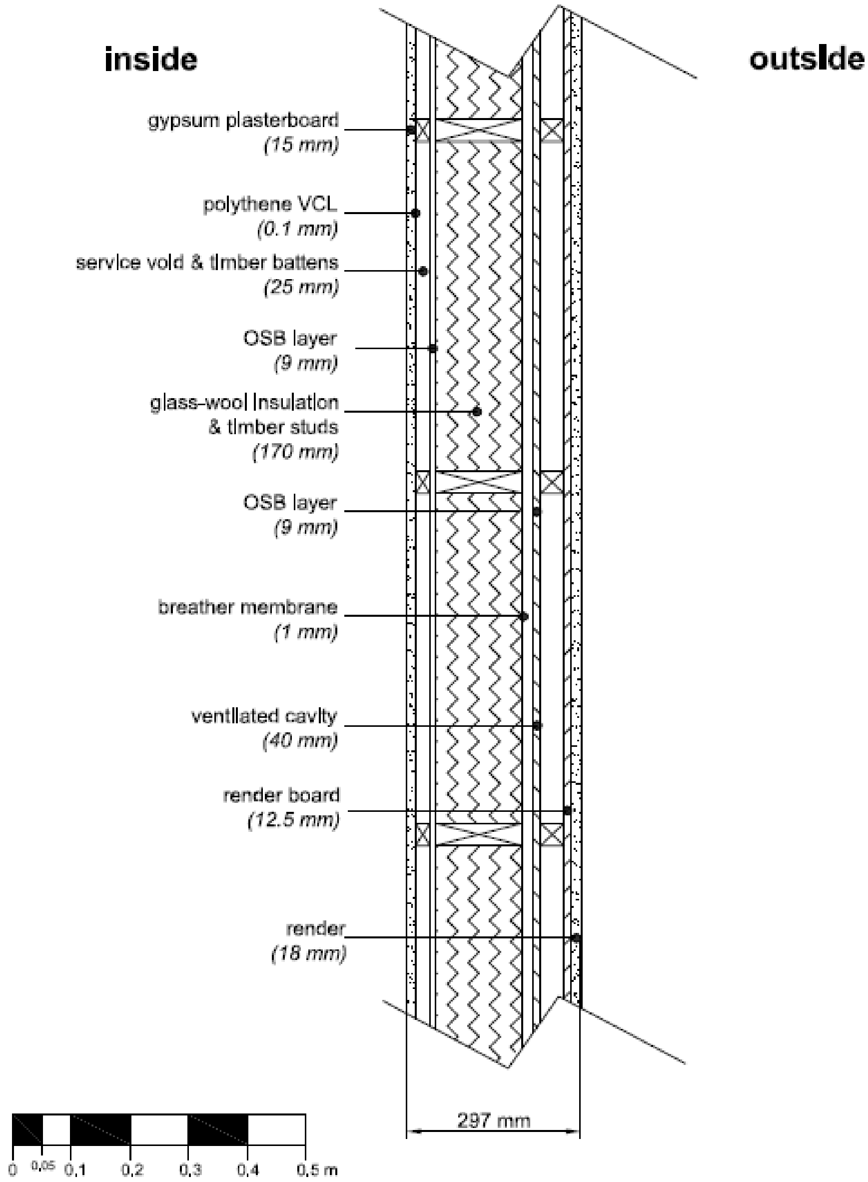


FIGURE F.7 Wall B2 (closed-panel timber frame, external solution: render on boards), horizontal section.

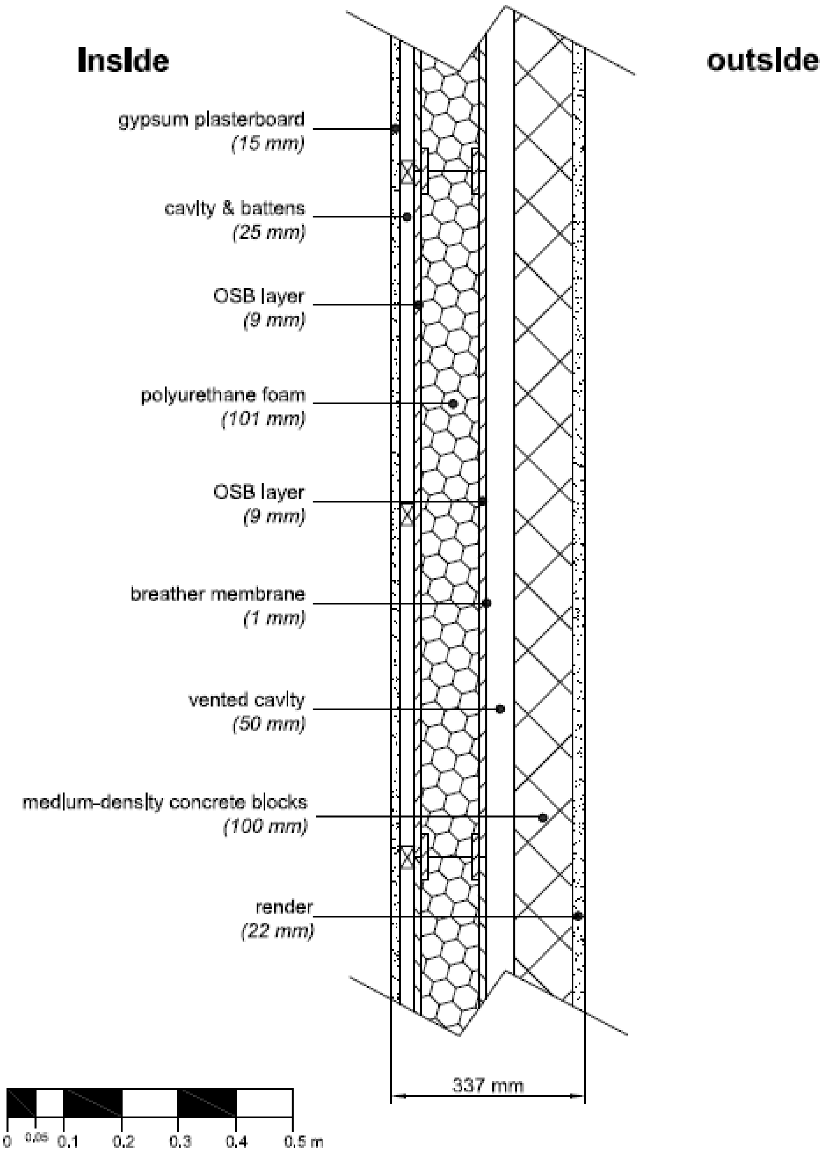


FIGURE F.8 Wall C1 (structural insulated panels (SIPs), external solution: render on blockwork), horizontal section.

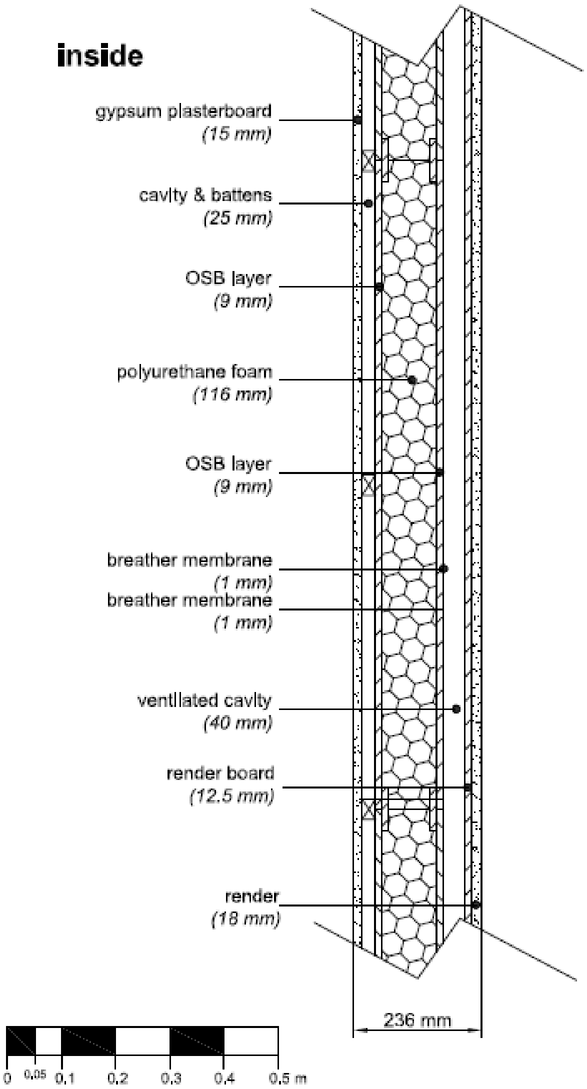


FIGURE F.9 Wall C2 (structural insulated panels (SIPs), external solution: render on boards), horizontal section.

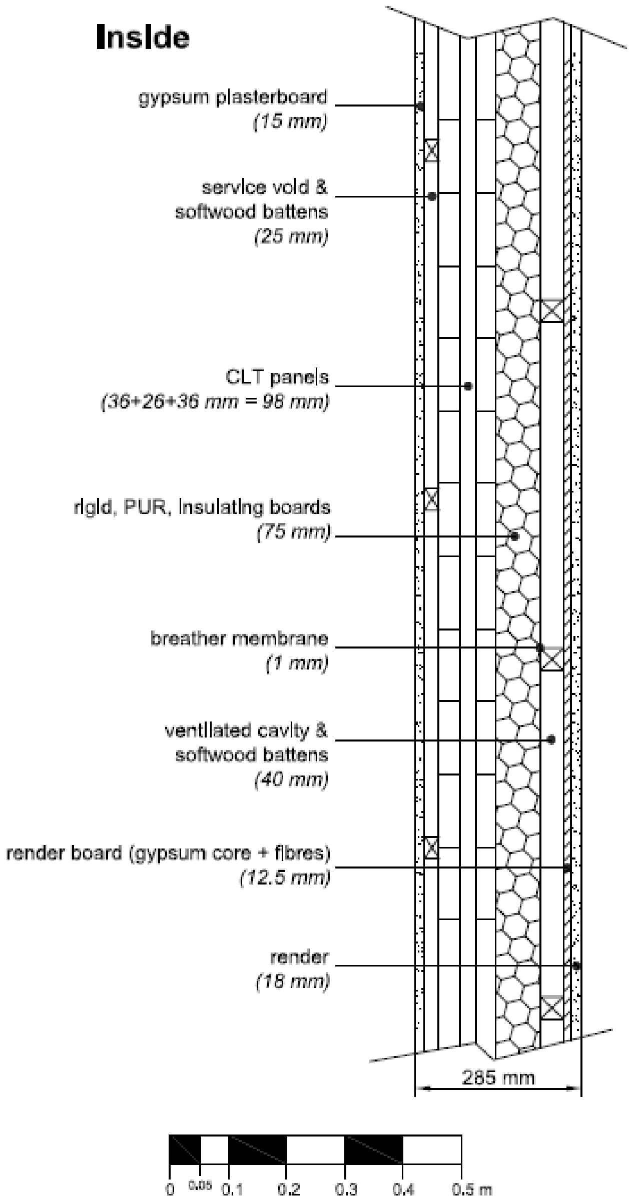


FIGURE F.10 Wall D1 (cross-laminated timber (CLT), external solution: render on boards), horizontal section.

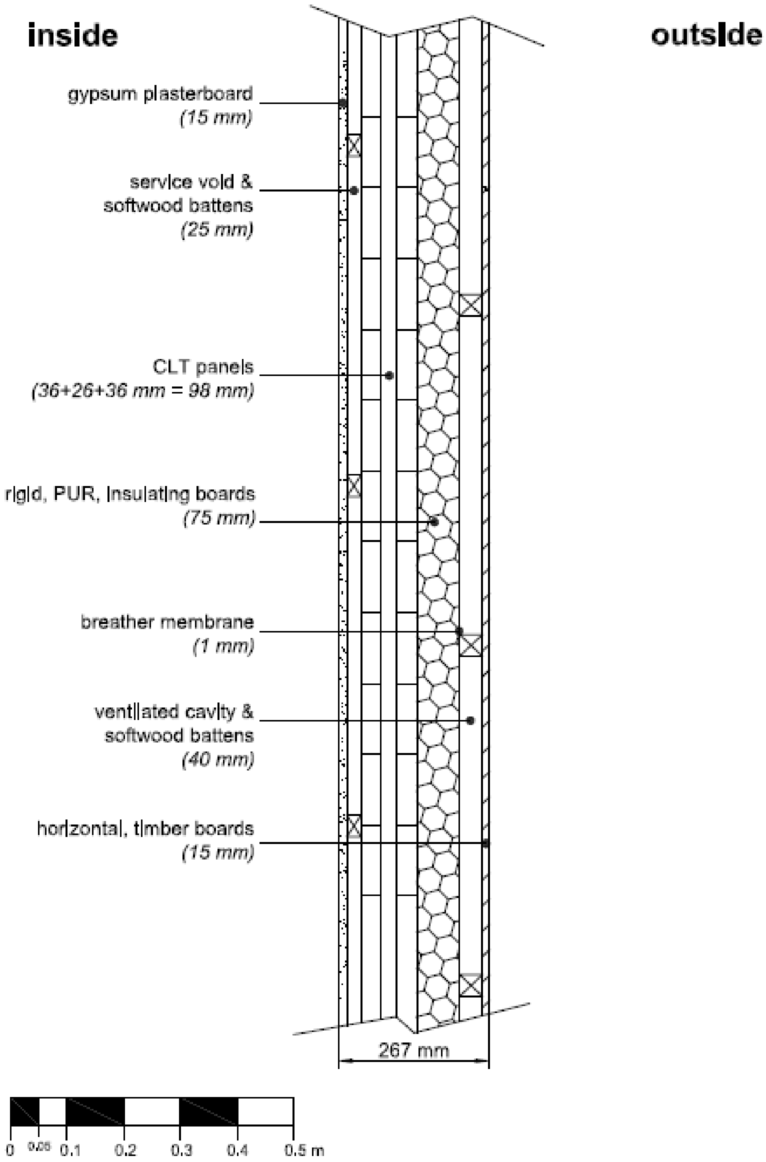


FIGURE F.11 Wall D2 (cross-laminated timber (CLT), external solution: timber cladding), horizontal section.

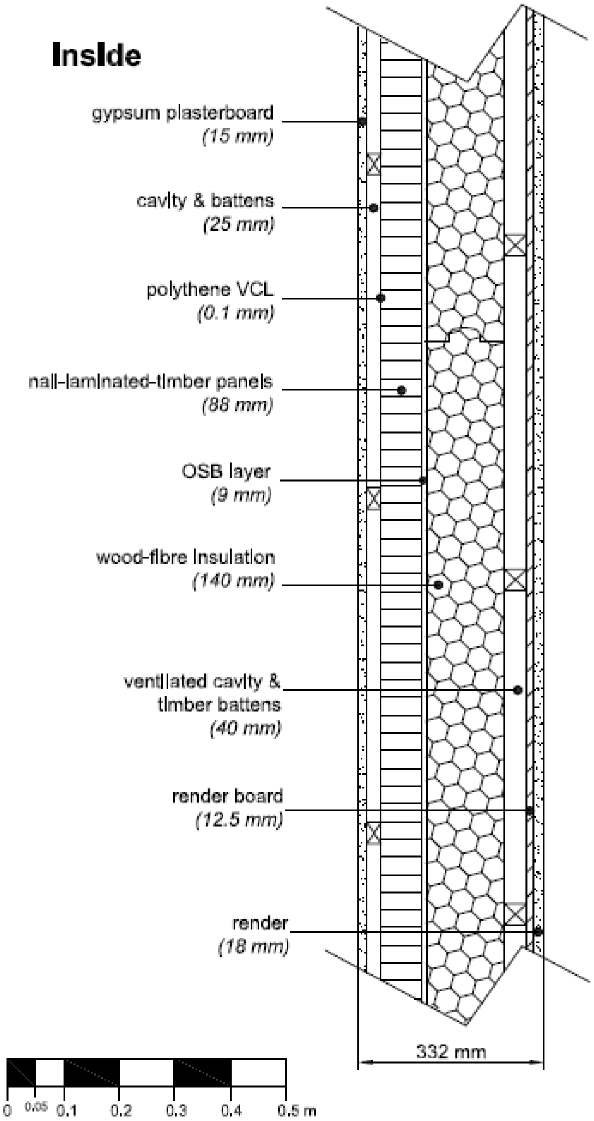


FIGURE F.12 Wall E1 (nail-laminated timber (NLT), external solution: render on boards), horizontal section.

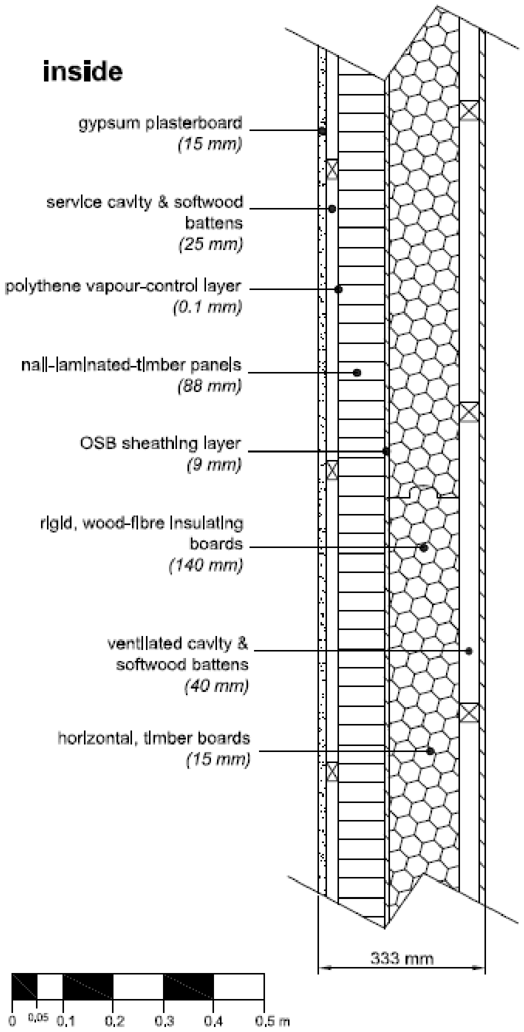


FIGURE F.13 Wall E2 (nail-laminated timber (NLT), external solution: timber cladding), horizontal section.

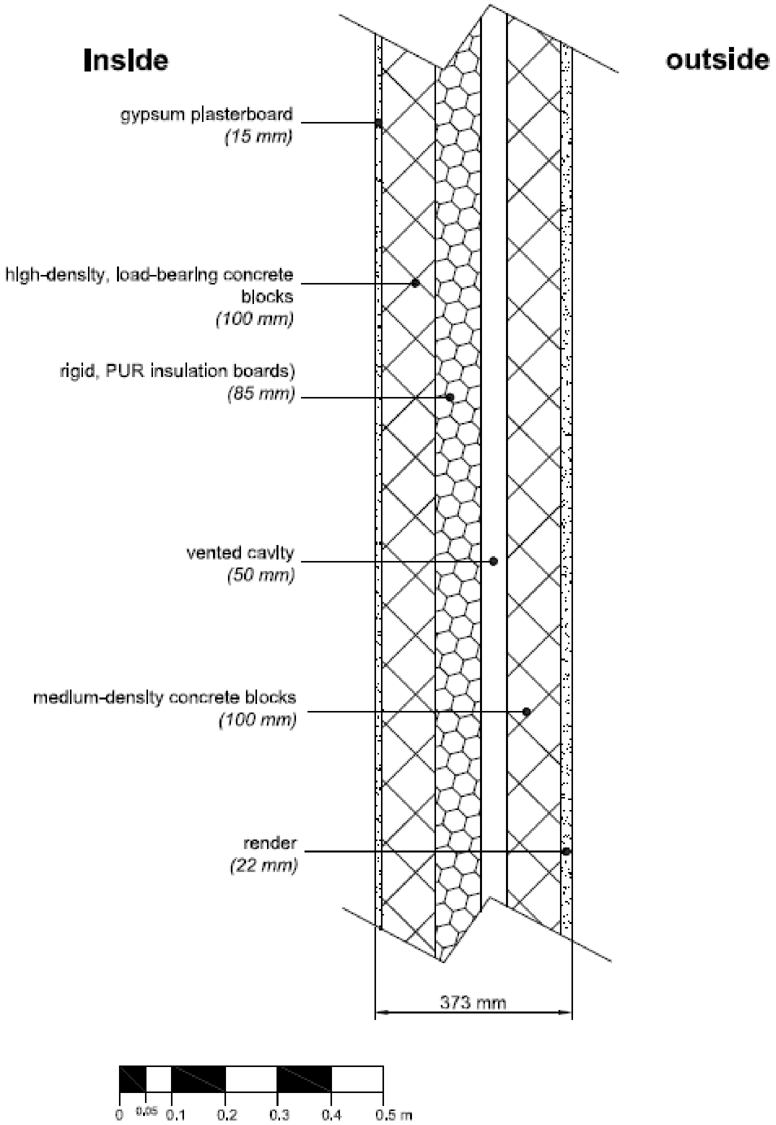


FIGURE F.14 Wall F (load-bearing masonry), horizontal section.

F.2.2 Internal walls

F.2.2.1 Party walls

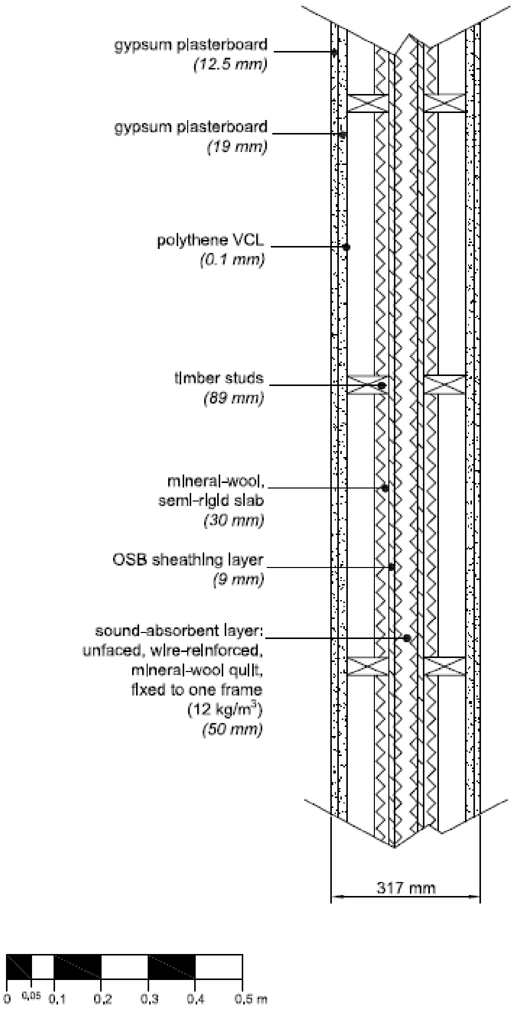


FIGURE F.15 Party wall A (traditional, open-panel timber frame), horizontal section.

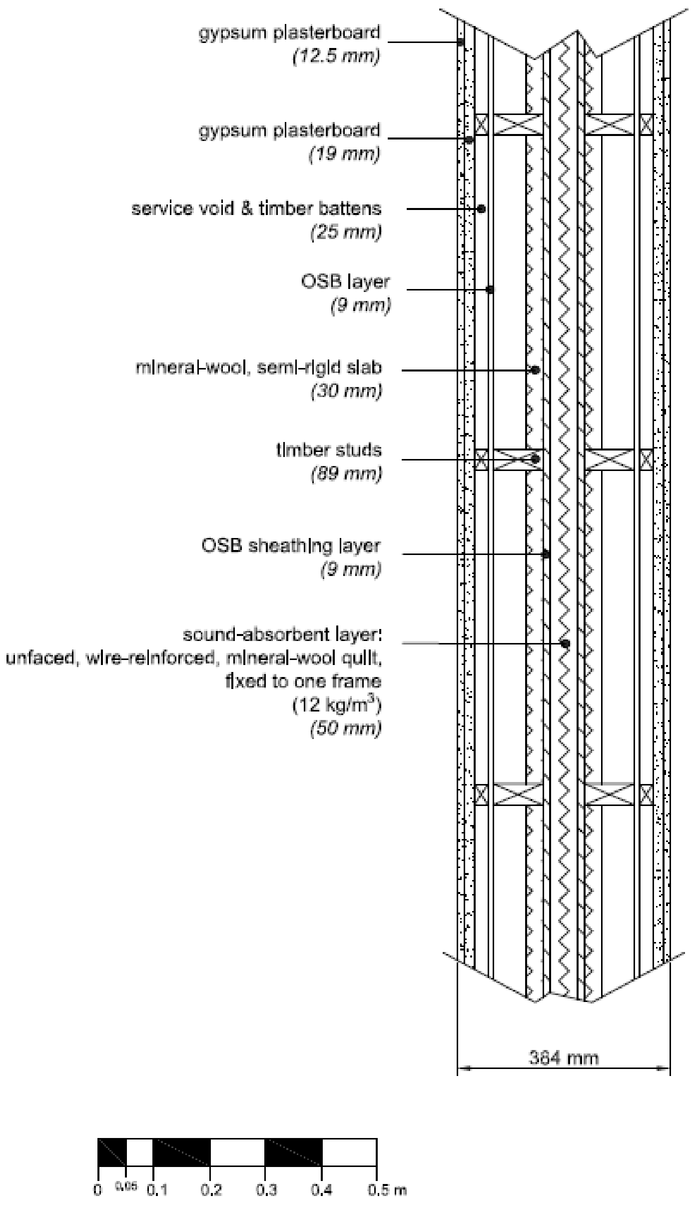


FIGURE F.16 Party wall B (closed-panel timber frame), horizontal section.

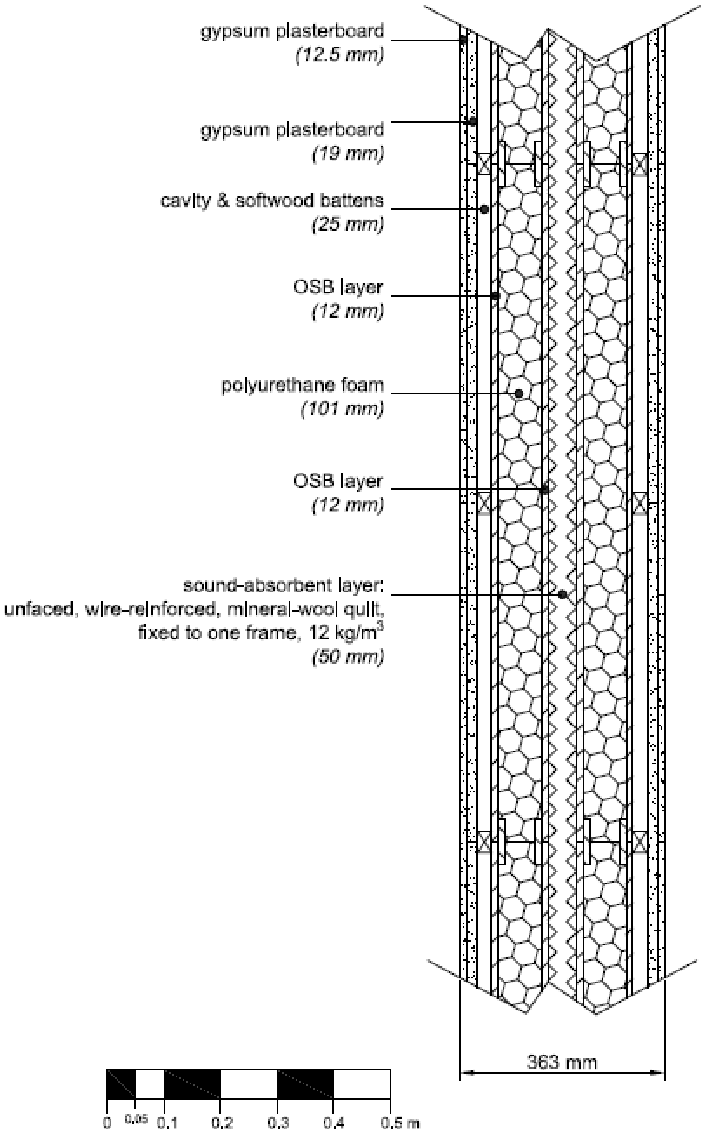


FIGURE F.17 Party wall C (structural insulated panels (SIPs)), horizontal section.

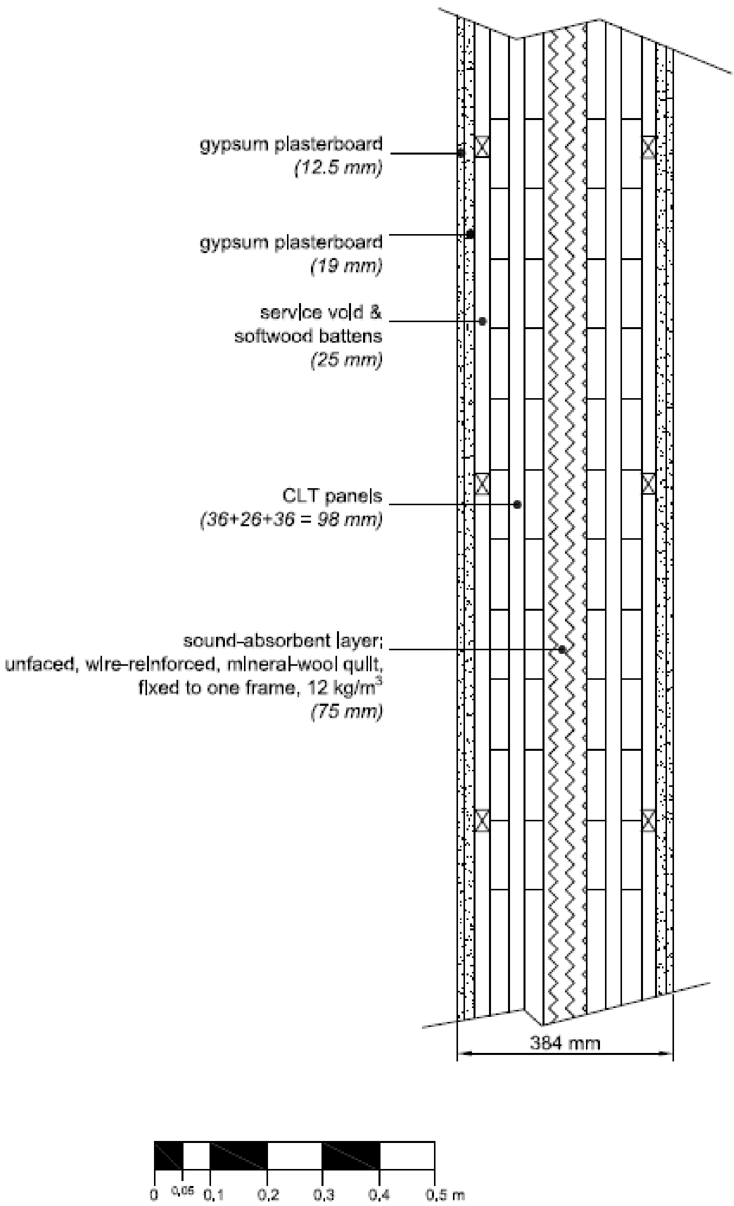


FIGURE F.18 Party wall D (cross-laminated timber (CLT)), horizontal section.

F.2.2.2 Partition walls

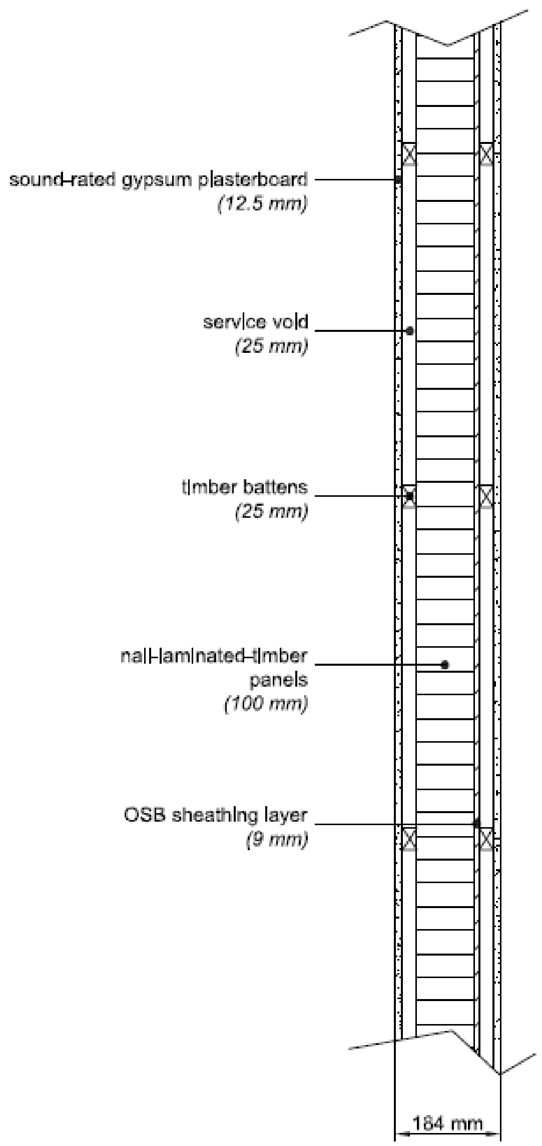


FIGURE F.19 Partition wall E (nail-laminated timber), horizontal section.

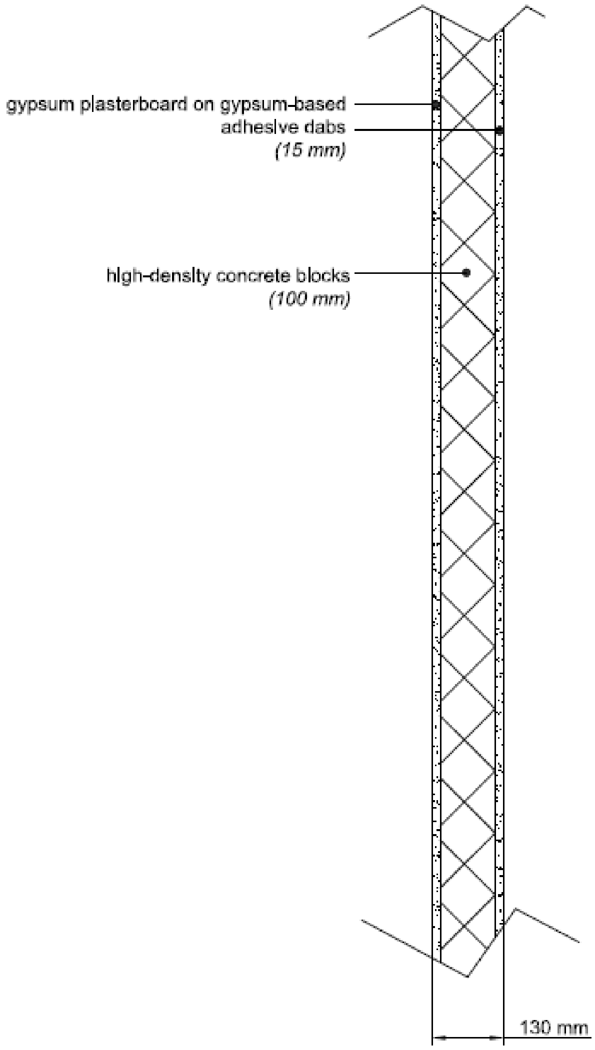


FIGURE F.20 Partition wall F (load-bearing masonry), horizontal section.

F.3 Floors

F.3.1 Ground floors

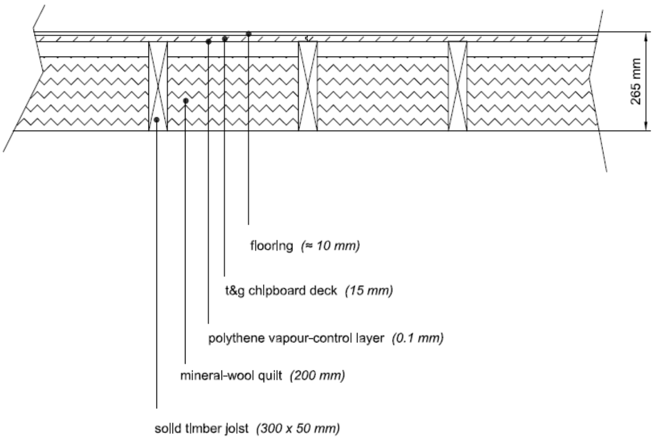


FIGURE F.21 Ground floor TF (timbre frame), cross-section.

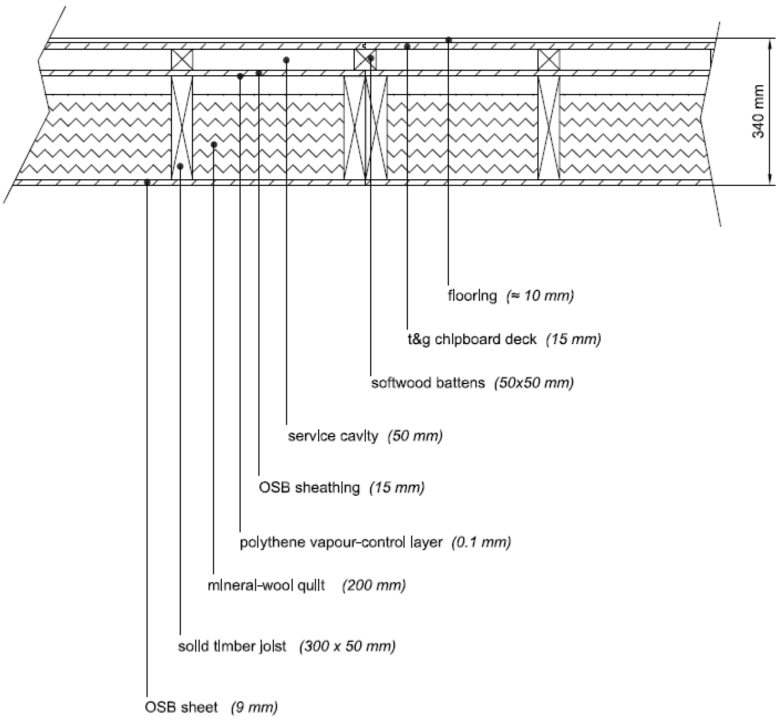


FIGURE F.22 Ground floor B (timber frame, cassetted floor), cross-section.

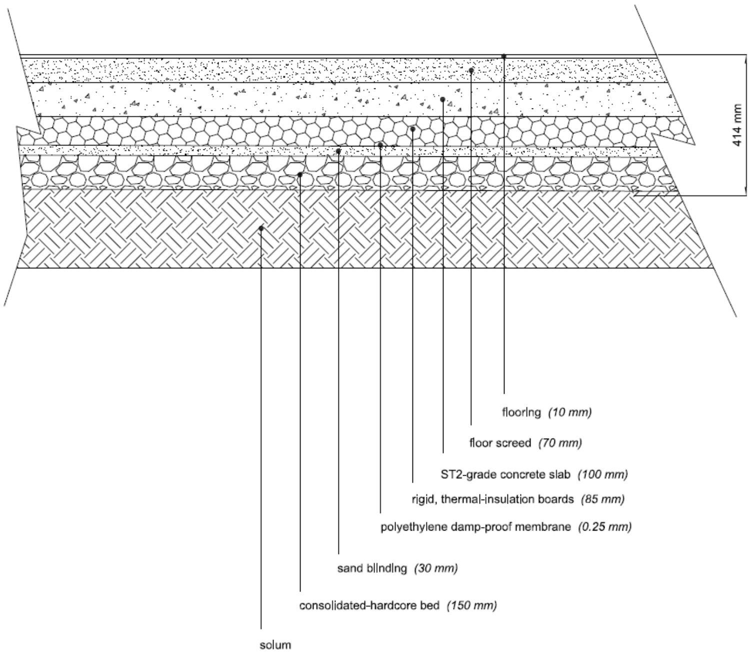


FIGURE F.23 Ground floor D1 (ground-supported concrete floor), cross-section.

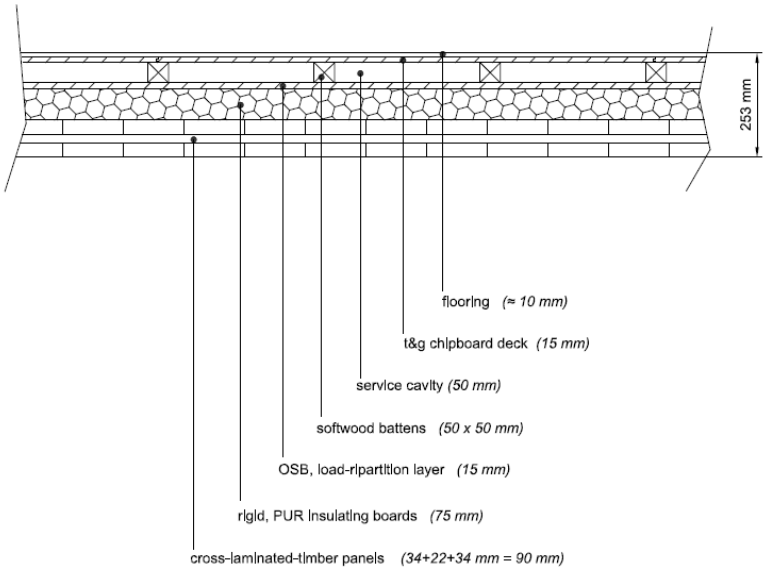


FIGURE F.24 Ground floor D2 (suspended, cross-laminated timber (CLT) floor), cross-section.

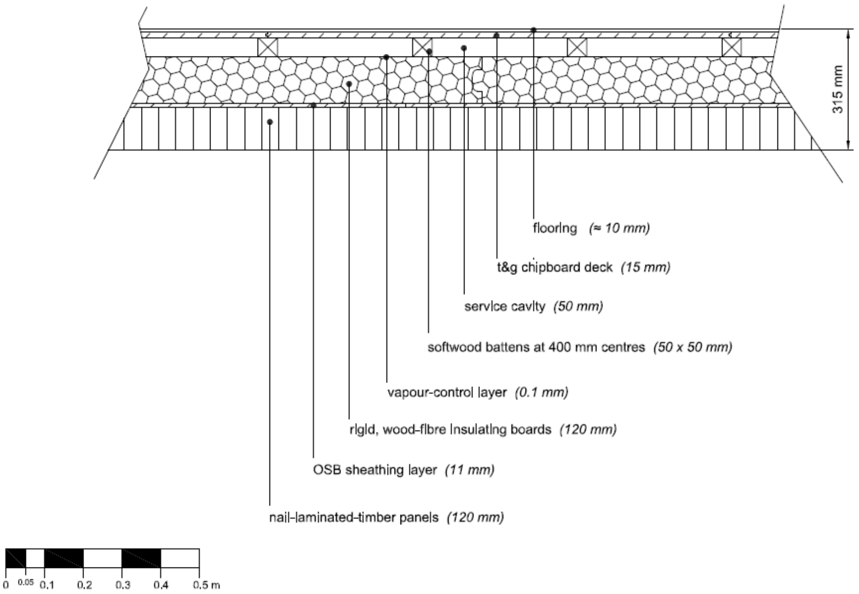


FIGURE F.25 Ground floor E (suspended, nail-laminated timber (NLT) floor), cross-section.

F.3.2 Intermediate floors

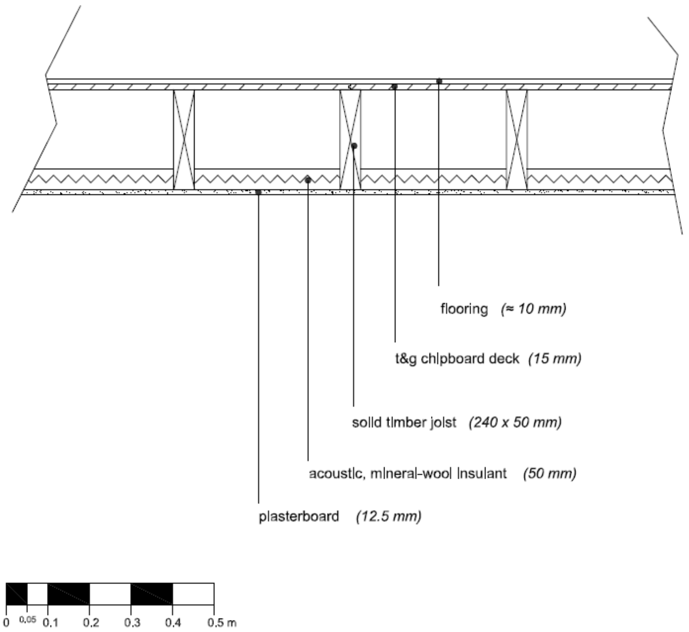


FIGURE F.26 Intermediate floor TF (timber frame, constructed in situ), cross-section.

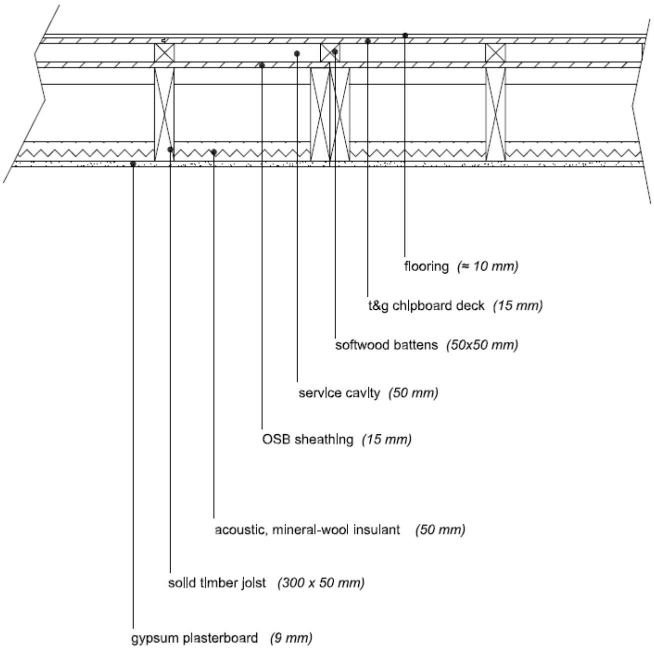


FIGURE F.27 Intermediate floor B (timber frame, cassetted floor), cross-section.

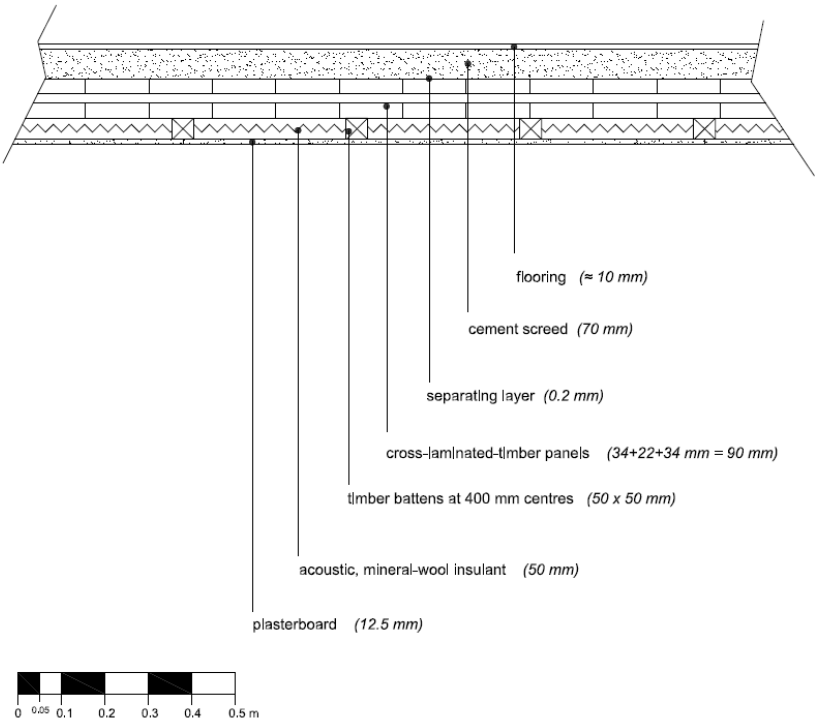


FIGURE F.28 Intermediate floor D1 (cross-laminated timber (CLT) with cement screed), cross-section.

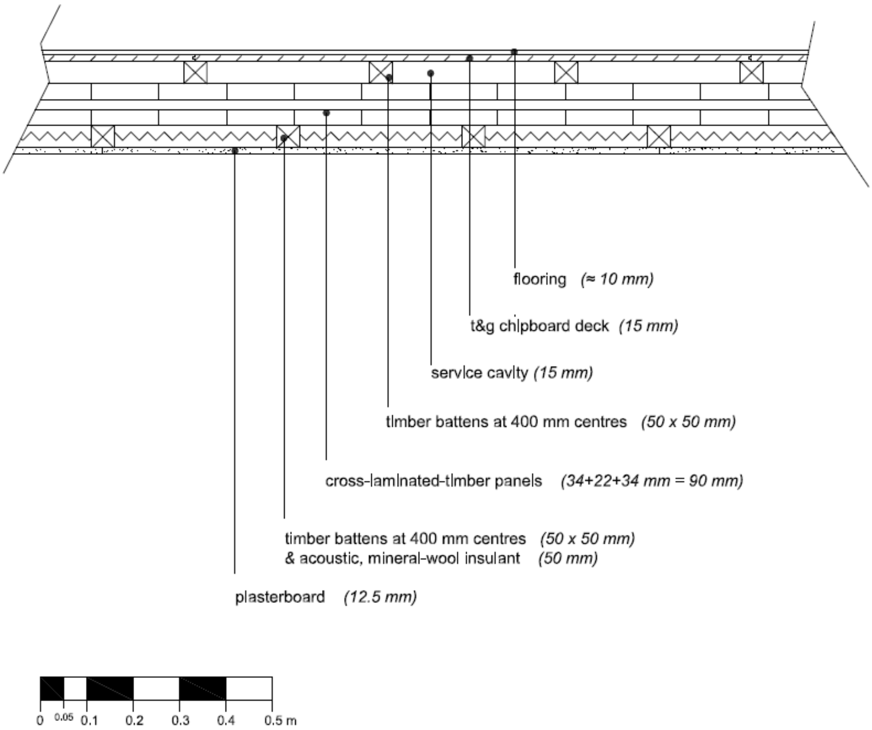


FIGURE F.29 Intermediate floor D2 (cross-laminated timber (CLT) without cement screed), cross-section.

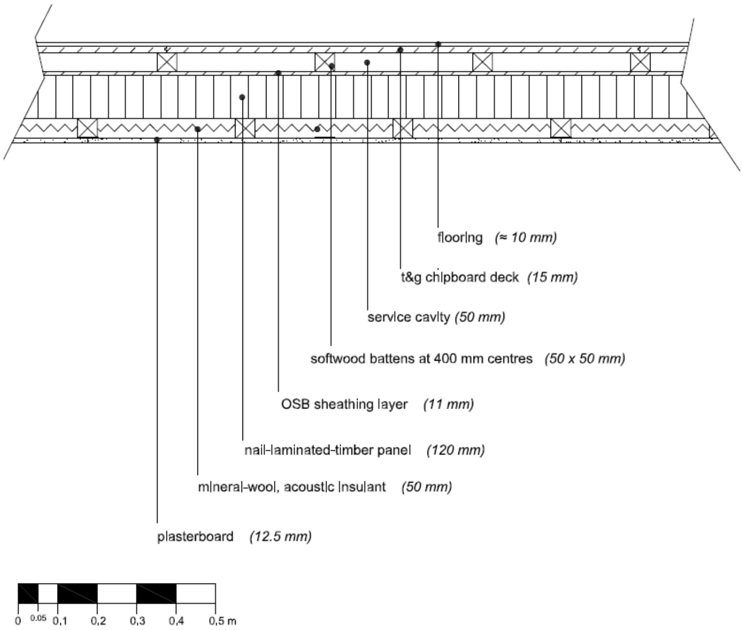


FIGURE F.30 Intermediate floor E (nail-laminated timber), cross-section.

F.4 Roofs

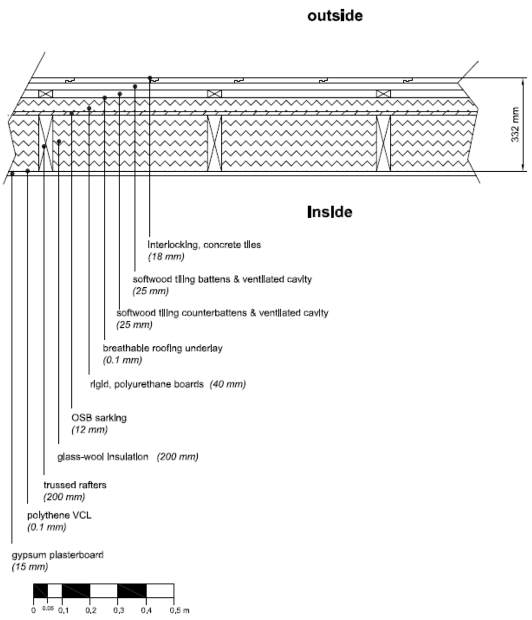


FIGURE F.31 Roof TF (trussed rafters), cross-section.

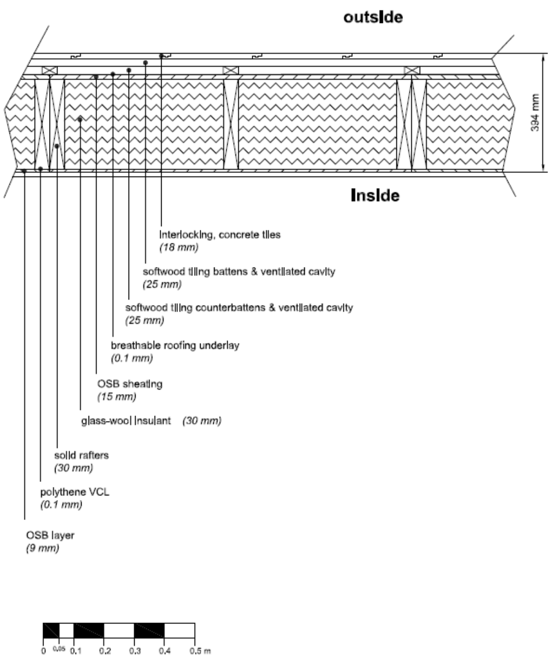


FIGURE F.32 Roof B (pre-fabricated and pre-insulated cassettes), cross-section.

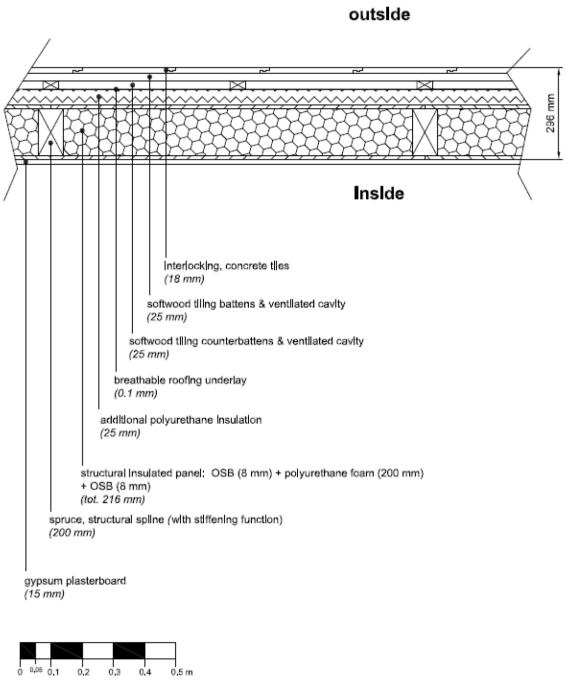


FIGURE F.33 Roof C (structural insulated panels (SIPs)), cross-section.

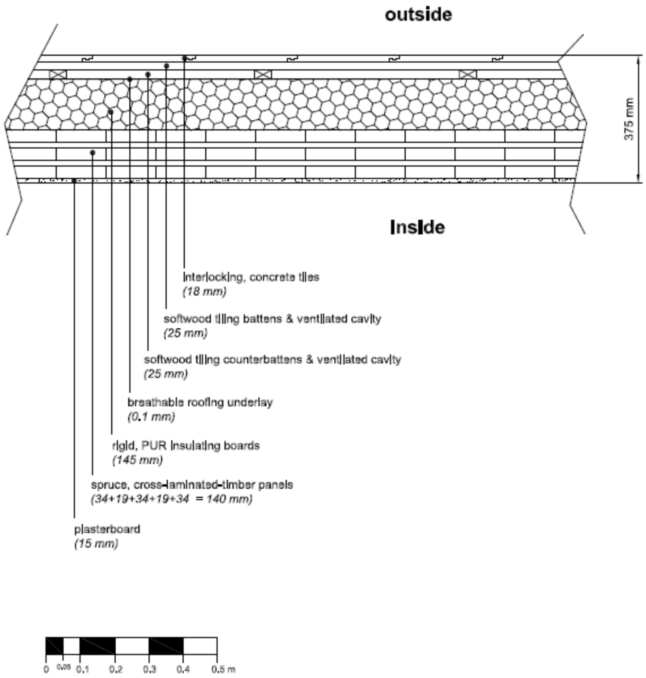


FIGURE F.34 Roof D (cross-laminated timber(CLT)), cross-section.

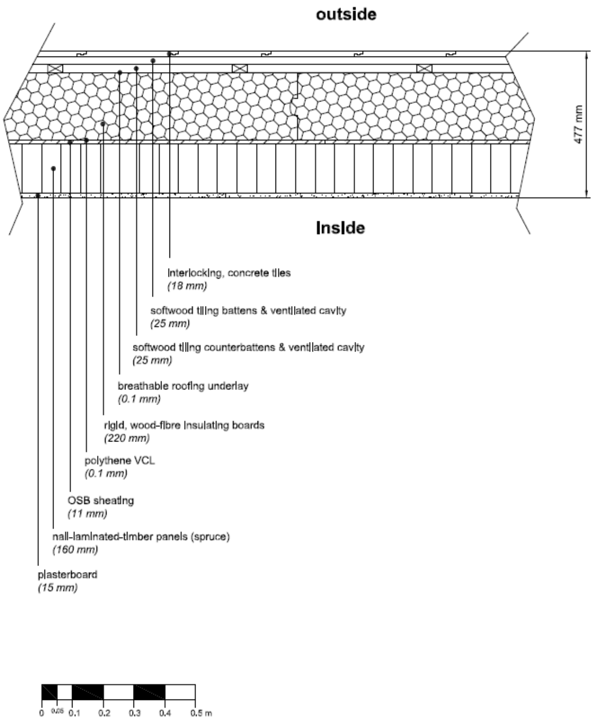


FIGURE F.35 Roof E (nail-laminated timber (NLT)), cross-section.

G Inventory of building components (notional buildings)

The following tables provide details of the components used for the notional buildings, based on information gathered from the Environmental Product Declarations (EPDs) used in the LCA study (CHAPTER 5).

TABLE G.1 Inventory of building components.

Code	EPD declaration number	Building component	Product category: generic/ specific	Manufacturer/ Manufacturers association	EPD programme	Product Description	D.U.	Int. /ext. validation	Expiry date	Geographical Coverage	Used in buildings:
103		mineral-wool insulation	generic	EURIMA	Thinkstep	Thermo-physical properties: • k: 0.035 W/(K·m) • R: 3.00 m^2·K/W Material composition: glass (sand and cullets) and stone wool (slag and basalts)	1 m^2	external	16/04/17	Europe	A, B1, B2, C1, C2, F
106	EPD-PUE-20130285-CBE-EN	polyurethane insulation board	generic	PU Europe	Institut Bauen und Unwelt e. V (IBU)	Geometry: • thicks.: 11.5 cm Thermo-physical properties: • d_{gross}: 31 kg/m^3 • k: 0.23 W/(K·m) • R: 5 m^2·K/W • w: 3.87 kg/m^2 Material composition: polyurethane from MDI (60.5%), polyols (29%), pentane (5%), additives (5.5%)	1 m^2	external	26/02/19	Europe	A, C1, C2, D1, D2, F
107	BREG EN EPD NO: 000072	Isover Acoustic Partition Roll	specific	Isover Saint-Gobain)	BRE	Geometry: • thicks.: 50 mm • dim.: 2x600x13000 mm Thermo-physical properties: • d_{gross}: 12 kg/m^3 • k: 0.039 W/(K·m) • R: 1.25 m^2·K/W Material composition: mineral wools (95%), binder (5%)	1 m^2	external	27/08/20	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F

TABLE G.2 Inventory of building components.

Code	EPD declaration number	Building component	Product category: generic/ specific	Manufacturer/ Manufacturers association	EPD programme	Product Description	D.U.	Int. /ext. validation	Expiry date	Geographical Coverage	Used in buildings:
152	EPD-STE-20150327-IBD1-EN	STEICO wood fibre insulation materials	specific	STEICO SE	Institut Bauen und Unwelt e. V (IBU)	<u>Thermo-physical properties:</u> • d_{gross}: 50-265 kg/m³ • k: 0.038 W/(K·m) • S_{ten}: 0.025 N/mm² • WPDR: 5 <u>Material composition:</u> coniferous wood (82.8%), water (6.0%), adhesives (1.2%), bi-component fibres, (1.3%), recycled paper (6.3%), flame retardants (2.4%)	1 m³	external	04/02/21	Europe	E1, E2
203	EPD-MPA-20140025-CAG1-EN	UK Average Portland Cement	generic	MPA, CEMEX, UK, Hanson UK, Lafarge Tarmac, Hope Construction Materials	Institut Bauen und Unwelt e. V (IBU)	<u>Thermo-physical properties:</u> • S_{cpmp}: 32.5 N/mm² <u>Material composition:</u> clinker (86.1%), Gypsum (4.15%), fly ash (4%), ground granulated blast furnace slag (GGBS) (1.1%).	1 ton	external	04/02/19	UK	A, B1, B2, C1, C2, D1, D2, E1, E2, F
251	S-P-00528	Holcim's Stancesti and Gligoresti aggregates	specific	Holcim Romania	International EPD® system	<u>Material composition:</u> mineral materials excavated from natural quarries, washed, sorted or crushed for distribution.	1 kg	external	01/04/19	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F
381		galvanised steel sheet	generic		PE international (for Wood for Good)		1kg	external		UK	A, B1, B2, C1, C2, D1, D2, E1, E2, F

TABLE G.3 Inventory of building components.

Code	EPD declaration number	Building component	Product category: generic/ specific	Manufacturer/ Manufacturers association	EPD programme	Product Description	D.U.	Int. /ext. validation	Expiry date	Geographical Coverage	Used in buildings:
402	S-P-00682	Enviroblock dense blocks	specific	Aggregate Industries	International EPD® system	<u>Geometry:</u> • length: 290-440 mm • width: 100-140 mm • height: 215 mm <u>Thermo-physical properties:</u> • S_{comp}: 3.5-10.4 N/mm^2 <u>Material composition:</u> recycled dust (70-76%), aggregate (15-20%), cement CEM 1 (<10%), water (<5%)	1 m^3	external	26/02/20	UK	B2, C2, D1, D2, E1, E2
403	S-P-00683	Enviroblock Lightweight Blocks	specific	Aggregate Industries	International EPD® system	<u>Geometry:</u> • length: 440 mm • width: 140 mm • height: 215 mm <u>Thermo-physical properties:</u> • S_{comp}: 3.5-10.4 N/mm^2 <u>Material composition:</u> recycled dust* 82-88%, lightweight aggregate 5-8%, cement 1 <8%, water <5%	1 m^3	external	26/02/20	UK	A, B1, C1, F
441	EPD-ETE-201500xxx-CBA1-EN	Eternit tiles Sneldek	specific	Eternit N.V.	Institut Bauen und Unwelt e. V (IBU)	<u>Geometry:</u> • dim.: 332-420 mm <u>Thermo-physical properties:</u> • d_{gross}: 2510 kg/m^3 <u>Material composition:</u> sand (78.6%), cement CEMIII 42.5 (21.8%), coating (0.9%), pigments (0.7%)	100 m^2	external	13/07/21	UK	A, B1, B2, C1, C2, D1, D2, E1, E2, F

TABLE G.4 Inventory of building components.

Code	EPD declaration number	Building component	Product category: generic/ specific	Manufacturer/ Manufacturers association	EPD programme	Product Description	D.U.	Int. /ext. validation	Expiry date	Geographical Coverage	Used in buildings:
452	not given	Cembrit cement render-carrier board	specific	Cembrit Construction	EPD Denmark www.epddanmark.dk"	Thermo-physical properties: • d_{gross}: 1550 kg/m^3 Material composition: Portland cement (35-60%), inert filler (limestone, mica) (32-61%), cellulose 4-(6%), PVA (0-2%), light filler (0-12%)	1 ton	external	25/04/21	Europe	B2, C2, D1, E1
471	EPD-MAR-20160004-IBC2-EN	Marazzi Glazed Porcelain Tile	specific	Marazzi Group	Institut Bauen und Unwelt e. V (IBU)	Geometry: • thicks.: 10-10.5 mm • dim.: 30-60 cm Thermo-physical properties: • S_{comp}: >35 N/mm^2	1 m^2	external	22/08/21	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F
501	EPD-EGG-20140247-IBA1-EN	EGGER sawn timber dried softwood	specific	EGGER	Institut Bauen und Unwelt e. V (IBU)	Geometry: • thicks.: 12 mm • dim.: 30-60 cm Thermo-physical properties: • d_{gross}: 310-420 kg/m^3 • S_{comp}: 17-26 N/mm^2 • MC: 12-18 % Material composition: spruce and pine	1 m^3	external	07/04/17	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F

TABLE G.5 Inventory of building components.

Code	EPD declaration number	Building component	Product category: generic/ specific	Manufacturer/ Manufacturers association	EPD programme	Product Description	D.U.	Int. /ext. validation	Expiry date	Geographical Coverage	Used in buildings:
531	EPD-KLH-2012111-E	KLH solid timber panels	generic	KLH Massivholz GmbH	Institut Bauen und Unwelt e. V (IBU)	Geometry: • dim.: 16.50x2.95 x0.50 m • thicks.: 57 mm Thermo-physical properties: • d: 488 kg/m^3 • k: 0.13 W/(K·m) • MC: 12 % Material composition: adhesive content adhesives (2.0%), melamine urea formaldehyde (MUF) (1.4%), polyurethane (PUR) (0.5%), emulsion polymer isocyanate (EPI) (0.1%)	1 m^3	external	31/01/18	Europe	D1, D2
551	NEPD-409-288-EN	Kebony Character Cladding	specific	Kebony AS	Norwegian EPD Foundation	Thermo-physical properties: • S_{comp}: 20-30 N/mm^2 Material composition: Scots pine (82.8%), bio-based chemicals (17.2 %)	1 m^3	external	21/06/21	Europe	D2, E2
561	EPD-KRO-20150067-IBD1-EN.	OSB 3 sheets	specific	Krono OSB	Institut Bauen und Unwelt e. V (IBU)	Geometry: • dim.: 1350x575 mm • thicks.: 40-220 mm Thermo-physical properties: • d_{gross}: 55 kg/m^3 • k: 0.038 W/(K·m) • MC: 8 % Material composition: wood (80%) pine, binding fibres (BiKo) 3 (8%), MC (4 - 8%), ammonia phosphate (6-8%)	1 m^3	external	14/06/20	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F

TABLE G.6 Inventory of building components.

Code	EPD declaration number	Building component	Product category: generic/ specific	Manufacturer/ Manufacturers association	EPD programme	Product Description	D.U.	Int. /ext. validation	Expiry date	Geographical Coverage	Used in buildings:
571	EPD-EGG-20140003-IBD1-EN	EUROSPAN® raw-chipboard sheets	specific	EUROSPAN®	Institut Bauen und Unwelt e. V (IBU)	Geometry: • dim.: 5610x2070-2800x2070 mm • thicks.: 8-40 mm Thermo-physical properties: • d_{gross}: 660 kg/m³ • k: 0.12 W/(K·m) • MC: 5-13 % Material composition: wood (84-86%), water (4-7%), UF glue (8-10%), paraffin emulsion (<1%)	1 m³	external	22/06/19	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F
601	S-P-00388	Gyproc® Normal – Standard Plasterboard	specific	Gyproc® (Saint-Gobain)	International EPD® System	Geometry: • height: 12.5 mm • thicks.: 40-220 mm Thermo-physical properties: • w 8.8 kg/m²	1 m²	external	13/01/21	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F
651 / 652	NEPD00290E	Weber-base KC 50/50, cement-lime render and masonry mortar	specific	Weber (Saint-Gobain)	EPD Norge	Geometry: • dim.: 1350x575 mm • thicks.: 40-220 mm Thermo-physical properties: • S_{comp}: 5 N/mm² Material composition: cement (6.84%), aggregate (80.18%), Filler (10.64%), packaging (2.34%)	1 kg	external	01/12/19	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F
800	not given	vapour-control layer	generic	Plastics Europe	Plastics Europe (pre-EN 15804 standard)	Thermo-physical properties: • d_{gross}: 940 kg/m³	kg	external	not given	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F

TABLE G.7 Inventory of building components.

Code	EPD declaration number	Building component	Product category: generic/ specific	Manufacturer/ Manufacturers association	EPD programme	Product Description	D.U.	Int. /ext. validation	Expiry date	Geographical Coverage	Used in buildings:
851	EPD-DUP-20150237-IBE1-EN	DuPont™ Tyvek® 2507B breather membrane	specific	DuPont de Nemours	Institut Bauen und Umwelt e. V (IBU)	Geometry: • length: 50 m • width: 1.5 m Thermo-physical properties: • d_{gross}: 210 kg/m^3 • k: 0.044 W/(K·m) • w: 0.145 kg/m^2 Material composition: Tyvek® HDPE nonwoven (40%), spunbond PP (50%), adhesive (<10%), HALS (< 1%)	1 m^2	external	07/06/21	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F
861	EPD-BAL-20130250-CCA1-EN	Bogolan roll tufted carpet	specific	Balsan	Institut Bauen und Umwelt e. V (IBU)	Geometry: • thicks: 5.2 mm Thermo-physical properties: • w: 1960 g/m^2 Material composition: polyamide 6 (34.7%), polypropylene 97.5%), limestone (42.0%), SBR-latex (15.2%), additives (0.6%)	1 m^2	external	09/03/19	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F
931	EPD000102	Crown Trade undercoat paint	specific	Crown Paints Ltd	BRE	Material composition: water (25-28%), inorganic minerals (26-31%), binder (29%), additives (13-10%)	1 m^2	external	17/02/21	UK	A, B1, B2, C1, C2, D1, D2, E1, E2, F
932	EPD-KEI-2012111-E	Biosil external paint	specific	KEIMFARBEN GmbH	Institut Bauen und Umwelt e. V (IBU)	Thermo-physical properties: • d_{gross}: 1.5 g/cm^3 Material composition: binders (15–35%), fillers (20–45%), water (20–35%), pigments (5–15%), other components (1–5%)	1 m^2	external	29/11/17	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F
935	EPD-KEI-2012211-E	Soldalit external paint	specific	KEIMFARBEN GmbH	Institut Bauen und Umwelt e. V (IBU)	Thermo-physical properties: • d_{gross}: 1.6 g/cm^3 Material composition: binders (25–45%), fillers (15–40%), water (15–35%), pigments (5–15%), other components (1–5%)	1 m^2	external	29/11/17	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F

TABLE G.8 Inventory of building components.

Code	EPD declaration number	Building component	Product category: generic/ specific	Manufacturer/ Manufacturers association	EPD programme	Product Description	D.U.	Int. /ext. validation	Expiry date	Geographical Coverage	Used in buildings:
990	EPD-ERF-2013311-E	resilient vinyl floor covering with foam layer	generic	European Resilient Flooring Manufacturers Institute	Institut Bauen und Unwelt e. V (IBU)	<u>Thermo-physical properties:</u> • thicks: 3.25 mm <u>Material composition:</u> additives (1.7%), filler (26.0%), flame retardant (aluminium hydroxide) (0.1%), plasticizer (19.5 %), pigments (0.8%), polymers (PVC) (38.6 %), auxiliaries (1.7%), lacquer (0.7%), flooring recyclate (PVC) 11.0 %	1 m^2	external	31/03/18	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F
995	not given	LDPE damp-proof membrane	generic	Plastics Europe	Plastics Europe (pre-EN 15804 standard)	<u>Thermo-physical properties:</u> • d_{gross}: 940 kg/m^3	kg	external	not given	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F
996	not given	LDPE damp-proof course	generic	Plastics Europe	Plastics Europe (pre-EN 15804 standard)	<u>Thermo-physical properties:</u> • d_{gross}: 0.87 kg/m^2	1 m^2	external	not given	Europe	A, B1, B2, C1, C2, D1, D2, E1, E2, F

H Bills of quantities (notional buildings)

The bills of quantities for the notional buildings (except for building A, whose bill of quantities is presented in CHAPTER 4) are offered below. The quantities of building materials per m^2_{GFA} (the functional unit for the LCA study) form the basis for the calculation of the environmental scores, as discussed in CHAPTER 5.

TABLE H.1 Bill of quantities for building B1.

building material		scenario 1 (baseline, zero wastage)	scenario 2 (low wastage)						scenario 3 (high wastage)					
category	item		lower bound		middle value		upper bound		lower bound		middle value		upper bound	
			absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [b]	absolute value	relative difference [b]	absolute value	relative difference [b]
		kg/m^2_{GFA}	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%
wood-based	softwood components (excl. cladding)	51.37	52.07	1%	52.39	2%	52.70	3%	52.07	1%	52.39	2%	52.70	3%
	softwood cladding	/	/	/	/	/	/	/	/	/	/	/	/	/
	CLT panels	/	/	/	/	/	/	/	/	/	/	/	/	/
	OSB-3 sheathing	38.35	39.11	2%	39.30	2%	39.50	3%	39.11	2%	39.30	2%	39.50	3%
	chipboard decking	14.85	15.14	2%	15.22	3%	15.29	3%	15.96	8%	16.33	10%	16.70	13%
	wood-fibre thermal insul.	/	/	/	/	/	/	/	/	/	/	/	/	/
minerals	cement & lime blocklaying or screed mortar	27.02	28.78	6%	29.05	8%	29.32	9%	28.93	7%	29.05	8%	29.32	9%
	cement & lime rendering mortar	30.48	32.46	7%	32.77	8%	33.07	9%	32.46	7%	32.77	8%	33.07	9%
	cement board	/	/	/	/	/	/	/	/	/	/	/	/	/
	Portland cement (for concrete)	22.27	23.72	7%	23.94	8%	24.16	9%	23.45	5%	23.67	6%	23.90	7%
	aggregrate	149.68	155.67	4%	157.16	5%	158.66	6%	155.67	4%	157.16	5%	158.66	6%
	HD concrete blocks	156.52	162.78	4%	164.35	5%	165.91	6%	162.78	4%	164.35	5%	165.91	6%
	MD concrete blocks	136.69	142.16	4%	143.53	5%	144.90	6%	142.16	4%	143.53	5%	144.90	6%
	concrete roof tiles	24.00	25.92	8%	26.40	10%	26.88	12%	25.92	8%	26.40	10%	26.88	12%
	ceramic wall/floor tiles	37.17	40.15	8%	40.89	10%	41.64	12%	40.15	8%	40.89	10%	41.64	12%
	gypsum plasterboard	48.79	50.49	4%	51.23	5%	51.96	6%	50.49	4%	51.23	5%	51.96	6%
	glass-fibre acoustic insul.	1.05	1.06	1%	1.07	1%	1.07	2%	1.06	1%	1.07	1%	1.15	9%
	glass-fibre thermal insul.	8.76	8.85	1%	8.89	1%	8.93	2%	8.85	1%	8.89	1%	9.59	9%
metals	galvanised steel	4.61	4.80	4%	4.84	5%	4.89	6%	4.80	4%	4.84	5%	4.89	6%
plastics	PP & HDPE breather membrane	0.22	0.23	4%	0.23	5%	0.24	6%	0.23	4%	0.23	5%	0.24	6%
	LDPE vapour barrier	0.31	0.33	4%	0.33	5%	0.33	6%	0.33	4%	0.33	5%	0.33	6%
	LDPE damp-proof course	0.28	0.30	7%	0.30	8%	0.31	10%	0.30	7%	0.30	8%	0.31	10%
	LDPE damp-proof membrane	0.10	0.11	7%	0.11	8%	0.11	10%	0.11	7%	0.11	8%	0.11	10%
	PVC flooring	1.49	1.55	4%	1.56	5%	1.58	6%	1.55	4%	1.56	5%	1.58	6%
	PUR insulation	/	/	/	/	/	/	/	/	/	/	/	/	/
hybrid	undercoat paint	1.38	1.44	4%	1.45	5%	1.46	6%	1.44	4%	1.45	5%	1.46	6%
	internal paint	0.99	1.03	4%	1.04	5%	1.05	6%	1.03	4%	1.07	9%	1.12	14%
	external paint	0.42	0.44	4%	0.45	5%	0.45	6%	0.44	4%	0.45	5%	0.45	6%
	carpet flooring	1.08	1.12	4%	1.14	5%	1.15	6%	1.12	4%	1.14	5%	1.15	6%

Notes

a difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen2} - Quantity_{scen1}}{Quantity_{scen1}}$

b difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen3} - Quantity_{scen1}}{Quantity_{scen1}}$

TABLE H.2 Bill of quantities for building B2.

building material		scenario 1 (baseline, zero wastage)	scenario 2 (low wastage)						scenario 3 (high wastage)					
category	item		lower bound		middle value		upper bound		lower bound		middle value		upper bound	
			absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [b]	absolute value	relative difference [b]	absolute value	relative difference [b]
		kg/m^2_{GFA}	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%
wood-based	softwood components (excl. cladding)	51.75	52.66	2%	53.04	2%	53.41	3%	52.66	2%	53.04	2%	53.41	3%
	softwood cladding	/	/	/	/	/	/	/	/	/	/	/	/	/
	CLT panels	/	/	/	/	/	/	/	/	/	/	/	/	/
	OSB-3 sheathing	37.75	38.51	2%	38.70	2%	38.89	3%	38.51	2%	38.70	2%	38.89	3%
	chipboard decking	14.85	15.96	8%	16.33	10%	16.70	13%	15.96	8%	16.33	10%	16.70	13%
	wood-fibre thermal insul.	/	/	/	/	/	/	/	/	/	/	/	/	/
minerals	cement & lime blocklaying or screed mortar	9.68	10.31	6%	10.41	8%	10.50	9%	10.31	6%	10.41	8%	10.50	9%
	cement & lime rendering mortar	24.49	26.08	7%	26.33	7%	26.57	9%	26.08	7%	26.33	7%	26.57	9%
	cement board	25.83	27.51	7%	27.77	8%	28.03	8%	27.51	7%	27.77	8%	28.03	8%
	Portland cement (for concrete)	16.96	18.06	7%	18.23	8%	18.40	9%	18.06	7%	18.23	8%	18.40	9%
	aggregrate	115.41	120.03	4%	121.19	5%	122.34	6%	120.03	4%	121.19	5%	122.34	6%
	HD concrete blocks	125.22	130.23	4%	131.48	5%	132.73	6%	130.23	4%	131.48	5%	132.73	6%
	MD concrete blocks	/	/	/	/	/	/	/	/	/	/	/	/	/
	concrete roof tiles	23.10	24.95	8%	25.41	10%	25.87	12%	24.95	8%	25.41	10%	25.87	12%
	ceramic wall/floor tiles	37.10	40.07	8%	40.81	10%	41.55	12%	40.07	8%	40.81	10%	41.55	12%
	gypsum plasterboard	48.37	50.07	4%	50.79	5%	51.52	6%	50.07	4%	50.79	5%	51.52	6%
	glass-fibre acoustic insul.	1.05	1.06	1%	1.07	1%	1.07	2%	1.06	1%	1.07	1%	1.07	2%
	glass-fibre thermal insul.	9.16	9.25	1%	9.30	2%	9.34	2%	9.25	1%	9.30	2%	9.34	2%
metals	galvanised steel	3.92	4.08	4%	4.12	5%	4.15	6%	4.08	4%	4.12	5%	4.15	6%
plastics	PP & HDPE breather membrane	0.22	0.23	4%	0.23	5%	0.23	6%	0.23	4%	0.23	5%	0.23	6%
	LDPE vapour barrier	0.31	0.32	4%	0.32	5%	0.33	6%	0.32	4%	0.32	5%	0.33	6%
	LDPE damp-proof course	0.28	0.30	7%	0.30	8%	0.31	10%	0.30	7%	0.30	8%	0.31	10%
	LDPE damp-proof membrane	0.10	0.11	7%	0.11	8%	0.11	10%	0.11	7%	0.11	8%	0.11	10%
	PVC flooring	1.49	1.55	4%	1.56	5%	1.58	6%	1.55	4%	1.56	5%	1.58	6%
	PUR insulation	/	/	/	/	/	/	/	/	/	/	/	/	/
hybrid	undercoat paint	1.36	1.42	4%	1.43	5%	1.45	6%	1.42	4%	1.43	5%	1.45	6%
	internal paint	1.06	1.10	4%	1.11	5%	1.12	6%	1.10	4%	1.15	9%	1.21	14%
	external paint	0.42	0.43	4%	0.44	5%	0.44	6%	0.43	4%	0.44	5%	0.44	6%
	carpet flooring	1.08	1.12	4%	1.14	5%	1.15	6%	1.12	4%	1.14	5%	1.15	6%

Notes

a difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen2} - Quantity_{scen1}}{Quantity_{scen1}}$

b difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen3} - Quantity_{scen1}}{Quantity_{scen1}}$

TABLE H.3 Bill of quantities for building C1.

building material		scenario 1 (baseline, zero wastage)	scenario 2 (low wastage)						scenario 3 (high wastage)					
category	item		lower bound		middle value		upper bound		lower bound		middle value		upper bound	
			absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [b]	absolute value	relative difference [b]	absolute value	relative difference [b]
		kg/m^2_{GFA}	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%
wood-based	softwood components (excl. cladding)	19.31	20.76	8%	21.24	10%	21.73	13%	20.76	8%	21.24	10%	21.73	13%
	softwood cladding	/	/	/	/	/	/	/	/	/	/	/	/	/
	CLT panels	/	/	/	/	/	/	/	/	/	/	/	/	/
	OSB-3 sheathing	45.74	50.68	11%	50.92	11%	51.17	12%	50.68	11%	50.92	11%	51.17	12%
	chipboard decking	14.85	15.96	8%	16.33	10%	16.70	13%	15.96	8%	16.33	10%	16.70	13%
	wood-fibre thermal insul.	/	/	/	/	/	/	/	/	/	/	/	/	/
minerals	cement & lime blocklaying or screed mortar	26.59	28.32	6%	28.59	8%	28.85	9%	28.32	6%	28.59	8%	28.85	9%
	cement & lime rendering mortar	29.60	31.52	6%	31.82	8%	32.11	8%	31.52	6%	31.82	8%	32.11	8%
	cement board	/	/	/	/	/	/	/	/	/	/	/	/	/
	Portland cement (for concrete)	22.72	24.20	7%	24.43	8%	24.65	9%	24.20	7%	24.43	8%	24.65	9%
	aggregrate	152.61	158.71	4%	160.24	5%	161.76	6%	158.71	4%	160.24	5%	161.76	6%
	HD concrete blocks	156.52	162.78	4%	164.35	5%	165.91	6%	162.78	4%	164.35	1%	165.91	6%
	MD concrete blocks	132.74	138.05	4%	139.38	5%	140.71	6%	138.05	4%	139.38	1%	140.71	6%
	concrete roof tiles	23.67	25.56	8%	26.03	10%	26.51	12%	25.56	8%	26.03	2%	26.51	12%
	ceramic wall/floor tiles	37.06	40.02	8%	40.76	10%	41.50	12%	40.02	8%	40.76	2%	41.50	12%
	gypsum plasterboard	55.36	57.30	4%	58.13	5%	58.96	7%	57.30	4%	58.13	1%	58.96	7%
	glass-fibre acoustic insul.	0.70	0.75	7%	0.77	9%	0.79	12%	0.75	7%	0.77	2%	0.79	12%
	glass-fibre thermal insul.	1.62	1.72	7%	1.76	9%	1.80	12%	1.72	7%	1.76	2%	1.80	12%
metals	galvanised steel	4.56	4.75	4%	4.79	5%	4.84	6%	4.75	4%	4.79	1%	4.84	6%
plastics	PP & HDPE breather membrane	0.22	0.23	7%	0.24	8%	0.24	10%	0.23	7%	0.24	1%	0.24	10%
	LDPE vapour barrier	0.22	0.23	6%	0.24	8%	0.24	9%	0.23	6%	0.24	1%	0.24	9%
	LDPE damp-proof course	0.28	0.30	7%	0.30	8%	0.31	10%	0.30	7%	0.30	1%	0.31	10%
	LDPE damp-proof membrane	0.10	0.11	7%	0.11	8%	0.11	10%	0.11	7%	0.11	1%	0.11	10%
	PVC flooring	1.49	1.55	4%	1.56	5%	1.58	6%	1.55	4%	1.56	1%	1.58	6%
	PUR insulation	10.90	11.80	8%	11.86	9%	11.92	9%	11.80	8%	11.86	0%	11.92	9%
hybrid	undercoat paint	1.36	1.42	4%	1.43	5%	1.44	6%	1.42	4%	1.43	1%	1.44	6%
	internal paint	1.06	1.10	4%	1.11	5%	1.12	6%	1.10	4%	1.16	5%	1.21	14%
	external paint	0.41	0.43	4%	0.43	5%	0.44	6%	0.43	4%	0.43	1%	0.44	6%
	carpet flooring	1.08	1.12	4%	1.14	5%	1.15	6%	1.12	4%	1.14	1%	1.15	6%

Notes

a difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen2} - Quantity_{scen1}}{Quantity_{scen1}}$

b difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen3} - Quantity_{scen1}}{Quantity_{scen1}}$

TABLE H.4 Bill of quantities for building C2.

building material		scenario 1 (baseline, zero wastage)	scenario 2 (low wastage)						scenario 3 (high wastage)					
category	item		lower bound		middle value		upper bound		lower bound		middle value		upper bound	
			absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [b]	absolute value	relative difference [b]	absolute value	relative difference [b]
		kg/m^2_{GFA}	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%
wood-based	softwood components (excl. cladding)	20.41	21.94	8%	22.45	10%	22.96	13%	21.94	8%	22.45	10%	22.96	13%
	softwood cladding	/	/	/	/	/	/	/	/	/	/	/	/	/
	CLT panels	/	/	/	/	/	/	/	/	/	/	/	/	/
	OSB-3 sheathing	45.02	49.93	11%	50.18	11%	50.42	12%	49.93	11%	50.18	11%	50.42	12%
	chipboard decking	14.85	15.96	8%	16.33	10%	16.70	13%	15.96	8%	16.33	10%	16.70	13%
	wood-fibre thermal insul.	/	/	/	/	/	/	/	/	/	/	/	/	/
minerals	cement & lime blocklaying or screed mortar	9.68	10.31	6%	10.41	8%	10.50	9%	10.31	6%	10.41	8%	10.50	9%
	cement & lime rendering mortar	23.78	25.33	6%	25.57	8%	25.80	9%	25.33	6%	25.57	8%	25.80	9%
	cement board	25.08	26.71	7%	26.96	8%	27.21	9%	26.71	7%	26.96	8%	27.21	9%
	Portland cement (for concrete)	16.39	17.45	6%	17.62	8%	17.78	8%	17.45	6%	17.62	8%	17.78	8%
	aggregrate	111.70	116.17	4%	117.29	5%	118.40	6%	116.17	4%	117.29	5%	118.40	6%
	HD concrete blocks	125.22	130.23	4%	131.48	5%	132.73	6%	130.23	4%	131.48	5%	132.73	6%
	MD concrete blocks	/	/	/	/	/	/	/	/	/	/	/	/	/
	concrete roof tiles	22.77	24.60	8%	25.05	10%	25.51	12%	24.60	8%	25.05	10%	25.51	12%
	ceramic wall/floor tiles	36.98	39.94	8%	40.68	10%	41.42	12%	39.94	8%	40.68	10%	41.42	12%
	gypsum plasterboard	54.95	56.87	4%	57.70	5%	58.52	7%	56.87	4%	57.70	5%	58.52	7%
	glass-fibre acoustic insul.	0.70	0.75	7%	0.77	9%	0.79	12%	0.75	7%	0.77	9%	0.79	12%
	glass-fibre thermal insul.	1.62	1.72	7%	1.76	9%	1.80	12%	1.72	7%	1.76	9%	1.80	12%
metals	galvanised steel	3.89	4.05	4%	4.09	5%	4.13	6%	4.05	4%	4.09	5%	4.13	6%
plastics	PP & HDPE breather membrane	0.21	0.23	7%	0.23	8%	0.23	9%	0.23	7%	0.23	8%	0.23	9%
	LDPE vapour barrier	0.21	0.23	7%	0.23	8%	0.23	10%	0.23	7%	0.23	8%	0.23	10%
	LDPE damp-proof course	0.28	0.30	7%	0.30	8%	0.31	10%	0.30	7%	0.30	8%	0.31	10%
	LDPE damp-proof membrane	0.10	0.11	7%	0.11	8%	0.11	10%	0.11	7%	0.11	8%	0.11	10%
	PVC flooring	1.49	1.55	4%	1.56	5%	1.58	6%	1.55	4%	1.56	5%	1.58	6%
	PUR insulation	11.12	12.09	9%	12.15	9%	12.21	10%	12.09	9%	12.15	9%	12.21	10%
hybrid	undercoat paint	1.35	1.40	4%	1.41	5%	1.43	6%	1.40	4%	1.41	5%	1.43	6%
	internal paint	1.05	1.09	4%	1.10	5%	1.11	6%	1.09	4%	1.14	9%	1.20	14%
	external paint	0.40	0.42	4%	0.42	5%	0.43	6%	0.42	4%	0.42	5%	0.43	6%
	carpet flooring	1.08	1.12	4%	1.14	5%	1.15	6%	1.12	4%	1.14	5%	1.15	6%

Notes

a difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen2} - Quantity_{scen1}}{Quantity_{scen1}}$

b difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen3} - Quantity_{scen1}}{Quantity_{scen1}}$

TABLE H.5 Bill of quantities for building D1.

building material		scenario 1 (baseline, zero wastage)	scenario 2 (low wastage)						scenario 3 (high wastage)					
category	item		lower bound		middle value		upper bound		lower bound		middle value		upper bound	
			absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [b]	absolute value	relative difference [b]	absolute value	relative difference [b]
		kg/m^2_{GFA}	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%
wood-based	softwood components (excl. cladding)	7.56	7.64	1%	7.68	2%	7.71	2%	8.13	8%	8.32	10%	8.51	13%
	softwood cladding	/	/	/	/	/	/	/	/	/	/	/	/	/
	CLT panels	168.52	169.36	1%	170.21	1%	171.05	2%	181.84	8%	182.75	8%	183.65	9%
	OSB-3 sheathing	/	/	/	/	/	/	/	/	/	/	/	/	/
	chipboard decking	/	/	/	/	/	/	/	/	/	/	/	/	/
	wood-fibre thermal insul.	/	/	/	/	/	/	/	/	/	/	/	/	/
minerals	cement & lime blocklaying or screed mortar	131.49	140.03	6%	141.35	8%	142.66	9%	140.03	6%	141.35	8%	142.66	9%
	cement & lime rendering mortar	32.10	34.19	6%	34.51	8%	34.83	8%	34.19	6%	34.51	8%	34.83	8%
	cement board	24.88	26.49	7%	26.74	8%	26.99	9%	26.49	7%	26.74	8%	26.99	9%
	Portland cement (for concrete)	21.44	22.84	7%	23.05	8%	23.27	9%	22.84	7%	23.05	8%	23.27	9%
	aggregrate	270.59	281.41	4%	284.11	5%	286.82	6%	281.41	4%	284.11	5%	286.82	6%
	HD concrete blocks	125.22	130.23	4%	131.48	5%	132.73	6%	130.23	4%	131.48	5%	132.73	6%
	MD concrete blocks	/	/	/	/	/	/	/	/	/	/	/	/	/
	concrete roof tiles	23.24	25.10	8%	25.56	10%	26.03	12%	25.10	8%	25.56	10%	26.03	12%
	ceramic wall/floor tiles	36.95	39.91	8%	40.65	10%	41.38	12%	39.91	8%	40.65	10%	41.38	12%
	gypsum plasterboard	43.25	44.76	4%	45.41	5%	46.06	7%	44.76	4%	45.41	5%	46.06	7%
	glass-fibre acoustic insul.	0.85	0.93	9%	0.93	9%	0.95	12%	0.91	7%	0.93	9%	0.95	12%
	glass-fibre thermal insul.	/	/	/	/	/	/	/	/	/	/	/	/	/
metals	galvanised steel	2.95	3.07	4%	3.10	5%	3.13	6%	3.07	4%	3.10	5%	3.13	6%
plastics	PP & HDPE breather membrane	0.21	0.23	7%	0.23	8%	0.23	10%	0.23	7%	0.23	8%	0.23	10%
	LDPE vapour barrier	0.30	0.32	7%	0.33	8%	0.33	9%	0.32	7%	0.33	8%	0.33	9%
	LDPE damp-proof course	0.28	0.30	7%	0.30	8%	0.31	10%	0.30	7%	0.30	8%	0.31	10%
	LDPE damp-proof membrane	0.10	0.11	7%	0.11	8%	0.11	10%	0.11	7%	0.11	8%	0.11	10%
	PVC flooring	1.49	1.55	4%	1.56	5%	1.58	6%	1.55	4%	1.56	5%	1.58	6%
	PUR insulation	5.26	5.61	7%	5.65	8%	5.69	8%	6.05	15%	6.31	20%	6.57	25%
hybrid	undercoat paint	1.34	1.40	4%	1.41	5%	1.43	6%	1.40	4%	1.41	5%	1.43	6%
	internal paint	1.05	1.09	4%	1.10	5%	1.11	6%	1.09	4%	1.14	9%	1.20	14%
	external paint	0.40	0.42	4%	0.42	5%	0.43	6%	0.42	4%	0.42	5%	0.43	6%
	carpet flooring	1.08	1.12	4%	1.14	5%	1.15	6%	1.12	4%	1.14	5%	1.15	6%

Notes

a difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen2} - Quantity_{scen1}}{Quantity_{scen1}}$

b difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen3} - Quantity_{scen1}}{Quantity_{scen1}}$

TABLE H.6 Bill of quantities for building D2.

	building material	scenario 1 (baseline, zero wastage)	scenario 2 (low wastage)						scenario 3 (high wastage)					
category	item		lower bound		middle value		upper bound		lower bound		middle value		upper bound	
			absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [b]	absolute value	relative difference [b]	absolute value	relative difference [b]
		kg/m^2_{GFA}	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%
wood-based	**softwood components (excl. cladding)**	12.31	12.43	1%	12.49	2%	12.56	2%	13.23	7%	13.54	10%	13.85	13%
	softwood cladding	8.51	8.60	1%	8.64	1%	8.68	2%	9.15	7%	9.36	10%	9.58	13%
	CLT panels	184.80	185.72	1%	186.65	1%	187.57	2%	198.20	7%	199.19	8%	200.18	8%
	OSB-3 sheathing	3.61	3.68	2%	3.70	3%	3.72	3%	3.88	8%	3.97	10%	4.06	13%
	chipboard decking	14.85	15.14	2%	15.22	3%	15.29	3%	15.96	8%	16.33	10%	16.70	13%
	wood-fibre thermal insul.	/	/	/	/	/	/	/	/	/	/	/	/	/
minerals	**cement & lime blocklaying or screed mortar**	9.68	10.31	6%	10.41	8%	10.50	9%	10.31	6%	10.41	8%	10.50	9%
	cement & lime rendering mortar	/	/	/	/	/	/	/	/	/	/	/	/	/
	cement board	/	/	/	/	/	/	/	/	/	/	/	/	/
	Portland cement (for concrete)	16.28	17.34	6%	17.50	8%	17.67	9%	17.34	6%	17.50	8%	17.67	9%
	aggregrate	111.03	115.47	4%	116.58	5%	117.69	6%	115.47	4%	116.58	5%	117.69	6%
	HD concrete blocks	125.22	130.23	4%	131.48	5%	132.73	6%	130.23	4%	131.48	5%	132.73	6%
	MD concrete blocks	/	/	/	/	/	/	/	/	/	/	/	/	/
	concrete roof tiles	23.08	24.93	8%	25.39	10%	25.85	12%	24.93	8%	25.39	10%	25.85	12%
	ceramic wall/floor tiles	36.93	39.88	8%	40.62	10%	41.36	12%	39.88	8%	40.62	10%	41.36	12%
	gypsum plasterboard	51.68	53.49	4%	54.26	5%	55.04	6%	53.49	4%	54.26	5%	55.04	6%
	glass-fibre acoustic insul.	0.85	0.91	7%	0.93	9%	0.95	12%	0.91	7%	0.93	9%	0.95	12%
	glass-fibre thermal insul.	/	/	/	/	/	/	/	/	/	/	/	/	/
metals	**galvanised steel**	3.18	3.30	4%	3.34	5%	3.37	6%	3.30	4%	3.34	5%	3.37	6%
plastics	**PP & HDPE breather membrane**	0.21	0.23	7%	0.23	8%	0.23	10%	0.23	7%	0.23	8%	0.23	10%
	LDPE vapour barrier	0.21	0.23	7%	0.23	8%	0.23	10%	0.23	7%	0.23	8%	0.23	10%
	LDPE damp-proof course	0.28	0.30	7%	0.30	8%	0.31	10%	0.30	7%	0.30	8%	0.31	10%
	LDPE damp-proof membrane	0.10	0.11	7%	0.11	8%	0.11	10%	0.11	7%	0.11	8%	0.11	10%
	PVC flooring	1.49	1.55	4%	1.56	5%	1.58	6%	1.55	4%	1.56	5%	1.58	6%
	PUR insulation	5.11	5.45	7%	5.49	8%	5.53	8%	5.88	15%	6.13	20%	6.39	25%
hybrid	**undercoat paint**	1.34	1.39	4%	1.41	5%	1.42	6%	1.39	4%	1.41	5%	1.42	6%
	internal paint	1.05	1.09	4%	1.10	5%	1.11	6%	1.09	4%	1.14	9%	1.19	14%
	external paint	0.40	0.41	4%	0.42	5%	0.42	6%	0.41	4%	0.42	5%	0.42	6%
	carpet flooring	1.08	1.12	4%	1.14	5%	1.15	6%	1.12	4%	1.14	5%	1.15	6%

Notes

a difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen2} - Quantity_{scen1}}{Quantity_{scen1}}$

b difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen3} - Quantity_{scen1}}{Quantity_{scen1}}$

TABLE H.7 Bill of quantities for building E1.

building material		scenario 1 (baseline, zero wastage)	scenario 2 (low wastage)						scenario 3 (high wastage)					
category	item		lower bound		middle value		upper bound		lower bound		middle value		upper bound	
			absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [b]	absolute value	relative difference [b]	absolute value	relative difference [b]
		kg/m^2_{GFA}	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%
wood-based	softwood components (excl. cladding)	225.11	228.09	1%	229.44	2%	230.79	3%	228.09	1%	229.44	2%	230.79	3%
	softwood cladding	/	/	/	/	/	/	/	/	/	/	/	/	/
	CLT panels	/	/	/	/	/	/	/	/	/	/	/	/	/
	OSB-3 sheathing	24.16	24.64	2%	24.76	2%	24.88	3%	24.64	2%	24.76	2%	24.88	3%
	chipboard decking	14.85	15.14	2%	15.22	3%	15.29	3%	15.96	8%	16.33	10%	16.70	13%
	wood-fibre thermal insul.	47.80	51.01	7%	51.39	8%	51.77	8%	54.97	15%	57.36	20%	59.75	25%
minerals	cement & lime blocklaying or screed mortar	9.68	10.31	6%	10.41	8%	10.50	9%	10.31	6%	10.41	8%	10.50	9%
	cement & lime rendering mortar	32.67	34.79	7%	35.12	7%	35.44	9%	34.79	7%	35.12	7%	35.44	9%
	cement board	25.32	26.96	7%	27.21	8%	27.47	8%	26.96	7%	27.21	8%	27.47	8%
	Portland cement (for concrete)	16.60	17.68	7%	17.84	7%	18.01	9%	17.68	7%	17.84	7%	18.01	9%
	aggregrate	113.05	117.57	4%	118.70	5%	119.83	6%	117.57	4%	118.70	5%	119.83	6%
	HD concrete blocks	125.22	130.23	4%	131.48	5%	132.73	6%	130.23	4%	131.48	5%	132.73	6%
	MD concrete blocks	/	/	/	/	/	/	/	/	/	/	/	/	/
	concrete roof tiles	23.67	25.56	8%	26.03	10%	26.51	12%	25.56	8%	26.03	10%	26.51	12%
	ceramic wall/floor tiles	37.02	39.98	8%	40.72	10%	41.46	12%	39.98	8%	40.72	10%	41.46	12%
	gypsum plasterboard	46.11	47.72	4%	48.42	5%	49.11	6%	47.72	4%	48.42	5%	49.11	6%
	glass-fibre acoustic insul.	0.85	0.91	7%	0.93	9%	0.95	12%	0.91	7%	0.93	9%	0.95	12%
	glass-fibre thermal insul.	/	/	/	/	/	/	/	/	/	/	/	/	/
metals	galvanised steel	4.81	5.00	4%	5.05	5%	5.10	6%	5.00	4%	5.05	5%	5.10	6%
plastics	PP & HDPE breather membrane	0.22	0.23	7%	0.23	8%	0.24	10%	0.23	7%	0.23	8%	0.24	10%
	LDPE vapour barrier	0.22	0.23	6%	0.23	8%	0.24	10%	0.23	6%	0.23	8%	0.24	10%
	LDPE damp-proof course	0.28	0.30	7%	0.30	8%	0.31	10%	0.30	7%	0.30	8%	0.31	10%
	LDPE damp-proof membrane	0.10	0.11	7%	0.11	8%	0.11	10%	0.11	7%	0.11	8%	0.11	10%
	PVC flooring	1.49	1.55	4%	1.56	5%	1.58	6%	1.55	4%	1.56	5%	1.58	6%
	PUR insulation	/	/	/	/	/	/	/	/	/	/	/	/	/
hybrid	undercoat paint	1.36	1.41	4%	1.43	5%	1.44	6%	1.41	4%	1.43	5%	1.44	6%
	internal paint	1.06	1.10	4%	1.11	5%	1.12	6%	1.10	4%	1.15	9%	1.21	14%
	external paint	0.41	0.42	4%	0.43	5%	0.43	6%	0.42	4%	0.43	5%	0.43	6%
	carpet flooring	1.08	1.12	4%	1.14	5%	1.15	6%	1.12	4%	1.14	5%	1.15	6%

Notes

a difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen2} - Quantity_{scen1}}{Quantity_{scen1}}$

b difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen3} - Quantity_{scen1}}{Quantity_{scen1}}$

TABLE H.8 Bill of quantities for building E2.

building material		scenario 1 (baseline, zero wastage)	scenario 2 (low wastage)						scenario 3 (high wastage)					
category	item		lower bound		middle value		upper bound		lower bound		middle value		upper bound	
			absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [b]	absolute value	relative difference [b]	absolute value	relative difference [b]
		kg/m^2_{GFA}	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%
wood-based	softwood components (excl. cladding)	225.11	228.09	1%	229.44	2%	230.79	3%	228.09	1%	229.44	2%	230.79	3%
	softwood cladding	8.71	9.36	8%	9.58	10%	9.80	13%	9.36	8%	9.58	10%	9.80	13%
	CLT panels	/	/	/	/	/	/	/	/	/	/	/	/	/
	OSB-3 sheathing	24.16	24.64	2%	24.76	2%	24.88	3%	24.64	2%	24.76	2%	24.88	3%
	chipboard decking	14.85	15.14	2%	15.22	3%	15.29	3%	15.96	8%	16.33	10%	16.70	13%
	wood-fibre thermal insul.	47.80	51.01	7%	51.39	8%	51.77	8%	54.97	15%	57.36	20%	59.75	25%
minerals	cement & lime blocklaying or screed mortar	9.68	10.31	6%	10.41	8%	10.50	9%	10.31	6%	10.41	8%	10.50	9%
	cement & lime rendering mortar	/	/	/	/	/	/	/	/	/	/	/	/	/
	cement board	/	/	/	/	/	/	/	/	/	/	/	/	/
	Portland cement (for concrete)	16.28	17.34	6%	17.50	8%	17.67	9%	17.34	6%	17.50	8%	17.67	9%
	aggregrate	111.03	115.47	4%	116.58	5%	117.69	6%	115.47	4%	116.58	5%	117.69	6%
	HD concrete blocks	125.22	130.23	4%	131.48	5%	132.73	6%	130.23	4%	131.48	5%	132.73	6%
	MD concrete blocks	/	/	/	/	/	/	/	/	/	/	/	/	/
	concrete roof tiles	23.67	25.56	8%	26.03	10%	26.51	12%	25.56	8%	26.03	10%	26.51	12%
	ceramic wall/floor tiles	37.02	39.98	8%	40.72	10%	41.46	12%	39.98	8%	40.72	10%	41.46	12%
	gypsum plasterboard	46.11	47.72	4%	48.42	5%	49.11	6%	47.72	4%	48.42	5%	49.11	6%
	glass-fibre acoustic insul.	0.85	0.91	7%	0.93	9%	0.95	12%	0.91	7%	0.93	9%	0.95	12%
	glass-fibre thermal insul.	/	/	/	/	/	/	/	/	/	/	/	/	/
metals	galvanised steel	4.81	5.00	4%	5.05	5%	5.10	6%	5.00	4%	5.05	5%	5.10	6%
plastics	PP & HDPE breather membrane	0.22	0.23	7%	0.23	8%	0.24	10%	0.23	7%	0.23	8%	0.24	10%
	LDPE vapour barrier	0.22	0.23	6%	0.23	8%	0.24	10%	0.23	6%	0.23	8%	0.24	10%
	LDPE damp-proof course	0.28	0.30	7%	0.30	8%	0.31	10%	0.30	7%	0.30	8%	0.31	10%
	LDPE damp-proof membrane	0.10	0.11	7%	0.11	8%	0.11	10%	0.11	7%	0.11	8%	0.11	10%
	PVC flooring	1.49	1.55	4%	1.56	5%	1.58	6%	1.55	4%	1.56	5%	1.58	6%
	PUR insulation	/	/	/	/	/	/	/	/	/	/	/	/	/
hybrid	undercoat paint	1.36	1.41	4%	1.43	5%	1.44	6%	1.41	4%	1.43	5%	1.44	6%
	internal paint	1.06	1.10	4%	1.11	5%	1.12	6%	1.10	4%	1.15	9%	1.21	14%
	external paint	0.41	0.42	4%	0.43	5%	0.43	6%	0.42	4%	0.43	5%	0.43	6%
	carpet flooring	1.08	1.12	4%	1.14	5%	1.15	6%	1.12	4%	1.14	5%	1.15	6%

Notes

a difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen2} - Quantity_{scen1}}{Quantity_{scen1}}$

b difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen3} - Quantity_{scen1}}{Quantity_{scen1}}$

TABLE H.9 Bill of quantities for building F.

building material		scenario 1 (baseline, zero wastage)	scenario 2 (low wastage)						scenario 3 (high wastage)					
category	item		lower bound		middle value		upper bound		lower bound		middle value		upper bound	
			absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [a]	absolute value	relative difference [b]	absolute value	relative difference [b]	absolute value	relative difference [b]
		kg/m^2_{GFA}	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%	kg/m^2_{GFA}	%
wood-based	softwood components (excl. cladding)	21.08	21.36	1%	21.48	2%	21.61	3%	21.59	2%	21.79	3%	21.99	4%
	softwood cladding	/	/	/	/	/	/	/	/	/	/	/	/	/
	CLT panels	/	/	/	/	/	/	/	/	/	/	/	/	/
	OSB-3 sheathing	4.33	4.65	8%	4.76	10%	4.87	13%	4.65	8%	4.76	10%	4.87	13%
	chipboard decking	14.85	15.14	2%	15.22	3%	15.29	3%	15.96	8%	16.33	10%	16.70	13%
	wood-fibre thermal insul.	/	/	/	/	/	/	/	/	/	/	/	/	/
minerals	cement & lime blocklaying or screed mortar	62.12	66.16	6%	66.78	8%	67.40	8%	66.16	6%	66.78	8%	67.40	8%
	cement & lime rendering mortar	38.86	41.38	7%	41.77	8%	42.16	9%	41.38	7%	41.77	8%	42.16	9%
	cement board	/	/	/	/	/	/	/	/	/	/	/	/	/
	Portland cement (for concrete)	22.95	24.44	6%	24.67	7%	24.90	9%	24.44	6%	24.67	7%	24.90	9%
	aggregrate	142.49	147.01	3%	148.14	4%	149.27	5%	147.01	3%	148.14	4%	149.27	5%
	HD concrete blocks	335.09	342.23	2%	344.01	3%	345.80	3%	342.23	2%	344.01	3%	345.80	3%
	MD concrete blocks	325.43	338.44	4%	341.70	5%	344.95	6%	338.44	4%	341.70	5%	344.95	6%
	concrete roof tiles	23.85	25.75	8%	26.23	10%	26.71	12%	25.75	8%	26.23	10%	26.71	12%
	ceramic wall/floor tiles	37.06	40.02	8%	40.76	10%	41.50	12%	40.02	8%	40.76	10%	41.50	12%
	gypsum plasterboard	43.22	44.74	4%	45.39	5%	46.03	7%	44.74	4%	45.39	5%	46.03	7%
	glass-fibre acoustic insul.	0.85	0.91	7%	0.93	9%	0.95	12%	0.91	7%	0.93	9%	0.95	12%
	glass-fibre thermal insul.	2.59	2.76	7%	2.82	9%	2.88	12%	2.76	7%	2.82	9%	2.88	12%
metals	galvanised steel	3.13	3.25	4%	3.28	5%	3.31	6%	3.25	4%	3.28	5%	3.31	6%
plastics	PP & HDPE breather membrane	0.09	0.09	7%	0.09	8%	0.09	10%	0.09	7%	0.09	8%	0.09	10%
	LDPE vapour barrier	0.11	0.12	7%	0.12	8%	0.12	10%	0.12	7%	0.12	8%	0.12	10%
	LDPE damp-proof course	0.28	0.30	7%	0.30	8%	0.31	10%	0.30	7%	0.30	8%	0.31	10%
	LDPE damp-proof membrane	0.10	0.11	7%	0.11	8%	0.11	10%	0.11	7%	0.11	8%	0.11	10%
	PVC flooring	1.49	1.55	4%	1.56	5%	1.58	6%	1.55	4%	1.56	5%	1.58	6%
	PUR insulation	3.15	3.62	15%	3.78	20%	3.93	25%	3.62	15%	3.78	20%	3.93	25%
hybrid	undercoat paint	1.36	1.42	4%	1.43	5%	1.45	6%	1.42	4%	1.43	5%	1.45	6%
	internal paint	1.06	1.10	4%	1.12	5%	1.13	6%	1.10	4%	1.16	9%	1.21	14%
	external paint	0.41	0.43	4%	0.43	5%	0.44	6%	0.43	4%	0.43	5%	0.44	6%
	carpet flooring	1.08	1.12	4%	1.14	5%	1.15	6%	1.12	4%	1.14	5%	1.15	6%

Notes

a difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen2} - Quantity_{scen1}}{Quantity_{scen1}}$

b difference relative to scenario 1 (baseline), calculated as: $\frac{Quantity_{scen3} - Quantity_{scen1}}{Quantity_{scen1}}$

I List of EPD programmes

This appendix provides a list and a description of all the programmes-holders whose EPDs have been used as a source of information for the LCA study. The inventory codes refer to the inventory presented in APPENDIX G.

TABLE I.1 List of EPD programmes used in this study.

PROGRAMME NAME	COUNTRY	ADDRESS	WEBSITE	INVENTORY CODE	COMMENTS
BRE	UK	Bucknalls Lane Watford WD25 9XX	Homepage: www.bre.co.uk EPD database: www.greenbooklive.com	107, 931	
EPD Danmark	Denmark	Teknologiparken Kongsvang Allé 29 DK-8000 Aarhus C	Homepage: www.epddanmark.dk EPD database: www.epddanmark.dk/site/ download_eng.html	452	
EPD Norge	Norway	P.O. Box 5250 Majorstuen N-0303 Oslo	Homepage: epd-norge.no EPD database: epd-norge.no/epder/	551, 651, 652	
Institut Bauen und Unwelt e.V.	Germany	Panoramastraße 1 10178 Berlin	Homepage: ibu-epd.com EPD database: ibu-epd.com/en/epd-program/published-epds	106, 152, 203, 441, 501, 531, 561, 571, 851, 861, 932, 935, 990	
International EPD® system	Sweden	EPD International AB Box 210 60 SE-100 31 Stockholm	Homepage: www.environdec.com EPD database: www.environdec.com/en/ EPD-Search	251, 402, 403, 601	
Plastics Europe	Belgium	Avenue E. Van Nieuwenhuyse 4/3 1160 Brussels Belgium	Homepage: http://www.plasticseurop e.org	800, 995, 996	EPDs carried out before BS EN 15804
Thinkstep (PE International)	UK International	Euston Tower - Level 33, 286 Euston Road, London NW1 3DP	Homepage: www.thinkstep.com 'Wood for good' EPD database: woodforgood.com/lifecycl e-database/	103, 381	formerly known as PE international used for EPDs for Wood for Good and EURIMA

J Overview of life-cycle impact assessment (LCIA) methodologies

The main principles of different LCIA methodologies are laid out in the tables below. As explained in CHAPTERS 2 and 4, CML is the method required by LCA standards; however, this overview reveals the theoretical debate between endpoint and midpoint approaches to life-cycle studies.

TABLE J.1 Eco-indicator 99 overview.

Eco-indicator 99		
contact person(s) (affiliation)	characteristics	impact categories included
M. Goedkoop and R. Spriensma (PRé)	endpoint and midpoint approach spatial reference global and regional (Europe) time horizon short (c. 100 year) for individualist perspective, long/indefinite for other perspectives	midpoint climate change (38) ozone layer depletion (24) acidification/eutrophication (combined) (3) carcinogenic (61) respiratory organic (11) respiratory inorganic (121) ionizing radiation (48) ecotoxicity (52) land-use (12) mineral resources (12) fossil resources (9) impact categories human health ecosystem quality resource depletion

TABLE J.2 EDIP 2003 overview.

EDIP 2003		
contact person(s) (affiliation)	**characteristics**	**impact categories included**
Michael Hauschild (DTU, Technical University of Denmark)	midpoint approach spatial reference global and regional (Europe) time horizon infinity	global warming ozone depletion acidification terrestrial eutrophication aquatic eutrophication aquatic eutrophication ozone formation (human) human toxicity (exposure route via air) human toxicity (exposure route via water) human toxicity (exposure route via soil) ecotoxicity (water acute) ecotoxicity (water chronic) ecotoxicity (soil chronic) hazardous waste slags/ashes bulk waste radioactive waste resources

TABLE J.3 EPS 2000 overview.

EPS 2000		
contact person(s) (affiliation)	**characteristics**	**impact categories included**
Bengt Steen (Chalmers University of Technology)	endpoint approach spatial reference global and local (Sweden) time horizon present time	human health [pers.yr] life expectancy severe morbidity and suffering morbidity severe nuisance nuisance natural environment [kg] crop production capacity wood production capacity fish and meat production capacity base cation capacity [h+] production capacity for water (drinking water) share of species extinction [nex] natural resources [kg] depletion of element reserves (element) depletion of fossil reserves (gas) depletion of fossil reserves (oil) depletion of fossil reserves (coal) depletion of mineral reserves (ore)

TABLE J.4 IMPACT 2002+ overview.

IMPACT 2002+		
contact person(s) (affiliation)	characteristics	impact categories included
Olivier Jolliet (University of Michigan)	midpoint and endpoint approach spatial reference regional (Europe) time horizon infinity	midpoint human toxicity respiratory effects ionizing radiation ozone depletion photochemical oxidant formation aquatic ecotoxicity terrestrial ecotoxicity aquatic eutrophication terrestrial eutrophication and acidification land occupation global warming non-renewable energy mineral extraction endpoint human health ecosystem quality climate change (as life supporting function) resources

TABLE J.5 ReCiPe overview.

ReCiPe		
contact person(s) (affiliation)	**characteristics**	**impact categories included**
M. Goedkoop (PRé) M. Huijbregts (Rabdoud University) R.Heijungs (University of Leiden), J. Struijs (RIVM**)**	midpoint and endpoint approach spatial reference global and regional (Europe) time horizon 20 years, 100 years or indefinite, depending on the cultural perspective	midpoint climate change ozone depletion terrestrial acidification freshwater eutrophication marine eutrophication human toxicity photochemical oxidant formation particulate matter formation terrestrial ecotoxicity freshwater ecotoxicity marine ecotoxicity ionising radiation agricultural land occupation urban land occupation natural land transformation depletion of fossil fuel resources depletion of mineral resources depletion of freshwater resources endpoint human health ecosystem quality resources (surplus cost)

TABLE J.6 MEEuP overview.

MEEuP		
contact person(s) (affiliation)	**characteristics**	**impact categories included**
René Kemna (VHK)	midpoint approach spatial reference global and regional (EU) time horizon 20 years, 100 years or indefinite,	energy total gross energy requirement primary electricity water process water cooling water waste hazardous solid waste non-hazardous waste emissions to air global warming global warming potential for a time horizon of 100 years stratospheric ozone depletion depletion potential acidification potential pop. persistent organic pollutants, in this case only dioxins and furans volatile organic compounds heavy metals emissions to water: • eutrophication potential • heavy metals

K Pedigree matrices for LCA uncertainty analysis

Below are the details of the scores used for the uncertainty analysis within the LCA study, as described in CHAPTER 5.

TABLE K.1 Pedigree matrix applied to the data sources of wood-based products used for the LCA.

Inv. code	Item designation	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation			Sample size			overall var.
		Q.I.	description	U_{rel}	Q.I.	description	U_{com}	Q.I.	description	U_{tem}	Q.I.	description	U_{geo}	Q.I.	description	U_{tec}	Q.I.	description	U_{sam}	GSD^2
	wood-based products																			
501	**softwood components (excl. cladding)**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	2	average data from larger area in which the area under study is included	1.01	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.05	1.17
501.2	**softwood components (excl. cladding) [a]**	2	verified data partially based on assumptions or non-verified data based on measurements	1.05	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	4	less than 15 years of difference to the time period of the data set	1.20	2	average data from larger area in which the area under study is included	1.01	3	data from processes and materials under study, but from different technology	1.20	3		1.05	1.32
551	**softwood cladding**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	2	average data from larger area in which the area under study is included	1.01	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.05	1.17
551.2	**softwood cladding [a]**	2	verified data partially based on assumptions or non-verified data based on measurements	1.05	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	4	less than 15 years of difference to the time period of the data set	1.20	2	average data from larger area in which the area under study is included	1.01	3	data from processes and materials under study, but from different technology	1.20	3		1.05	1.32
531	**CLT panels**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.02	3	less than 10 years of difference to the time period of the data set	1.10	1	data from area under study	1.00	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.05	1.16
531.2	**CLT panels withut [a]**	2	verified data partially based on assumptions or non-verified data based on measurements	1.05	4	representative data from only one site relevant for the market considered or from some sites, but from shorter periods	1.10	4	less than 15 years of difference to the time period of the data set	1.20	2	average data from larger area in which the area under study is included	1.01	3	data from processes and materials under study, but from different technology	1.20	3		1.05	1.33
561	**OSB-3 sheathing**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	2	average data from larger area in which the area under study is included	1.01	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.02	1.17
561.2	**OSB-3 sheathing [a]**	2	verified data partially based on assumptions or non-verified data based on measurements	1.05	4	representative data from only one site relevant for the market considered or from some sites, but from shorter periods	1.10	4	less than 15 years of difference to the time period of the data set	1.20	2	average data from larger area in which the area under study is included	1.01	3	data from processes and materials under study, but from different technology	1.20	3		1.05	1.33
571	**chipboard decking**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	2	average data from larger area in which the area under study is included	1.01	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.05	1.17
571.2	**chipboard decking without carbon sequestration**	2	verified data partially based on assumptions or non-verified data based on measurements	1.05	2	representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	1.02	4	less than 15 years of difference to the time period of the data set	1.20	2	average data from larger area in which the area under study is included	1.01	3	data from processes and materials under study, but from different technology	1.20	3		1.05	1.31
152	**wood-fibre thermal insul.**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	1	data from area under study	1.00	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.05	1.17
152.2	**wood-fibre thermal insul. [a]**	2	verified data partially based on assumptions or non-verified data based on measurements	1.05	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	4	less than 10 years of difference to the time period of the data set	1.20	1	data from area under study	1.00	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3		1.05	1.26

Abbreviations

GSD	geometric standard deviation	U	uncertainty
inv.	inventory	var.	variance
Q.I.	quality indicator		

Notes

a	source for calculation excluding carbon sequestration

TABLE K.2 Pedigree matrix applied to the data sources of mineral products used for the LCA.

Inv. code	item designation	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation			Sample size			overall var.
		Q.I.	description	U_{rel}	Q.I.	description	U_{com}	Q.I.	description	U_{tem}	Q.I.	description	U_{geo}	Q.I.	description	U_{tec}	Q.I.	description	U_{sam}	GSD^2
	minerals																			
652	**cement & lime blocklaying or screed mortar**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	3	data from area with similar production conditions	1.02	3	data from processes and materials under study, but from different technology	1.20	3	>10	1.05	1.25
651	**cement & lime rendering mortar**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	3	data from are with similar production conditions	1.02	3	data from processes and materials under study, but from different technology	1.20	3	>10	1.05	1.25
452	**cement board**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	3	data from area with similar production conditions	1.02	3	data from processes and materials under study, but from different technology	1.20	3	>10	1.05	1.25
203	**Portland cement (for concrete)**	1	verified data based on measurements	1.00	2	representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	1.02	3	less than 10 years of difference to the time period of the data set	1.10	1	data from area under study	1.00	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	2	>20	1.02	1.16
251	**aggregrate**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	4	data from area with slightly similar production conditions	1.05	3	data from processes and materials under study, but from different technology	1.20	3	>10	1.05	1.26
402	**HD concrete blocks**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	1	data from area under study	1.00	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.05	1.17
403	**MD concrete blocks**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	1	data from area under study	1.00	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.05	1.17
441	**concrete roof tiles**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	3	data from are with similar production conditions	1.02	3	data from processes and materials under study, but from different technology	1.20	3	>10	1.05	1.25
471	**ceramic wall/floor tiles**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	2	average data from larger area in which the area under study is included	1.01	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.05	1.17
601	**gypsum plasterboard**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	3	data from area with similar production conditions	1.02	3	data from processes and materials under study, but from different technology	1.20	3	>10	1.05	1.25
107	**glass-fibre acoustic insul.**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	1	data from area under study	1.00	1	data from enterprises, processes and materials under study	1.00	3	>10	1.05	1.14
103	**glass-fibre thermal insul.**	1	verified data based on measurements	1.00	2	representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	1.02	3	less than 10 years of difference to the time period of the data set	1.10	2	average data from larger area in which the area under study is included	1.01	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.05	1.17

Abbreviations

GSD	geometric standard deviation	U	uncertainty
inv.	inventory	var.	variance
Q.I.	quality indicator		

Notes

a	source for calculation excluding carbon sequestration

TABLE K.3 Pedigree matrix applied to the data sources of metal and plastic products used for the LCA.

Inv. code	item designation	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation			Sample size			overall var.
		Q.I.	description	U_{rel}	Q.I.	description	U_{com}	Q.I.	description	U_{tem}	Q.I.	description	U_{geo}	Q.I.	description	U_{tec}	Q.I.	description	U_{sam}	GSD^2
	metals																			
381	**galvanised steel**	2	verified data partially based on assumptions or non-verified data based on measurements	1.05	2	representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	1.02	3	less than 10 years of difference to the time period of the data set	1.10	1	data from area under study	1.00	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	2	>20	1.02	1.17
	plastics																			
851	**PP & HDPE breather membrane**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 15 years of difference to the time period of the data set	1.10	3	data from area with similar production conditions	1.02	3	data from processes and materials under study, but from different technology	1.20	3	>10	1.05	1.25
800	**LDPE vapour barrier**	2	verified data partially based on assumptions or non-verified data based on measurements	1.05	2	representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	1.02	4	less than 15 years of difference to the time period of the data set	1.20	2	average data from larger area in which the area under study is included	1.01	3	data from processes and materials under study, but from different technology	1.20	3	>10	1.05	1.31
996	**LDPE damp-proof course**	2	verified data partially based on assumptions or non-verified data based on measurements	1.05	2	representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	1.02	4	less than 15 years of difference to the time period of the data set	1.20	2	average data from larger area in which the area under study is included	1.01	3	data from processes and materials under study, but from different technology	1.20	3	>10	1.05	1.31
995	**LDPE damp-proof membrane**	2	verified data partially based on assumptions or non-verified data based on measurements	1.05	2	representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	1.02	4		1.20	2	average data from larger area in which the area under study is included	1.01	3	data from processes and materials under study, but from different technology	1.20	3	>10	1.05	1.31
990	**PVC flooring**	1	verified data based on measurements	1.00	2	representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	1.02	3	less than 10 years of difference to the time period of the data set	1.10	2	average data from larger area in which the area under study is included	1.01	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.05	1.17
106	**PUR insulation**	1	verified data based on measurements	1.00	2	representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	1.02	3	less than 10 years of difference to the time period of the data set	1.10	2	average data from larger area in which the area under study is included	1.01	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.05	1.17

Abbreviations

GSD	geometric standard deviation	U	uncertainty
inv.	inventory	var.	variance
Q.I.	quality indicator		

Notes

a	source for calculation excluding carbon sequestration

TABLE K.4 Pedigree matrix applied to the data sources of hybrid products used for the LCA.

Inv. code	item designation	Reliability			Completeness			Temporal correlation			Geographical correlation			Further technological correlation			Sample size			overall var.
		Q.I.	description	U_{rel}	Q.I.	description	U_{com}	Q.I.	description	U_{tem}	Q.I.	description	U_{geo}	Q.I.	description	U_{tec}	Q.I.	description	U_{sam}	GSD^2
	other / hybrid																			
931	**undercoat paint**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	1	data from area under study	1.00	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.05	1.17
932	**internal paint**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	2	average data from larger area in which the area under study is included	1.01	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.05	1.17
935	**external paint**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	2	average data from larger area in which the area under study is included	1.01	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.05	1.17
861	**carpet flooring**	1	verified data based on measurements	1.00	3	representative data from only some sites (<50%) relevant for the market considered or from >50% of sites, but from shorter periods	1.05	3	less than 10 years of difference to the time period of the data set	1.10	2	average data from larger area in which the area under study is included	1.01	2	data from processes and materials under study (i.e. identical technology), but from different entreprises	1.10	3	>10	1.05	1.17

Abbreviations			
GSD	geometric standard deviation	U	uncertainty
inv.	inventory	var.	variance
Q.I.	quality indicator		
Notes			
a	source for calculation excluding carbon sequestration		

L LCA results: contribution analysis

The graphs below accompany CHAPTER 5 and, in particular, SECTION 5.6.1. They illustrate, in a detailed manner, the results of the contribution analyses carried out for each building, in terms of environmental impacts caused, primary energy consumed and waste produced.

For each building, the analysis consists of:

- a **bar chart** showing the contributions by building element (with sub-totals for envelope and non-envelope) with a further distinction in terms of material type;
- a **pie chart** showing the contributions by structural role of the components (*i.e.,* structural *versus* non-structural components). Here, the "insulation" category refers to thermal insulation, the "finishes" category refers to products such as paint, tiles and flooring, and "hybrid" refers to other non-structural components.

L.1 Building A

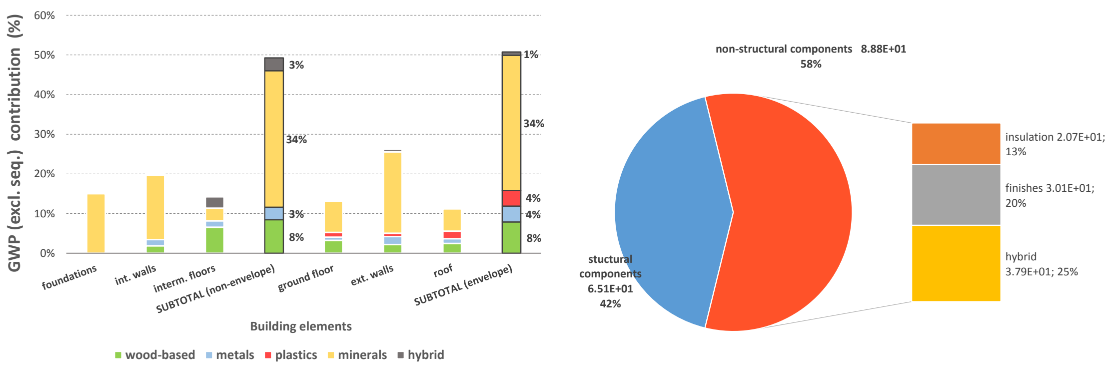


FIGURE L.1 GWP (excluding sequestration) of building A: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CO_2-eq./m^2_{GFA}.

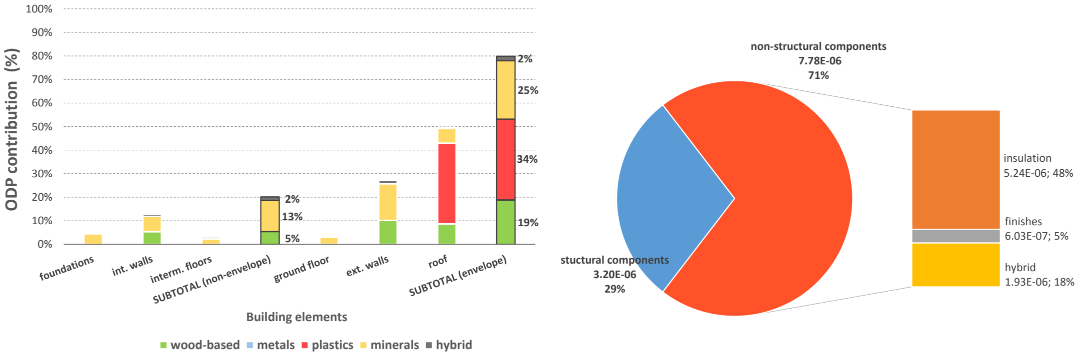


FIGURE L.2 ODP of building A: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CFC 11-eq./m$^2_{GFA}$).

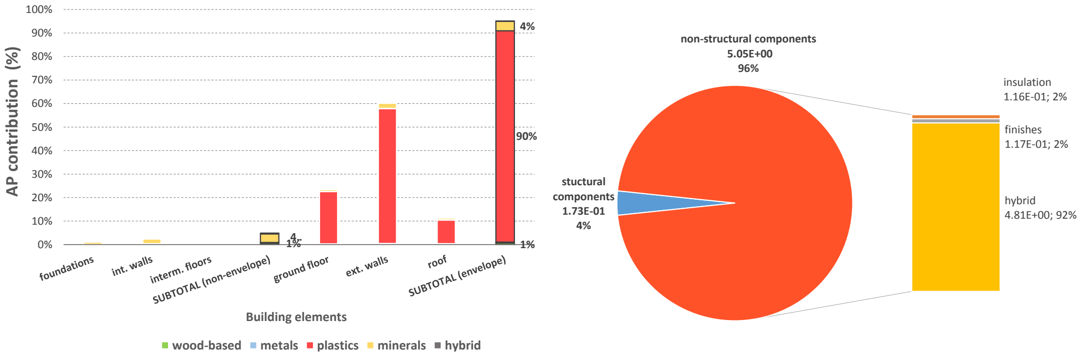


FIGURE L.3 AP of building A: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg SO_2-eq./m$^2_{GFA}$.

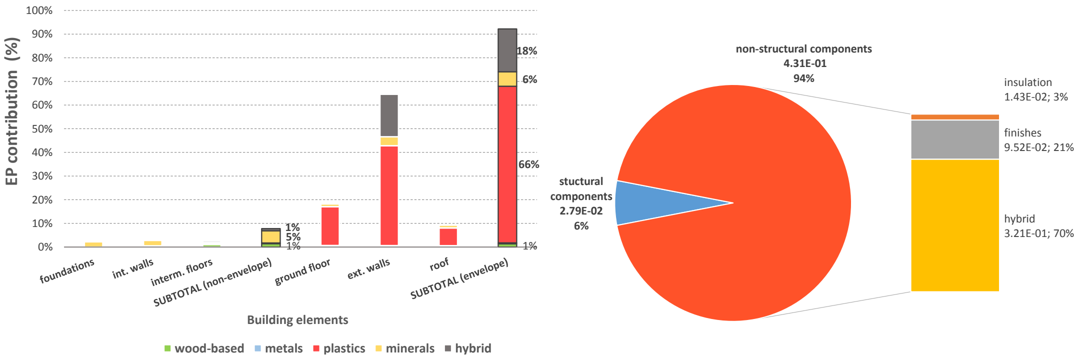


FIGURE L.4 EP of building A: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg PO_4-eq./m$^2_{GFA}$.

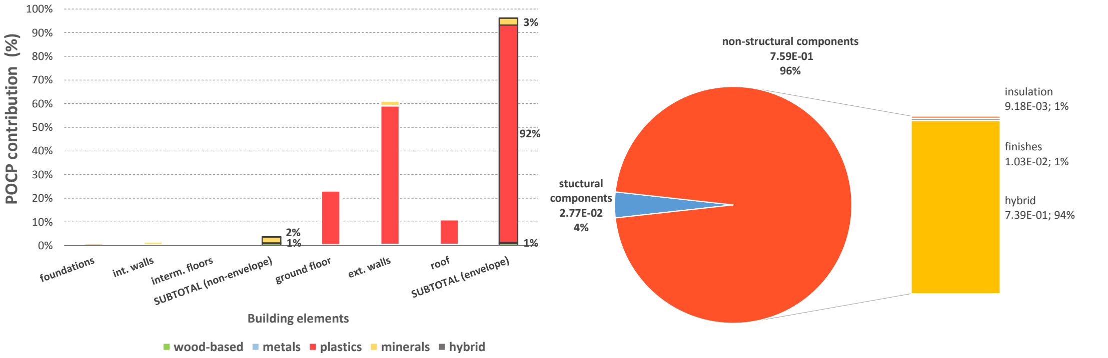


FIGURE L.5 POCP of building A: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg ethene-eq./m$^2_{GFA}$.

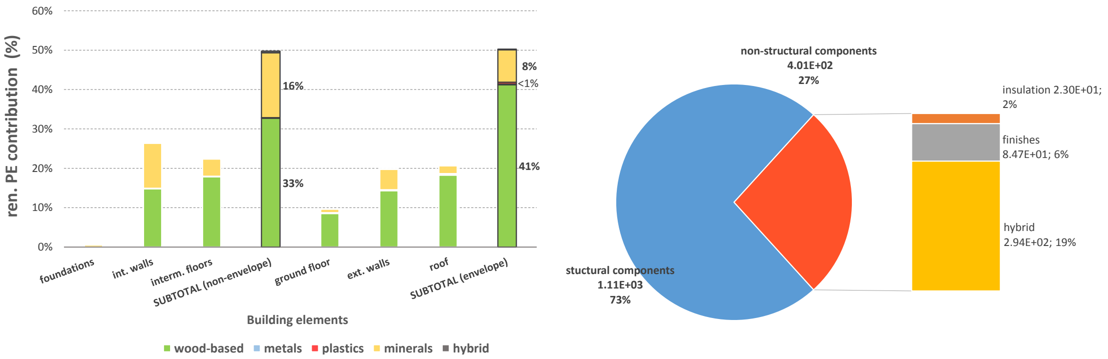


FIGURE L.6 Renewable PE of building A: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m$^2_{GFA}$.

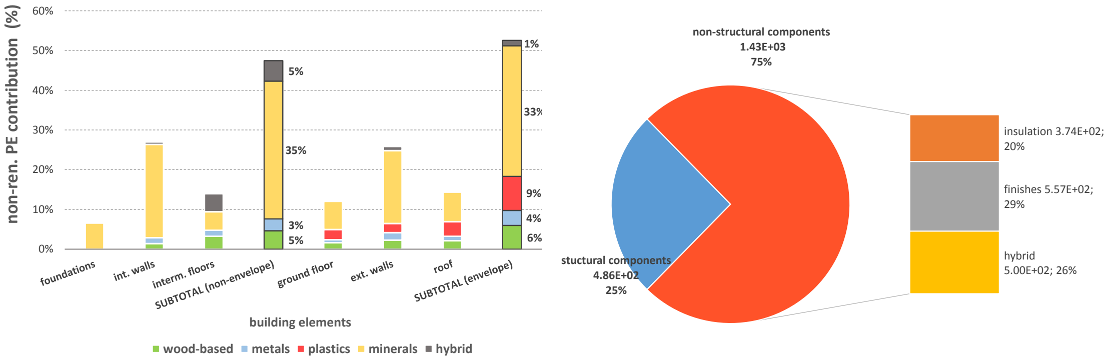


FIGURE L.7 Non-renewable PE of building A: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m$^2_{GFA}$.

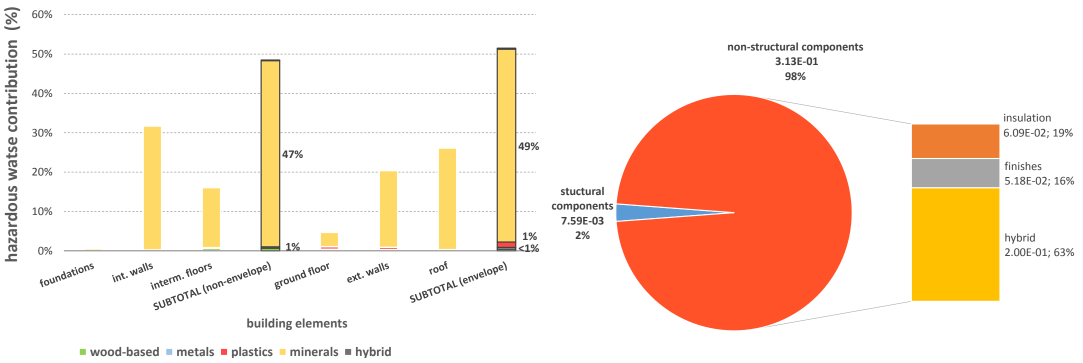


FIGURE L.8 Hazardous waste of building A: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m²$_{GFA}$.

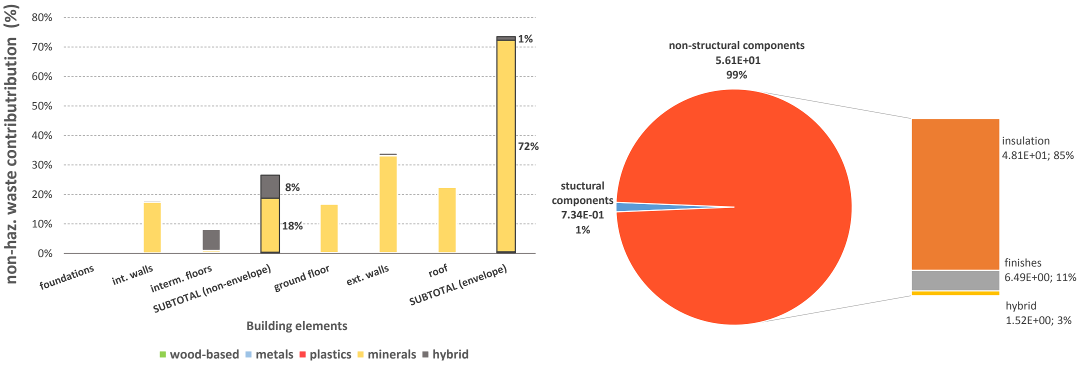


FIGURE L.9 Non-hazardous waste of building A: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m²$_{GFA}$.

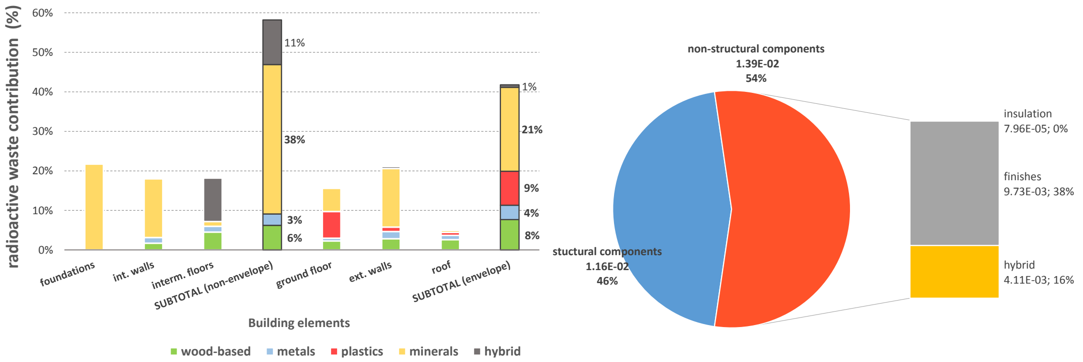


FIGURE L.10 Radioactive waste of building A: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m²$_{GFA}$.

L.2 Building B1

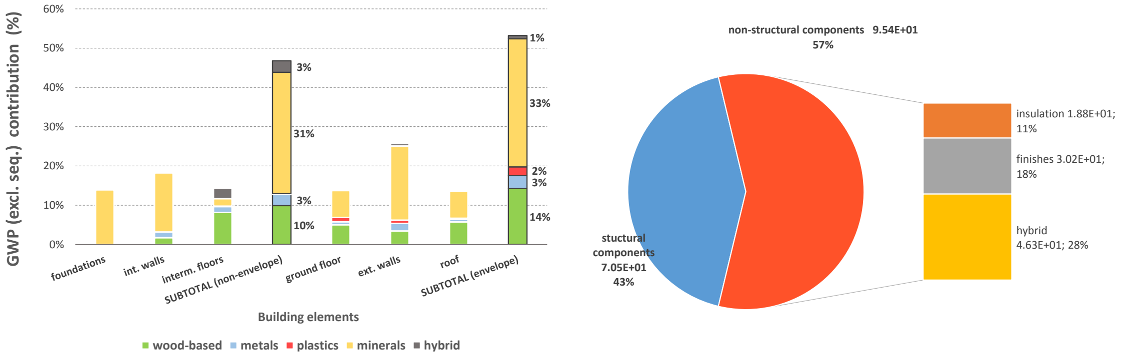


FIGURE L.11 GWP (excluding sequestration) of building B1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CO_2-eq./m^2_{GFA}.

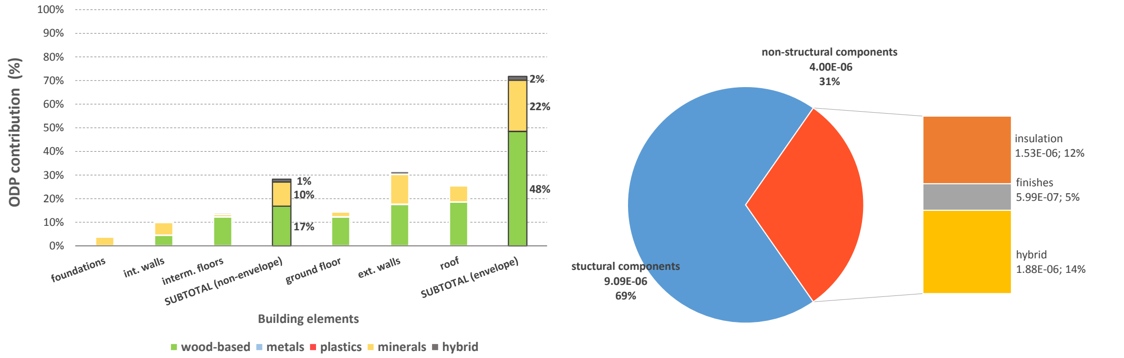


FIGURE L.12 ODP of building B1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CFC 11-eq./m^2_{GFA}).

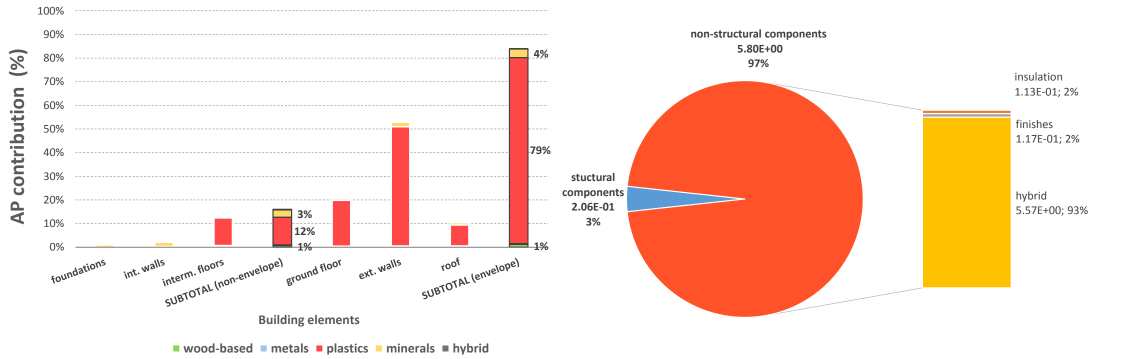


FIGURE L.13 AP of building B1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg SO_2-eq./m^2_{GFA}.

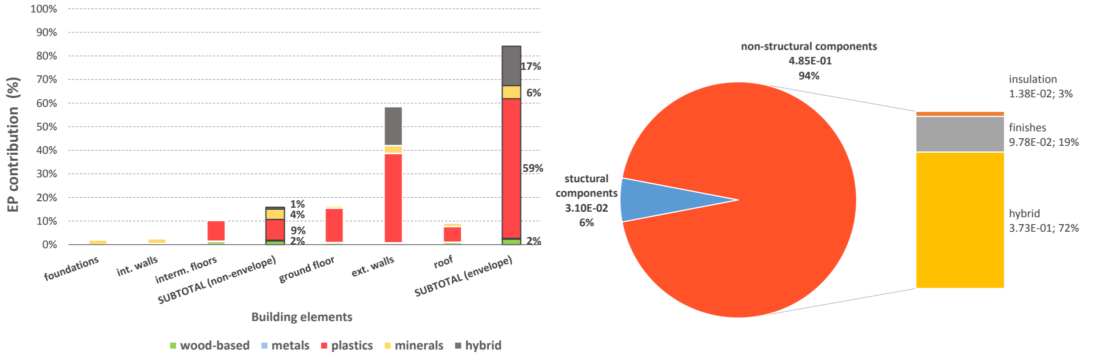


FIGURE L.14 EP of building B1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg PO_4-eq./m^2_{GFA}.

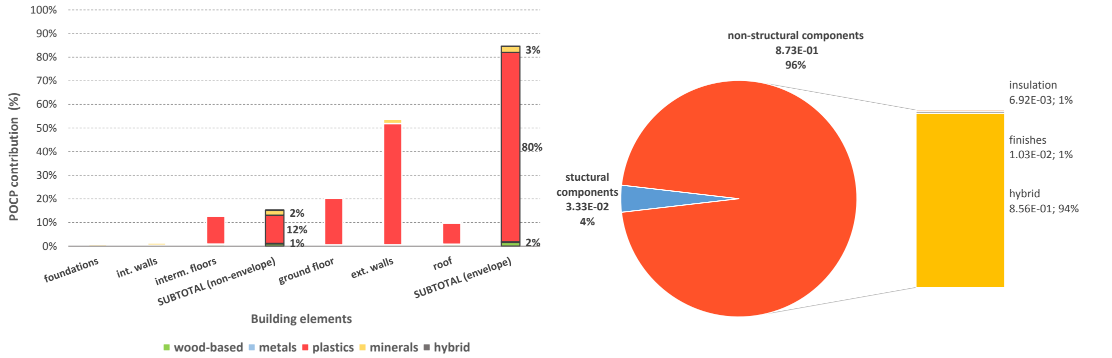


FIGURE L.15 POCP of building B1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg ethene-eq./m^2_{GFA}.

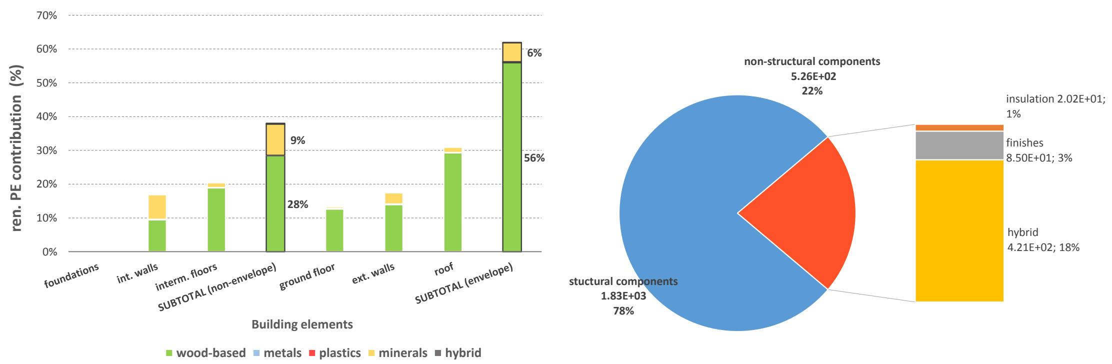


FIGURE L.16 Renewable PE of building B1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m^2_{GFA}.

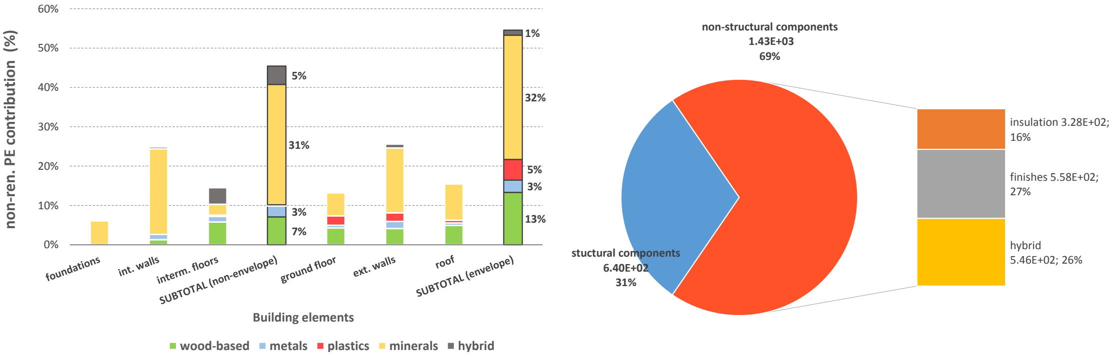


FIGURE L.17 Non-renewable PE of building B1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m²$_{GFA}$.

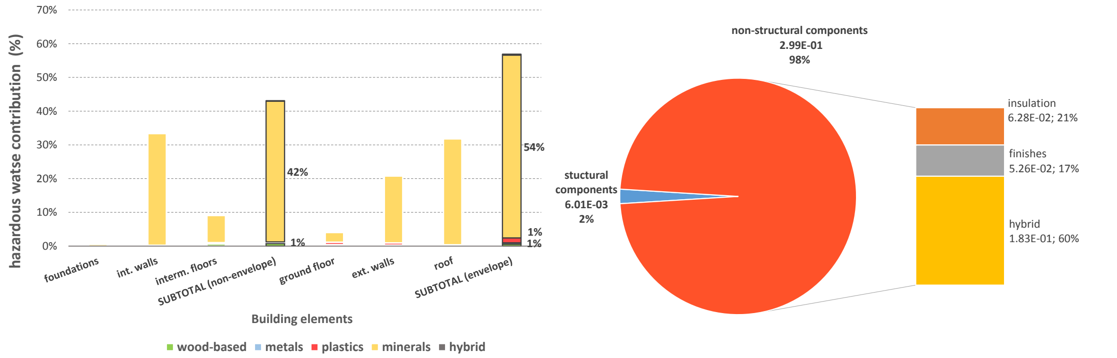


FIGURE L.18 Hazardous waste of building B1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m²$_{GFA}$.

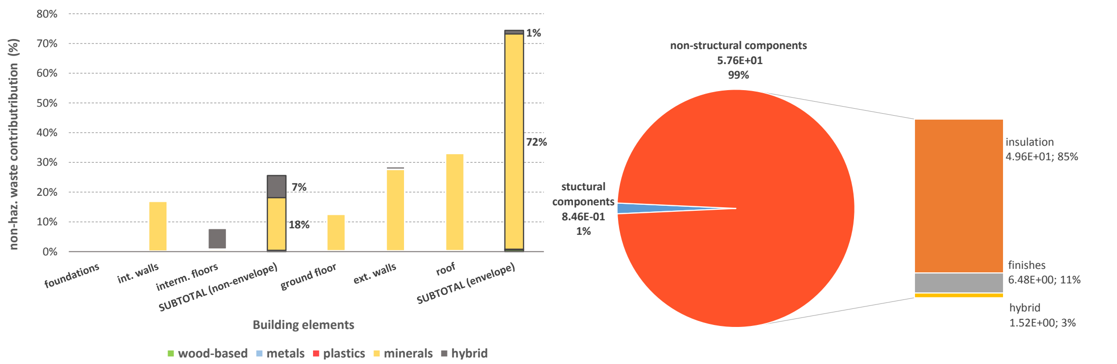


FIGURE L.19 Non-hazardous waste of building B1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m²$_{GFA}$.

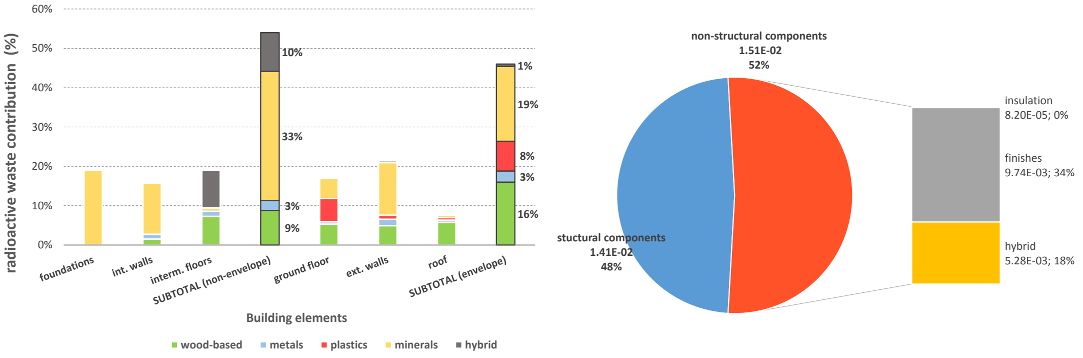


FIGURE L.20 Radioactive waste of building B1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m²$_{GFA}$.

L.3 Building B2

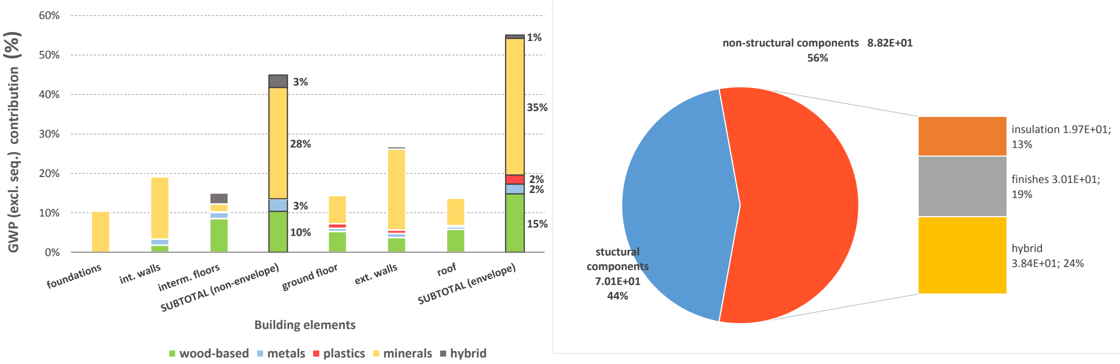


FIGURE L.21 GWP (excluding sequestration) of building B2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CO_2-eq./m^2_{GFA}.

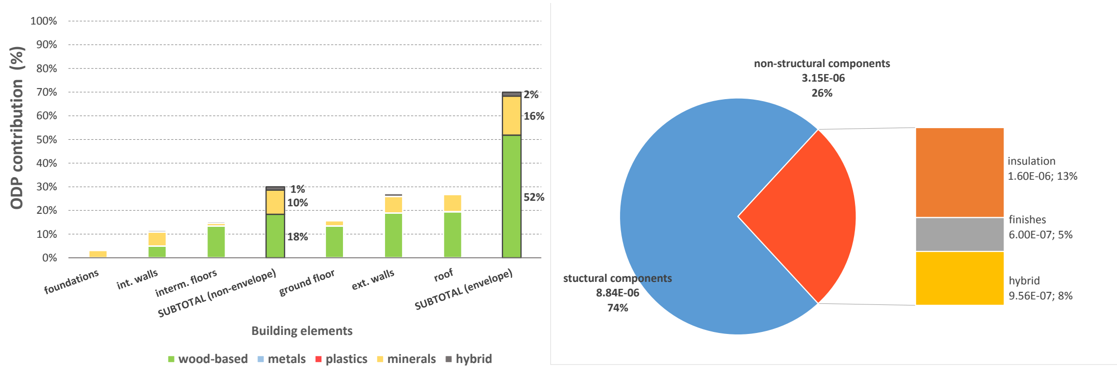


FIGURE L.22 ODP of building B2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CFC 11-eq./m^2_{GFA}).

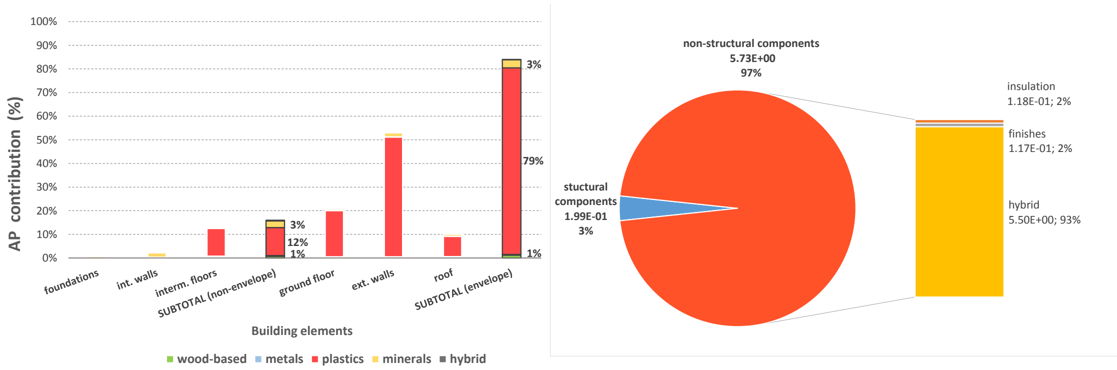


FIGURE L.23 AP of building B2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg SO_2-eq./m^2_{GFA}.

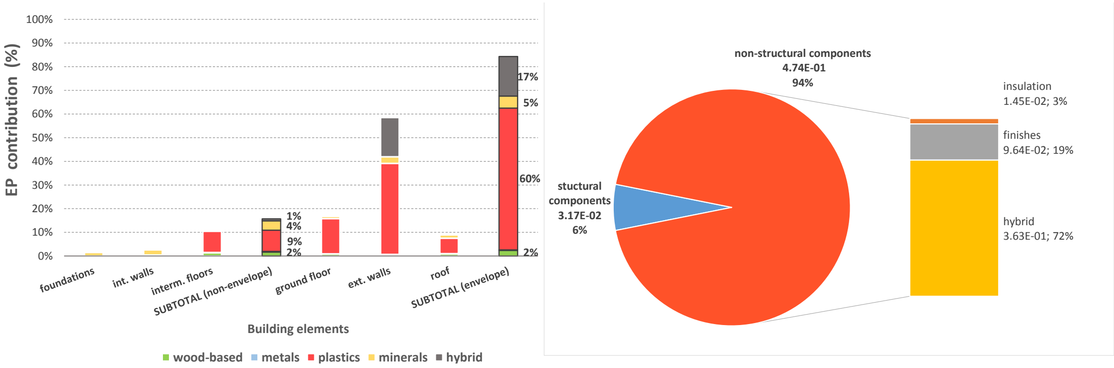


FIGURE L.24 EP of building B2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg PO_4-eq./m^2_{GFA}.

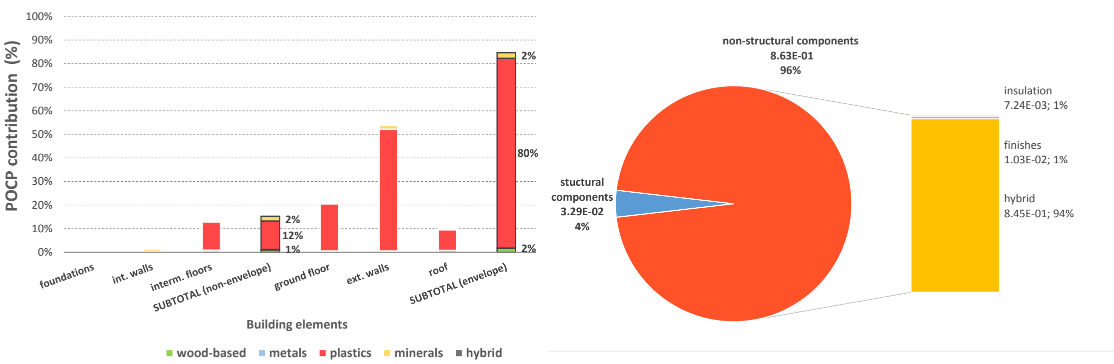


FIGURE L.25 POCP of building B2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg ethene-eq./m^2_{GFA}.

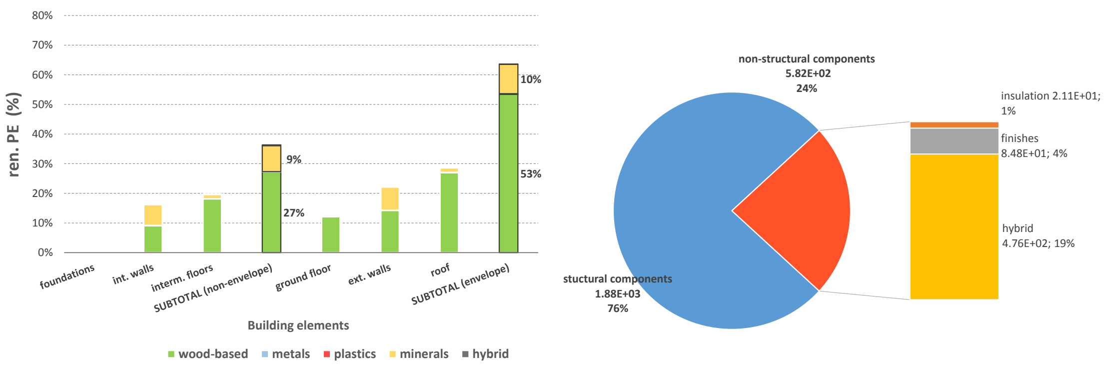


FIGURE L.26 renewable PE of building B2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m^2_{GFA}.

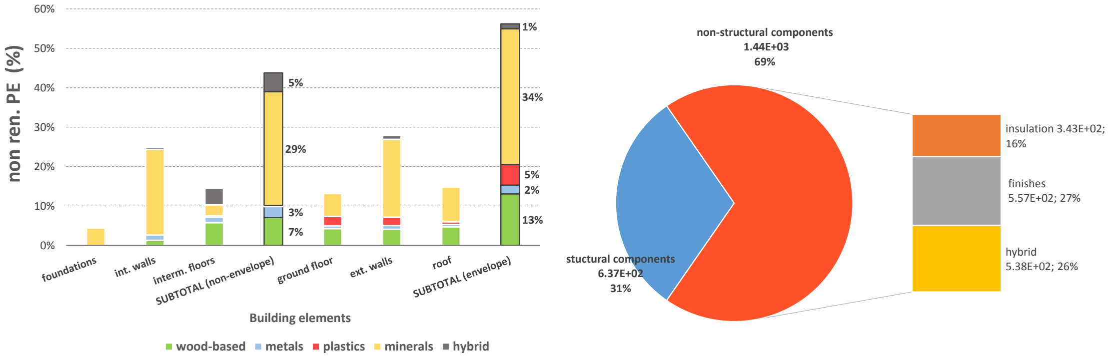


FIGURE L.27 Non-renewable PE of building B2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m²$_{GFA}$.

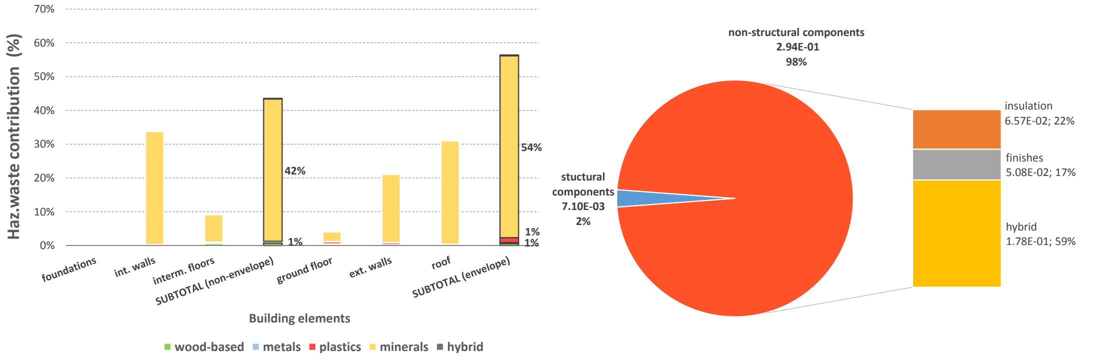


FIGURE L.28 Hazardous waste of building B2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m²$_{GFA}$.

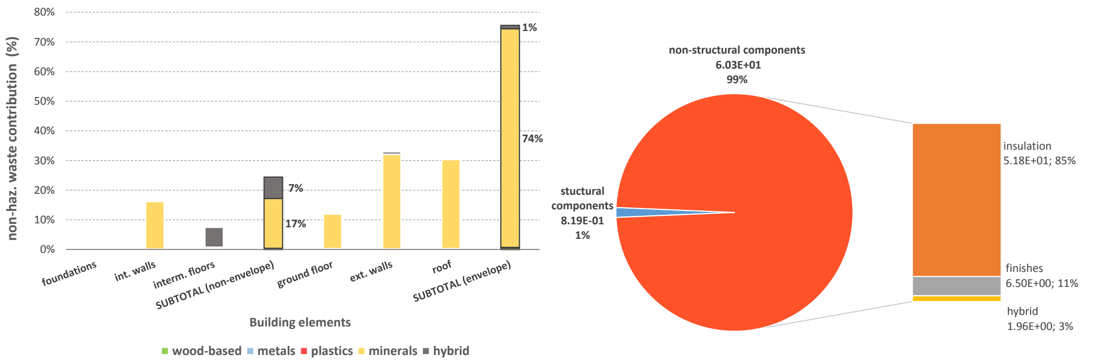


FIGURE L.29 Non-hazardous waste of building B2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m²$_{GFA}$.

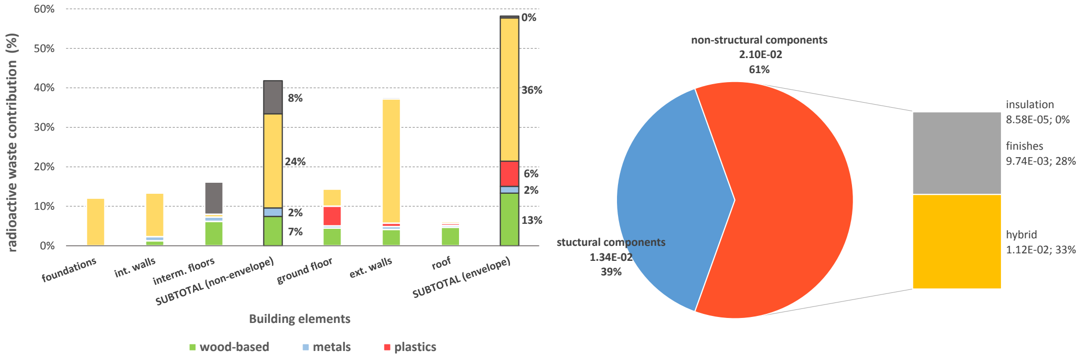


FIGURE L.30 Radioactive waste of building B2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m$^2_{GFA}$.

L.4 Building C1

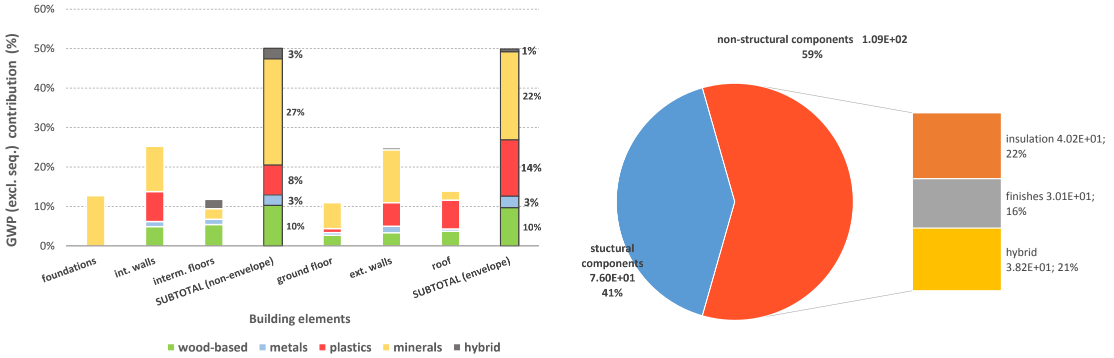


FIGURE L.31 GWP (excluding sequestration) of building C1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CO_2-eq./m^2_{GFA}.

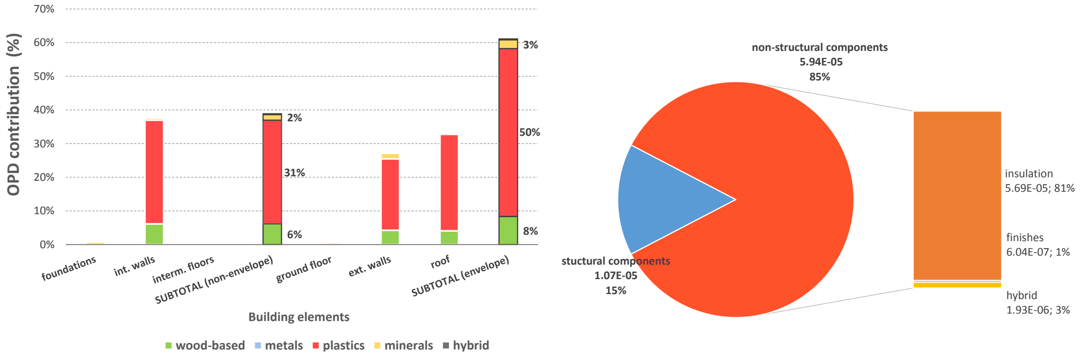


FIGURE L.32 ODP of building C1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CFC 11-eq./m^2_{GFA}).

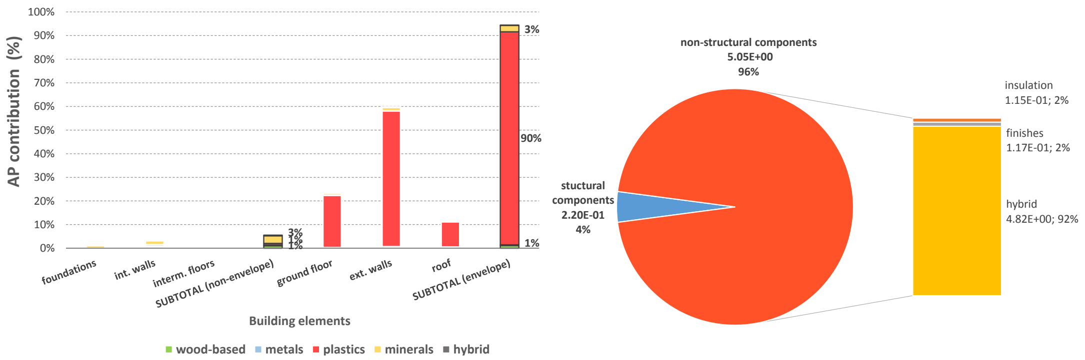


FIGURE L.33 AP of building C1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg SO_2-eq./m^2_{GFA}.

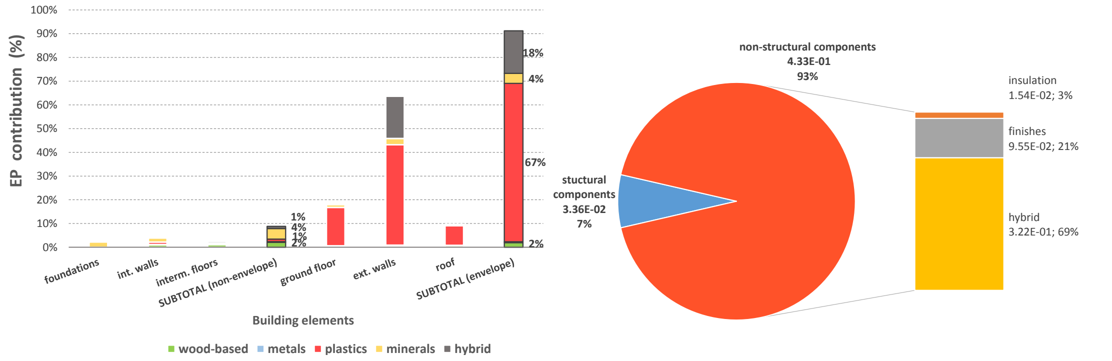


FIGURE L.34 EP of building C1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg PO_4-eq./m^2_{GFA}.

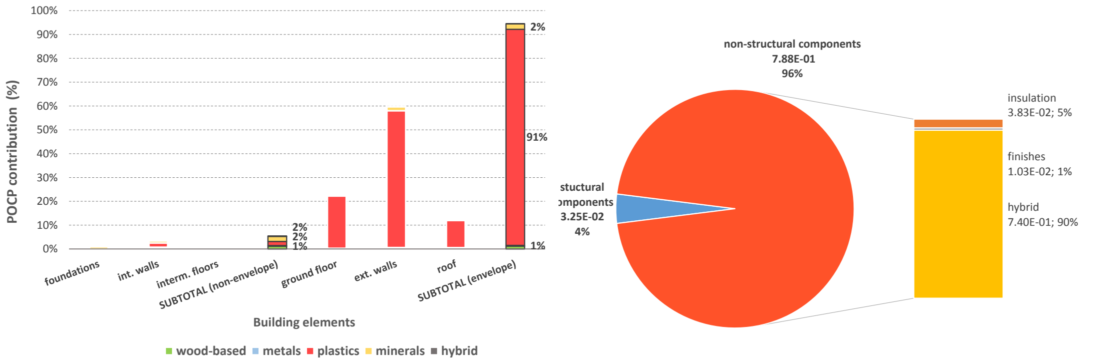


FIGURE L.35 POCP of building C1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg ethene-eq./m^2_{GFA}.

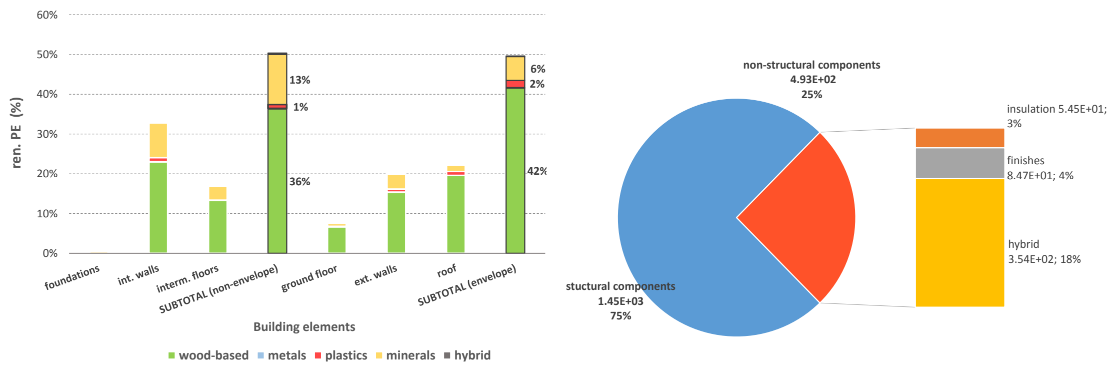


FIGURE L.36 Renewable PE of building C1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m^2_{GFA}.

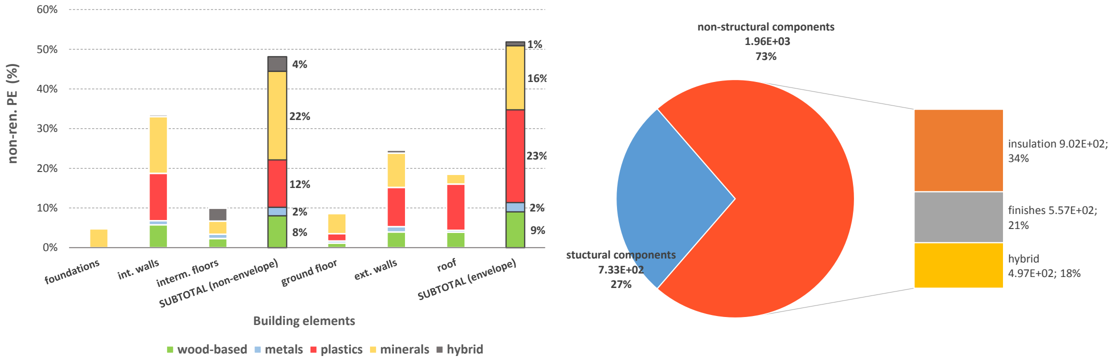


FIGURE L.37 Non-renewable PE of building C1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m²$_{GFA}$.

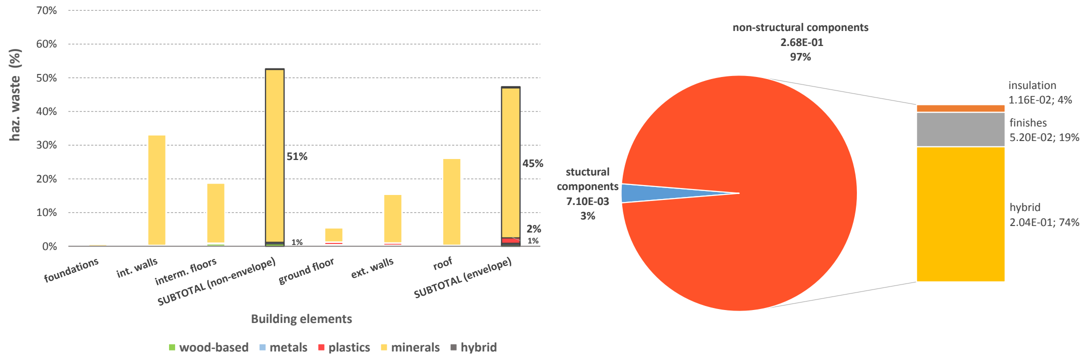


FIGURE L.38 Hazardous waste of building C1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m²$_{GFA}$.

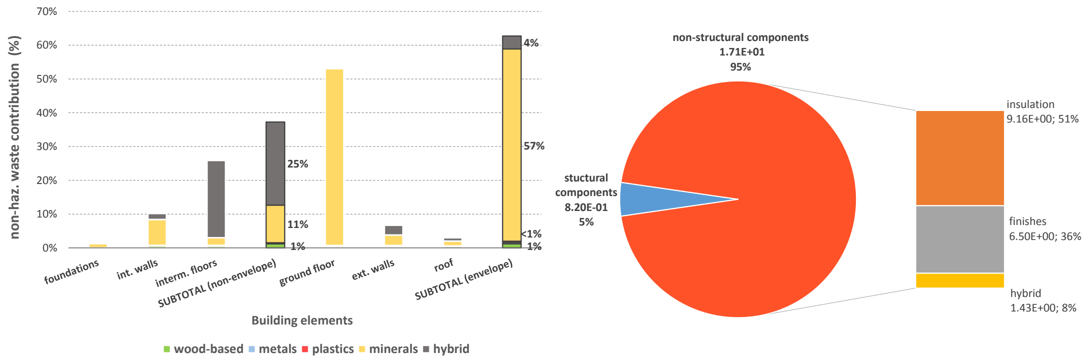


FIGURE L.39 Non-hazardous waste of building C1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m²$_{GFA}$.

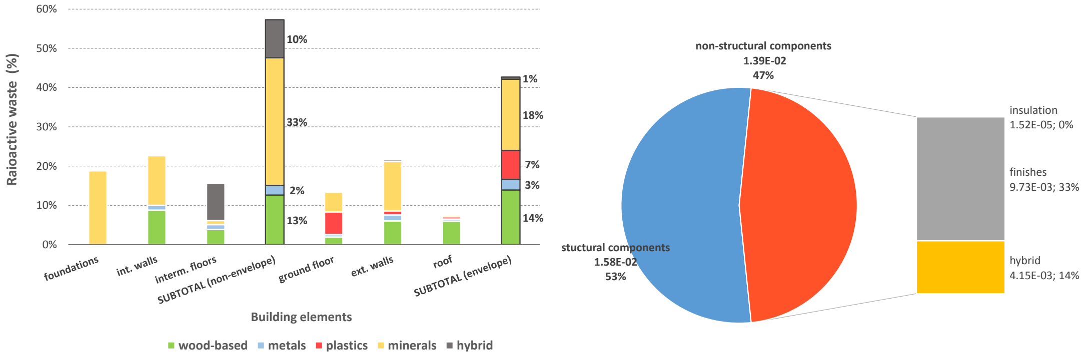


FIGURE L.40 Radioactive waste of building C1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m$^2_{GFA}$.

L.5 Building C2

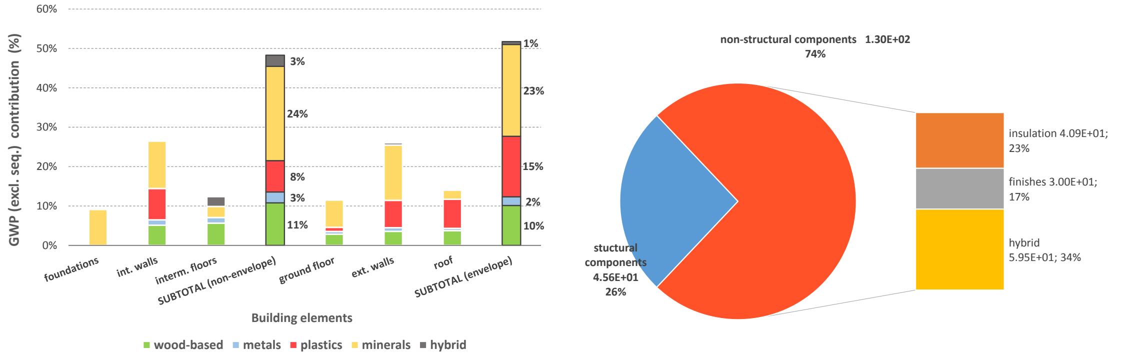


FIGURE L.41 GWP (excluding sequestration) of building C2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CO_2-eq./m^2_{GFA}.

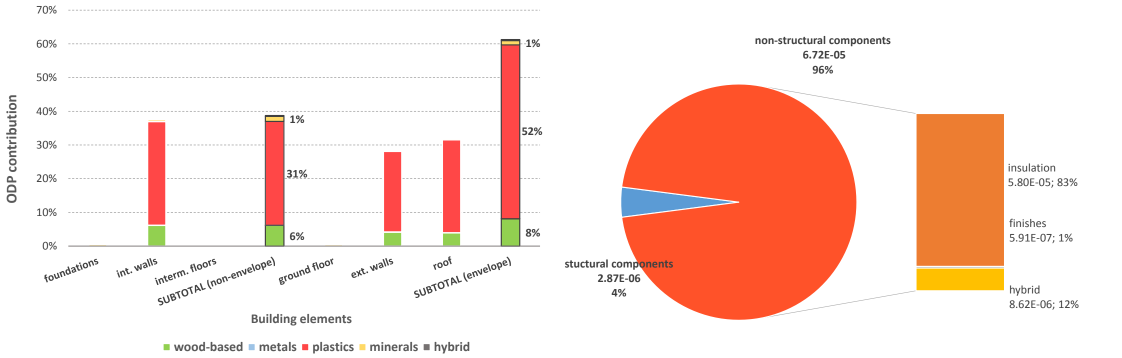


FIGURE L.42 ODP of building C2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CFC 11-eq./m^2_{GFA}).

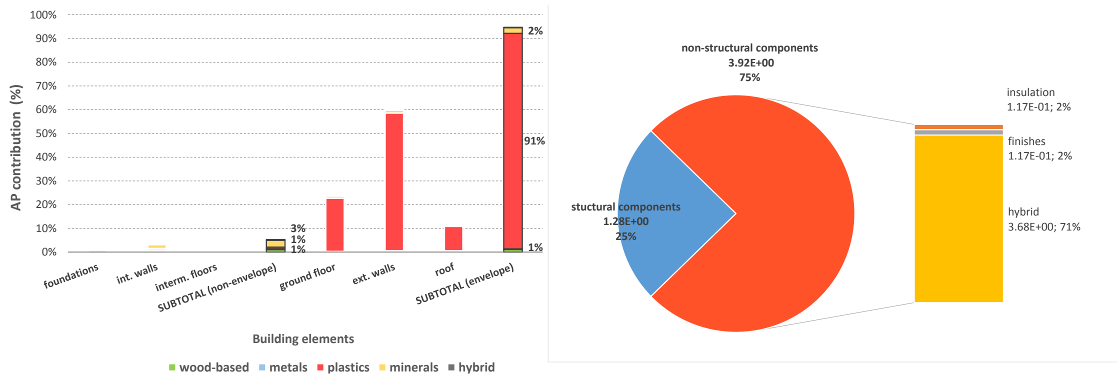


FIGURE L.43 AP of building C2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg SO_2-eq./m^2_{GFA}.

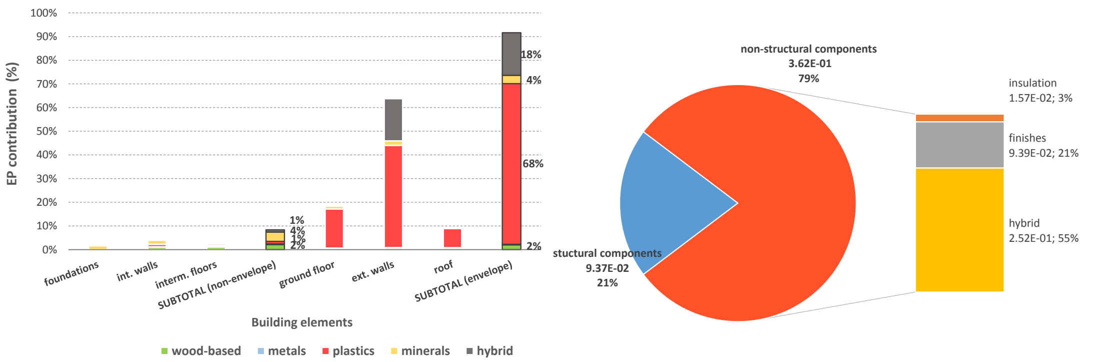


FIGURE L.44 EP of building C2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg PO_4-eq./m^2_{GFA}.

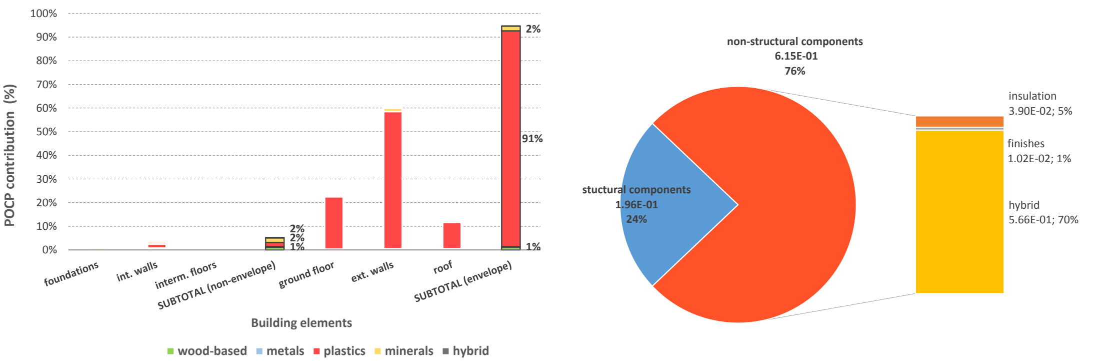


FIGURE L.45 POCP of building C2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg ethene-eq./m^2_{GFA}.

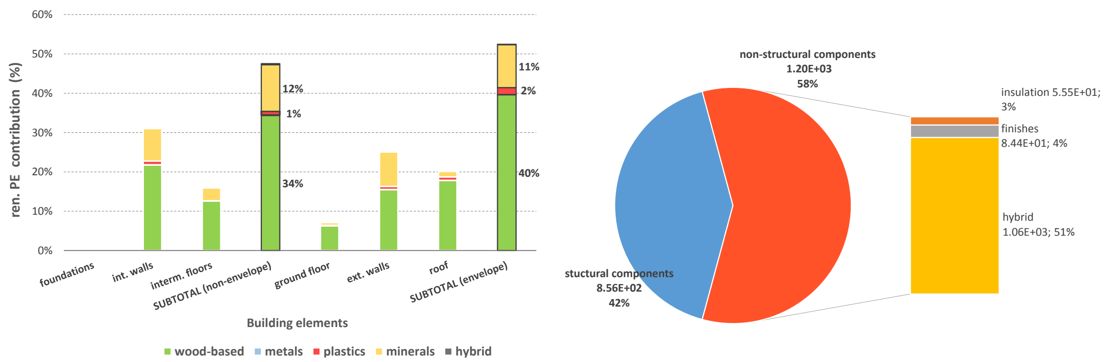


FIGURE L.46 Renewable PE of building C2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m^2_{GFA}.

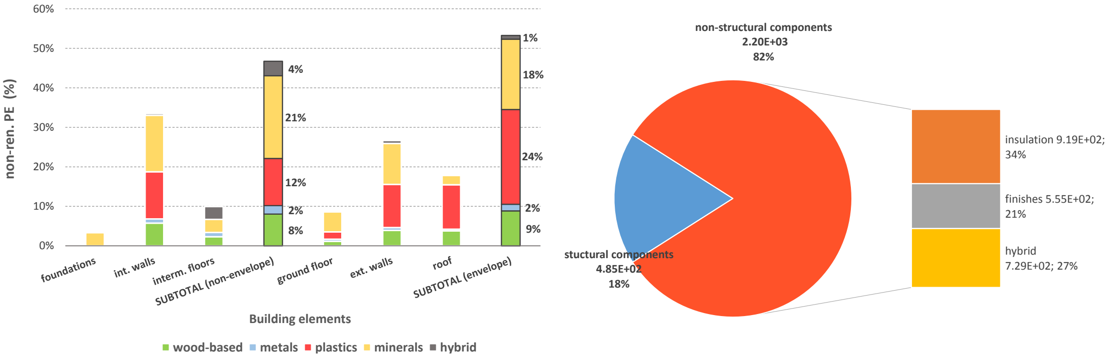


FIGURE L.47 Non-renewable PE of building C2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m$^2_{GFA}$.

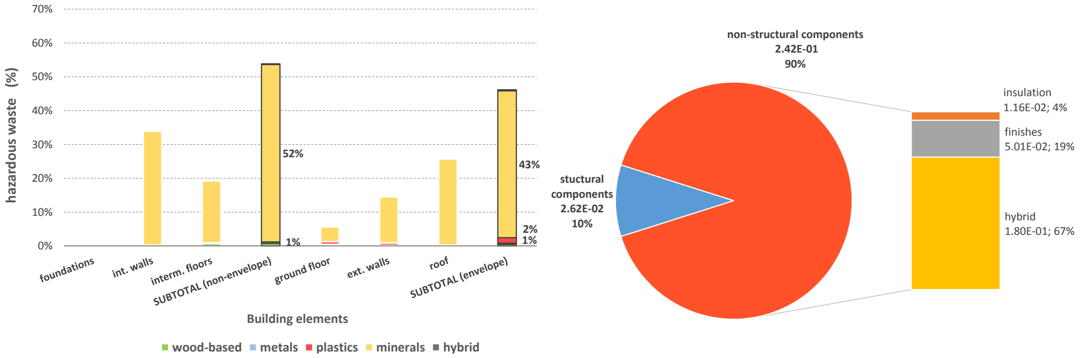


FIGURE L.48 Hazardous waste of building C2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m$^2_{GFA}$.

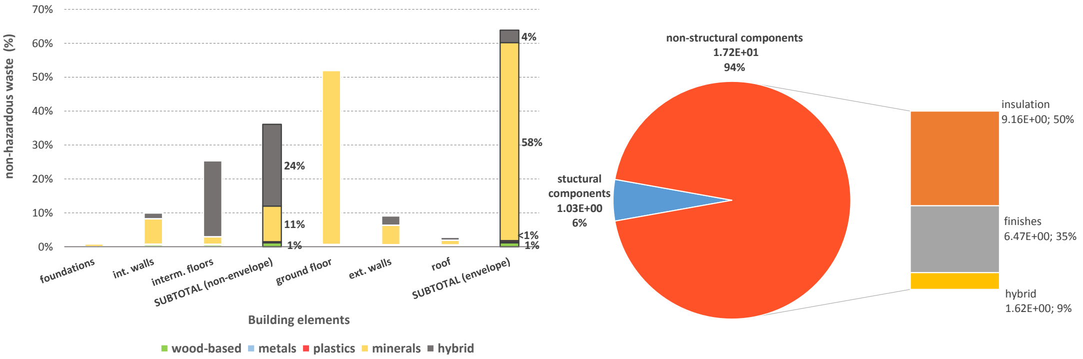


FIGURE L.49 Non-hazardous waste of building C2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m$^2_{GFA}$.

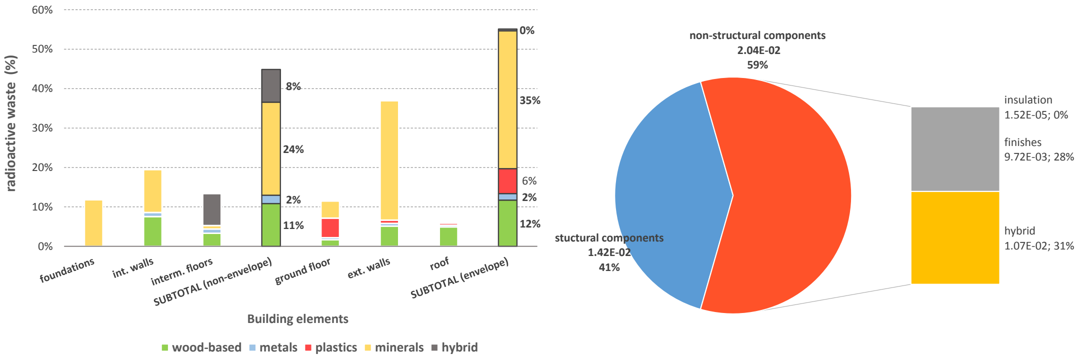


FIGURE L.50 Radioactive waste of building C2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m$^2_{GFA}$.

L.6 Building D1

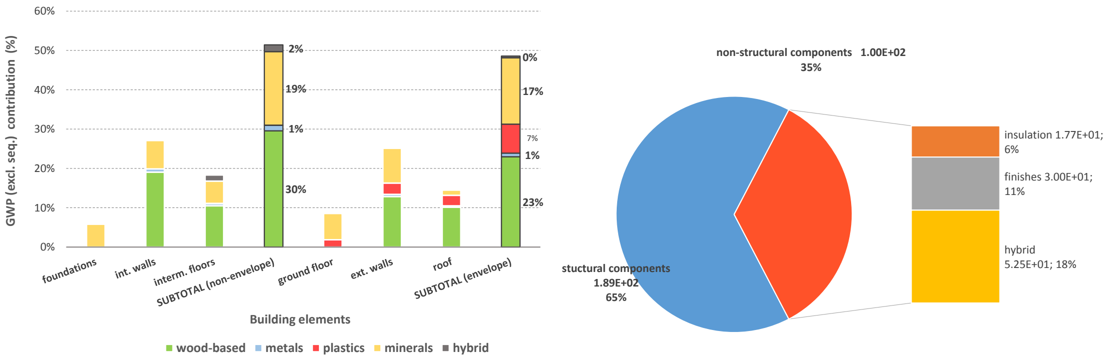


FIGURE L.51 GWP (excluding sequestration) of building D1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CO_2-eq./m^2_{GFA}.

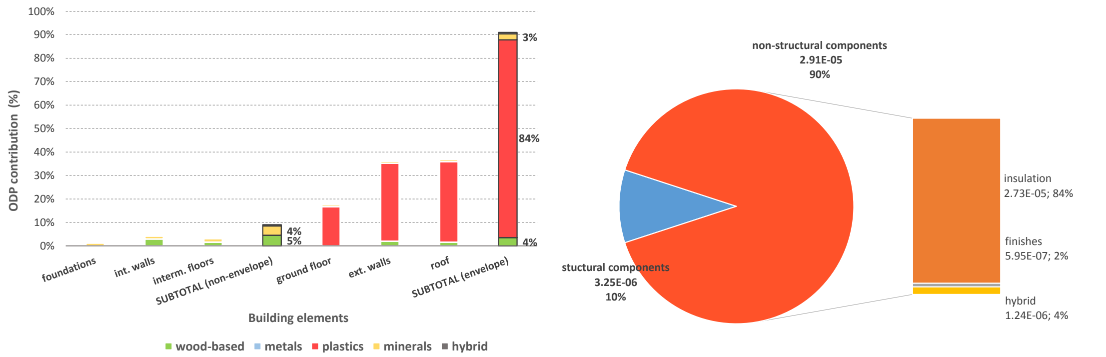


FIGURE L.52 ODP of building D1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CFC 11-eq./m^2_{GFA}).

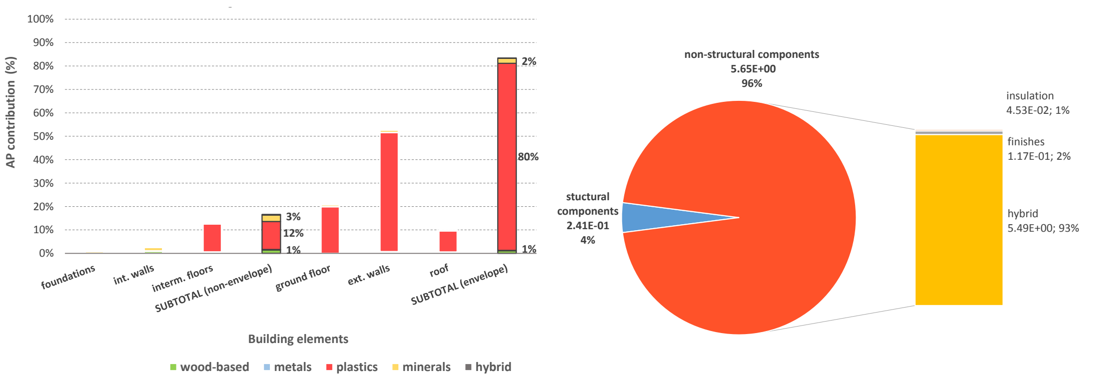


FIGURE L.53 AP of building D1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg SO_2-eq./m^2_{GFA}.

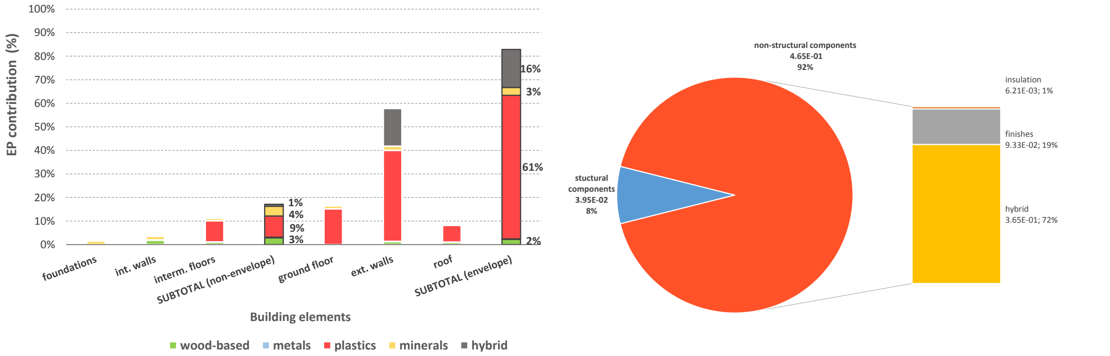


FIGURE L.54 EP of building D1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg PO_4-eq./m^2_{GFA}.

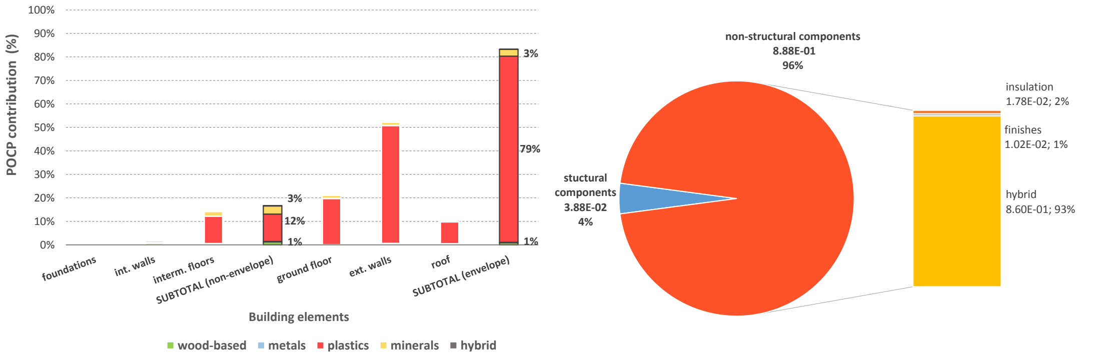


FIGURE L.55 POCP of building D1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg ethene-eq./m^2_{GFA}.

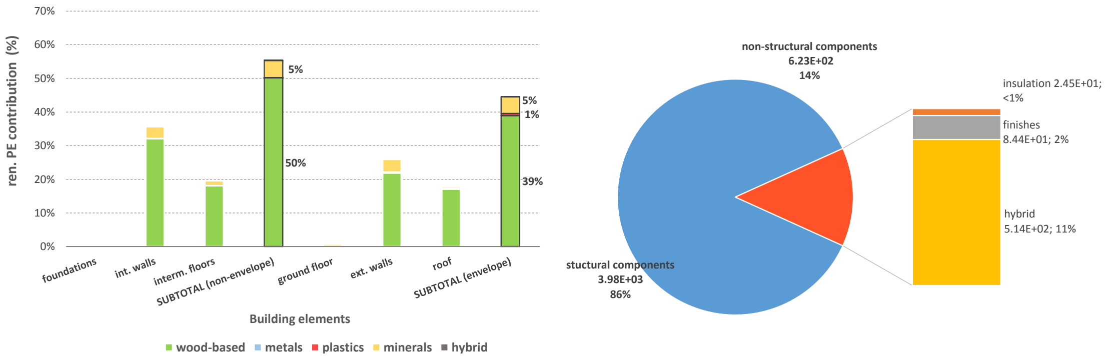


FIGURE L.56 Renewable PE of building D1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m^2_{GFA}.

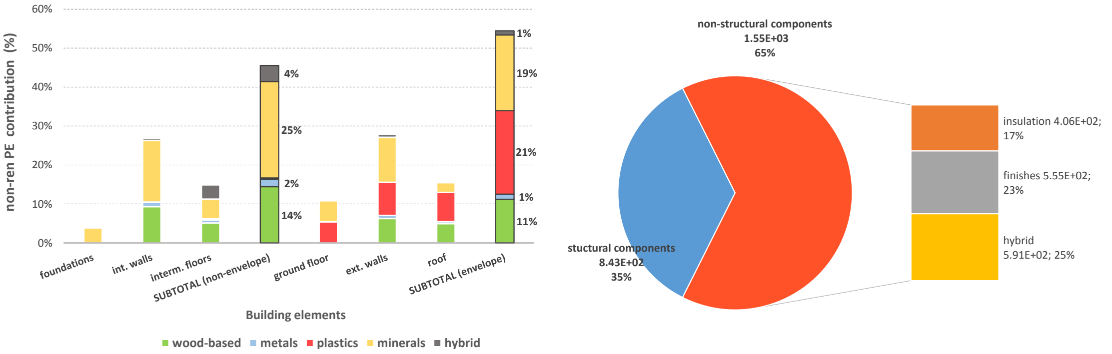


FIGURE L.57 Non-renewable PE of building D1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m$^2_{GFA}$.

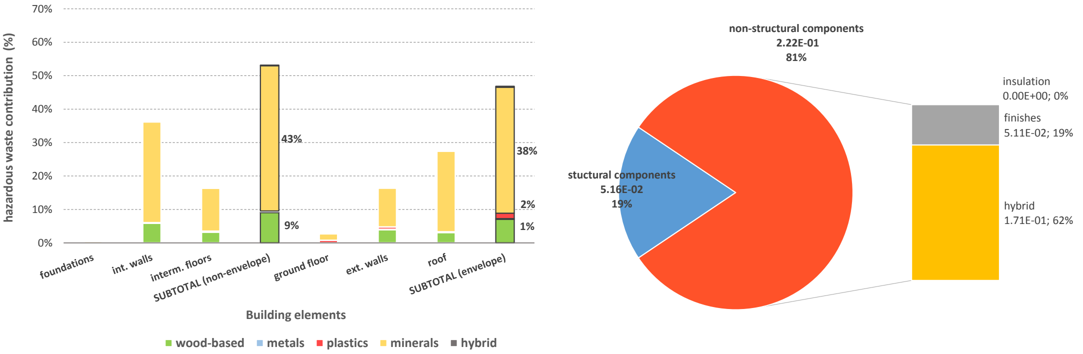


FIGURE L.58 Hazardous waste of building D1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m$^2_{GFA}$.

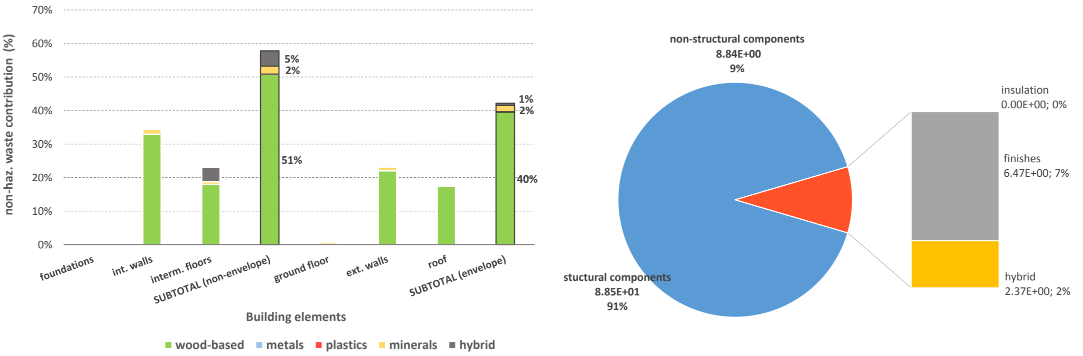


FIGURE L.59 Non-hazardous waste of building D1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m$^2_{GFA}$.

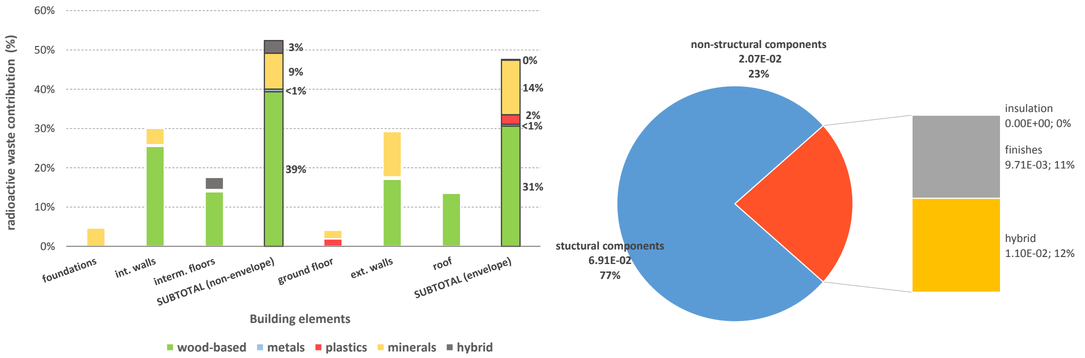


FIGURE L.60 Radioactive waste of building D1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m^2_{GFA}.

L.7 Building D2

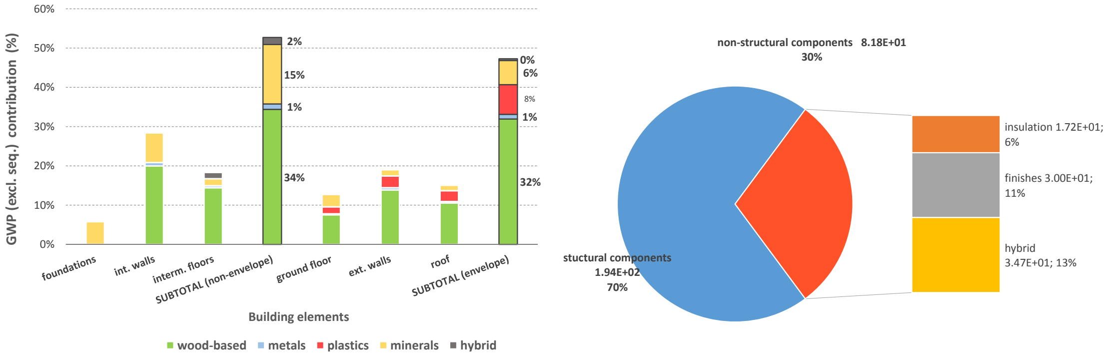


FIGURE L.61 GWP (excluding sequestration) of building D2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CO_2-eq./m^2_{GFA}.

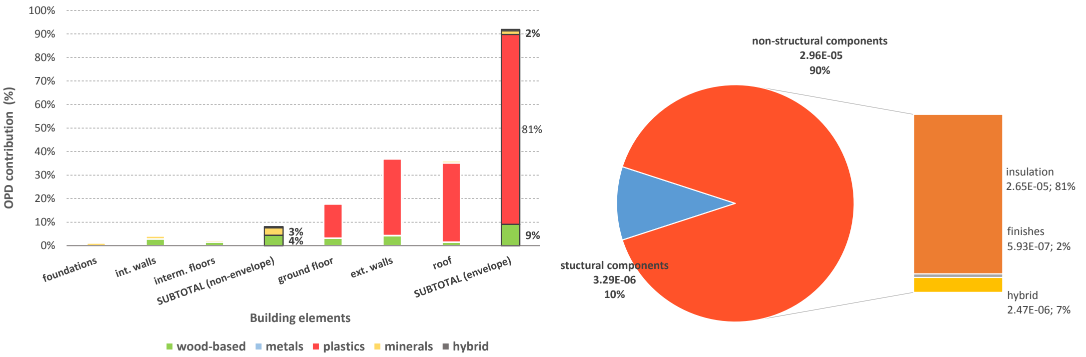


FIGURE L.62 ODP of building D2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CFC 11-eq./m^2_{GFA}).

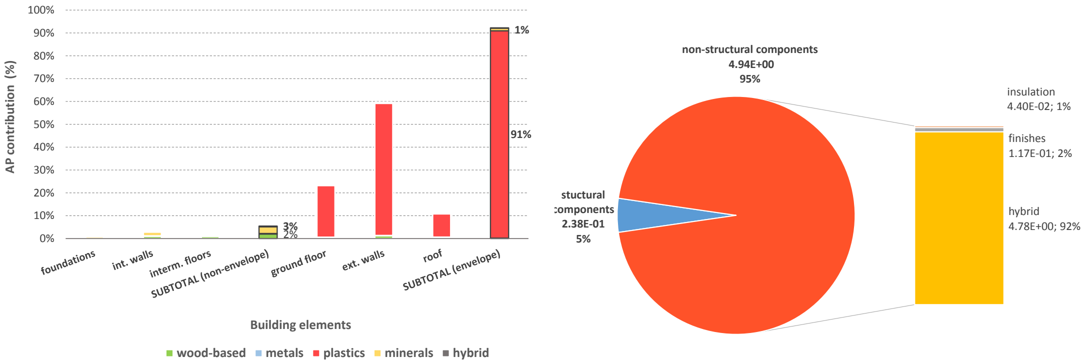


FIGURE L.63 AP of building D2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg SO_2-eq./m^2_{GFA}.

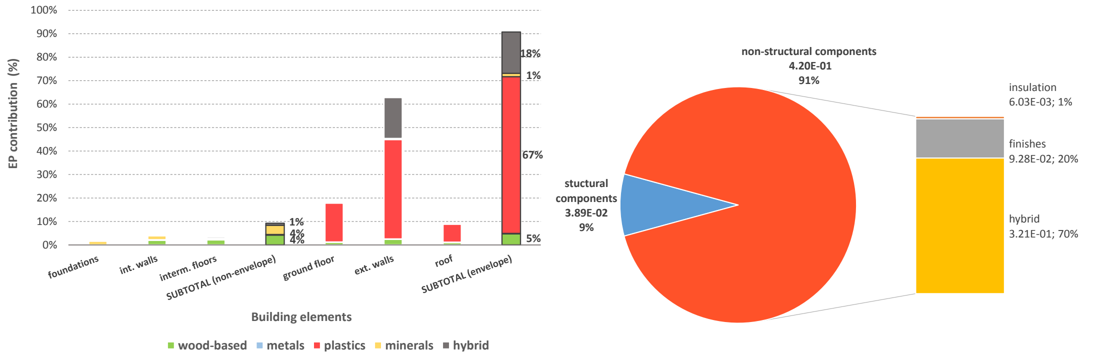


FIGURE L.64 EP of building D2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg PO_4-eq./m^2_{GFA}.

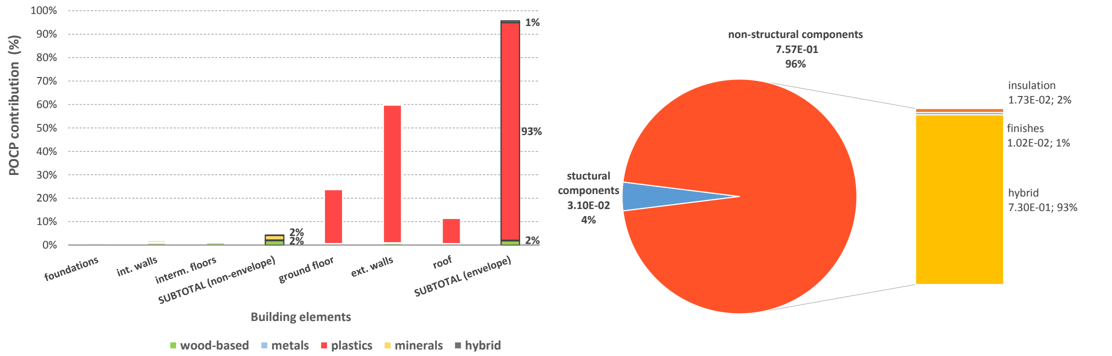


FIGURE L.65 POCP of building D2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg ethene-eq./m^2_{GFA}.

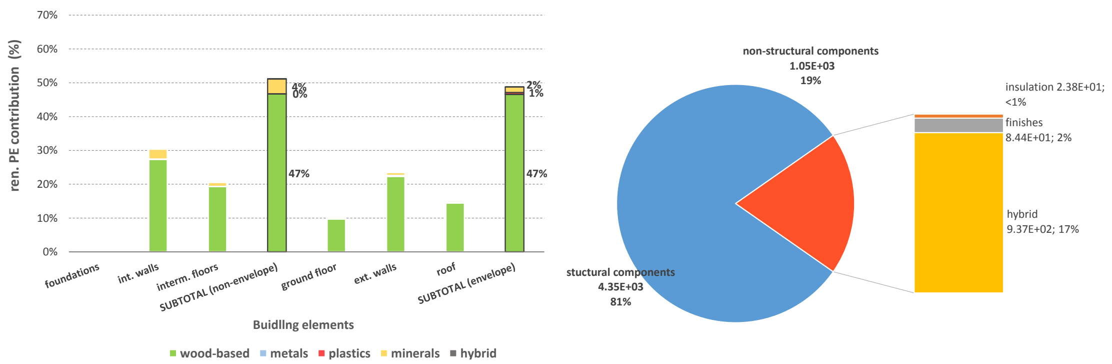


FIGURE L.66 Renewable PE of building D2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m^2_{GFA}.

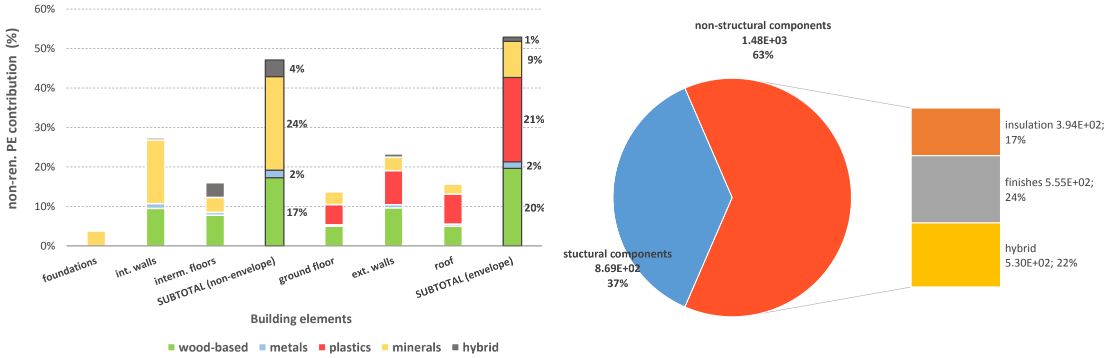


FIGURE L.67 Non-renewable PE of building D2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m$^2{}_{GFA}$.

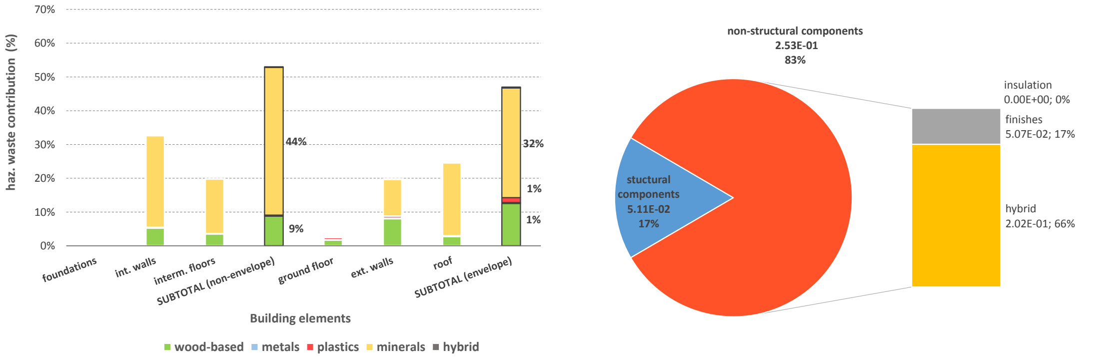


FIGURE L.68 Hazardous waste of building D2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m$^2{}_{GFA}$.

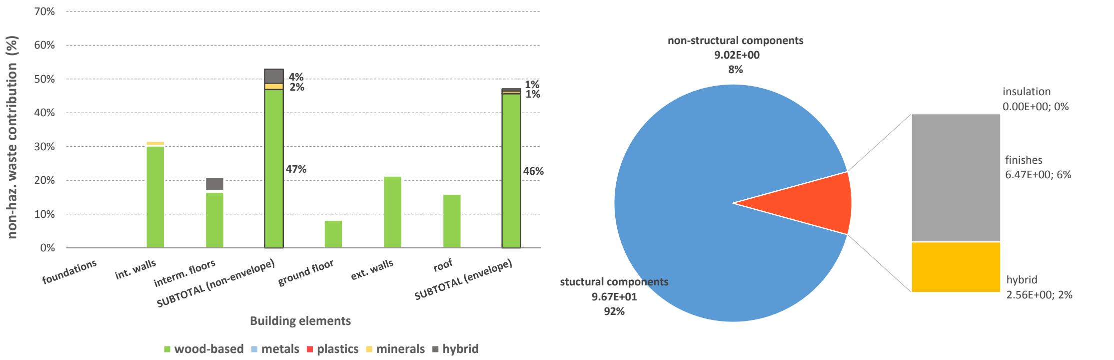


FIGURE L.69 Non-hazardous waste of building D2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m$^2{}_{GFA}$.

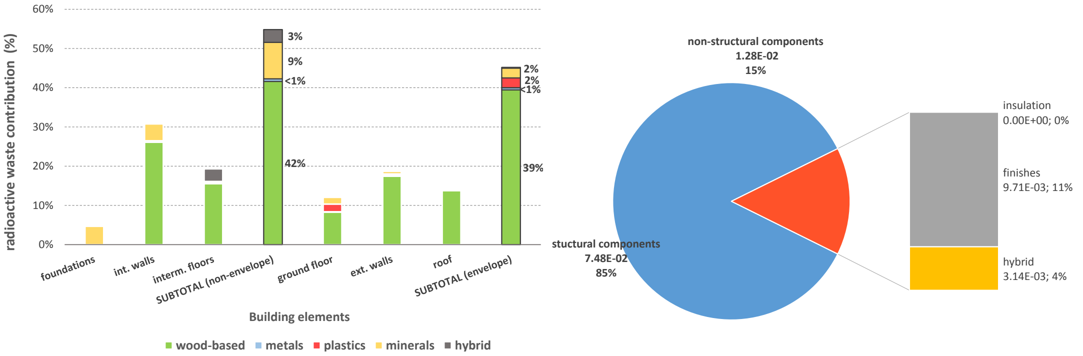


FIGURE L.70 Radioactive waste of building D2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m$^2{}_{GFA}$.

L.8 Building E1

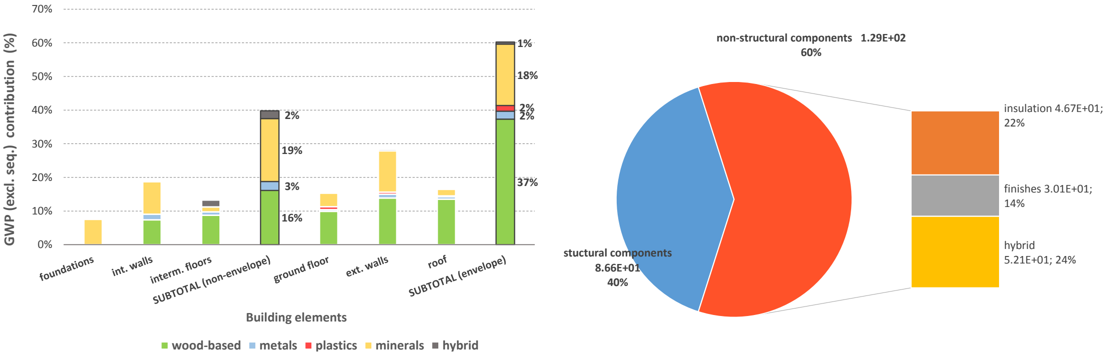


FIGURE L.71 GWP (excluding sequestration) of building E1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CO_2-eq./m^2_{GFA}.

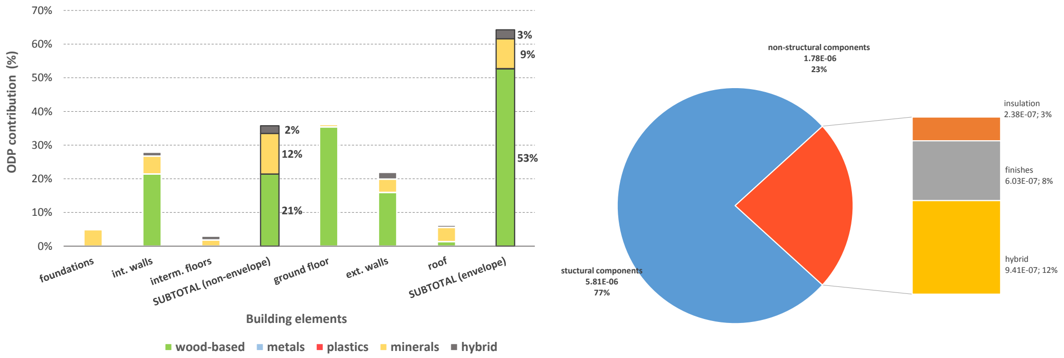


FIGURE L.72 ODP of building E1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CFC 11-eq./m^2_{GFA}).

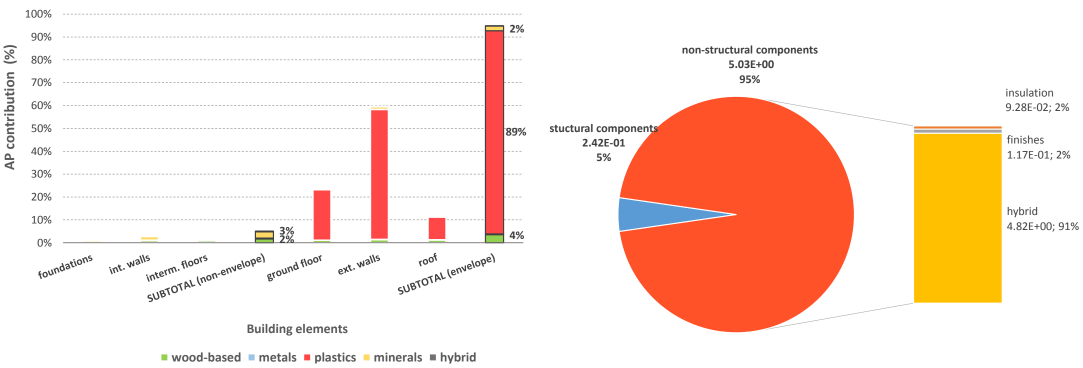


FIGURE L.73 AP of building E1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg SO_2-eq./m^2_{GFA}.

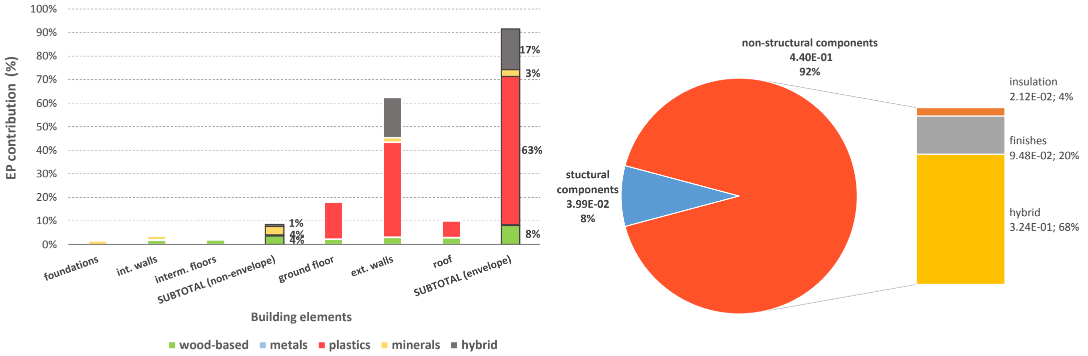


FIGURE L.74 EP of building E1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg PO_4-eq./m^2_{GFA}.

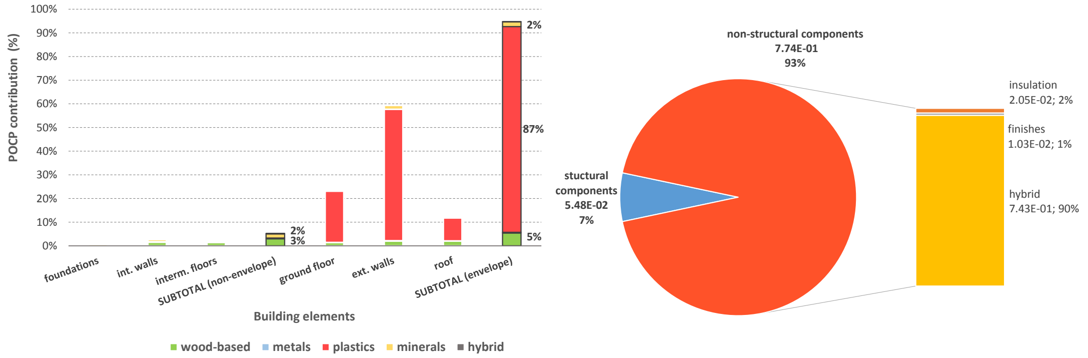


FIGURE L.75 POCP of building E1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg ethene-eq./m^2_{GFA}.

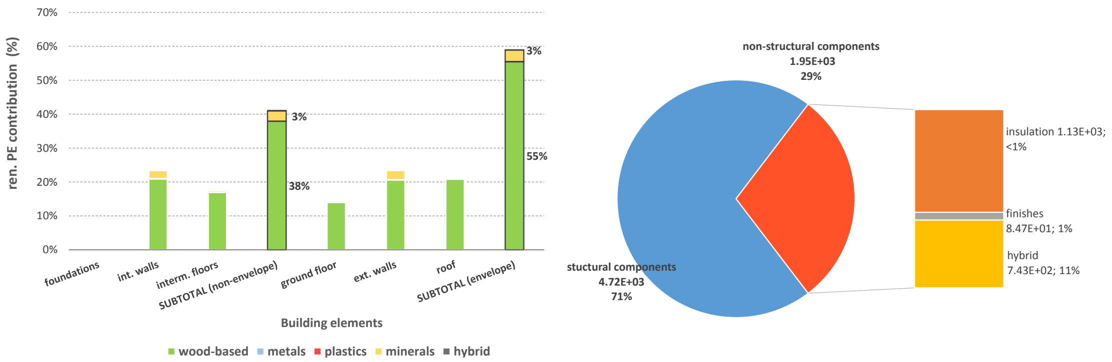


FIGURE L.76 Renewable PE of building E1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m^2_{GFA}.

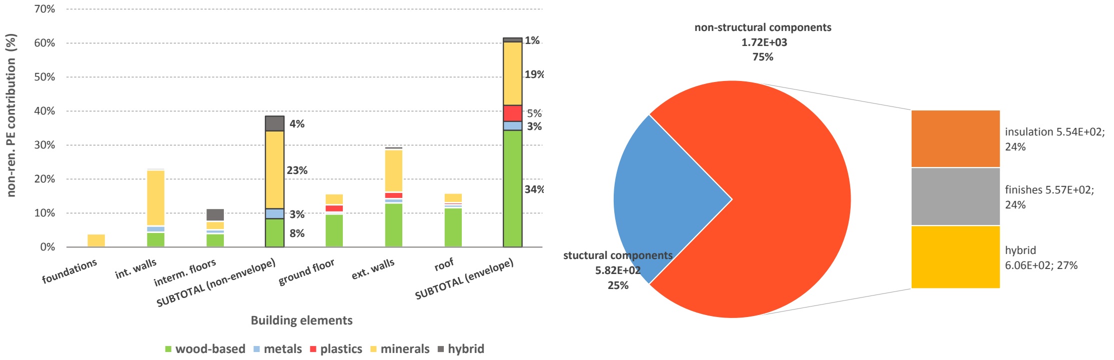


FIGURE L.77 Non-renewable PE of building E1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m$^2_{GFA}$.

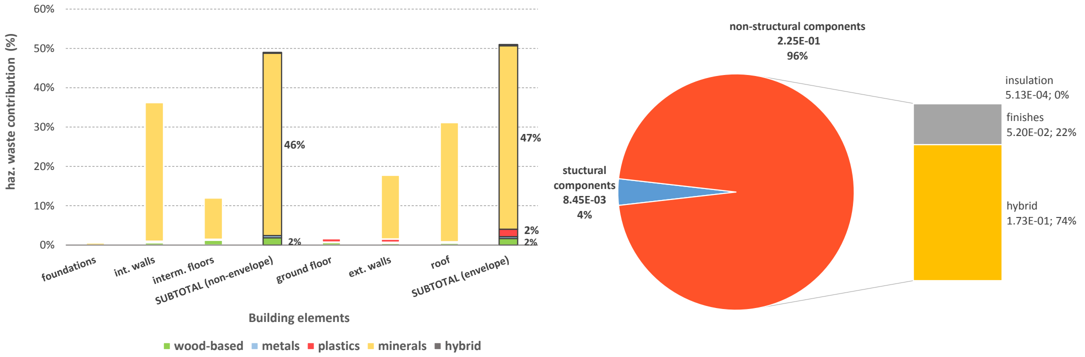


FIGURE L.78 Hazardous waste of building E1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m$^2_{GFA}$.

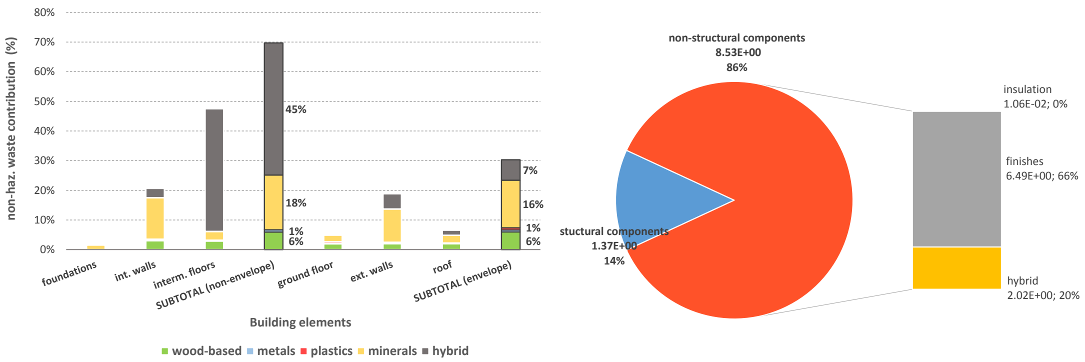


FIGURE L.79 Non-hazardous waste of building E1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m$^2_{GFA}$.

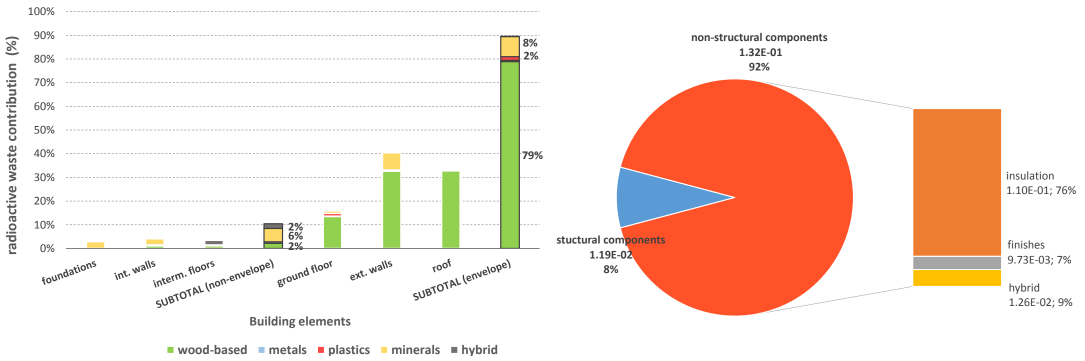


FIGURE L.80 Radioactive waste of building E1: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m$^2_{GFA}$.

L.9 Building E2

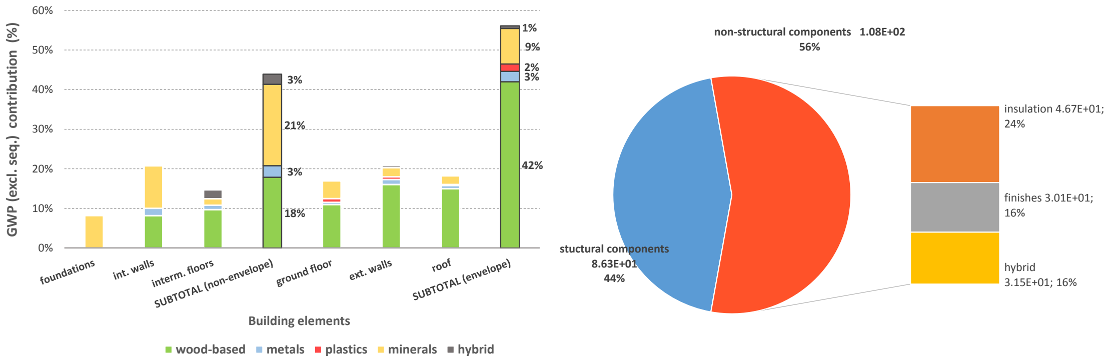


FIGURE L.81 GWP (excluding sequestration) of building E2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CO_2-eq./m^2_{GFA}.

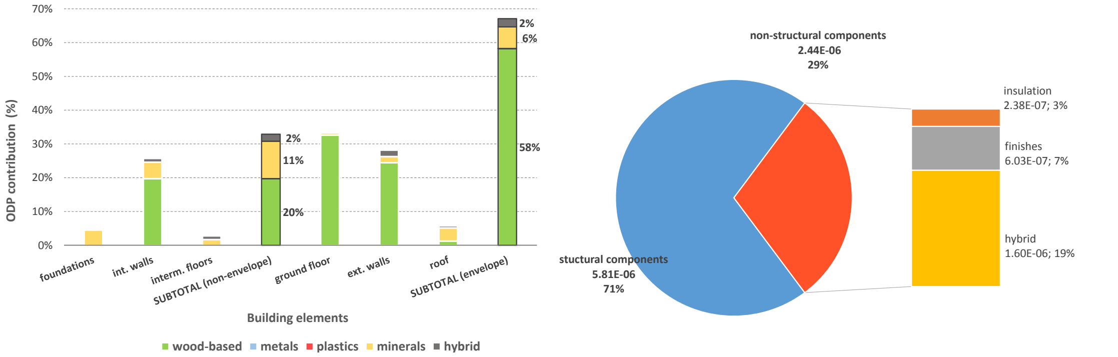


FIGURE L.82 ODP of building E2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CFC 11-eq./m^2_{GFA}).

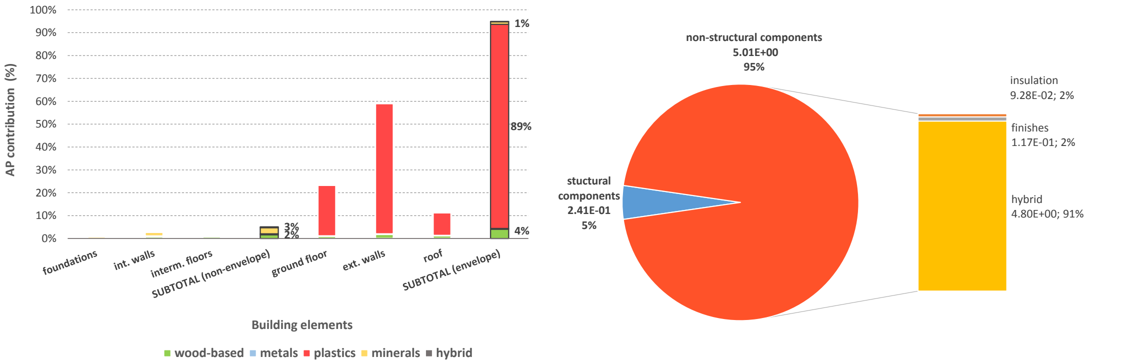


FIGURE L.83 AP of building E2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg SO_2-eq./m^2_{GFA}.

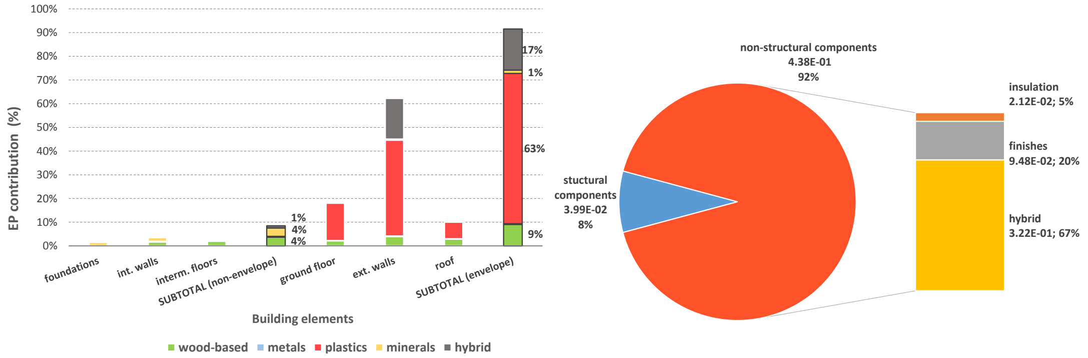


FIGURE L.84 EP of building E2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg PO_4-eq./m^2_{GFA}.

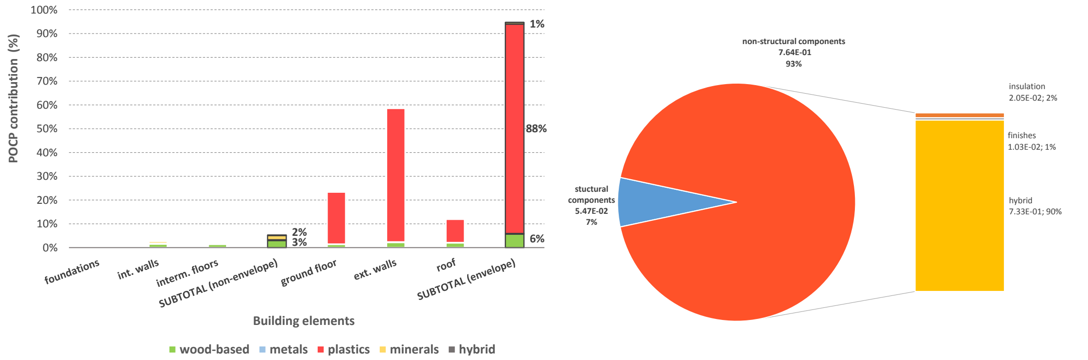


FIGURE L.85 POCP of building E2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg ethene-eq./m^2_{GFA}.

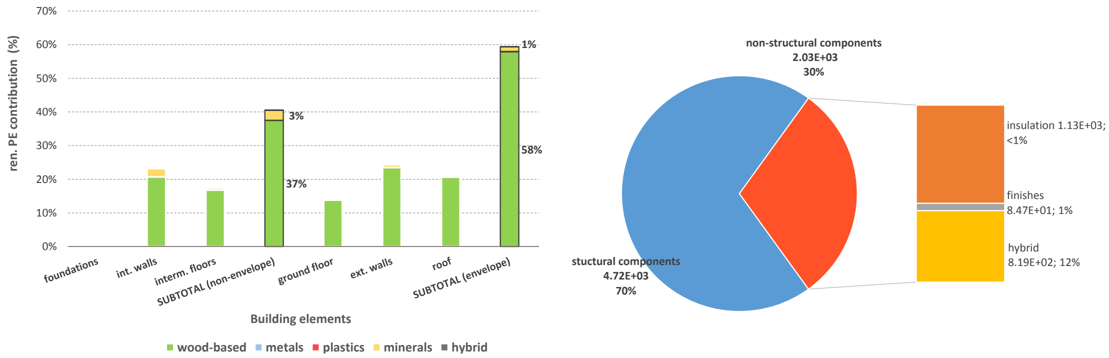


FIGURE L.86 Renewable PE of building E2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m^2_{GFA}.

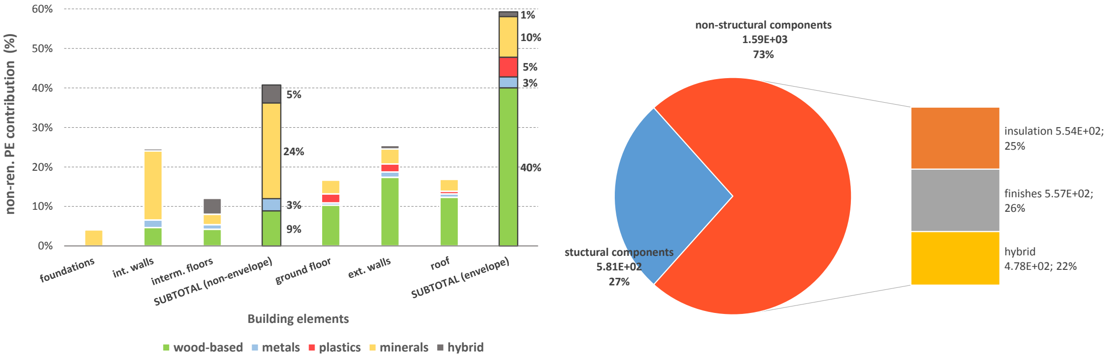


FIGURE L.87 Non-renewable PE of building E2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m$^2_{GFA}$.

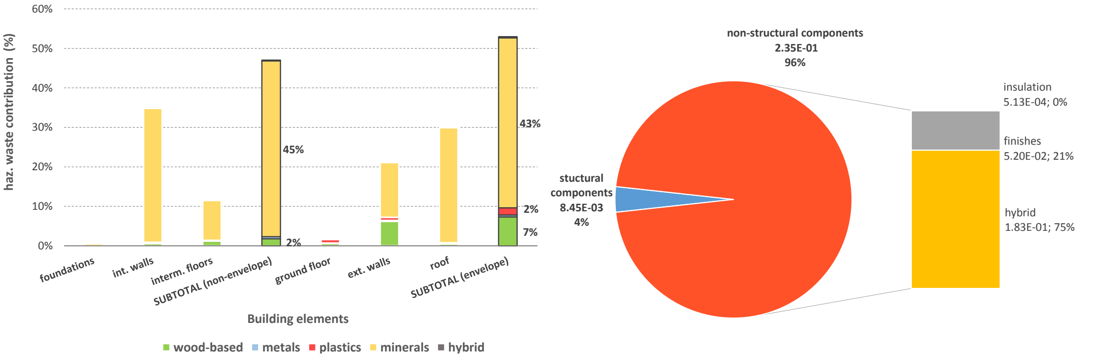


FIGURE L.88 Hazardous waste of building E2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m$^2_{GFA}$.

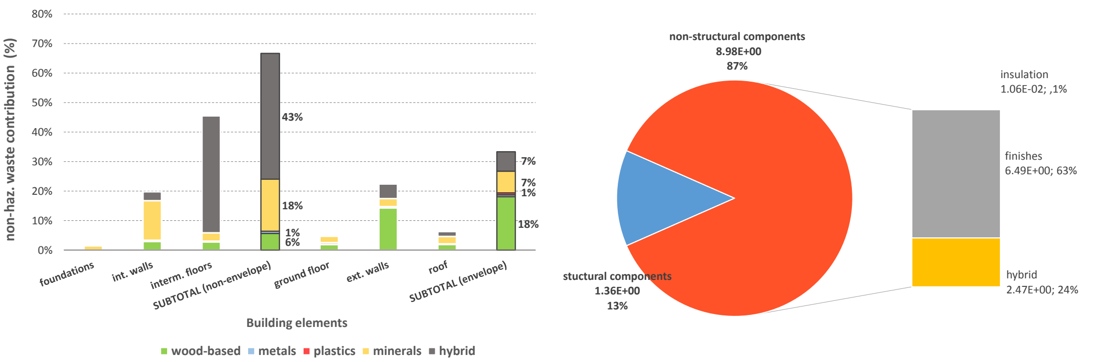


FIGURE L.89 Non-hazardous waste of building E2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m$^2_{GFA}$.

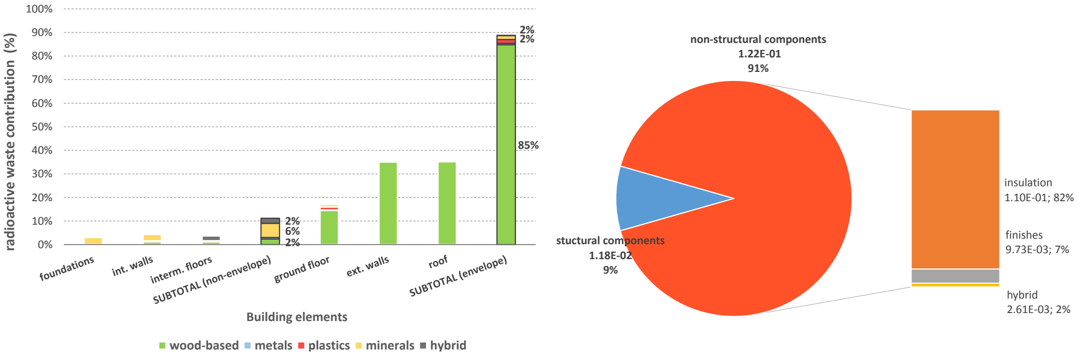


FIGURE L.90 Radioactive waste of building E2: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m²$_{GFA}$.

L.10 Building F

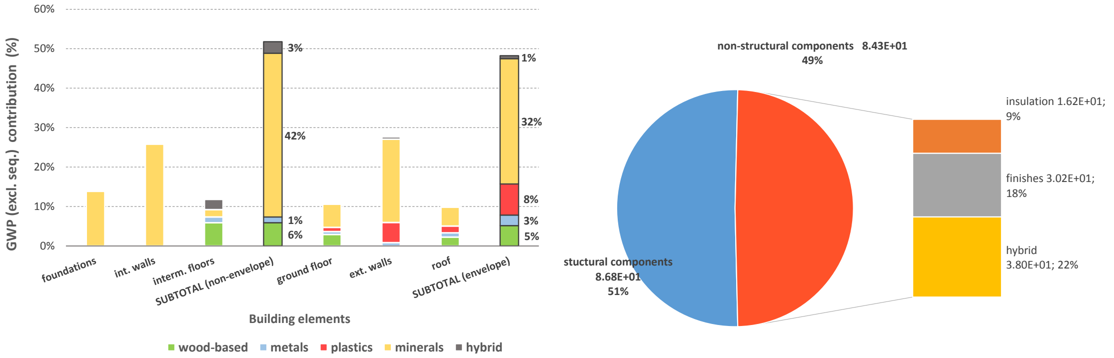


FIGURE L.91 GWP (excluding sequestration) of building F: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CO_2-eq./m^2_{GFA}.

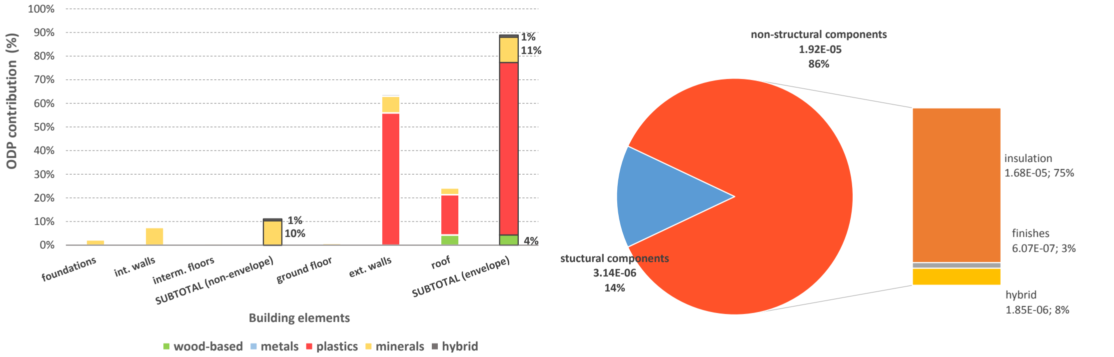


FIGURE L.92 ODP of building F: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg CFC 11-eq./m^2_{GFA}).

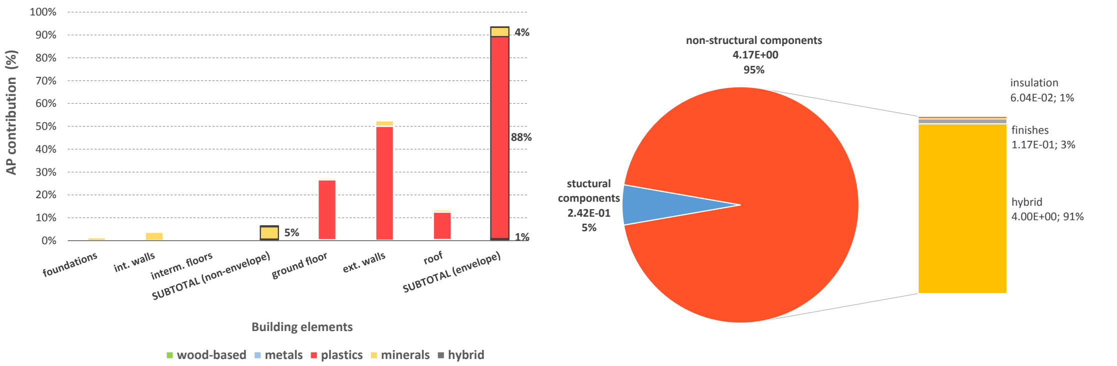


FIGURE L.93 AP of building F: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg SO_2-eq./m^2_{GFA}.

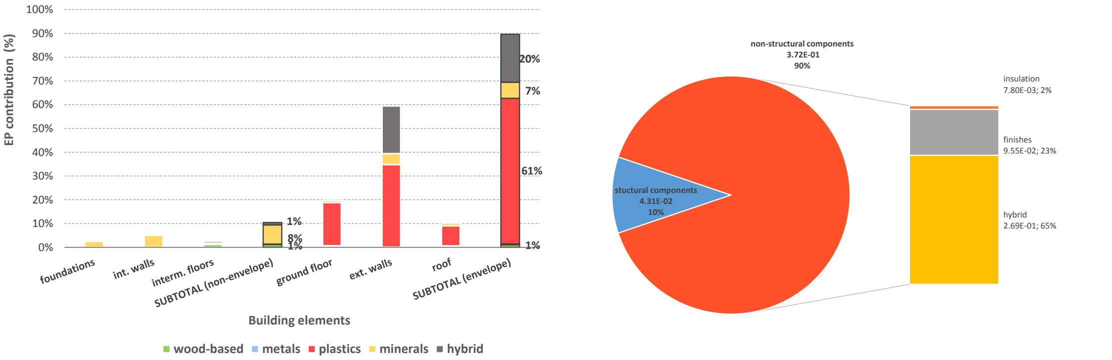


FIGURE L.94 EP of building F: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg PO_4-eq./m^2_{GFA}.

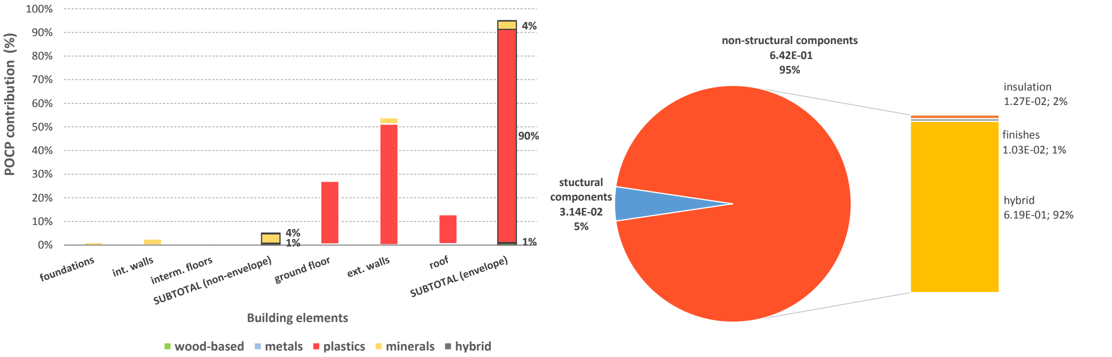


FIGURE L.95 POCP of building F: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg ethene-eq./m^2_{GFA}.

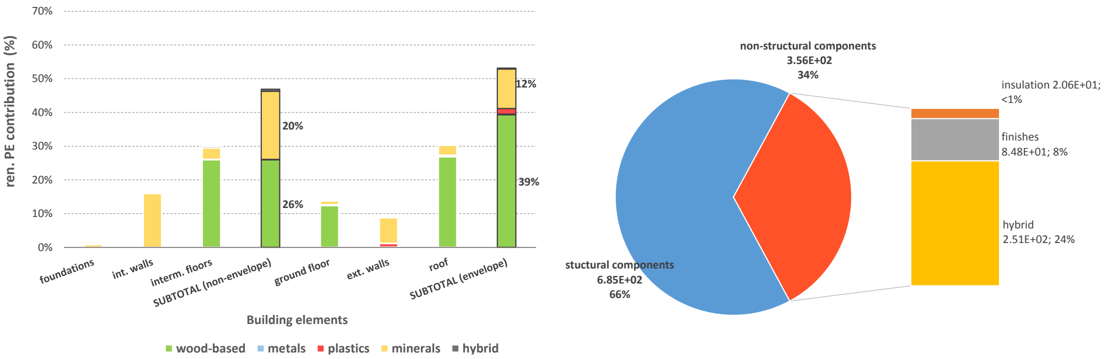


FIGURE L.96 Renewable PE of building F: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m^2_{GFA}.

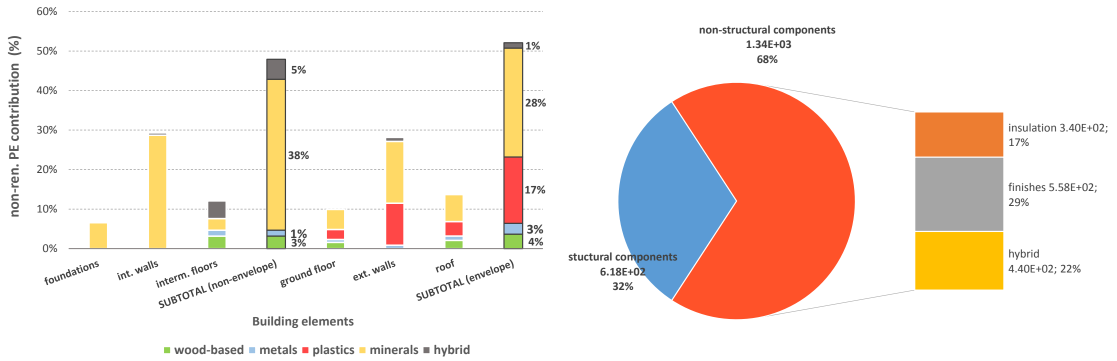


FIGURE L.97 Non-renewable PE of building F: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in MJ/m^2$_{GFA}$.

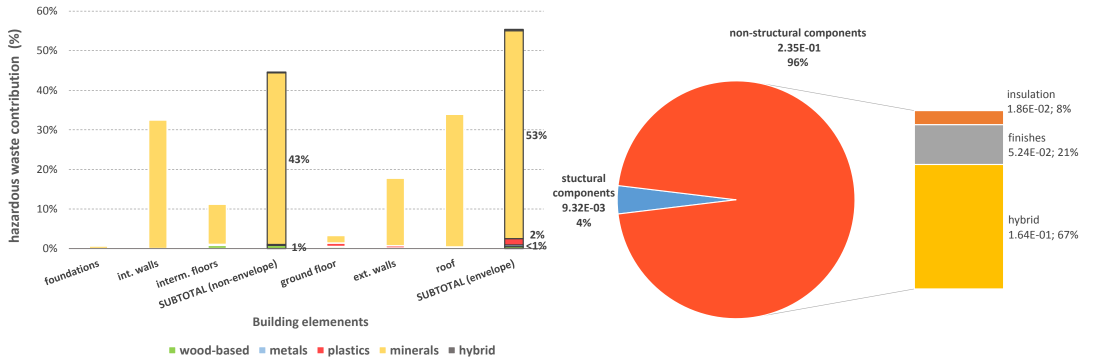


FIGURE L.98 Hazardous waste of building F: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m^2$_{GFA}$.

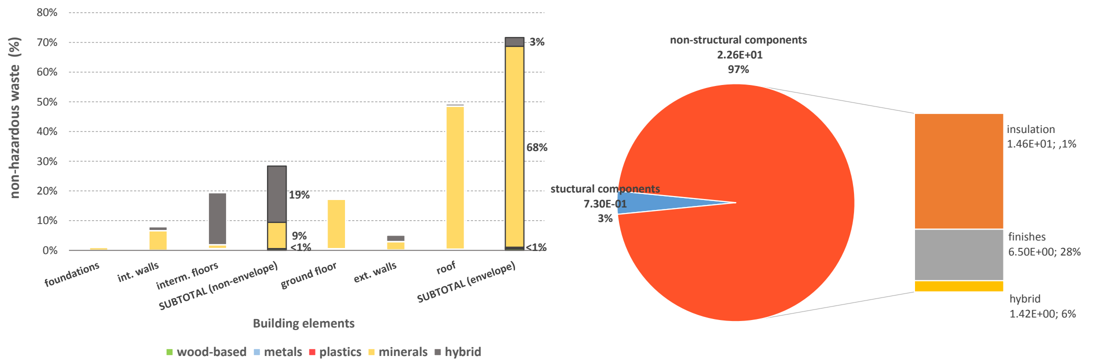


FIGURE L.99 Non-hazardous waste of building F: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m^2$_{GFA}$.

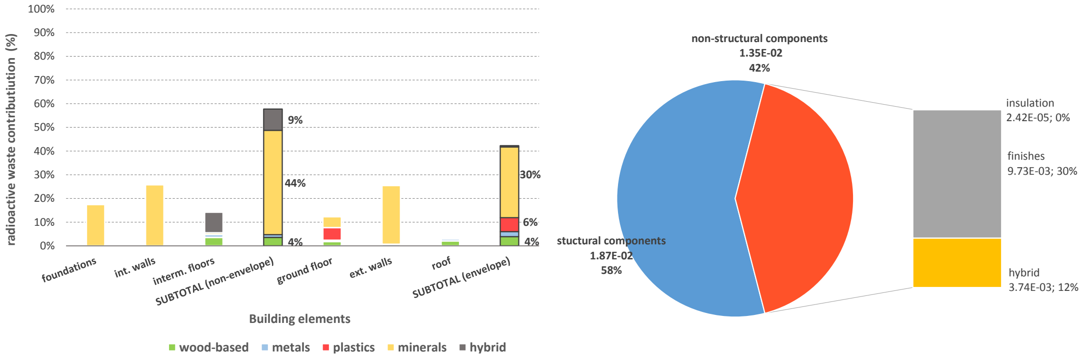


FIGURE L.100 Radioactive waste of building F: contribution analysis by building element and material (left) and by structural role (right). The absolute values in the pie chart are expressed in kg/m^2$_{GFA}$.

M LCA results: impact analysis (absolute values for each building)

The following tables present the absolute results for environmental impacts, consumption of primary energy and production of waste, in tabulated and graphic form. These results have been discussed in CHAPTER 5.

TABLE M.1 Impact results and associated uncertainties (in terms of GSD²) for all buildings.

Building	Global warming pot. (GWP), excl. sequestration		Global warming pot. (GWP), incl. sequestration [a]	Ozone-depletion pot. (ODP)		Acidification pot. (AP)		Eutrophication pot. (EP)		Photochemical ozone-creation pot. (POCP)	
	impact	GSD^2	impact	impact	GSD^2	impact	GSD^2	impact	GSD^2	impact	GSD^2
	kg CO_2-eq. / m^2_{GFA}	(/)	kg CO_2-eq. / m^2_{GFA}	kg CFC_{11}-eq. / m^2_{GFA}	(/)	kg SO_2-eq. / m^2_{GFA}	(/)	kg PO_4-eq. / m^2_{GFA}	(/)	kg ethene-eq./ m^2_{GFA}	(/)
A	1.54E+02	1.05	3.85E+01	1.10E-05	1.10	5.22E+00	1.16	4.59E-01	1.12	7.86E-01	1.17
B1	1.66E+02	1.06	-2.36E+01	1.31E-05	1.21	6.00E+00	1.16	5.16E-01	1.13	9.06E-01	1.17
B2	1.58E+02	1.06	-3.08E+01	1.20E-05	1.23	5.93E+00	1.17	5.06E-01	1.13	8.96E-01	1.17
C1	1.84E+02	1.06	4.10E+01	7.01E-05	1.14	5.27E+00	1.16	4.66E-01	1.12	8.21E-01	1.16
C2	1.76E+02	1.06	3.17E+01	7.01E-05	1.14	5.19E+00	1.16	4.56E-01	1.12	8.11E-01	1.16
D1	2.89E+02	1.16	-1.64E+02	3.24E-05	1.14	5.89E+00	1.17	5.04E-01	1.13	9.27E-01	1.16
D2	2.76E+02	1.19	-2.76E+02	3.29E-05	1.13	5.18E+00	1.16	4.59E-01	1.12	7.89E-01	1.16
E1	2.16E+02	1.09	-3.66E+02	7.59E-06	1.23	5.27E+00	1.16	4.80E-01	1.12	8.29E-01	1.16
E2	1.95E+02	1.10	-4.36E+02	8.24E-06	1.21	5.25E+00	1.16	4.78E-01	1.12	8.19E-01	1.16
F	1.71E+02	1.05	9.44E+01	2.24E-05	1.12	4.42E+00	1.17	4.15E-01	1.12	6.73E-01	1.17

Abbreviations

GFA	gross (internal) floor area
GSD	geometric standard deviation

Notes

a	value of GSD^2 not available for this impact (since negative emissions are not accounted for by method employed for uncertainty estimation)

TABLE M.2 Primary-energy consumption and associated uncertainties (in terms of GSD²) for all buildings.

Building	Renewable primary energy		Non-renewable primary energy	
	energy MJ / m^2_{GFA}	GSD^2 (/)	energy MJ / m^2_{GFA}	GSD^2 (/)
A	1.51E+03	1.15	1.92E+03	1.06
B1	2.36E+03	1.17	2.07E+03	1.07
B2	2.46E+03	1.16	2.08E+03	1.07
C1	1.94E+03	1.17	2.69E+03	1.07
C2	2.06E+03	1.16	2.69E+03	1.07
D1	4.60E+03	1.28	2.39E+03	1.09
D2	5.39E+03	1.26	2.35E+03	1.10
E1	6.68E+03	1.21	2.30E+03	1.08
E2	6.75E+03	1.20	2.17E+03	1.08
F	1.04E+03	1.14	1.96E+03	1.05
Abbreviations				
GFA	gross (internal) floor area			
GSD	geometric standard deviation			
Notes				
a	value not available for this impact (since negative emissions are not accounted for by method employed for uncertainty estimation)			

TABLE M.3 Waste production and associated uncertainties (in terms of GSD²) for all buildings.

Building	Hazardous waste		Non-hazardous waste		Radioactive waste	
	waste kg / m^2_{GFA}	GSD^2 (/)	waste kg / m^2_{GFA}	GSD^2 (/)	waste kg / m^2_{GFA}	GSD^2 (/)
A	3.21E-01	1.15	5.68E+01	1.14	2.55E-02	1.06
B1	3.05E-01	1.14	5.84E+01	1.14	2.92E-02	1.07
B2	3.01E-01	1.15	6.11E+01	1.14	3.44E-02	1.09
C1	2.75E-01	1.18	1.79E+01	1.09	2.97E-02	1.08
C2	2.68E-01	1.18	1.83E+01	1.09	3.46E-02	1.09
D1	2.74E-01	1.15	9.73E+01	1.30	8.98E-02	1.23
D2	3.04E-01	1.16	1.06E+02	1.30	8.77E-02	1.25
E1	2.34E-01	1.18	9.89E+00	1.08	1.44E-01	1.19
E2	2.44E-01	1.17	1.03E+01	1.08	1.34E-01	1.21
F	2.44E-01	1.16	2.33E+01	1.11	3.22E-02	1.07
Abbreviations						
GFA	gross (internal) floor area					
GSD	geometric standard deviation					
Notes						
a	value not available for this impact (since negative emissions are not accounted for by method employed for uncertainty estimation)					

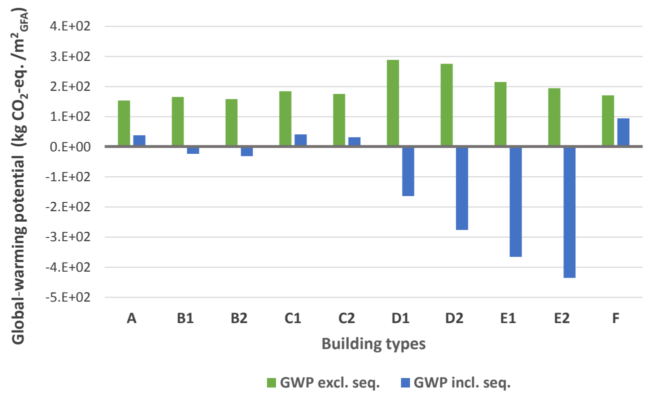


FIGURE M.1 Global-warming potentials, estimated including and excluding biogenic carbon sequestration: results by building.

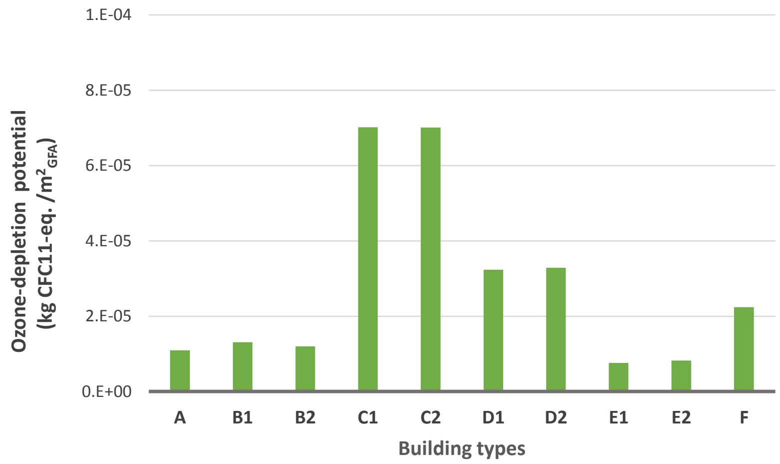


FIGURE M.2 Ozone-depletion potential: results by building

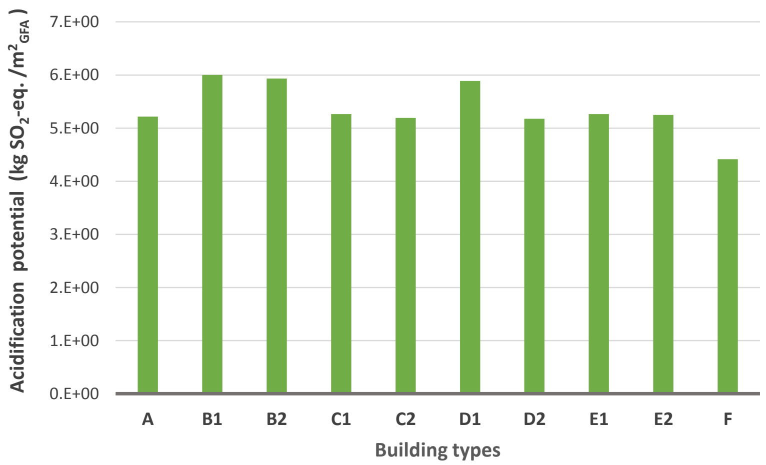


FIGURE M.3 Acidification potential: results by building.

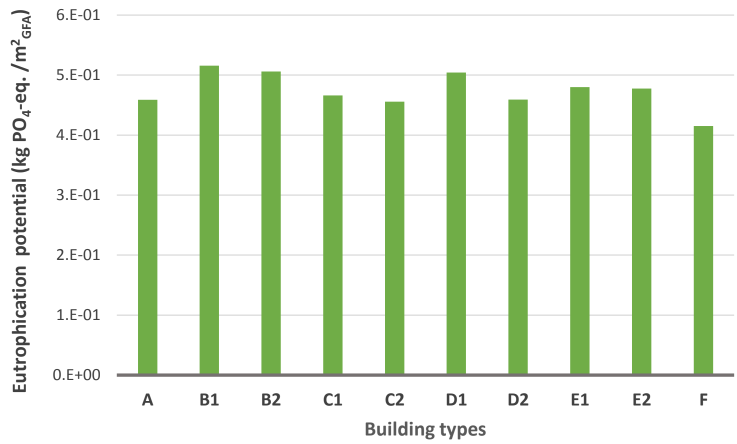


FIGURE M.4 Eutrophication potential: results by building.

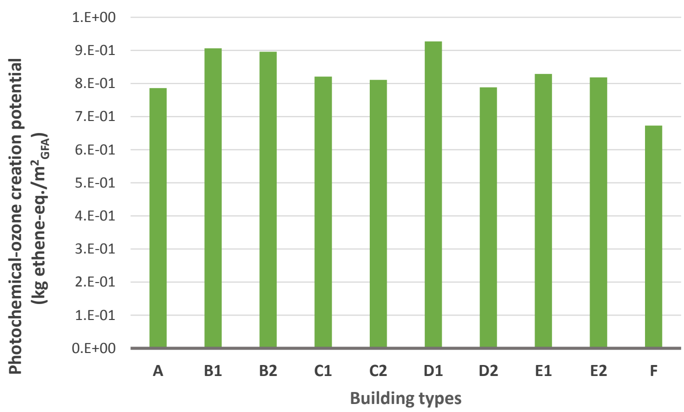


FIGURE M.5 Photochemical-ozone-creation potential: results by building

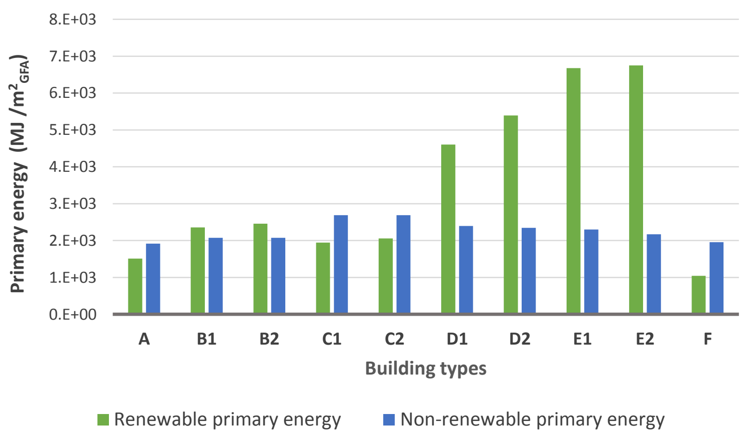


FIGURE M.6 Primary-energy consumption: results by building.

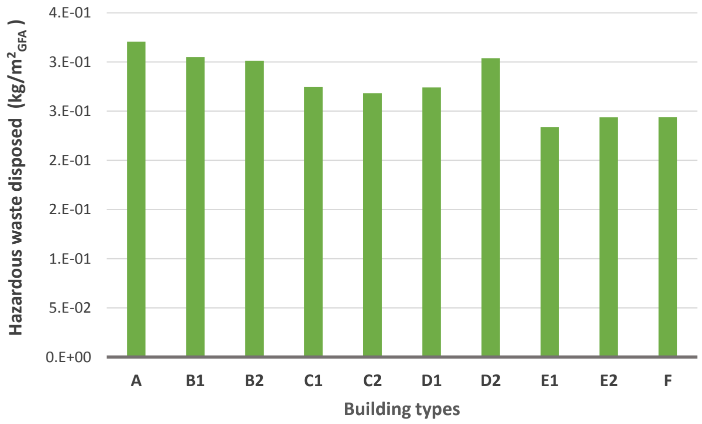


FIGURE M.7 Hazardous waste produced: results by building.

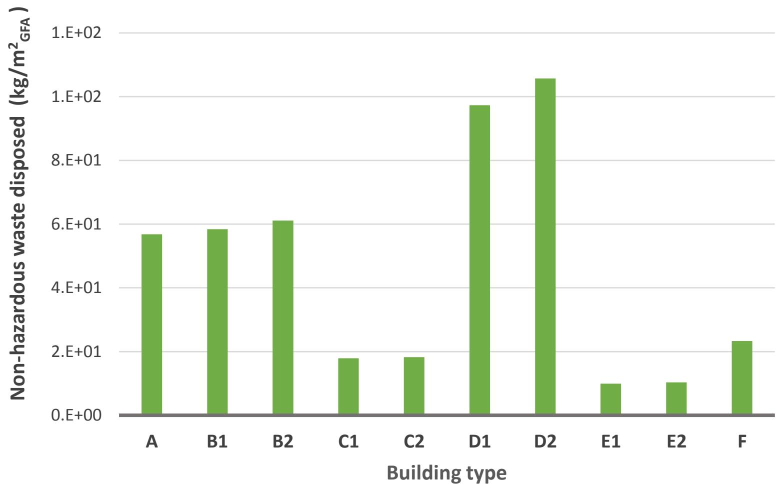


FIGURE M.8 Non-hazardous waste produced: results by building.

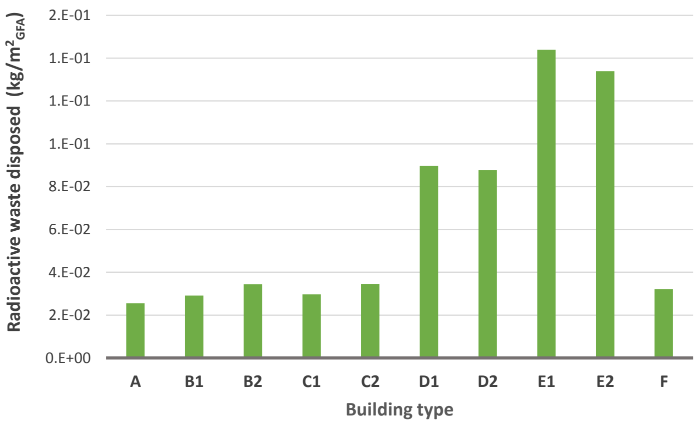


FIGURE M.9 Radioactive waste produced: results by building.

N LCA results: impact analysis (values normalised with respect to building F)

The following tables present the absolute results for environmental impacts, consumption of primary energy and production of waste, in tabulated form. The same results have been provided in graphic form in CHAPTER 5.

TABLE N.1 Primary-energy consumption normalised with respect to building F and measures of comparative uncertainty (GSD^2 and probability) for buildings A-E2.

Building	Renewable primary energy			Non-renewable primary energy		
	relative difference [a]	GSD^2	$P(PE_X<PE_F)$	relative difference [a]	GSD^2	$P(PE_X<PE_F)$
	(%)	(/)	(%)	(%)	(/)	(%)
A	45%	1.03	0%	-2%	1.03	90%
B1	126%	1.08	0%	6%	1.05	1%
B2	136%	1.08	0%	6%	1.06	1%
C1	87%	1.14	0%	37%	1.05	0%
C2	97%	1.13	0%	37%	1.06	0%
D1	342%	1.32	0%	22%	1.08	0%
D2	418%	1.29	0%	20%	1.09	0%
E1	541%	1.10	0%	18%	1.07	0%
E2	548%	1.10	0%	11%	1.08	0%
Abbreviations						
GSD	geometric standard deviation			PE	primary energy	
P	probability					
Notes						
a	difference relative to building F, calculated as: $\frac{PE_{building\ X} - PE_{building\ F}}{PE_{building\ F}}$					

TABLE N.2 Impact results normalised with respect to building F and measures of comparative uncertainty (GSD^2 and probability) for buildings A-E2.

Building	Global-warming potential (GWP), excl. sequestration			Global-warming potential (GWP), incl. sequestration [b]	Ozone-depletion potential (ODP)			Acidification potential (AP)			Eutrophication potential (EP)			Photochemical ozone-creation potential (POCP)		
	relative difference [a]	GSD^2	$P(I_X<I_F)$	relative difference [a]	relative difference [a]	GSD^2	$P(I_X<I_F)$	relative difference [a]	GSD^2	$P(I_X<I_F)$	relative difference [a]	GSD^2	$P(I_X<I_F)$	relative difference [a]	GSD^2	$P(I_X<I_F)$
	(%)	(/)	(%)	(%)	(%)	(/)	(%)	(%)	(/)	(%)	(%)	(/)	(%)	(%)	(/)	(%)
A	-10%	1.03	100%	-59%	-51%	1.09	100%	18%	1.04	0%	11%	1.03	0%	17%	1.04	0%
B1	-3%	1.04	95%	-125%	-41%	1.23	100%	36%	1.07	0%	24%	1.05	0%	35%	1.07	0%
B2	-8%	1.05	100%	-133%	-46%	1.25	100%	34%	1.07	0%	22%	1.05	0%	33%	1.07	0%
C1	8%	1.04	0%	-57%	213%	1.04	0%	19%	1.04	0%	12%	1.03	0%	22%	1.04	0%
C2	3%	1.06	16%	-66%	213%	1.04	0%	18%	1.04	0%	10%	1.03	0%	20%	1.04	0%
D1	69%	1.17	0%	-274%	45%	1.04	0%	33%	1.07	0%	21%	1.05	0%	38%	1.07	0%
D2	61%	1.19	0%	-393%	47%	1.03	0%	17%	1.04	0%	11%	1.03	0%	17%	1.04	0%
E1	26%	1.09	0%	-488%	-66%	1.25	100%	19%	1.04	0%	16%	1.03	0%	23%	1.04	0%
E2	14%	1.09	0%	-562%	-63%	1.23	100%	19%	1.04	0%	15%	1.03	0%	22%	1.04	0%

Abbreviations

GSD	geometric standard deviation	p	probability
I	impact		

Notes

a	difference relative to building F, calculated as : $\frac{Impact_{building\ X} - Impact_{building\ F}}{Impact_{building\ F}}$	b	value not available for this impact (since negative emissions are not accounted for by method employed for uncertainty estimation)

TABLE N.3 Waste production with respect to building F and measures of comparative uncertainty (GSD^2 and probability) for buildings A-E2.

Building	Hazardous waste			Non-hazardous waste			Radioactive waste		
	relative difference [a]	GSD^2	$P(W_X<W_F)$	relative difference [a]	GSD^2	$P(W_X<W_F)$	relative difference [a]	GSD^2	$P(W_X<W_F)$
	(%)	(/)	(%)	(%)	(/)	(%)	(%)	(/)	(%)
A	31%	1.02	0%	144%	1.04	0%	-21%	1.03	100%
B1	25%	1.03	0%	151%	1.04	0%	-9%	1.06	100%
B2	23%	1.03	0%	162%	1.04	0%	7%	1.09	7%
C1	13%	1.02	0%	-23%	1.02	100%	-8%	1.06	100%
C2	10%	1.02	0%	-22%	1.02	100%	8%	1.09	6%
D1	12%	1.05	0%	318%	1.32	0%	179%	1.23	0%
D2	25%	1.05	0%	354%	1.32	0%	172%	1.26	0%
E1	-4%	1.02	100%	-58%	1.11	100%	347%	1.20	0%
E2	0%	1.02	53%	-56%	1.12	100%	316%	1.22	0%
Abbreviations									
GSD	geometric standard deviation				W	waste			
P	probability								
Notes									
a	difference relative to building F, calculated as :				$\frac{Waste_{building\ X} - Waste_{building\ F}}{Waste_{building\ F}}$				

O LCA results: uncertainty analysis

O.1 Uncertainty analysis: absolute results

The following graphs show the estimated absolute uncertainties (for each building and each environmental impact) that have been discussed in CHAPTER 5. The graphs for buildings A and B1 have been shown in SECTION 5.6.5.

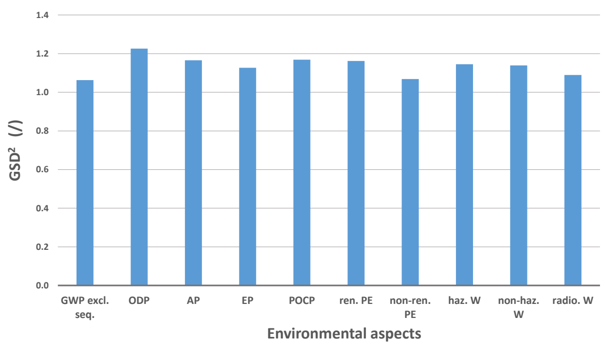


FIGURE O.1 Estimated absolute uncertainties relating to the impact results of building B2, expressed in terms of squared geometric standard deviations, GSD^2 (i.e., variance).

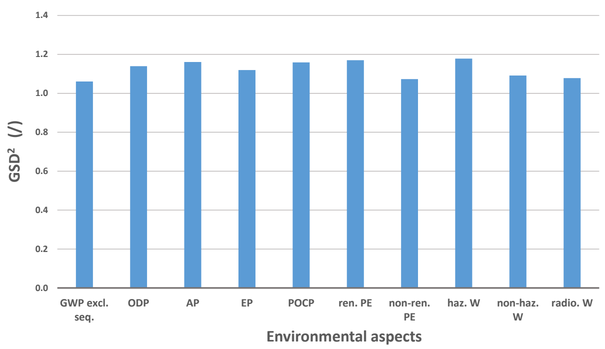


FIGURE O.2 Estimated absolute uncertainties relating to the impact results of building C1, expressed in terms of squared geometric standard deviations, GSD^2 (i.e., variance).

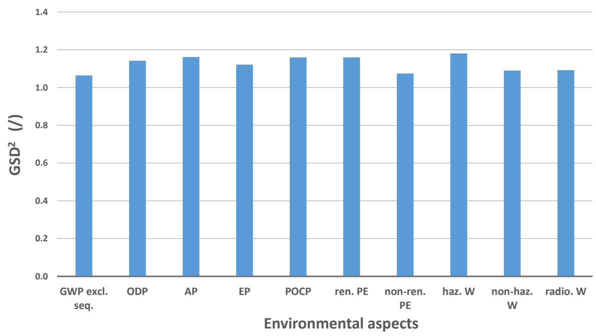


FIGURE O.3 Estimated absolute uncertainties relating to the impact results of building C2, expressed in terms of squared geometric standard deviations, GSD^2 (i.e., variance).

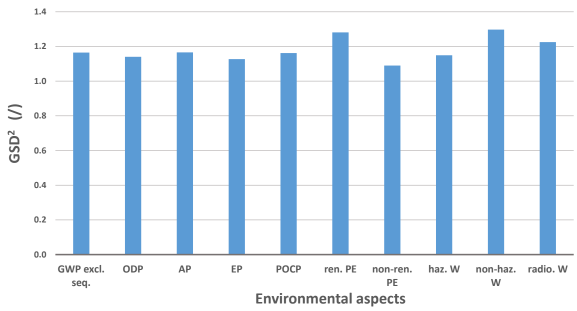


FIGURE O.4 Estimated absolute uncertainties relating to the impact results of building D1, expressed in terms of squared geometric standard deviations, GSD^2 (i.e., variance).

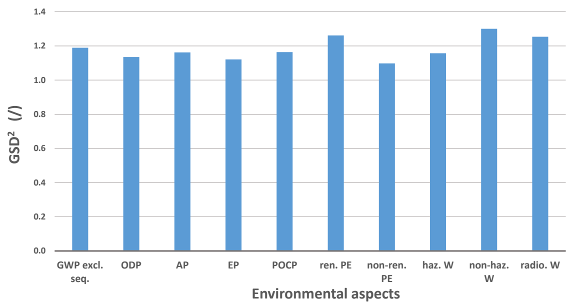


FIGURE O.5 Estimated absolute uncertainties relating to the impact results of building D2, expressed in terms of squared geometric standard deviations, GSD^2 (i.e., variance).

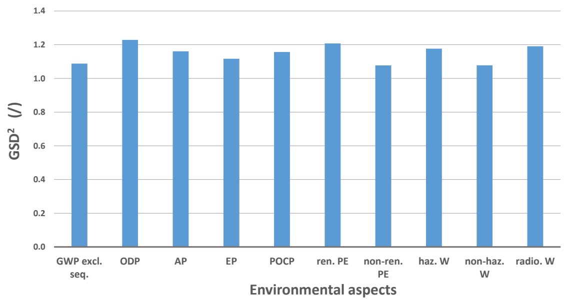


FIGURE O.6 Estimated absolute uncertainties relating to the impact results of building E1, expressed in terms of squared geometric standard deviations, GSD² (i.e., variance).

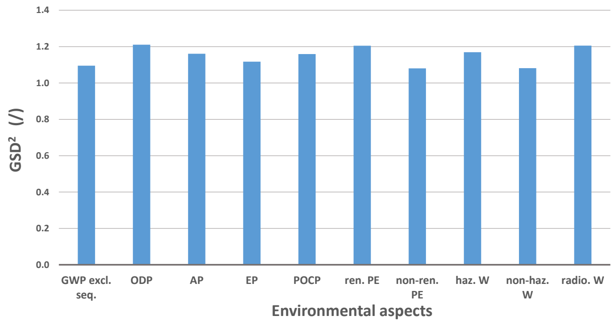


FIGURE O.7 Estimated absolute uncertainties relating to the impact results of building E2, expressed in terms of squared geometric standard deviations, GSD² (i.e., variance).

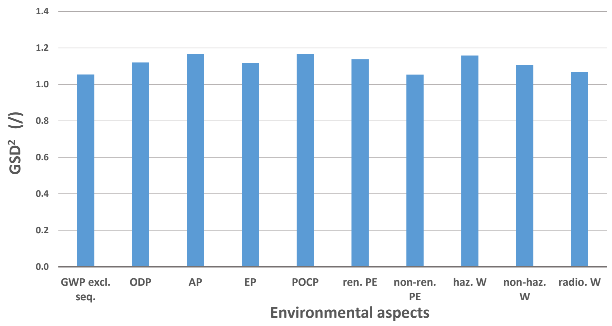


FIGURE O.8 Estimated absolute uncertainties relating to the impact results of building F, expressed in terms of squared geometric standard deviations, GSD² (i.e., variance).

O.2 Uncertainty analysis: comparative results

The following graphs accompany CHAPTER 5 and show the probability values and relative contributions to comparative uncertainty, for all buildings and for each environmental aspect. The graphs for three aspects ($GWP_{excl.seq.}$, hazardous and radioactive waste) have been shown in SECTION 5.6.5.2.

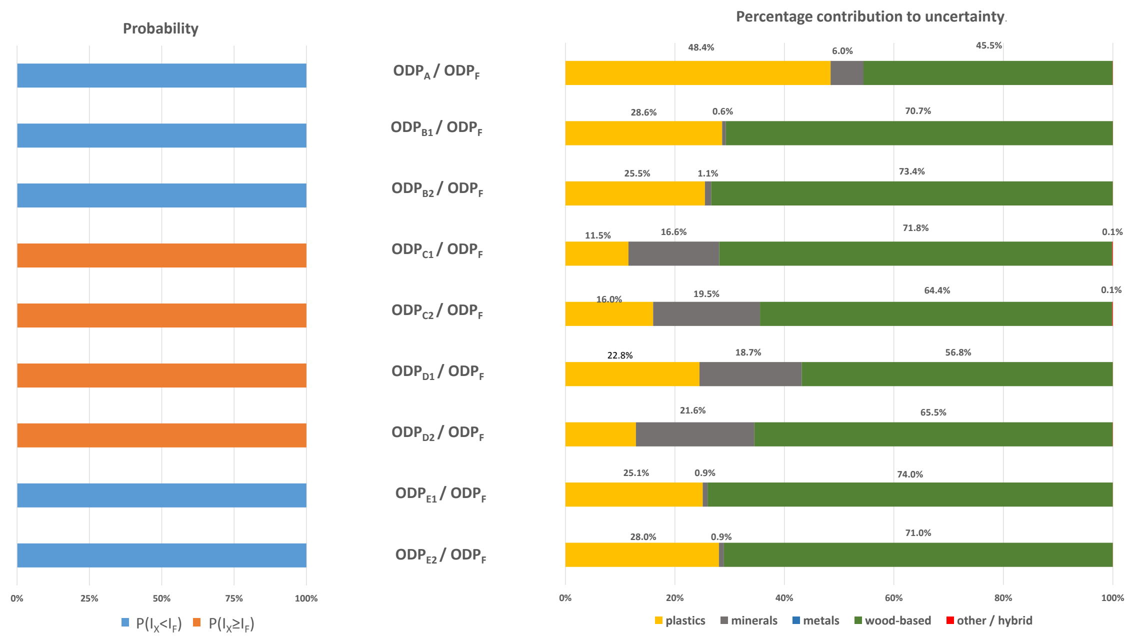


FIGURE O.9 Estimated uncertainties associated with the comparisons of timber buildings with reference building F, for ODP. Indication of probability (left) and relative contribution to uncertainty (right).

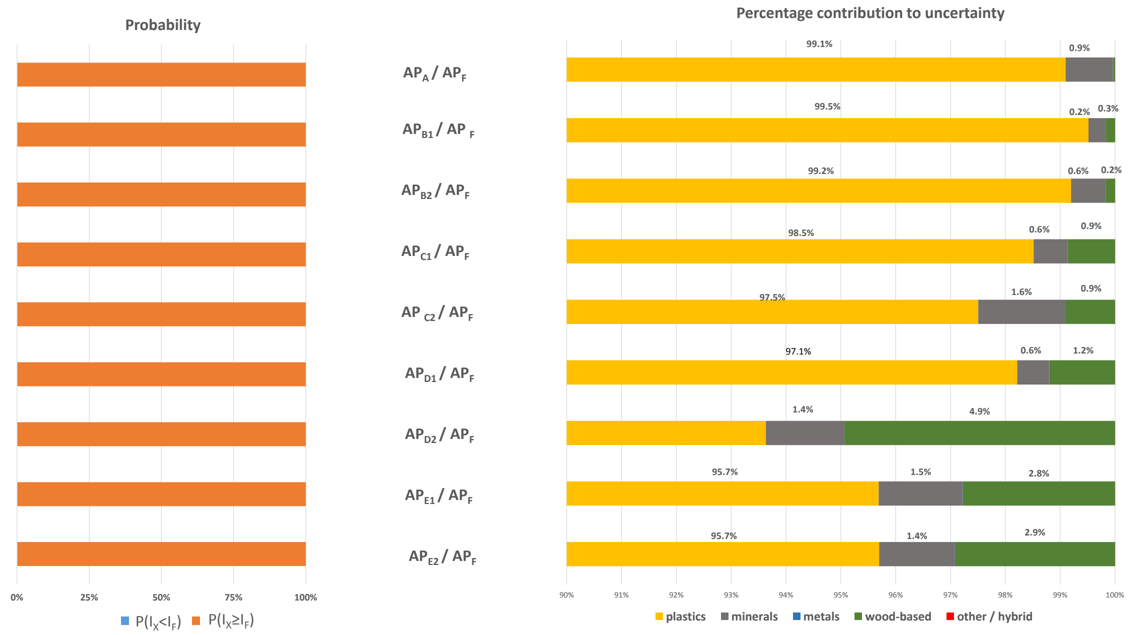


FIGURE O.10 Estimated uncertainties associated with the comparisons of timber buildings with reference building F, for AP. Indication of probability (left) and relative contribution to uncertainty (right).

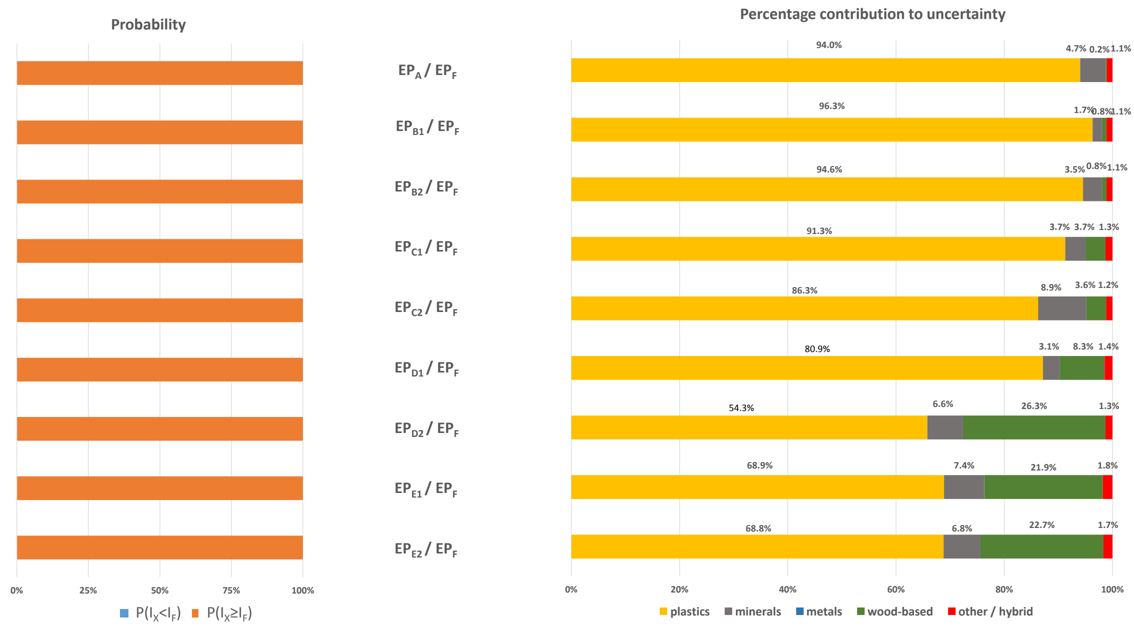


FIGURE O.11 Estimated uncertainties associated with the comparisons of timber buildings with reference building F, for EP. Indication of probability (left) and relative contribution to uncertainty (right).

FIGURE O.12 Estimated uncertainties associated with the comparisons of timber buildings with reference building F, for POCP. Indication of probability (left) and relative contribution to uncertainty (right).

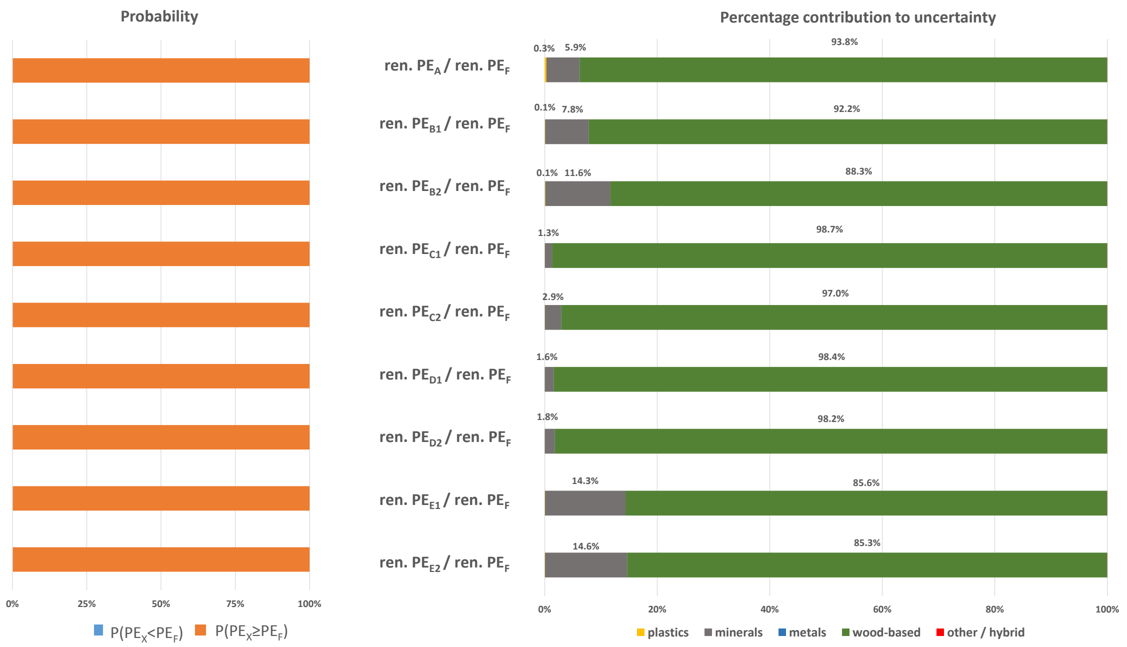


FIGURE O.13 Estimated uncertainties associated with the comparisons of timber buildings with reference building F, for renewable PE. Indication of probability (left) and relative contribution to uncertainty (right).

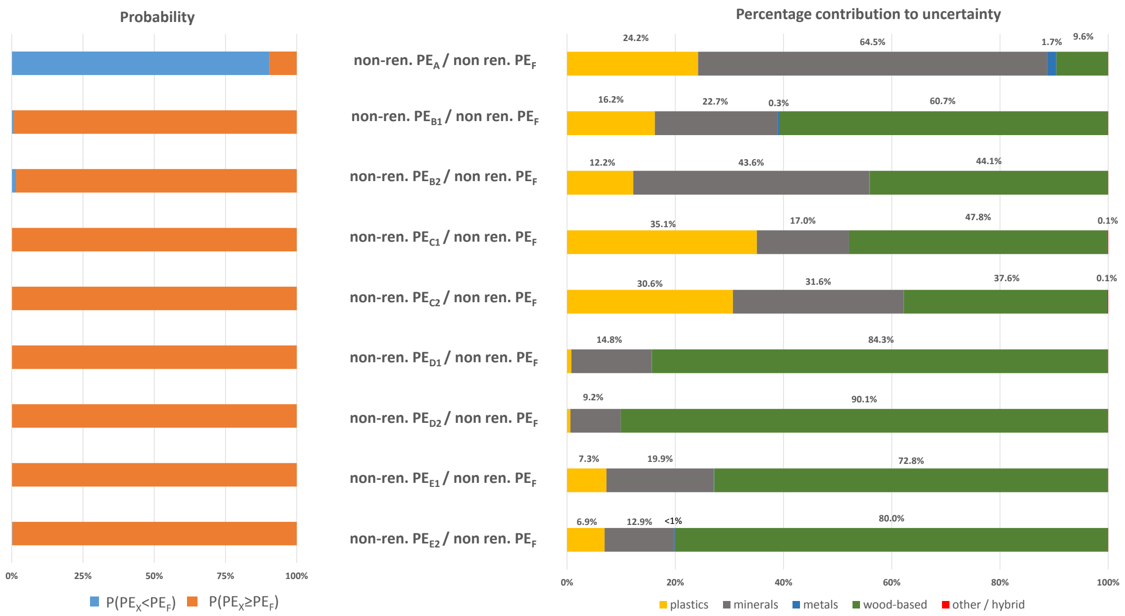


FIGURE O.14 Estimated uncertainties associated with the comparisons of timber buildings with reference building F, for non-renewable PE. Indication of probability (left) and relative contribution to uncertainty (right). See also FIGURE O.15.

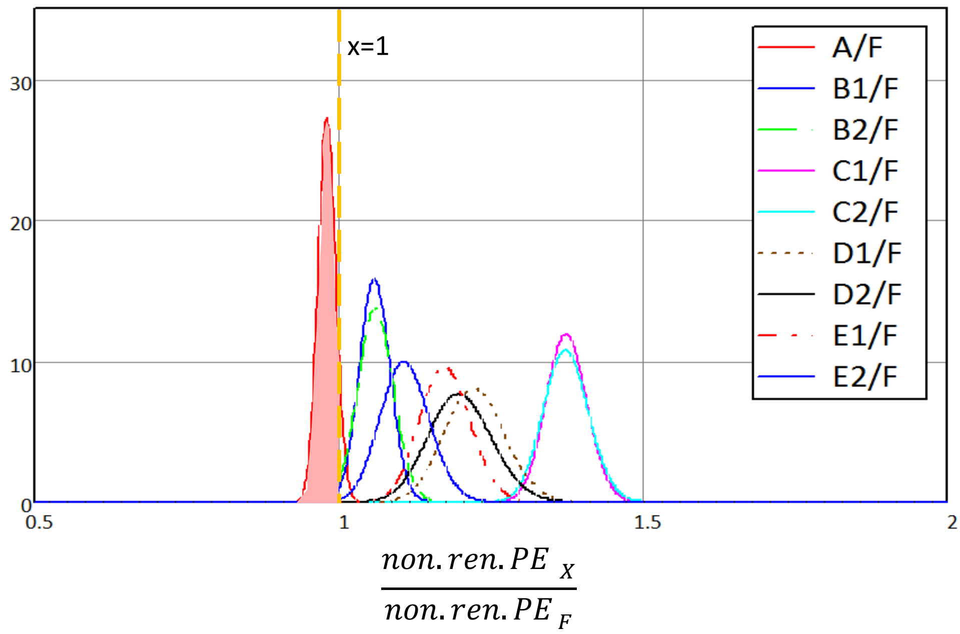


FIGURE O.15 Comparative uncertainty: non-renewable primary energy. Probability-density functions representing the ratio between the non-renewable PE of each timber building (X) and that of the masonry building (F). The area of the shaded region (bounded by the curve for house A and vertical line x=1) represents the probability that the non-ren. PE needed for A is less than that needed for F.

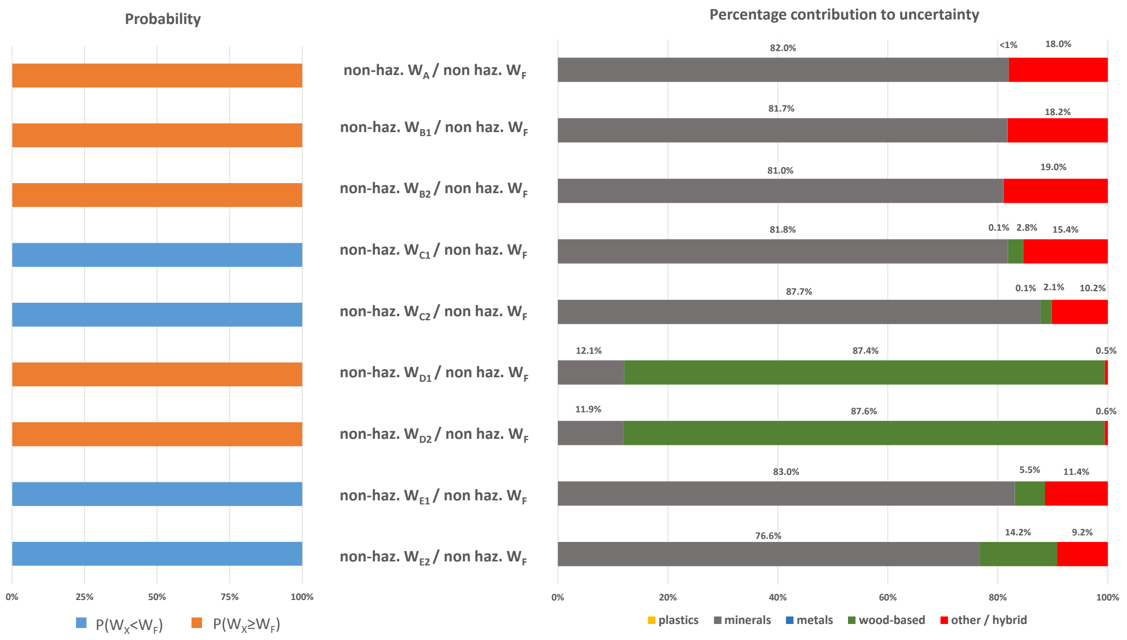


FIGURE O.16 Estimated uncertainties associated with the comparisons of timber buildings with reference building F, for non-hazardous waste. Indication of probability (left) and relative contribution to uncertainty (right).

P LCA results: sensitivity analysis (wastage scenarios 2 and 3)

TABLES P.1 to P.3 offer the results of wastage scenarios 1 (no wastage), 2 (low wastage) and 3 (high wastage) in tabulated form (these have been presented in graphic form in CHAPTER 5).

TABLE P.1 Wastage scenarios: waste production for all buildings (including differences relative to the baseline, i.e., scenario 1).

Waste categ.	Building	Scenario 1 (baseline, zero wastage)	Scenario 2 (low wastage)						Scenario 3 (high wastage)					
			lower bound		average		upper bound		lower bound		average		upper bound	
			waste value	relative diff. [a]	waste value	relative diff. [a]	waste value	relative diff. [a]	waste value	relative diff. [b]	waste value	relative diff. [b]	waste value	relative diff. [b]
		kg / m^2_{GFA}	kg / m^2_{GFA}	(%)	kg / m^2_{GFA}	(%)	kg / m^2_{GFA}	(%)	kg / m^2_{GFA}	(%)	kg / m^2_{GFA}	(%)	kg / m^2_{GFA}	(%)
hazardous	A	3.21E-01	3.33E-01	4%	3.37E-01	5%	3.42E-01	7%	3.36E-01	5%	3.42E-01	7%	3.48E-01	8%
	B1	3.05E-01	3.17E-01	4%	3.21E-01	5%	3.25E-01	6%	3.17E-01	4%	3.21E-01	5%	3.30E-01	8%
	B2	3.01E-01	3.13E-01	4%	3.17E-01	5%	3.21E-01	6%	3.13E-01	4%	3.17E-01	5%	3.21E-01	6%
	C1	2.75E-01	2.87E-01	5%	2.92E-01	6%	2.96E-01	8%	2.87E-01	5%	2.92E-01	6%	2.96E-01	8%
	C2	2.68E-01	2.80E-01	5%	2.85E-01	6%	2.89E-01	8%	2.80E-01	5%	2.85E-01	6%	2.89E-01	8%
	D1	2.74E-01	2.85E-01	4%	2.89E-01	5%	2.93E-01	7%	2.89E-01	5%	2.92E-01	7%	2.96E-01	8%
	D2	3.04E-01	3.15E-01	4%	3.19E-01	5%	3.23E-01	6%	3.19E-01	5%	3.24E-01	7%	3.28E-01	8%
	E1	2.34E-01	2.44E-01	5%	2.48E-01	6%	2.52E-01	8%	2.45E-01	5%	2.48E-01	6%	2.52E-01	8%
	E2	2.44E-01	2.55E-01	5%	2.59E-01	6%	2.63E-01	8%	2.55E-01	5%	2.59E-01	6%	2.63E-01	8%
	F	2.44E-01	2.56E-01	5%	2.60E-01	6%	2.64E-01	8%	2.56E-01	5%	2.60E-01	7%	2.64E-01	8%
non-hazardous	A	5.68E+01	5.77E+01	2%	5.80E+01	2%	5.84E+01	3%	6.04E+01	6%	6.17E+01	9%	6.30E+01	11%
	B1	5.84E+01	5.93E+01	2%	5.96E+01	2%	6.00E+01	3%	5.93E+01	2%	6.15E+01	5%	6.38E+01	9%
	B2	6.11E+01	6.21E+01	2%	6.24E+01	2%	6.28E+01	3%	6.21E+01	2%	6.25E+01	2%	6.28E+01	3%
	C1	1.79E+01	1.89E+01	6%	1.93E+01	8%	1.96E+01	10%	1.89E+01	6%	1.93E+01	8%	1.97E+01	10%
	C2	1.83E+01	1.93E+01	6%	1.97E+01	8%	2.00E+01	10%	1.93E+01	6%	1.97E+01	8%	2.01E+01	10%
	D1	9.73E+01	9.82E+01	1%	9.88E+01	2%	9.93E+01	2%	1.05E+02	8%	1.05E+02	8%	1.06E+02	9%
	D2	1.06E+02	1.07E+02	1%	1.07E+02	1%	1.08E+02	2%	1.13E+02	7%	1.14E+02	8%	1.15E+02	8%
	E1	9.89E+00	1.03E+01	5%	1.05E+01	6%	1.06E+01	7%	1.03E+01	5%	1.05E+01	6%	1.06E+01	7%
	E2	1.03E+01	1.08E+01	5%	1.10E+01	6%	1.11E+01	7%	1.08E+01	5%	1.10E+01	6%	1.12E+01	8%
	F	2.33E+01	2.47E+01	6%	2.51E+01	8%	2.56E+01	10%	2.47E+01	6%	2.52E+01	8%	2.57E+01	10%
radioactive	A	2.55E-02	2.67E-02	5%	2.70E-02	6%	2.73E-02	7%	2.69E-02	5%	2.73E-02	7%	2.76E-02	8%
	B1	2.92E-02	3.04E-02	4%	3.07E-02	5%	3.10E-02	6%	3.05E-02	5%	3.08E-02	6%	3.12E-02	7%
	B2	3.44E-02	3.62E-02	5%	3.66E-02	6%	3.70E-02	8%	3.62E-02	5%	3.66E-02	6%	3.70E-02	8%
	C1	2.97E-02	3.17E-02	7%	3.20E-02	8%	3.24E-02	9%	3.17E-02	7%	3.20E-02	8%	3.24E-02	9%
	C2	3.46E-02	3.70E-02	7%	3.74E-02	8%	3.78E-02	9%	3.70E-02	7%	3.74E-02	8%	3.78E-02	9%
	D1	8.98E-02	9.17E-02	2%	9.23E-02	3%	9.29E-02	4%	9.63E-02	7%	9.70E-02	8%	9.77E-02	9%
	D2	8.77E-02	8.90E-02	1%	8.96E-02	2%	9.01E-02	3%	9.38E-02	7%	9.44E-02	8%	9.51E-02	8%
	E1	1.44E-01	1.53E-01	6%	1.54E-01	7%	1.55E-01	8%	1.62E-01	13%	1.68E-01	18%	1.74E-01	21%
	E2	1.34E-01	1.42E-01	6%	1.43E-01	7%	1.45E-01	8%	1.51E-01	13%	1.57E-01	17%	1.63E-01	22%
	F	3.22E-02	3.36E-02	4%	3.39E-02	5%	3.43E-02	6%	3.37E-02	5%	3.41E-02	6%	3.44E-02	7%

Notes

a difference relative to scenario 1 (baseline), calculated as : $\frac{Waste_{scen2} - Waste_{scen1}}{Waste_{scen1}}$

b difference relative to scenario 1 (baseline), calculated as : $\frac{Waste_{scen3} - Waste_{scen1}}{Waste_{scen1}}$

TABLE P.2 Wastage scenarios: impact results for all buildings (including differences relative to scenario 1).

Impact	Building	Scenario 1 (baseline, zero wastage)	Scenario 2 (low wastage)						Scenario 3 (high wastage)					
			lower bound		average		upper bound		lower bound		average		upper bound	
			impact value	relative diff. [a]	impact value	relative diff. [a]	impact value	relative diff. [a]	impact value	relatiive diff. [b]	impact value	relatiive diff. [b]	impact value	relatiive diff. [b]
GWP (excl. seq.)		kg CO_2-eq. / m^2_{GFA}	kg CO_2-eq. / m^2_{GFA}	(%)	kg CO_2-eq. / m^2_{GFA}	(%)	kg CO_2-eq. / m^2_{GFA}	(%)	kg CO_2-eq. / m^2_{GFA}	(%)	kg CO_2-eq. / m^2_{GFA}	(%)	kg CO_2-eq. / m^2_{GFA}	(%)
	A	1.54E+02	1.61E+02	4%	1.63E+02	6%	1.64E+02	7%	1.63E+02	6%	1.65E+02	7%	1.68E+02	9%
	B1	1.66E+02	1.73E+02	4%	1.74E+02	5%	1.76E+02	6%	1.73E+02	4%	1.75E+02	6%	1.79E+02	8%
	B2	1.58E+02	1.66E+02	5%	1.67E+02	6%	1.69E+02	7%	1.66E+02	5%	1.68E+02	6%	1.69E+02	7%
	C1	1.84E+02	1.97E+02	7%	1.99E+02	8%	2.02E+02	9%	1.97E+02	7%	1.99E+02	8%	2.02E+02	9%
	C2	1.76E+02	1.89E+02	7%	1.91E+02	8%	1.93E+02	10%	1.89E+02	7%	1.91E+02	8%	1.93E+02	10%
	D1	2.89E+02	2.98E+02	3%	3.01E+02	4%	3.03E+02	5%	3.11E+02	8%	3.14E+02	9%	3.18E+02	10%
	D2	2.76E+02	2.83E+02	2%	2.85E+02	3%	2.87E+02	4%	2.96E+02	7%	2.99E+02	9%	3.03E+02	10%
	E1	2.16E+02	2.26E+02	5%	2.28E+02	6%	2.30E+02	7%	2.30E+02	7%	2.34E+02	9%	2.39E+02	11%
	E2	1.95E+02	2.03E+02	4%	2.05E+02	5%	2.07E+02	6%	2.08E+02	7%	2.12E+02	9%	2.16E+02	11%
	F	1.71E+02	1.80E+02	5%	1.83E+02	7%	1.85E+02	8%	1.81E+02	6%	1.84E+02	7%	1.87E+02	9%
GWP (incl. seq.)		kg CO_2-eq. / m^2_{GFA}	kg CO_2-eq. / m^2_{GFA}	(%)	kg CO_2-eq. / m^2_{GFA}	(%)	kg CO_2-eq. / m^2_{GFA}	(%)	kg CO_2-eq. / m^2_{GFA}	(%)	kg CO_2-eq. / m^2_{GFA}	(%)	kg CO_2-eq. / m^2_{GFA}	(%)
	A	3.85E+01	4.35E+01	13%	4.47E+01	16%	4.58E+01	19%	4.28E+01	11%	4.37E+01	14%	4.46E+01	16%
	B1	-2.36E+01	-2.08E+01	12%	-2.05E+01	13%	-2.01E+01	15%	-2.20E+01	7%	-2.12E+01	10%	-2.04E+01	13%
	B2	-3.08E+01	-2.99E+01	3%	-3.02E+01	2%	-3.06E+01	1%	-2.99E+01	3%	-3.02E+01	2%	-3.05E+01	1%
	C1	4.10E+01	4.03E+01	-2%	4.05E+01	-1%	4.06E+01	-1%	4.03E+01	-2%	4.05E+01	-1%	4.07E+01	-1%
	C2	3.17E+01	3.09E+01	-2%	3.09E+01	-2%	3.09E+01	-2%	3.09E+01	-2%	3.10E+01	-2%	3.10E+01	-2%
	D1	-1.64E+02	-1.57E+02	4%	-1.57E+02	4%	-1.57E+02	4%	-1.78E+02	-8%	-1.77E+02	-8%	-1.76E+02	-8%
	D2	-2.76E+02	-2.73E+02	1%	-2.74E+02	1%	-2.74E+02	1%	-2.96E+02	-7%	-2.97E+02	-8%	-2.98E+02	-8%
	E1	-3.66E+02	-3.69E+02	-1%	-3.71E+02	-1%	-3.73E+02	-2%	-3.75E+02	-2%	-3.79E+02	-4%	-3.83E+02	-5%
	E2	-4.36E+02	-4.42E+02	-1%	-4.44E+02	-2%	-4.46E+02	-2%	-4.47E+02	-3%	-4.52E+02	-4%	-4.57E+02	-5%
	F	9.44E+01	1.02E+02	8%	1.04E+02	10%	1.06E+02	12%	1.01E+02	7%	1.02E+02	8%	1.03E+02	10%
ODP		kg CFC 11-eq. / m^2_{GFA}	kg CFC 11-eq. / m^2_{GFA}	(%)	kg CFC 11-eq. / m^2_{GFA}		kg CFC 11-eq. / m^2_{GFA}	(%)	kg CFC 11-eq. / m^2_{GFA}	(%)	kg CFC 11-eq. / m^2_{GFA}	(%)	kg CFC 11-eq. / m^2_{GFA}	(%)
	A	1.10E-05	1.18E-05	7%	1.20E-05	9%	1.22E-05	11%	1.20E-05	9%	1.23E-05	12%	1.27E-05	15%
	B1	1.31E-05	1.34E-05	2%	1.35E-05	3%	1.36E-05	4%	1.34E-05	2%	1.35E-05	3%	1.37E-05	5%
	B2	1.20E-05	1.23E-05	2%	1.23E-05	3%	1.24E-05	4%	1.23E-05	2%	1.23E-05	3%	1.24E-05	4%
	C1	7.01E-05	7.61E-05	8%	7.65E-05	9%	7.69E-05	10%	7.61E-05	8%	7.65E-05	9%	7.69E-05	10%
	C2	7.01E-05	7.63E-05	9%	7.67E-05	9%	7.71E-05	10%	7.63E-05	9%	7.67E-05	9%	7.71E-05	10%
	D1	3.24E-05	3.43E-05	6%	3.46E-05	7%	3.49E-05	8%	3.68E-05	14%	3.82E-05	18%	3.96E-05	22%
	D2	3.29E-05	3.48E-05	6%	3.50E-05	7%	3.53E-05	7%	3.73E-05	13%	3.87E-05	18%	4.01E-05	22%
	E1	7.59E-06	7.81E-06	3%	7.86E-06	4%	7.92E-06	4%	7.83E-06	3%	7.90E-06	4%	7.97E-06	5%
	E2	8.24E-06	8.51E-06	3%	8.59E-06	4%	8.66E-06	5%	8.53E-06	3%	8.62E-06	5%	8.71E-06	6%
	F	2.24E-05	2.51E-05	12%	2.60E-05	16%	2.69E-05	20%	2.51E-05	12%	2.60E-05	16%	2.69E-05	20%
AP		kg SO_2-eq. / m^2_{GFA}	kg SO_2-eq. / m^2_{GFA}	(%)	kg SO_2-eq. / m^2_{GFA}	(%)	kg SO_2-eq. / m^2_{GFA}	(%)	kg SO_2-eq. / m^2_{GFA}	(%)	kg SO_2-eq. / m^2_{GFA}	(%)	kg SO_2-eq. / m^2_{GFA}	(%)
	A	5.22E+00	5.55E+00	6%	5.62E+00	8%	5.70E+00	9%	5.55E+00	6%	5.63E+00	8%	5.71E+00	9%
	B1	6.00E+00	6.32E+00	5%	6.39E+00	6%	6.47E+00	8%	6.32E+00	5%	6.39E+00	6%	6.48E+00	8%
	B2	5.93E+00	6.25E+00	5%	6.32E+00	7%	6.40E+00	8%	6.25E+00	5%	6.32E+00	7%	6.40E+00	8%
	C1	5.27E+00	5.61E+00	7%	5.69E+00	8%	5.77E+00	9%	5.61E+00	7%	5.69E+00	8%	5.77E+00	9%
	C2	5.19E+00	5.53E+00	7%	5.61E+00	8%	5.69E+00	10%	5.53E+00	7%	5.61E+00	8%	5.69E+00	10%
	D1	5.89E+00	6.26E+00	6%	6.35E+00	8%	6.43E+00	9%	6.28E+00	7%	6.37E+00	8%	6.45E+00	10%
	D2	5.18E+00	5.50E+00	6%	5.57E+00	8%	5.65E+00	9%	5.52E+00	7%	5.59E+00	8%	5.67E+00	10%
	E1	5.27E+00	5.60E+00	6%	5.67E+00	8%	5.75E+00	9%	5.61E+00	6%	5.69E+00	8%	5.77E+00	10%
	E2	5.25E+00	5.58E+00	6%	5.66E+00	8%	5.73E+00	9%	5.59E+00	6%	5.67E+00	8%	5.75E+00	10%
	F	4.42E+00	4.70E+00	6%	4.76E+00	8%	4.83E+00	9%	4.70E+00	6%	4.76E+00	8%	4.83E+00	9%
EP		kg PO_4-eq. / m^2_{GFA}	kg PO_4-eq. / m^2_{GFA}	(%)	kg PO_4-eq. / m^2_{GFA}	(%)	kg PO_4-eq. / m^2_{GFA}	(%)	kg PO_4-eq. / m^2_{GFA}	(%)	kg PO_4-eq. / m^2_{GFA}	(%)	kg PO_4-eq. / m^2_{GFA}	(%)
	A	4.59E-01	4.85E-01	6%	4.91E-01	7%	4.97E-01	8%	4.86E-01	6%	4.93E-01	7%	4.99E-01	9%
	B1	5.16E-01	5.41E-01	5%	5.47E-01	6%	5.53E-01	7%	5.41E-01	5%	5.47E-01	6%	5.55E-01	8%
	B2	5.06E-01	5.31E-01	5%	5.37E-01	6%	5.43E-01	7%	5.31E-01	5%	5.37E-01	6%	5.43E-01	7%
	C1	4.66E-01	4.94E-01	6%	5.01E-01	7%	5.07E-01	9%	4.94E-01	6%	5.01E-01	7%	5.07E-01	9%
	C2	4.56E-01	4.84E-01	6%	4.90E-01	8%	4.96E-01	9%	4.84E-01	6%	4.90E-01	8%	4.96E-01	9%
	D1	5.04E-01	5.33E-01	6%	5.40E-01	7%	5.47E-01	8%	5.35E-01	6%	5.43E-01	8%	5.50E-01	9%
	D2	4.59E-01	4.84E-01	5%	4.90E-01	7%	4.96E-01	8%	4.87E-01	6%	4.94E-01	8%	5.01E-01	9%
	E1	4.80E-01	5.07E-01	6%	5.13E-01	7%	5.20E-01	8%	5.09E-01	6%	5.17E-01	8%	5.24E-01	9%
	E2	4.78E-01	5.05E-01	6%	5.11E-01	7%	5.17E-01	8%	5.07E-01	6%	5.14E-01	8%	5.21E-01	9%
	F	4.15E-01	4.39E-01	6%	4.44E-01	7%	4.50E-01	8%	4.39E-01	6%	4.45E-01	7%	4.51E-01	9%
POCP		kg ethene-eq. / m^2_{GFA}	kg ethene-eq. / m^2_{GFA}	(%)	kg ethene-eq. / m^2_{GFA}	(%)	kg ethene-eq. / m^2_{GFA}	(%)	kg ethene-eq. / m^2_{GFA}	(%)	kg ethene-eq. / m^2_{GFA}	(%)	kg ethene-eq. / m^2_{GFA}	(%)
	A	7.86E-01	8.36E-01	6%	8.48E-01	8%	8.59E-01	9%	8.37E-01	6%	8.49E-01	8%	8.61E-01	9%
	B1	9.06E-01	9.54E-01	5%	9.65E-01	7%	9.77E-01	8%	9.54E-01	5%	9.66E-01	7%	9.78E-01	8%
	B2	8.96E-01	9.43E-01	5%	9.55E-01	7%	9.66E-01	8%	9.43E-01	5%	9.55E-01	7%	9.66E-01	8%
	C1	8.21E-01	8.75E-01	7%	8.87E-01	8%	8.99E-01	9%	8.75E-01	7%	8.87E-01	8%	8.99E-01	9%
	C2	8.11E-01	8.65E-01	7%	8.76E-01	8%	8.88E-01	10%	8.65E-01	7%	8.76E-01	8%	8.88E-01	10%
	D1	9.27E-01	9.86E-01	6%	9.99E-01	8%	1.01E+00	9%	9.89E-01	7%	1.00E+00	8%	1.02E+00	10%
	D2	7.89E-01	8.38E-01	6%	8.49E-01	8%	8.61E-01	9%	8.41E-01	7%	8.54E-01	8%	8.66E-01	10%
	E1	8.29E-01	8.80E-01	6%	8.92E-01	8%	9.03E-01	9%	8.82E-01	6%	8.95E-01	8%	9.07E-01	9%
	E2	8.19E-01	8.69E-01	6%	8.81E-01	8%	8.93E-01	9%	8.71E-01	6%	8.84E-01	8%	8.96E-01	9%
	F	6.73E-01	7.17E-01	7%	7.27E-01	8%	7.37E-01	10%	7.17E-01	7%	7.27E-01	8%	7.38E-01	10%

Notes

a difference relative to scenario 1 (baseline), calculated as : $\frac{Impact_{scen2} - Impact_{scen1}}{Impact_{scen1}}$

b difference relative to scenario 1 (baseline), calculated as : $\frac{Impact_{scen3} - Impact_{scen1}}{Impact_{scen1}}$

TABLE P.3 Wastage scenarios: primary-energy consumption for all buildings (including differences relative to scenario 1).

Energy cat.	Energy subcat.	Building	Scenario 1 (baseline, zero wastage)	Scenario 2 (low wastage)						Scenario 3 (high wastage)					
				lower bound		average		upper bound		lower bound		average		upper bound	
				primary energy value	relative diff. [a]	primary energy value	relative diff. [a]	primary energy value	relative diff. [a]	primary energy value	relative diff. [b]	primary energy value	relative diff. [b]	primary energy value	relative diff. [b]
			MJ / m^2_{GFA}	MJ / m^2_{GFA}	(%)	MJ / m^2_{GFA}	(%)	MJ / m^2_{GFA}	(%)	MJ / m^2_{GFA}	(%)	MJ / m^2_{GFA}	(%)	MJ / m^2_{GFA}	(%)
renewable primary energy	energy carrier	A	2.95E+02	3.06E+02	4%	3.09E+02	5%	3.12E+02	6%	3.10E+02	5%	3.14E+02	7%	3.19E+02	8%
		B1	3.73E+02	3.85E+02	3%	3.89E+02	4%	3.92E+02	5%	3.87E+02	4%	3.91E+02	5%	3.97E+02	6%
		B2	4.70E+02	4.90E+02	4%	4.96E+02	5%	5.01E+02	7%	4.90E+02	4%	4.96E+02	5%	5.01E+02	7%
		C1	3.32E+02	3.58E+02	8%	3.63E+02	9%	3.68E+02	11%	3.58E+02	8%	3.63E+02	9%	3.68E+02	11%
		C2	4.27E+02	4.60E+02	8%	4.66E+02	9%	4.72E+02	10%	4.60E+02	8%	4.66E+02	9%	4.72E+02	10%
		D1	3.11E+02	3.28E+02	5%	3.31E+02	7%	3.35E+02	8%	3.34E+02	8%	3.39E+02	9%	3.44E+02	11%
		D2	2.98E+02	3.09E+02	4%	3.12E+02	5%	3.15E+02	6%	3.21E+02	8%	3.27E+02	10%	3.33E+02	12%
		E1	1.26E+03	1.31E+03	4%	1.32E+03	5%	1.33E+03	5%	1.34E+03	6%	1.37E+03	8%	1.40E+03	10%
		E2	1.20E+03	1.25E+03	4%	1.26E+03	5%	1.27E+03	5%	1.28E+03	6%	1.31E+03	8%	1.33E+03	11%
		F	2.44E+02	2.57E+02	5%	2.61E+02	7%	2.64E+02	8%	2.59E+02	6%	2.64E+02	8%	2.68E+02	10%
	raw materials	A	9.90E+02	1.01E+03	2%	1.01E+03	2%	1.01E+03	2%	1.01E+03	2%	1.01E+03	2%	1.01E+03	2%
		B1	1.78E+03	1.81E+03	2%	1.81E+03	2%	1.81E+03	2%	1.81E+03	2%	1.81E+03	2%	1.81E+03	2%
		B2	1.79E+03	1.83E+03	2%	1.83E+03	2%	1.83E+03	2%	1.83E+03	2%	1.83E+03	2%	1.83E+03	2%
		C1	1.38E+03	1.51E+03	10%	1.51E+03	10%	1.51E+03	10%	1.51E+03	10%	1.51E+03	10%	1.51E+03	10%
		C2	1.40E+03	1.53E+03	10%	1.53E+03	10%	1.53E+03	10%	1.53E+03	10%	1.53E+03	10%	1.53E+03	10%
		D1	4.11E+03	4.14E+03	1%	4.14E+03	1%	4.14E+03	1%	4.14E+03	1%	4.14E+03	1%	4.14E+03	1%
		D2	4.88E+03	4.91E+03	1%	4.91E+03	1%	4.91E+03	1%	4.91E+03	1%	4.91E+03	1%	4.91E+03	1%
		E1	5.22E+03	5.33E+03	2%	5.33E+03	2%	5.33E+03	2%	5.33E+03	2%	5.33E+03	2%	5.33E+03	2%
		E2	5.36E+03	5.48E+03	2%	5.48E+03	2%	5.48E+03	2%	5.48E+03	2%	5.48E+03	2%	5.48E+03	2%
		F	6.16E+02	6.32E+02	3%	6.32E+02	3%	6.32E+02	3%	6.32E+02	3%	6.32E+02	3%	6.32E+02	3%
	total	A	1.51E+03	1.55E+03	2%	1.56E+03	3%	1.57E+03	4%	1.57E+03	4%	1.59E+03	5%	1.61E+03	7%
		B1	2.36E+03	2.41E+03	2%	2.42E+03	3%	2.44E+03	4%	2.42E+03	3%	2.44E+03	3%	2.46E+03	4%
		B2	2.46E+03	2.53E+03	3%	2.55E+03	4%	2.57E+03	5%	2.53E+03	3%	2.55E+03	4%	2.57E+03	5%
		C1	1.94E+03	2.11E+03	9%	2.14E+03	10%	2.16E+03	11%	2.11E+03	9%	2.14E+03	10%	2.16E+03	11%
		C2	2.06E+03	2.23E+03	9%	2.26E+03	10%	2.28E+03	11%	2.23E+03	9%	2.26E+03	10%	2.28E+03	11%
		D1	4.60E+03	4.65E+03	1%	4.68E+03	2%	4.71E+03	2%	4.96E+03	8%	4.99E+03	8%	5.02E+03	9%
		D2	5.39E+03	5.44E+03	1%	5.47E+03	1%	5.50E+03	2%	5.78E+03	7%	5.83E+03	8%	5.87E+03	9%
		E1	6.68E+03	6.85E+03	3%	6.89E+03	3%	6.94E+03	4%	6.95E+03	4%	7.05E+03	6%	7.14E+03	7%
		E2	6.75E+03	6.93E+03	3%	6.98E+03	3%	7.03E+03	4%	7.03E+03	4%	7.13E+03	6%	7.23E+03	7%
		F	1.04E+03	1.08E+03	3%	1.09E+03	4%	1.10E+03	6%	1.09E+03	5%	1.11E+03	6%	1.12E+03	8%
non-renewable primary energy	energy carrier	A	1.75E+03	1.83E+03	5%	1.85E+03	6%	1.88E+03	7%	1.86E+03	6%	1.89E+03	8%	1.92E+03	10%
		B1	1.90E+03	1.97E+03	4%	1.99E+03	5%	2.01E+03	6%	1.98E+03	4%	2.00E+03	5%	2.05E+03	8%
		B2	1.89E+03	1.97E+03	4%	1.99E+03	5%	2.02E+03	7%	1.97E+03	4%	1.99E+03	5%	2.02E+03	7%
		C1	2.24E+03	2.40E+03	7%	2.42E+03	8%	2.45E+03	9%	2.40E+03	7%	2.42E+03	8%	2.45E+03	9%
		C2	2.22E+03	2.39E+03	7%	2.41E+03	9%	2.44E+03	10%	2.39E+03	7%	2.41E+03	9%	2.44E+03	10%
		D1	1.47E+03	1.56E+03	6%	1.58E+03	8%	1.60E+03	9%	1.58E+03	8%	1.61E+03	10%	1.64E+03	12%
		D2	1.34E+03	1.42E+03	6%	1.44E+03	7%	1.46E+03	8%	1.45E+03	8%	1.48E+03	10%	1.51E+03	13%
		E1	2.08E+03	2.19E+03	5%	2.21E+03	6%	2.24E+03	8%	2.23E+03	7%	2.28E+03	10%	2.32E+03	12%
		E2	1.96E+03	2.06E+03	5%	2.08E+03	6%	2.11E+03	8%	2.11E+03	8%	2.15E+03	10%	2.20E+03	12%
		F	1.74E+03	1.85E+03	6%	1.88E+03	8%	1.91E+03	10%	1.85E+03	6%	1.88E+03	8%	1.92E+03	10%
	raw materials	A	1.18E+02	1.25E+02	6%	1.27E+02	8%	1.29E+02	9%	1.27E+02	8%	1.30E+02	10%	1.33E+02	12%
		B1	1.28E+02	1.33E+02	4%	1.34E+02	5%	1.35E+02	5%	1.34E+02	5%	1.36E+02	6%	1.38E+02	7%
		B2	1.38E+02	1.45E+02	5%	1.46E+02	6%	1.48E+02	7%	1.45E+02	5%	1.46E+02	6%	1.48E+02	7%
		C1	4.02E+02	4.35E+02	8%	4.38E+02	9%	4.41E+02	10%	4.35E+02	8%	4.38E+02	9%	4.41E+02	10%
		C2	4.17E+02	4.52E+02	8%	4.55E+02	9%	4.58E+02	10%	4.52E+02	8%	4.55E+02	9%	4.58E+02	10%
		D1	7.51E+02	7.67E+02	2%	7.71E+02	3%	7.76E+02	3%	8.17E+02	9%	8.28E+02	10%	8.38E+02	12%
		D2	8.13E+02	8.29E+02	2%	8.34E+02	3%	8.39E+02	3%	8.81E+02	8%	8.92E+02	10%	9.03E+02	11%
		E1	1.75E+02	1.84E+02	5%	1.85E+02	6%	1.87E+02	7%	1.89E+02	8%	1.94E+02	11%	1.98E+02	13%
		E2	1.66E+02	1.74E+02	5%	1.75E+02	6%	1.77E+02	7%	1.80E+02	8%	1.84E+02	11%	1.88E+02	14%
		F	1.67E+02	1.83E+02	9%	1.87E+02	12%	1.92E+02	15%	1.84E+02	10%	1.89E+02	14%	1.95E+02	17%
	total	A	1.92E+03	2.01E+03	5%	2.03E+03	6%	2.06E+03	7%	2.03E+03	6%	2.07E+03	8%	2.11E+03	10%
		B1	2.07E+03	2.15E+03	4%	2.18E+03	5%	2.20E+03	6%	2.16E+03	4%	2.18E+03	5%	2.23E+03	8%
		B2	2.08E+03	2.17E+03	4%	2.19E+03	5%	2.21E+03	7%	2.17E+03	4%	2.19E+03	6%	2.22E+03	7%
		C1	2.69E+03	2.88E+03	7%	2.91E+03	8%	2.94E+03	9%	2.88E+03	7%	2.91E+03	8%	2.94E+03	9%
		C2	2.69E+03	2.89E+03	7%	2.92E+03	9%	2.95E+03	10%	2.89E+03	7%	2.92E+03	9%	2.95E+03	10%
		D1	2.39E+03	2.51E+03	5%	2.53E+03	6%	2.56E+03	7%	2.59E+03	8%	2.63E+03	10%	2.67E+03	12%
		D2	2.35E+03	2.44E+03	4%	2.47E+03	5%	2.49E+03	6%	2.53E+03	8%	2.58E+03	10%	2.62E+03	12%
		E1	2.30E+03	2.42E+03	5%	2.45E+03	6%	2.47E+03	8%	2.47E+03	7%	2.52E+03	10%	2.57E+03	12%
		E2	2.17E+03	2.28E+03	5%	2.31E+03	6%	2.33E+03	8%	2.33E+03	8%	2.39E+03	10%	2.44E+03	12%
		F	1.96E+03	2.08E+03	6%	2.12E+03	8%	2.15E+03	10%	2.09E+03	7%	2.12E+03	9%	2.16E+03	11%
grand total		A	3.43E+03	3.55E+03	4%	3.59E+03	5%	3.63E+03	6%	3.61E+03	5%	3.66E+03	7%	3.72E+03	8%
		B1	4.43E+03	4.56E+03	3%	4.60E+03	4%	4.64E+03	5%	4.57E+03	3%	4.62E+03	4%	4.69E+03	6%
		B2	4.54E+03	4.70E+03	4%	4.74E+03	5%	4.79E+03	6%	4.70E+03	4%	4.74E+03	5%	4.79E+03	6%
		C1	4.63E+03	4.99E+03	8%	5.05E+03	9%	5.10E+03	10%	4.99E+03	8%	5.05E+03	9%	5.10E+03	10%
		C2	4.74E+03	5.12E+03	8%	5.18E+03	9%	5.23E+03	10%	5.12E+03	8%	5.18E+03	9%	5.23E+03	10%
		D1	7.00E+03	7.16E+03	2%	7.21E+03	3%	7.26E+03	4%	7.54E+03	8%	7.62E+03	9%	7.70E+03	10%
		D2	7.74E+03	7.88E+03	2%	7.94E+03	3%	7.99E+03	3%	8.31E+03	7%	8.40E+03	9%	8.50E+03	10%
		E1	8.98E+03	9.27E+03	3%	9.34E+03	4%	9.41E+03	5%	9.42E+03	5%	9.57E+03	7%	9.72E+03	8%
		E2	8.92E+03	9.21E+03	3%	9.29E+03	4%	9.36E+03	5%	9.37E+03	5%	9.52E+03	7%	9.67E+03	8%
		F	3.00E+03	3.16E+03	5%	3.20E+03	7%	3.25E+03	9%	3.18E+03	6%	3.23E+03	8%	3.29E+03	10%

Notes

a	difference relative to scenario 1 (baseline), calculated as :	$\frac{PE_{scen2} - PE_{scen1}}{PE_{scen1}}$
b	difference relative to scenario 1 (baseline), calculated as :	$\frac{PE_{scen3} - PE_{scen1}}{PE_{scen1}}$

Q Thermal study: mathematical definitions and formulas

This appendix accompanies CHAPTER 6 and provides information on the formulas that have been used to carry out the statistical analysis of the experimental data and the regression analyses.

TABLE Q.1 Formulas for statistical and regression analysis relating to thermal tests. Notes are located at the end of the table.

Parameter type	Parameter designation	Symbol	Unit of measurement: for time lag	Unit of measurement: for decrem. factor	Comments	References
measure of location	arithmetic mean	$\bar{x}$	h	/	calculated as: $\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$	Madsen, 2011; Mills and Chang, 2004 (p.26)
measure of dispersion	standard deviation of the arithmetic mean	σ	h	/	calculated as: $\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}[(x_i - \bar{x})^2]}$	Madsen, 2011; Mills and Chang, 2004 (p.26)
	relative standard deviation of the arithmetic mean (or coefficient of variation)	σ_{rel}	%	%	calculated as: $\sigma_{rel} = \frac{\sigma}{\bar{x}} \cdot 100\%$	Madsen, 201; Faber, 2012 (p.25)
	statistical uncertainty of the mean (shown by each error bar in graphs)	U	h	/	calculated as: $U = \pm\sigma$ Error bars show upper and lower limits of the 68.3% confidence interval for the mean: $interval = \bar{x} \pm \mathrm{U} = \bar{x} \pm \sigma$	Madsen, 2011 (p.51, 144); Mills and Chang, 2004 (p.25); Faber, 2012 (p.65)
regression parameters	observed value of y	y_i	h	/		
	predicted or fitted values of y	$\hat{y}_i$	h	/	Calculated by method of least squares	
	calculated (least-square) estimate of the slope β. Regression coefficient.	$\hat{\beta}$	h/MJ	/	$\hat{\beta} = \frac{N\sum_{i=1}^{N} x_i y_i - (\sum_{i=1}^{N} x_i)(\sum_{i=1}^{N} y_i)}{N\sum_{i=1}^{N} x_i^2 - (\sum_{i=1}^{N} x_i)^2}$	Dekking et al., 2005 (p.331); Underwood, 1997 (p.422)
	estimate of the y-intercept θ	$\hat{\theta}$	h	/	$\hat{\theta} = \bar{y} - \hat{\beta}\bar{x}$	Dekking *et al.*, 2005 (p.331); Kaltenbach, 2012 (p.80)
	error (or residual)	err_i	h	/	$err_i = y_i - \hat{y}_i$	Montgomery, 2013 (p.453)
	error (or residual) sum of squares	SS_{err}	h^2	/	$SS_{err} = \sum_{i=1}^{N} err_i^2 = \sum_{i=1}^{N}(y_i - \hat{y}_i)^2$	Montgomery, 2013 (p.453); Kaltenbach, 2012 (p.87)

Parameter type	Parameter designation	Symbol	Unit of measurement		Comments	References
			for time lag	for decrem. factor		
regression parameters	regression sum of squares (or model sum of squares)	SS_{reg}	h^2	/	in terms of $\hat{y}_i$ and y_i: $SS_{reg} = \sum_{i=1}^{N} y_i^2 - \frac{1}{N}\left(\sum_{i=1}^{N} y_i\right)^2 - \sum_{i=1}^{N}(y_i - \hat{y}_i)^2$	Montgomery, 2013 (p.463)
					or, in terms of $\hat{y}_i$ and $\bar{y}$: $SS_{reg} = \sum_{i=1}^{N}(\hat{y}_i - \bar{y})^2$	Kaltenbach, 2012 (p.86)
	total sum of squares	SS_{tot}	h^2	/	$SS_{tot} = SS_{reg} + SS_{err} = \sum_{i=1}^{N} y_i^2 - \frac{1}{N}(\sum_{i=1}^{N} y_i)^2$	Montgomery, 2013 (p.463)
					or, in terms of y_i and $\bar{y}$: $SS_{tot} = \sum_{i=1}^{N}(y_i - \bar{y})^2$	Kaltenbach, 2012 (p.86)
	unbiased estimator of variance of the error σ^2	$\hat{\sigma}^2$	h^2	/	$\hat{\sigma}^2 = \frac{SS_{err}}{N-2} = \frac{1}{N-2}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2$	Montgomery, 2013 (p.453); Kaltenbach, 2012 (p.80)
	estimator of standard error of y	$\hat{\sigma}$	h	/	$\hat{\sigma} = \sqrt{\frac{1}{N-2}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}$	Faber, 2012 (p.101 & p.103)
	variance of x	$\hat{\sigma}_X^2$	MJ^2	/	$\hat{\sigma}_X^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2$	Kaltenbach, 2012 (p.81)
	variance of estimator $\hat{\beta}$	$\widehat{\mathrm{Var}}(\hat{\beta})$	h^2/MJ^2	/	$\widehat{\mathrm{Var}}(\hat{\beta}) = \frac{\hat{\sigma}^2}{\hat{\sigma}_X^2 N}$	Kaltenbach, 2012 (p.81)
	standard error of estimator $\hat{\beta}$	$\widehat{\mathrm{se}}(\hat{\beta})$	h/MJ	/	$\widehat{\mathrm{se}}(\hat{\beta}) = \sqrt{\widehat{\mathrm{Var}}(\hat{\beta})} = \frac{\hat{\sigma}}{\hat{\sigma}_X\sqrt{N}}$	Kaltenbach, 2012 (p.81)
	variance of estimator $\hat{\theta}$	$\widehat{\mathrm{Var}}(\hat{\theta})$	h^2	/	$\widehat{\mathrm{Var}}(\hat{\theta}) = \frac{\hat{\sigma}^2}{\hat{\sigma}_X^2 N^2}\sum_{i=1}^{N} x_i^2$	Kaltenbach, 2012 (p.81)

Parameter type	**Parameter designation**	**Symbol**	**Unit of measurement** for time lag	**Unit of measurement** for decrem. factor	**Comments**	**References**
	standard error of estimator $\hat{\theta}$	$\widehat{\mathrm{se}}(\hat{\theta})$	h	/	$\widehat{\mathrm{se}}(\hat{\theta}) = \sqrt{\widehat{\mathrm{Var}}(\hat{\theta})} = \frac{\hat{\sigma}}{\hat{\sigma}_X \sqrt{N}} \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2}$	Kaltenbach, 2012 (p.81)
	correlation coefficient	r	/	/	$r = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2 \sum_{i=1}^{N}(y_i - \bar{y})^2}}$	Dekking et al., 2005 (p.142)
regression parameters	coefficient of determination	r^2	/	/	$r^2 = \frac{SS_{reg}}{SS_{tot}} = 1 - \frac{SS_{err}}{SS_{tot}}$	Montgome-ry, 2013 (p.464)
	adjusted coefficient of determination	r^2_{adj}	/	/	$r_{adj}^2 = 1 - \frac{SS_{err}/(N-2)}{SS_{tot}/(N-1)} = 1 - \left(\frac{N-1}{N-2}\right)(1 - r^2)$	Montgome-ry, 2013 (p.464)

Symbols *(other than those defined above)*

N	sample size (*i.e.*,, number of observations)
x_i	value of x measured during the i^{th} observation

R Thermal study: summaries of regression analyses

This appendix contains a statistical summary of each regression analysis carried out for the thermal tests (CHAPTER 6).

TABLE R.1 Summary of regression analysis, regarding the correlation between solar energy and time lag, for wall B1.

Regression summary: statistics		
parameter designation	**symbol**	**value**
observations	N	65
correlation coefficient	r	0.832
coefficient of determination	r^2	0.958
adjusted coefficient of determination	r^2_{adj}	0.957
standard error of y	$\hat{\sigma}$	1.55

Regression equation
$$TL_{B1} = 0.95 \cdot E_{AM}$$

Parameter description			
designation	**symbol**	**value**	**standard error**
slope	$\hat{\beta}$	0.954	0.0259
y-intercept	$\hat{\theta}$	0	*n.a.*

Analysis of variance					
source of variation	**degrees of freedom**	**sum of squares**	**mean square**	**F-ratio**	**probability**
regression	1	3247	3247	1427	0.19
residual	63	143	2		
total variation	64	3391			

TABLE R.2 Summary of regression analysis, regarding the correlation between solar energy and decrement factor, for wall B1.

Regression summary: statistics		
parameter designation	**symbol**	**value**
observations	N	65
correlation coefficient	r	-0.362
coefficient of determination	r^2	0.131
adjusted coefficient of determination	r^2_{adj}	0.117
standard error of y	$\hat{\sigma}$	0.09

Regression equation

$$DF_{B1} = -0.012 \cdot E_{AM} + 0.37$$

Parameter description			
designation	**symbol**	**value**	**standard error**
slope	$\hat{\beta}$	-0.012	0.0040
y-intercept	$\hat{\theta}$	0.3687	0.0308

Analysis of variance					
source of variation	**degrees of freedom**	**sum of squares**	**mean square**	**F-ratio**	**probability**
regression	1	0	0	10	>>0.95
residual	63	0	0		
total variation	64	1			

TABLE R.3 Summary of regression analysis, regarding the correlation between solar energy and time lag, for wall D1.

Regression summary: statistics		
parameter designation	**symbol**	**value**
observations	N	65
correlation coefficient	r	0.853
coefficient of determination	r^2	0.962
adjusted coefficient of determination	r^2_{adj}	0.961
standard error of y	$\hat{\sigma}$	1.34

Regression equation

$$TL_{D1} = 0.87 \cdot E_{AM}$$

Parameter description			
designation	**symbol**	**value**	**standard error**
slope	$\hat{\beta}$	0.870	0.0225
y-intercept	$\hat{\theta}$	0	n.a.

Analysis of variance					
source of variation	**degrees of freedom**	**sum of squares**	**mean square**	**F-ratio**	**probability**
regression	1	2706	2706	1578	0.51
residual	63	108	2		
total variation	64	2814			

TABLE R.4 Summary of regression analysis, regarding the correlation between solar energy and decrement factor, for wall D1.

Regression summary: statistics		
parameter designation	**symbol**	**value**
observations	N	65
correlation coefficient	r	-0.541
coefficient of determination	r^2	0.292
adjusted coefficient of determination	r^2_{adj}	0.281
standard error of y	$\hat{\sigma}$	0.05

Regression equation
$DF_{D1} = -0.012 \cdot E_{AM} + 0.27$

Parameter description			
designation	**symbol**	**value**	**standard error**
slope	$\hat{\beta}$	-0.012	0.0025
y-intercept	$\hat{\theta}$	0.270	0.0025

Analysis of variance					
source of variation	**degrees of freedom**	**sum of squares**	**mean square**	**F-ratio**	**probability**
regression	1	0	0	26	>>0.95
residual	63	0	0		
total variation	64	0			

TABLE R.5 Summary of regression analysis, regarding the correlation between solar energy and time lag, for wall F.

Regression summary: statistics		
parameter designation	**symbol**	**value**
observations	N	65
correlation coefficient	r	0.875
coefficient of determination	r^2	0.950
adjusted coefficient of determination	r^2_{adj}	0.949
standard error of y	$\hat{\sigma}$	1.42

Regression equation
$TL_F = 0.80 \cdot E_{AM}$

Parameter description			
designation	**symbol**	**value**	**standard error**
slope	$\hat{\beta}$	0.798	0.0237
y-intercept	$\hat{\theta}$	0	n.a.

Analysis of variance					
source of variation	**degrees of freedom**	**sum of squares**	**mean square**	**F-ratio**	**probability**
regression	1	2275	2275	1191	0.20
residual	63	120	2		
total variation	64	2396			

TABLE R.6 Summary of regression analysis, regarding the correlation between solar energy and decrement factor, for wall F.

Regression summary: statistics		
parameter designation	**symbol**	**value**
observations	N	65
correlation coefficient	r	-0.441
coefficient of determination	r^2	0.195
adjusted coefficient of determination	r^2_{adj}	0.182
standard error of y	$\hat{\sigma}$	0.05

Regression equation
$DF_F = -0.008 \cdot E_{AM} + 0.19$

Parameter description			
designation	**symbol**	**value**	**standard error**
slope	$\hat{\beta}$	-0.008	0.0022
y-intercept	$\hat{\theta}$	0.187	0.0169

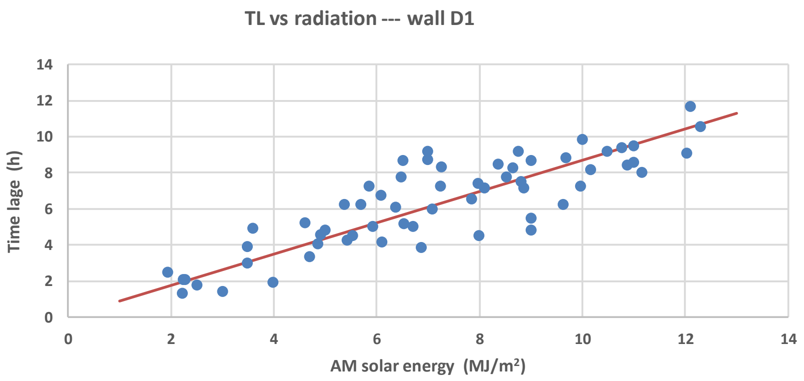
Analysis of variance					
source of variation	**degrees of freedom**	**sum of squares**	**mean square**	**F-ratio**	**probability**
regression	1	0	0	15	>>0.95
residual	63	0	0		
total variation	64	0			

S Thermal study: plots of regression analyses

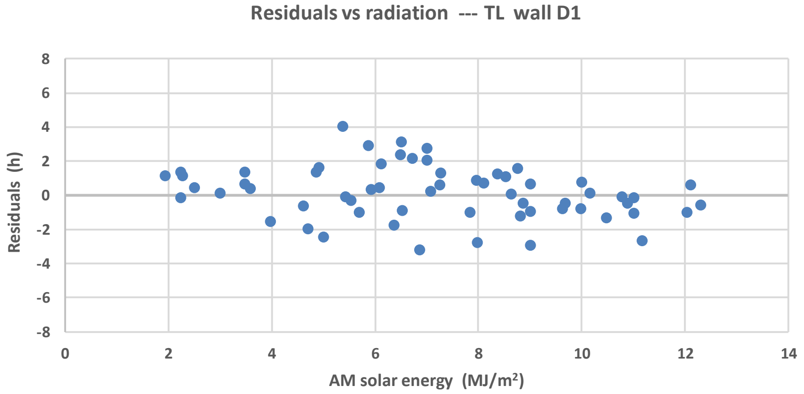
This appendix contains the regression-analysis plots regarding the functional relationships between TL and solar energy or DF and solar energy. These plots refer to walls D1 and F (the equivalent plots for wall B1 have been presented in SECTION 6.4.2).

Each figure contains three parts:

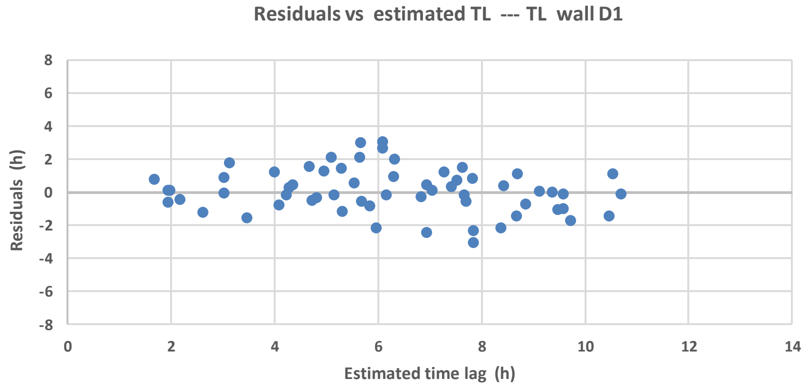
a) TL (or DF) values *versus* solar energy received in the morning, with regression line in red;
b) TL (or DF) residuals *versus* solar energy received in the morning;
c) TL (or DF) residuals *versus* estimated TL (or DF) values.



(a)

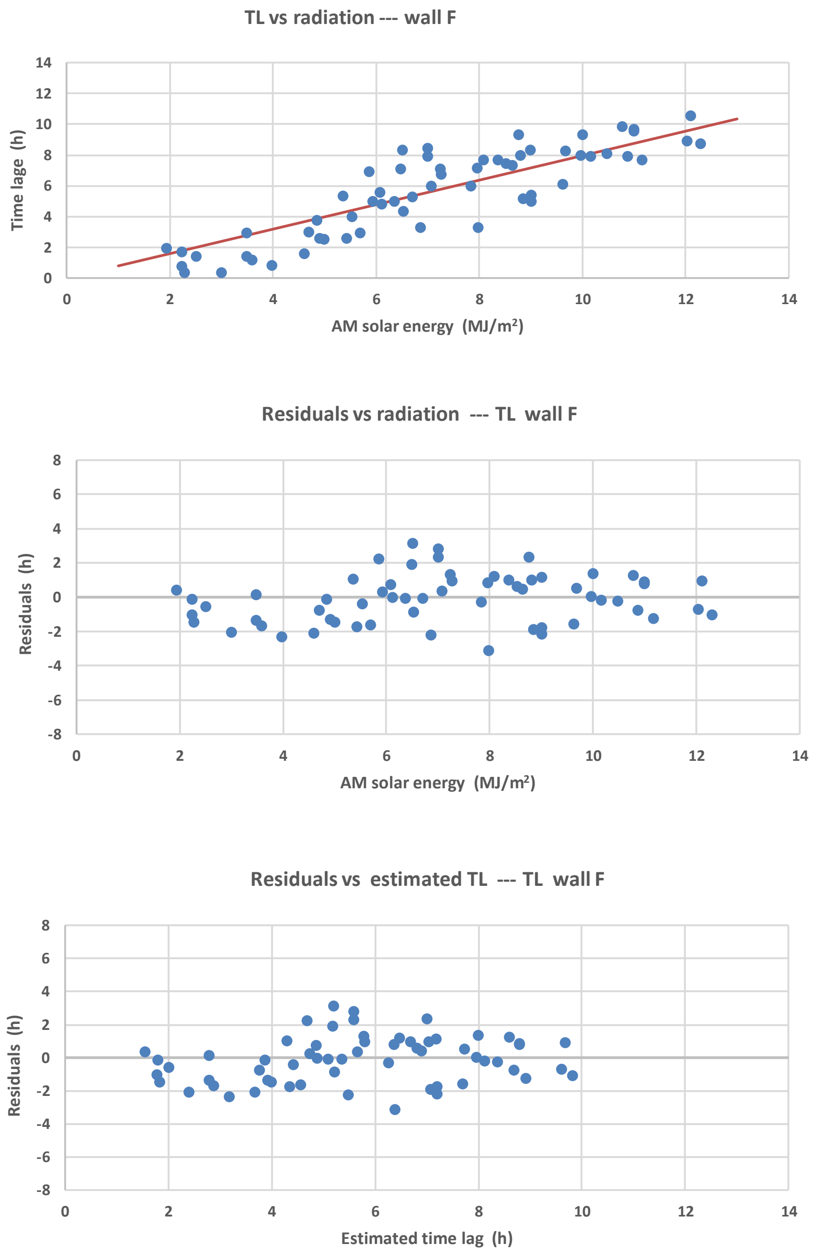


(b)



(c)

FIGURE S.1 Regression-analysis plots for the time lag of wall D1: TL versus solar energy and regression line (a), residuals versus solar energy (b) and residuals versus estimated TL (c).



(a)

(b)

(c)

FIGURE S.2 Regression-analysis plots for the time lag of wall F: TL versus solar energy and regression line (a), residuals versus solar energy (b) and residuals versus estimated TL (c).

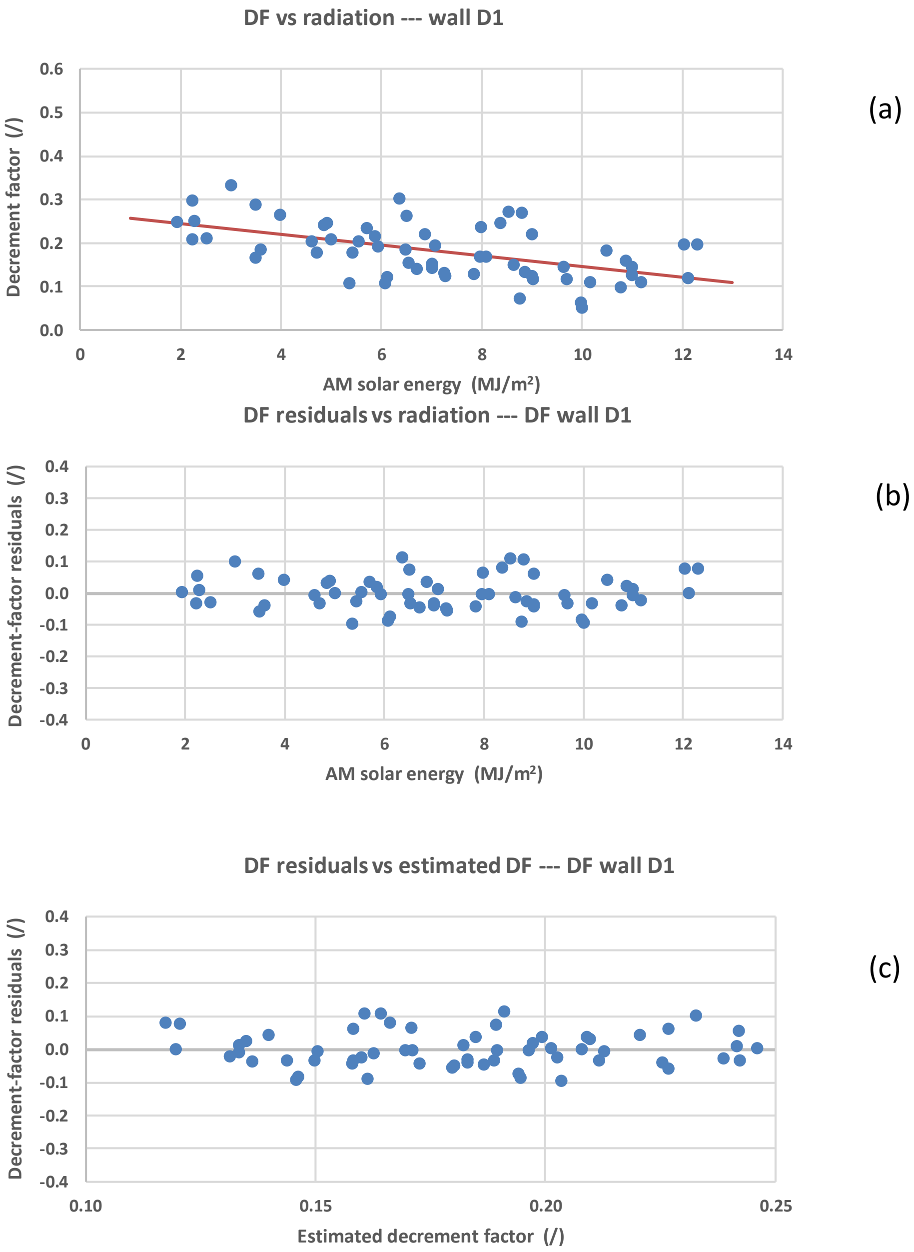
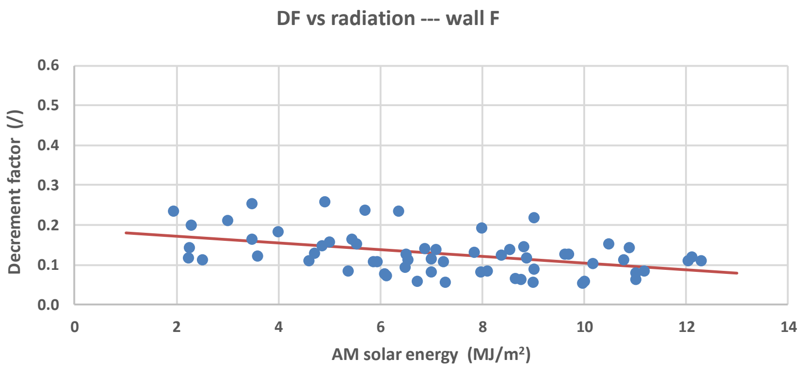
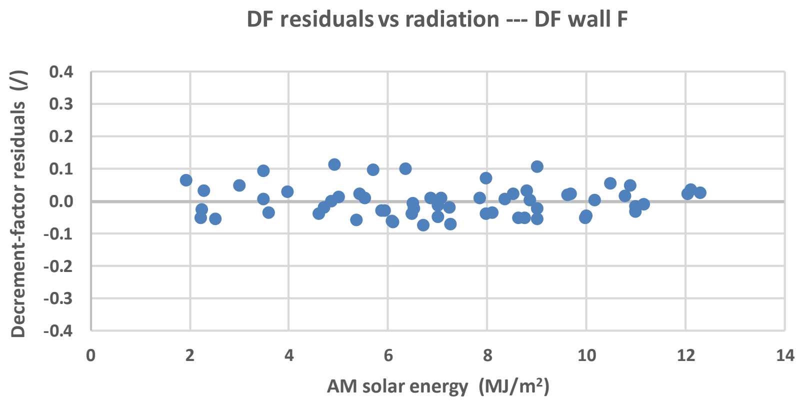


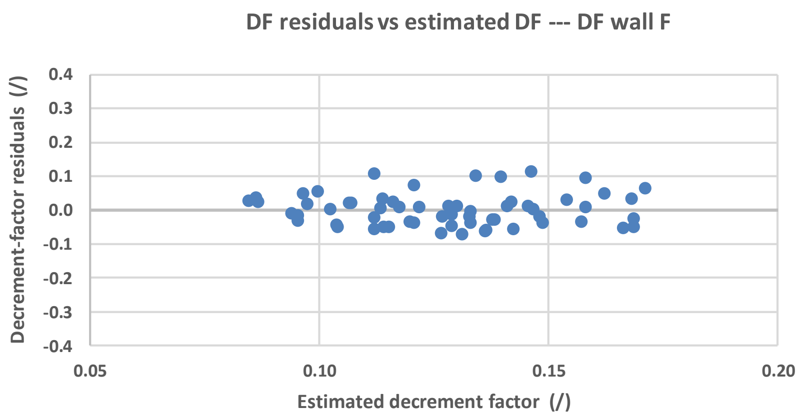
FIGURE S.3 Regression-analysis plots for the decrement factor of wall D1: DF versus solar energy and regression line (a), residuals versus solar energy (b) and residuals versus estimated DF (c).



(a)



(b)



(c)

FIGURE S.4 Regression-analysis plots for the decrement factor of wall F: DF versus solar energy and regression line (a), residuals versus solar energy (b) and residuals versus estimated DF (c).