Edinburgh Napier University

School of Engineering and the Built Environment

Fausto Sanna

Timber modern methods of construction: a comparative study

(Volume I)

May 2018

A thesis submitted in partial fulfilment of the requirements of Edinburgh Napier University, for the award of Doctor of Philosophy

Author’s declaration

I hereby declare that the present thesis is of my own composition and that it contains no material previously submitted for the award of any other degree. The research work reported in this thesis has been conducted by myself, except where due acknowledgement is made in the text.

Fausto Sanna

To my mother and Josema

Abstract

The doctoral research revolves around a comparative study of timber modern methods of construction for low-rise, residential buildings in Scotland.

The building techniques studied involve both timber-frame panel construction (open-panel and closed-panel systems and structural insulated panels) and massive-timber construction (cross-laminated and nail-laminated timber panels). A non-timber technique is also included in the study: more traditional, load-bearing masonry (blockwork).

These different building techniques have been analysed from two complementary aspects: environmental impacts and thermal performance.

The environmental study is based on the life-cycle assessment methodology and embraces various aspects: environmental impacts (*e.g.,* climate change, acidification, eutrophication, ozone depletion, *etc.*), consumption of energy (renewable and non-renewable resources) and production of waste (from non-hazardous to radioactive). The assessment takes a cradle-to-gate approach and, in its structure and method, is informed by the current recommendations of the international standards in the field (*i.e.,* ISO 14040 series).

Various environmental *trade-offs* between construction methods have been identified. In terms of global-warming potential (excluding biogenic carbon sequestration), results suggest that timber-frame buildings show a better performance than masonry buildings; this is particularly true for the open-panel system, which emits about 10% less carbon than the masonry counterpart. Massive-timber buildings tend to cause more carbon emissions than masonry ones.

In terms of consumption of non-renewable primary energy, timber buildings do not generally show significant advantages with respect to blockwork-based masonry. In particular, structural-insulated panel systems tend to show very high energy requirements.

Timber-based buildings show a tendency to cause increased acidification, eutrophication and creation of low ozone than their masonry counterpart.

The level of offsite fabrication that is employed for the erection of the buildings plays an important role in the magnitude of most environmental impacts, which show an average decrease between 5% and 10% when some of the operations are shifted from the construction site to the factory.

The thermal study investigates the performance of the building envelope, and, in particular, of external walls, by means of tests whereby the thermal behaviour of a sample of walls (of full-size section) has been observed and measured over time. On the outside, the walls were exposed to real, natural weather variations throughout the summer.

The study especially focuses on the time-dependent response of three different walling systems (which results from their individual cross-sectional arrangements of building components and the associated combination of heat-storage capacity and thermal resistance): a timber-framed wall, a cross-laminated-timber wall and a masonry wall. Thus, the main goal of the study was to characterise the thermal-inertia parameters of these walls.

This type of thermal behaviour is related to the repercussions of global climate change at UK level, especially in terms of increase in solar irradiance and temperature, which requires an adaptation of the building-envelope such that it can perform well both during wintertime and summertime, by providing maximum indoor comfort with minimum economic and environmental costs from the construction and operation of buildings.

The timber-framed wall possesses the greatest capacity to slow down the propagation of temperature waves from the outer surface to the inner surface (time lag), whereas the masonry wall performs best with respect to reducing the amplitude of temperature oscillation on the inner surface (decrement factor). The cross-laminated-timber wall exhibits intermediate values of both time lag and decrement factor, relative to the other two walls.

Both the thermal and life-cycle assessment of the construction alternatives aim at assisting the design and decision-making process in the residential field and at suggesting areas that need to be addressed and improved, towards a coherent evolution of the building techniques included in this study and a step forward in the realisation of sustainable, low-rise dwellings.

Key words: *timber, modern methods of construction, material wastage, climate change, overheating, life-cycle assessment, environmental impacts, burden trade-offs, building envelope, thermal inertia, thermal characterisation.*

Acknowledgments

First of all, I would like to thank my supervisors and, in particular, Dr Robert Hairstans, for their support, insight and guidance over the last years.

I am grateful to several people who have offered me invaluable advice, information and support:

- Mr Robin Dodyk (Oregon Timber Frame Limited);
- Mr Max Garcia (CLDB Limited);
- Mr Julio Bros-Williamson (Edinburgh Napier University);
- Dr Francesco Pomponi (Edinburgh Napier University);
- Dr Marcelle McManus (University of Bath);
- Dr Jennifer Monahan (University of East Anglia);
- Mr Mark Milne (Edinburgh Napier University);
- Mr Ian Campbell (Edinburgh Napier University);
- Mr Wojciech Plowas (Edinburgh Napier University);
- Dr David Binnie (Edinburgh Napier University);
- Prof Brian Sloan (Edinburgh Napier University);
- Dr Simona Gagliardi (Edinburgh Napier University);
- Mr Duncan Ball (Met Office).

I would also like to thank my employer, the Arts University Bournemouth, for granting me a research fellowship to facilitate the writing-up of this thesis.

Last, but not least, I would like to thank my family for their continued encouragement.

Contents: volume I

Contents: volume II

List of figures: volume I

All the figures are by the author, unless otherwise stated in the respective captions.

List of tables: volume I

All the tables are by the author, unless otherwise stated in the respective captions.

Note:

The full list of references can be found in volume II.

Nomenclature

Symbol	**Meaning**	**Unit**
AP	acidification potential of soil and water source	kg SO_2-eq.
BIS	Department for Business, Innovation and Skills	
BMCC	building material and component combination	
BoQ	bill of quantities	
BRE	Building Research Establishment	
BS	British standard	
BSI	British Standards Institution	
CDF	cumulative distribution function	
CEN	European Committee for Standardization (*Comité Européen de Normalisation*)	
CFCs	chlorofluorocarbons	
CIBSE	Chartered Institution of Building Services Engineers	
CIOB	Chartered Institute of Building	
CIRIA	Construction Industry Research and Information Association	
CITB	Construction Industry Training Board	
CLT	cross-laminated timber	

CML	Institute of Environmental Sciences (*Centrum voor Milieuwetenschappen)*	
CNC	computer numerical control	
d	density	kg/m^3
DECC	Department of Energy and Climate Change	
DEFRA	Department for Environment Food and Rural Affairs	
DF	decrement factor	/
dim.	dimensions	
EC	European Commission	
EN	European standard	
EP	eutrophication potential	kg PO_4-eq.
EPD	environmental product declaration	
EPS	Expanded polystyrene	
eq.	equivalents	
EU	European Union	
FMB	Federation of Master Builders	
GFA	gross internal floor area	m^2
GHGs	greenhouse gases	
GSD	geometric standard deviation	
GWP	global-warming potential	kg CO_2-eq.
h	convective-heat-transfer coefficient	$W/(m^2 \cdot K)$

hazW	hazardous waste disposed	kg
HCA	Homes and Communities Agency	
HFCs	hydrogenated halocarbons	
I	environmental impact	
IES	Institute for Environment and Sustainability	
ILCD	International Reference Life Cycle Data System	
Inp	Input	
ISO	International Organization for Standardization	
IBU	Institut Bauen und Umwelt	
IPCC	Intergovernmental Panel on Climate Change	
JRC	EU Joint Research Centre	
k	thermal conductivity	W/(m·K)
LCA	life-cycle assessment	
LCI	life-cycle inventory	
LCIA	life-cycle impact assessment	
LCT	life-cycle thinking	
ln	natural logarithm	
LoW	list of waste	
MC	moisture content	
MMC	modern methods of construction	

NAEI	National Atmospheric Emissions Inventory	
NLT	nailed-laminated timber	
OSB	oriented-strand board	
ODP	ozone-depletion potential	kg CFC-11-eq.
OPC	ordinary Portland cement	
P	phosphorus *or* probability	
PCM	phase-change material	
PCR	product-category rules	
PD	published document (BS, ISO, CEN standards)	
PDF	probability-density function	
PE	primary energy	
POCP	photochemical ozone-creation potential	kg ethane-eq.
POE	post-occupancy evaluation	
pot.	potential	
PUR	polyurethane	
PVC	polyvinyl chloride	
q	heat flux (heat flow per unit area)	W/m^2
R	thermal resistance	$m^2 \cdot K/W$
RCA	recycled concrete aggregate	
rel.	relative	

RIBA	Royal Institute of British Architects	
S	strength	N/mm^2
S_{comp}	compressive strength	N/mm^2
S_{ten}	tensile strength	N/mm^2
Sb	antimony	
SETAC	Society of Environmental Toxicology and Chemistry	
SME(s)	small- and medium-size enterprise(s)	
SO_2	sulphur dioxide	
SIP(s)	structural insulated panel(s)	
Sv	Sievert	
t	time	s
T	temperature	°C or K
TF	timber frame	
thicks.	thickness	
TL	time lag	hours
TR	technical report (BS, ISO and CEN standards)	
T&G	tongue and groove	
U_{com}	uncertainty factor for completeness	
U_{geo}	uncertainty factor for geographical correlation	
U_{rel}	uncertainty factor for reliability	

U_{sam}	uncertainty factor for sample size	
U_{tec}	uncertainty factor for technological correlation	
U_{tem}	uncertainty factor for temporal correlation	
UK	United Kingdom	
UKCES	UK Commission for Employment and Skills	
UN	United Nations	
UNEP	United Nations Environment Programme	
UNFCCC	United Nations Framework Convention on Climate Change	
VCL	vapour-control layer	
VOCs	volatile organic compounds	
w	weight	kg
W	waste	
WMO	World Meteorological Organization	
WPC	whole process of construction	
WRAP	Waste and Resources Action Programme	
XPS	extruded polystyrene	

Subscripts

Subscripts	**Meaning**	**Unit**
amb	ambient	
UDL	Uniform distributed load	KN/m

Greek letters

Symbol	**Meaning**	**Unit**
α	thermal diffusivity	m^2/s
μ	geometric mean	
ξ	mean of the ln(x)	
σ	standard deviation	

1 Introduction

1.1 Environmental impact of housing

1.1.1 Influence of legislation and policies on the research agenda

Current legislation across the world is, indirectly, encouraging life-cycle assessment (LCA) studies which focus on two environmental aspects: carbon emissions and energy consumption. This is due to the numerous policies that actively promote (and make compulsory) the reduction of these burdens. However, there is increasing attention, at least in academia, towards other environmental aspects. Avoiding unilateral focus and broadening the spectrum of environmental aspects to be taken into consideration is a recommendation of the international standards (BS EN ISO 14044) and of various academic studies published in the last ten years (Rønning & Brekke, 2014; Whitehead *et al.*, 2015).

Another factor that leads to researchers focusing on carbon and energy is the fact that these two parameters are strictly interlinked and background data is readily available, especially in comparison with other emissions.

Ibn-Mohammed *et al.* (2013) express the "urgency for a holistic policy framework" in the UK, explaining that the Government only focuses on, and promotes, the reduction of operational emissions in the built environment while neglecting the importance of embodied emission. Similarly, at the international level, some authors suggest that the EU directive on Energy Performance of Buildings should be revised to include embodied energy as well as operational energy (Pacheco Torgal and Jalali, 2011).

An extensive, pilot project promoted by the European Union (Nemry *et al.*, 2008) has also analysed housing from additional points of view: acidification, eutrophication, ozone-depletion potential and photochemical-ozone-depletion potential (see SECTION 2.7).

1.1.2 Impacts over a life cycle: embodied versus operational

The definition of "embodied" burdens[1] is not univocal in the literature and can cause some confusion (Guardigli, 2014; Dixit *et al.*, 2010; Sartori and Hestnes, 2007), especially when trying to compare research findings of varying authors. While this definition always includes the burdens occurring in the life-cycle phases of material extraction, transportation to the factory and manufacturing, it is only in some cases that it is meant to include transportation to site and construction.

The definition of "operational" (or "operating") burden[2] is much clearer, instead, and corresponds to the phase in which buildings are used (*i.e.,* B1).

It has been suggested (for instance, by Langston and Langston, 2008) that evaluating embodied energy is more complex and time-consuming than evaluating operational energy.

In the initial LCA studies applied to the built environment, researchers focused mostly on the operational stages, especially when assessing energy consumption for space heating or cooling and the resulting carbon emissions (Dixit *et al.*, 2010). This was due to the thermal performance of the envelope being generally very poor in comparison with today's standards, at least in the European context. Since heat losses in wintertime and heat gains in summertime used to be very high, a great amount of energy was needed to maintain thermal comfort inside the building. As a result, energy consumption during the building's useful life was approximately split in the following proportion: 15% embodied energy and 85% operational energy (with very similar figures for carbon emissions) (Adalberth, 2001).

Therefore, it was estimated that operational energy would overtake embodied energy soon after occupancy commenced (Ibn-Mohammed *et al.* 2013). BRE (1999), for

[1] Some authors define the burdens occurring at these stages as "initial embodied" burdens, to distinguish them from "recurring embodied" ones (*i.e.*, relating to maintenance, repair and refurbishment) and "demolition embodied burdens".

[2] However, there is high variability in the types of activities and functions that researchers decide to include when addressing the occupancy phase of the buildings. These activities can be limited to space heating/cooling or also include water heating, cooking, use of domestic appliances, *etc.* (Rønning & Brekke, 2014). Such choices affect the level of comparability across different LCAs.

instance, estimated that, in a 3-bedroom, detached house operational energy would equal embodied energy by the third or fifth year of utilisation.

More recent LCA studies, conducted after the thermal requirements for the building fabric have become much more stringent, have shown that the share of embodied and operational energy has changed (Iddon and Firth, 2013; Ibn-Mohammed *et al.*, 2013 and Monahan, 2013). Not only is this due to the fact that energy demand to achieve a satisfactory level of thermal comfort is significantly reduced, but also to the fact that the amount of materials incorporated in the envelope has increased, especially the amount of thermal insulants, whose manufacturing processes tend to cause much environmental burden.

By way of indication, it is worth mentioning that Ibn-Mohammed *et al.* (2013) compare the embodied-to-total proportions in more recent LCA literature and explain that, according to different authors, embodied energy in the UK might be up to 35% of total energy and carbon up to 62-80% of total carbon over the lifecycle[3]. Hamilton-MacLaren *et al.* (2009) point out that as energy efficiency increases and we move towards "zero-carbon" targets, embodied carbon and energy (asymptotically) tend to approach 100% of their total figures.

As a result, over the last ten years researchers have suggested increasingly more often the importance of assessing the initial phases of a building's life-cycle (*e.g.,* Dixit *et al.*, 2010; Monahan and Powell, 2011; Monahan, 2013 and Iddon and Firth, 2013) and more scientific efforts have been made in this direction.

At a global level, approximately 20% of total fuel use is associated with the production of building materials (Tiwari, 2001). Therefore, a higher degree of knowledge and awareness of the environmental implications of the manufacturing processes of different construction materials becomes fundamental in curbing energy and carbon embodied in buildings (Ding, 2004, p. 1239). According to Dixit *et al.* (2010), it is

[3] Once again, these figures must be interpreted with caution, as each study has been carried out within a different framework and considering different durations of useful life for a building (in some cases 60 years, in others 100 years, and so forth).

imperative to enhance aspects of the construction industry such as "design and engineering methods, construction techniques and manufacturing technology to tame energy consumption".

While "low-energy" buildings consume less energy during operation than their conventional equivalent, their embodied energy is higher (Sartori and Hestnes, 2007). However, the high efficiency of the low-energy buildings allows them to have a lower total energy throughout their useful life. This confirms that the higher embodied energy of low-energy solutions is paid back during the operation of the buildings.

The importance of an attentive analysis of the embodied-energy payback period is also stressed by other researchers, such as Dylewski and Adamczyk (2014), Khasreen *et al.* (2009) and Wilson and Young (1996): this applies to both strategies in the design of efficient envelopes and installation of equipment to use micro-renewables (*e.g.,* photovoltaic panels). Therefore, there is a trend of increasing embodied energy occurring in parallel with a trend of decreasing total energy.

When Sartori and Hestnes (2007) analysed the research results from published LCAs, they identified a rather strong linear relationship between total energy and operational energy. Since these mathematical analysis included studies from various countries, based on buildings located in very disparate climatic zones (both zones with mild and severe climatic conditions), Sartori and Hestnes suggest that this linear relationship might be generalised and does not only hold true for countries belonging to one specific climatic area. It is worth noticing that using energy- or emission-intensive materials, or a greater quantity of materials than in the past, to meet current thermal-performance standards poses problems not just in the *product* and *construction* stages of a building's life-cycle (initial embodied impact), but also in the subsequent stages (recurring embodied energy), when these materials need maintenance and, above all, replacement[4] (Rønning and Brekke, 2014).

[4] This aspect becomes even more significant when replacement rates are high and is interlinked with the durability of building components.

Sartori and Hestnes (2007) have determined that embodied energy in conventional buildings ranges between 2% and 38% of total energy, whereas it varies between 9% and 46% in more efficient buildings.

Iddon and Firth (2013) have assessed the embodied and operational carbon for new-build, low-rise housing in the UK and concluded that a drop in operational carbon releases is likely to be associated with a simultaneous increase of embodied emissions (both in absolute and proportional terms). These authors also show that the embodied carbon ranges between 20% and 26% (a relatively small interval) of total carbon depending on the thermal performance[5] of the envelope.[6]

The relationship between embodied carbon and embodied energy varies in the production and operational stages. Operational carbon is mostly due to space and water heating, and arises from the burning of fuels; therefore, for a given fuel mix, there is a rough proportionality between the two burdens[7] (Ayaz and Yang, 2010). Embodied energy and carbon, instead, do not have a direct correlation (Ibn-Mohammed *et al.*, 2013), since extraction/manufacturing processes can both release or sequester carbon and part of the emissions are not related to energy consumption (*e.g.,* those due to the chemical reactions during the production process of a building material).

As noted by Sartori and Hestnes (2007), LCAs have shown that the environmental loads arising from **transportation to site and erection of buildings** are comparatively low relative to the other life-cycle stages. This has been specifically demonstrated with regard to energy: the sum of the energy consumed during these stages is settled at about 1% of the total energy or below. Research undertaken by Monahan (2013) seems

---

[5] The thermal performance of the envelope, in the four scenarios they have analysed, varies considerably (the wall U-values being 0.15, 0.17, 0.29 and 0.35 $W/(m^2 \cdot K)$).

[6] However, since each of these scenarios also represents a different constructional technique, comparison of these findings is made difficult and requires caution, because the calculations are affected not just by the amount of insulants inside the build-up (or similar measures), but also by the completely-different construction methods considered (*i.e.*, two types of load-bearing masonry, closed-panel timber frame and structural insulated panels). See also discussion on comparability in SECTION 4.6.

[7] Ibn-Mohammed *et al.* (2013) warn that this mathematical correlation, however, can occasionally lead researchers to confusion and adoption of inappropriate terminology, for instance, by using "energy" and "carbon" as interchangeable terms.

to confirm these findings: carbon releases due to transportation is here estimated to represent 2% of the total embodied carbon.

With regard to carbon emissions, Peuportier (2001) performed an LCA of single-family houses in France and determined that the carbon associated with the phase of transportation of the building components to the construction site is likely to range between 1.5% and 2.4% (still very low) of the total emissions during the life cycle of the building, depending on whether the materials are sourced locally or from further afield (this was estimated through a sensitivity analysis of the different assumptions on the location where the building components are manufactured).

Therefore, some researchers deem the transport and/or construction phases negligible and exclude them from their studies even when they are carrying out extensive (such as cradle-to-grave) LCAs (*e.g.,* Iddon and Firth, 2013 and Nemry *et al.*, 2008).

Cuéllar-Franca and Azapagic (2012) have estimated the carbon emissions caused by the transport and construction phases of a semi-detached house in the UK with two-leaf, masonry walls at 10% and 1%, respectively, of the total embodied emissions.[8]

---

[8] Values derived by the present author, based on the data presented in Figure 8, page 93, of the cited source. Since in this study the operational energy includes more aspects (*e.g.,* impacts related to cooking, lighting and use of appliances) than it is usually the case, here only the production stage is considered.

1.2 Climate change and thermal performance of buildings

The projections from the Department of Energy, Food and Rural Affairs, DEFRA (2012) have identified that climate change in the UK will pose different challenges over time. The major challenge is foreseen to be flooding risk for the short-term (in the 2020s) and overheating risk for the medium term (in the 2050s and 2080s).

As a consequence of climate change, summers in Scotland and the rest of the UK have been predicted[9] to become warmer and drier over the coming decades and winters less cold but rainier (Tham *et al.*, 2011).

This ongoing change in climate has many repercussions on buildings, including residential ones. There is a high risk that houses become prone to overheating if they only rely on typical current levels of passive protection from outdoor conditions, *i.e.,* "free-running" buildings, using natural ventilation and not resorting to mechanical cooling (Tillson *et al.*, 2013; Kendrick *et al.*, 2012; Lomas and Porritt, 2017; BRE, 2014). For this reason, design of new houses should be such to avoid overheating risk (Beizaee *et al.*, 2013; Pathan *et al.*, 2017; Gupta *et al.*, 2015).

Some authors have indicated that overheating risk in Scotland is often underestimated and that this phenomenon is already a concern in the short term. According to Morgan *et al.* (2015) and Morgan *et al.* (2017), there is a risk of overheating in Scottish low-energy homes, which is attributable to a combination of warming climate, effective heat retention and recovery, users' behaviour, wrong installation of thermal equipment and inadequate design. Sharpe *et al.* (2014) have also studied low-energy houses in Scotland and reached similar conclusions: they indicate poor ventilation strategies as the main cause behind overheating in these houses.

In cases where natural ventilation is not sufficient, coupling it with mechanical ventilation (such as ceiling fans) might be a solution, or, in the worst scenarios, with modern and efficient air-conditioning systems with heat recovery for water heating, associated with thermal mass to reduce the cooling loads in the future (de Oliveira

[9] A more detailed review of climate projections will be provided in SECTION 2.5.

Fernandes, 2016; Tillson *et al.*, 2013; Gupta *et al.*, 2015). However, there are also concerns that mechanical-ventilation with heat-recovery (MVHR) systems – which are becoming more widespread in new builds – are being operated in a fashion that could increase overheating risk (McGill *et al.*, 2017; Fletcher *et al.*, 2017; DCLG, 2012).

Some authors (*inter alia*, Morgan *et al.*, 2017) have stressed the importance of occupants behaviour (in terms of house management, use of windows, use of mechanical ventilation, *etc.*) on the thermal performance of a dwelling in respect of overheating.

Some researchers have expressed concern over the fact that the increasing use of light-weight construction methods, with low thermal mass, might be particularly susceptible to overheating episodes, quick oscillations in internal temperatures (following outdoor oscillations), and, as a result, poor thermal comfort for the occupants (Adekunle and Nikolopoulou, 2016; Rodrigues *et al.*, 2016; Peacock *et al.*, 2010). In this sense, some authors also envisage a problem of tension between opposite actions: on the one hand, the shift towards lighter buildings with lower embodied environmental burdens and, on the other, the temptation to resort to heavy structures in order to provide dwellings with more thermal mass (Kendrick *et al.*, 2012). There is also a correlated concern that occupants living in inadequate buildings might have to resort more frequently to air-conditioning systems (Elias-Ozkan *et al.*, 2006), which would result in associated energy consumption and polluting emissions. Furthermore, since typical air-conditioning system release the heat removed from a building to the outside, they can contribute to the “heat island” phenomenon in urban areas (Gupta *et al.*, 2015).

According to recent studies (*e.g.,* Kendrick *et al.*, 2012; Holmes and Hacker, 2007), a combination of an optimum level of thermal mass (and its heat-storage capacity) within the build-up of the envelope associated with night cooling is considered to be the most successful passive strategy to maintain a satisfactory level of thermal comfort in the future scenarios.

If ventilation is to assume such a significant role for good thermal performance, then designers have to ensure that houses facilitate this practice: ventilation at night-time should be safe for the occupants, in terms of intrusion risk (Peacock *et al.*, 2010; Kendrick *et al.*, 2012) and not clash with noise- or pollution-related problems or concerns for the users (NHBC, 2012; Gupta and Gregg, 2013). Windows have to be designed in an adequate manner and positioned in such a way to make cross-ventilation easily achievable. When windows are not sufficient to guarantee the necessary level of ventilation, other means have been identified in wind towers, ventilation openings and passive stack ventilation (Kendrick *et al.*, 2012).

Kendrick *et al.* (2012) emphasize that within a house each type of space might need a different type of thermal performance and response to ambient conditions: living spaces might indeed have different requirements than bedrooms. Bedrooms might be enclosed by light-weight walls which exhibit a rapid response to outside temperatures and therefore be cool at night; whereas living spaces (used mostly during daytime) might benefit from higher thermal mass and stay cooler during the day and then be ventilated at night, when the temperature wave reaches the interior surface of the walls. This is an example of how the ideal thermal envelope might not be constant throughout a dwelling, but change depending upon the functions accommodated in a space and on its occupancy patterns.

Beizaee *et al.*, (2015) have conducted a field study[10] and post-occupancy-evaluation surveys and demonstrated that even under the current summer conditions, there is already a problem of overheating and low thermal comfort in houses across the UK, especially in bedrooms, where temperatures at night can be above the comfort threshold. Similar conclusions have been drawn by Gupta and Gregg (2013), after an analogous field investigation into overheating risks, by Sharpe *et al.* (2014) and by Morgan *et al.* (2015). This supports the thesis that the same homes will be prone to more frequent overheating episodes in the warmer summers ahead.

Thermal simulations by Gupta and Gregg (2013) have concluded that buildings with higher thermal resistance (equivalent to lower U-values) can be more prone to summertime overheating, especially in dwellings such as terraced houses and apartments. These authors point out the repercussions of the heat waves experienced

[10] By measuring temperature inside a large number of dwellings during their occupancy.

in Britain in 2003 and 2006 as an example of the scenarios that are likely to become increasingly frequent in the future.

A new strand of research is focussing on the definition of new metrics to develop weather files and predictive tools to assess overheating risk, since the ones currently available are not considered sufficiently reliable, adequate or accurate (Liu *et al*., 2016; Taylor *et al.*, 2016).

So far, the Scottish climate has prompted regulating authorities and designers to place emphasis on the optimisation of the thermal performance during wintertime, in order to reduce the costs from heating systems. However, due to the global warming trend, this approach will gradually lose part of its adequacy. Therefore, long-sighted, affordable design should take into consideration the future climate change and its consequences on housing. As Gupta and Gregg (2011) point out, adaptation to the warming climate is as important as the attempts to mitigate it, even though so far most efforts have been made towards the latter target. In other words, the concept of climate adaptation is still very recent in the UK.

As will be seen in SECTION 1.3, the investigation proposed in this thesis looks at climate change from the two complementary angles of mitigation of this phenomenon and adaptation to it.

Erecting houses that exhibit good thermal behaviour both during winter and summer and prove to be cost-effective and affordable in the long term certainly poses a challenge to the decision-makers in the construction industry. One of the aspects that are disregarded by the building regulations – and too often in professional practice – is thermal inertia and the time-dependent response of building components to the continuous oscillation of external weather conditions. Scottish building regulations (Building Standards Division, 2016), have so far encouraged designers to focus on parameters such as air tightness and, above all, the level of thermal insulation of the building envelope (in terms of U-values[11]). The main advantage to this streamlined approach lies in its high computational ease.

When correctly placed within assemblies and properly combined with insulation layers, high thermal mass can offer noticeable benefits by reducing the sensitivity of the interior space to external conditions and thus regulating its temperature.

From an LCA perspective, the optimisation of the building envelope leading to a reduction of energy consumption entails benefits on manifold levels. The environmental advantage lies in reduced depletion of both non-renewable resources and carbon-equivalent emissions from burning fuels. Economic savings are not only an advantage *per se*, but also have social effects such as wider access to housing and the wellbeing of its occupants. "Fuel poverty", indeed, prevents numerous households in Scotland from properly heating their houses during the cold season.

[11] Or "overall thermal transmittance".

1.3 Outline of the present research

1.3.1 Scope and aims

The present thesis deals with low-rise residential buildings in Scotland, with particular attention, but not limited to, affordable homes for the social and private sectors. The research presented here aims at providing better understanding of the embodied environmental burdens associated with the construction of houses that employ timber-based techniques. These environmental loads are also going to be compared with those of a more traditional construction method: load-bearing masonry.

This research is therefore conducted at the level of the whole building, not just of individual building components or elements considered in isolation.

The timber techniques embraced in this study belong to two main categories:

- "timber frame" construction in the broad sense of the expression, including timber-frame panel construction and structural insulated panels (SIPs);
- massive-timber techniques (including panels fabricated through different types of lamination: cross-laminated timber and nail-laminated timber).

Another criterion for the comparison of these methods of construction regards the operational life-cycle phase of houses and the thermal behaviour of their envelopes under changing climatic conditions. This strand of the thesis aims at evaluating the thermal response of external walls to outdoors conditions in light of the changes that the climate in Scotland and in the rest of the UK has been envisaged to undergo over the coming decades (as explained in SECTION 1.2).

The findings of this investigation aspire to provide various actors within the construction industry to have a deeper insight into the environmental repercussions of different construction methods and to be able to make informed decisions regarding the correct selection of one method over the others. Therefore, the groups of people who might benefit from the outputs of this project are building designers (architects, structural and civil engineers), building surveyors and their clients, commissioning bodies, managers of construction companies and developers, legislators and policy-makers (at the local, regional or national level) and council directors.

1.3.2 Knowledge gaps identified

The current research project has been designed around the following knowledge gaps, which were identified through a review of the existent literature:

① Previous research has focused on timber-framed panel construction and scarce information is available on solid-wood panelised systems, such as cross-laminated timber or nail-laminated timber. Furthermore, most studies are limited to energy consumption and carbon emissions: very little knowledge is available on other important aspects such as acidification, eutrophication, ozone depletion, production of hazardous and radioactive waste (the study of which is also encouraged by international standards).

Since timber techniques other than framed panels have received limited attention, not much is known about their environmental performance relative to masonry housing. The comparison between timber-framed buildings and traditional masonry buildings has mostly been carried out with reference to houses adopting a brick-and-block system for the external walls. Brick-and-block is very common in England and Wales but much less widespread in Scotland. This might seem a subtle, even negligible, difference, but since bricks tend to cause much greater environmental burdens than concrete blocks, it is important to consider this second option, too.

② Due to the lack of broad, multi-impact studies on timber buildings, little information is available on the burden trade-offs between such buildings. In other words, little is known in terms of environmental advantages and disadvantages of any given construction method in comparison with the others, in consideration of several environmental aspects.

③ Previous research has so far focused on the building products incorporated in a building, but almost no consideration has been given to the environmental repercussions of the processes through which it is erected. For the same final output (the completion of a house) different constructional processes lead, for instance, to different levels of building-material wastage. An accurate LCA should therefore take these practicalities into account and cast light on the consequences of opting for one construction process rather than the available alternatives.

④ So far, in the UK (especially in comparison with other countries), thermal mass has been seen as an advantage for wintertime performance of the envelope, as opposed to summertime performance. Even though there is a growing interest in the use of thermal mass and storage in housing to minimise overheating risk[12] during future, warmer summers; not much is yet known on the real advantages/disadvantages of thermal mass in the remit of the building techniques considered in this study, particularly those deploying timber massive panels. In addition, most studies published on the effects of thermal mass in the UK context are theoretical ones (*i.e.,* computer simulations) and not experimental, therefore more accurate quantitative studies based on, or supported by, empirical evidence are needed for a more robust appreciation of these issues.

⑤ Since rigorous studies on the benefits of thermal mass in the British climate are few (see point above), there is a gap in the comprehension of how, and to what extent, climatic variables and constructional features (lay-ups, materials, *etc.*) affect the thermal behaviour of timber-built walls and especially its aspects related to thermal inertia.

1.3.3 Research questions and objectives

Coherently with the current knowledge gaps identified through the literature review and articulated in five points, ① to ⑤, in the disciplinary areas and issues mentioned above, the present thesis aims at providing a contribution to knowledge by answering the following research questions:

① How do timber and masonry buildings perform in terms of mitigation of climate change and of other environmental impacts?

[12] See Section 2.5.

② When timber buildings are compared with one another and with a masonry building, what are the most significant trade-offs of environmental impacts?

③ How, and to what extent, does the manufacturing and construction process affect the embodied environmental impacts of timber constructional techniques?

④ How do timber and masonry wall systems compare, in terms of thermal-inertia properties, associated behaviour in summertime and consequent adaptation to climate change?

⑤ What constructional aspects and climatological variables critically affect the thermal inertia of timber and masonry walls during summertime, in Scotland?

While the work carried out to answer research questions ① to ③ follows within the remit of life-cycle assessment, the work to answer questions ④ and ⑤ entails a thermal study. Despite this difference in disciplinary and methodological approach, there is a fundamental linkage between these two strands of work: they both look at climate change from two complementary perspectives. The LCA work, indeed, looks at climate change from the viewpoint of mitigating its impact by reducing the relevant emissions arising from construction. The thermal work, on the other hand, accepts that climate change is already occurring – and is envisaged to increase in the future – and provides a contribution to knowledge by assessing the role of the building envelope in adapting to the warming climate.

In this sense, the design of the present research responds to the growing body of literature according to which the only manner to tackle climate change effectively is to embrace both **mitigation and adaptation strategies** (Taylor *et al.*, 2017; Howell *et al.*, 2016; Porritt *et al.*, 2012; Tillson *et al.*, 2013; HM Government, 2013), since neither of these alone could be successful. This research also acknowledges the urgency, raised by some researchers, to improve adaptive strategies and associated policies and regulatory measures (Dunk *et al.*, 2016; Boyd *et al.*, 2011), in such a way to respond to both short- and long-term envisaged issues and to reduce risk from both cold (wintertime) and heat (summertime) (Arbuthnott *et al.*, 2016).

With regard to climate change, the connections between the findings from the LCA and thermal parts of this research project, will be articulated and discussed in CHAPTER 7. In the final chapter, indeed, the role of the buildings studied will be illustrated in terms of the extent to which they can both mitigate this phenomenon and adapt to it, thanks to the behaviour of the building envelope, and, in particular, of external walls.

The main objectives of this thesis are:

- to develop a cradle-to-gate LCA model of a notional, semi-detached house built with nine timber techniques and a load-bearing-masonry technique, to estimate the following environmental aspects:
  - polluting emissions contributing to climate change, acidification, eutrophication, ozone depletion and creation of photochemical ozone;
  - energy consumption;
  - waste production.

  This objective is aligned with research question ①;
- to use the data defined above in a comparative perspective, in order to identify trade-offs of environmental impacts between the ten buildings modelled. This objective is aligned with research question ②;
- to consider and implement (within the above LCA models) three different scenarios, each depicting a different level of wastage of building materials as a consequence of the construction processes followed (for instance, how many operations carried out in the factory and how many on the construction site). This objective is aligned with research question ③;
- to conduct field experiments to characterize the thermal inertia of various wall systems (two timber-based and one masonry-based) under real, naturally-fluctuating weather conditions in Scotland. This objective is aligned with research questions ④ and ⑤.

1.4 Thesis structure

CHAPTER 2 offers background information that contextualises the reasons behind the need for this research and the object of the investigation, *i.e.*, timber buildings. It starts by outlining housing in the UK, with a particular focus on Scotland and describing the *status quo* of timber construction applied to the residential sector. It then moves on to explain how the housing stock is envisaged to cope to a warming climate. Finally, this chapter provides some background information on life-cycle assessment as a discipline and on the specific environmental aspects considered in this research.

CHAPTER 3 illustrates how life-cycle assessment can be applied to the built environment and summarises the existing knowledge of environmental impacts of housing in the UK and in the rest of Europe. CHAPTER 3 also contains a review of the literature on thermal performance of the building envelope, with particular reference to the effects of thermal inertia and its optimisation for external wall and roof constructions.

CHAPTER 4 explains the design of this research project and describes the ten types of buildings that are the object of this investigation.

CHAPTER 5 presents the results of the life-cycle assessment of the ten notional buildings and provides an answer to research questions ①, ② and ③.

CHAPTER 6 documents the thermal research carried out to better understand the inertia-related thermal response of three different wall systems under transient weather conditions. This chapter answers research questions ④ and ⑤.

Lastly, **CHAPTER 7** articulates final considerations on the investigation conducted within this doctoral project and proposes suggestions for future work.

2 Background

2.1 Chapter overview

This chapter outlines the context in which this thesis and its research work has been carried out. It thus provides relevant information that lays the foundation for the content proposed and discussed in the following chapters.

SECTION 2.2 explores housing in the UK (with a focus on Scotland) as well as the legislative framework that affects the construction industry and its relation with the environment.

SECTION 2.3 analyses modern methods of construction (MMC) in the UK: its adoption by the public and supply chains are discussed and a categorisation of possible off-site construction levels is given. SECTIONS 2.2 and 2.3 together explain the rationale behind the type of dwelling and the constructional techniques and materials that have been chosen as the object of both the environmental (life-cycle assessment) and thermal investigations of this thesis.

High wastage of building materials is associated with the construction industry. **SECTION 2.4** explores the main causes of waste in building activities. This information is the basis for the life-cycle assessment conducted by the present author, particularly for the modelling of different scenarios regarding the wastage of building materials in CHAPTER 5.

Climate change in the UK is briefly investigated in **SECTION 2.5**. This aspect links to new challenges in the housing sector, especially in relation to overheating risk.

Life-cycle assessment (LCA) is an emerging methodology for measuring the environmental impact of products. Its origins and structure are examined in **SECTION 2.6**, which also defines the organisation and content of Environmental Product Declarations (EPDs) as well as their application to LCA studies of housing. EPDs have been used in this thesis as the most important data source to inform the LCA documented in CHAPTER 5.

Finally, **SECTION 2.7** gives an overview of the definitions, principles and characterisation models for the environmental aspects considered within this study and **SECTION 2.8** offers a summary of this chapter's content.

2.2 Housing in Scotland

According to the 2016 statistics by the Scottish Government (2016a), Scotland's housing stock consists of 2,546,000 units, 62% of which are houses, including semi-detached and terraced dwellings. This compares to 38% of flats, demonstrating a low average urban density for Scotland (see TABLE 2.1 for details).

TABLE 2.1 Types of dwellings in Scotland, according to the 2016 national statistics (Scottish Government, 2016a).

Type of dwelling	Quantity	Percentage share
detached houses	539,838	21.2%
apartments	964,147	37.9%
semi-detached houses	503,719	19.8%
terraced houses	524,307	20.6%
unknown	14,372	0.6%

Another set of statistics by the Scottish Government (2016b) offers an overview of new builds from the 1920s onwards. These data show a clear progression from construction led by council and housing associations (especially prominent during the 1940s through to the mid-1970s) to construction led by private initiative (FIGURE 2.1).

Overall, these statistics show that new build in Scotland has stalled since the boom of the 1940s and 1960s, especially after the 2008 economic crisis.

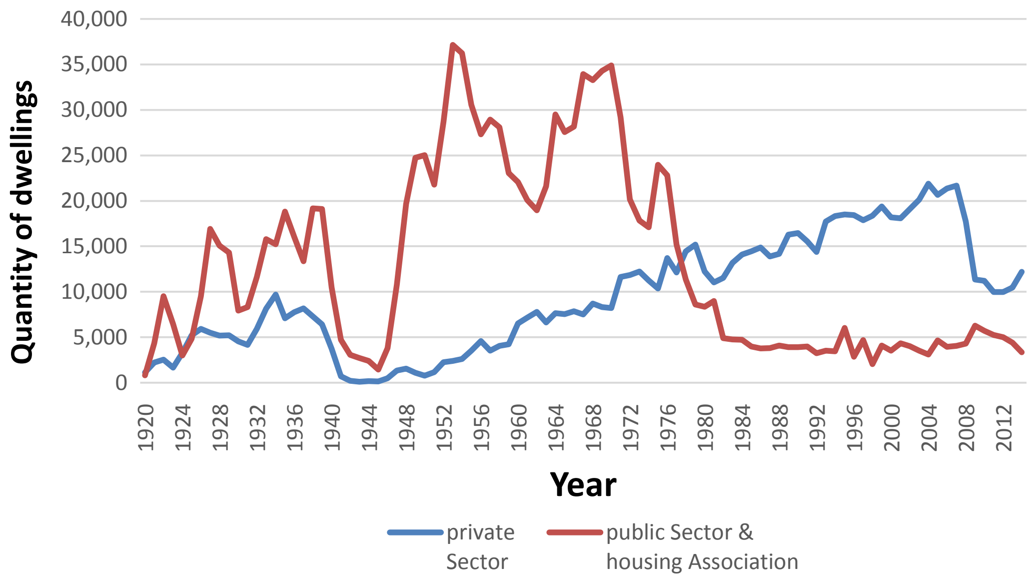

FIGURE 2.1 Scottish housing statistics, new builds since the 1920s, adapted from data by the Scottish Government (2016b).

2.2.1 Housing shortage and policies in Scotland

Scotland is undergoing a serious housing problem and must find ways to meet increased demand in the number of dwellings (Shelter Scotland, 2012; Scottish Government, 2016b). This is particularly true of the social-housing sector.

As shown in FIGURE 2.2, the building of social-housing units has slowed down and recent statistics (Scottish Government, 2016b) declare a total quantity of 316,553 dwellings of this type (TABLE 2.2 shows a breakdown of public-sector housing by type and FIGURE 2.2 illustrates the decrease in social housing in Scotland since 1998).

TABLE 2.2 Public-sector housing stock in Scotland (Scottish Government, 2016b)

Type of dwelling	Quantity	Share
houses	144,548	45%
high-rise flats	18,146	6%
tenements	63,448	20%
“four in a block”	59,123	19%
other flats, maisonettes	31,288	10%

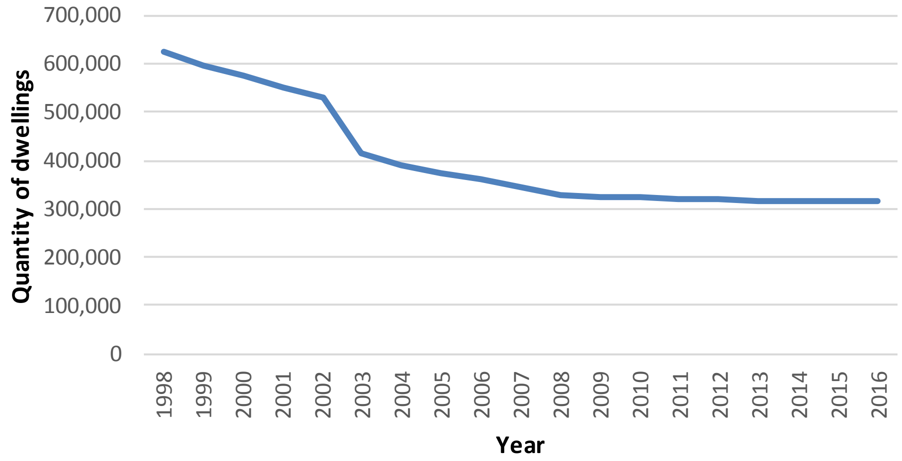

FIGURE 2.2 Social-housing stock in Scotland, based on data by the Scottish Government (2016b).

This decline in stock has translated into the inability of councils to accommodate every household who needs social housing and into longer waiting lists. The latest statistical release by the Scottish Government (2016a) reports that 151,500 households were on a waiting list in 2016 (FIGURE 2.3).

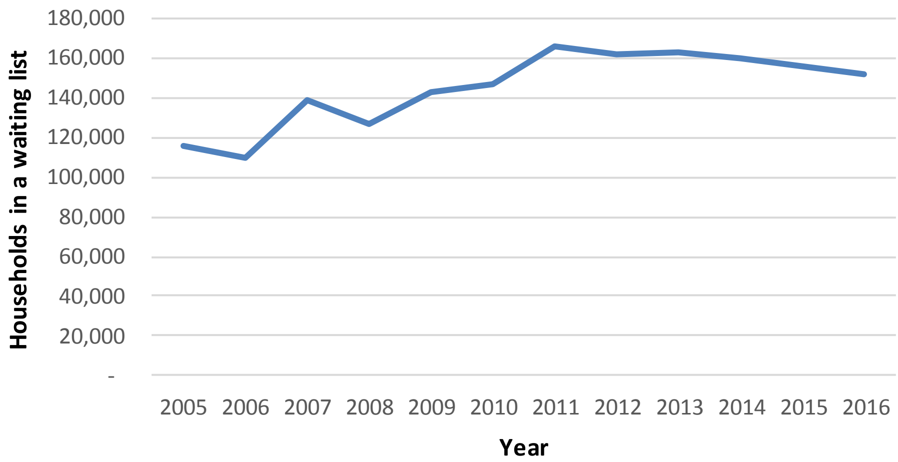

FIGURE 2.3 Number of households on waiting lists for social housing since 2005, based on data by the Scottish Government (2016a).

The Scottish Government's own projections (Scottish Government, 2011) anticipated that more than 400,000 houses would be needed in order to meet expected demand by 2033. This situation means that, alongside the social-housing sector, the private sector is also responsible for the provision of affordable housing. *Affordable housing and housing land audits, planning advice note 2/2010* (Scottish Government, 2010) stipulates that each new development should contain a variety of affordable housing for rent and sale.

2.2.2 Environmental legislation

The *Climate Change (Scotland) Act 2009* sets targets for greenhouse-gas emissions with a view to reduce them by 80% in 2050 with respect to baseline year 1990. Relating to this target and housing targets are the *Energy efficiency standard for social housing* (Scottish Government, 2014), which sets the minimum energy ratings for social housing in Scotland and the *Social-housing quality standards* (Scottish Government, 2011), which list the minimum criteria that social housing must satisfy. The environmental norms set by this standard include the need to meet a minimum energy rating of 50 for gas and 60 for other systems and a minimum of 100 mm of loft thermal-insulation layer.

2.2.3 Modern Methods of Construction and public policies

In Scotland, the current policies that oversee the application of environmental legislation in the built environment are *A low carbon economic strategy for Scotland* (Scottish Government, 2010), *Scotland's sustainable housing strategy* (Scottish Government, 2013a) and *Creating Places: a policy statement on architecture and place for Scotland* (Scottish Government, 2013b). All these policies, in vigour until 2020, support MMC through the introduction of additional modern apprentices, the *Greener homes innovation scheme (GHIS)* and extra funding for research.

At UK level, the *Review of housing supply*, commonly known as the *Barker Report,* encouraged the use of MMC and suggested that a quarter of publicly-funded housing must be MMC (Barker, 2004). In England, the housing crisis is exacerbated by a larger population and faster rate of growth. The *Shared ownership and affordable homes programme 2016 to 2021* aims at increasing the production of affordable housing in England, with particular consideration for offsite methods of construction as a viable way of delivering housing targets (HCA, 2016).

2.3 Offsite construction

2.3.1 Socio-cultural aspects: perception of offsite construction

Most timber buildings in Scotland are still clad in masonry, with an external leaf of rendered blockwork, or, more rarely, exposed brickwork. Timber cladding is, indeed, not very widespread, especially in mass construction (Owen, 2007; Hamilton-MacLaren, 2013). This preference in relation to cladding materials reveals trends in the property market: timber buildings are easily sold if they exhibit what potential buyers perceive as a "robust" and "safe" masonry wall (Hamilton-MacLaren, 2013). Timber cladding is more often used in one-off projects, where designers tend to experiment with materials and question the preferences of conventional construction.

This image of prefabrication is influenced by the experience of past application, in particular during the post-war period, when an unprecedented housing crisis led to the adoption of new building techniques to speed the delivery of new houses. Many prefabricated dwellings were only seen as a temporary solution (Owen, 2007; Hairstans, 2010a) and suffered from low quality, due to poor workmanship (Owen, 2007; Hairstans, 2010a; Forster *et al.*, 2015), lack of focus on the customer (Hairstans, 2010a) and poor design choices stemming from deficiencies in the knowledge of the structural behaviour of prefabrication techniques (Forster *et al.*, 2015). In contrast, there is larger acceptance of prefabricated construction for non-domestic buildings, since major clients favour efficiency and speed in the process (Phillipson, 2001).

Many of the prefabricated houses built between the 1940s and the 70s are considered to have a shorter lifespan than traditional buildings (Owen, 2007; Hairstans, 2010a; Forster *et al.*, 2015); therefore, the perception that offsite techniques only offer a temporary solution constitutes a significant barrier to the development of these systems. A survey (Inside Housing, 2003) found that 46% of social-housing tenants would object to being offered a home built with MMC.

In order to satisfy the public's preference for brick-finished houses (Owen, 2007; Hairstans, 2010a) innovative systems have been created, which include brick slips (mechanically fixed to the façade) that mimic a masonry building.

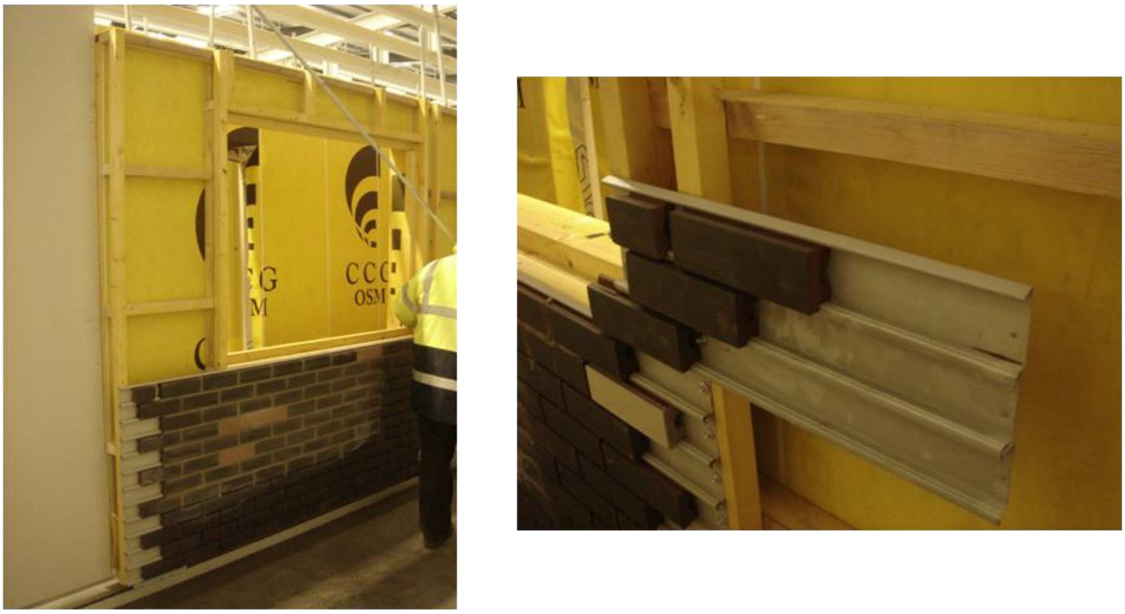

Figure 2.4 Cladding system mimicking brick facades, developed for timber-frame housing by CCG (OSM) Ltd, Glasgow.

Another aspect that slows the implementation of offsite solutions is perceived value. Property is considered an important possession in the UK and prefabrication is not seen as a good type of investment, based on historical experience (Hamilton-MacLaren *et al.*, 2013). However, non-residential clients are more likely to have a more in-depth appreciation of the investment value of their developments (Phillipson, 2001).

A study by Hamilton-MacLaren *et al.* (2013) confirms that traditional building techniques, namely brick and block, are still the most highly rated by consumers, because of their perceived durability and resistance to fire. Directly linked with the issue of public perception is the need to demonstrate the value of a timber house in order to obtain a mortgage (Owen, 2007). In this context, it becomes imperative to test timber construction in relation to thermal and environmental performance, as this thesis aims to do.

2.3.2 Supply chain

Softwood accounts for most of silvicultural practice in the UK. Coniferous forests are concentrated in Scotland and, to a lesser extent, Wales. The Scottish climate is, in comparison with net exporters of wood such as Scandinavia or Canada, a warmer region. Trees grow faster in this relatively-warm weather and, consequently, their annual rings are wider (Davies, 2011). The structural capacity of timber is influenced by ring width: wide rings in softwoods cause the woody material to have scarce density and to be more difficult to be worked by hand and by machine (Davies, 2011). Hence, the quality of conifers grown at a much slower rate in Scandinavia or Canada is generally higher than that of Scottish conifers (Ross, 2011). Consequently, Scottish home-grown timber is generally employed for products of lower value (*e.g.,* pallets, fences and packaging), according to the Forestry Commission Scotland (2016).

UK-wide statistics follow a very similar trend: in 2015, 38% of sawn softwood produced by larger sawmills was used for fencing and 30% for packaging and pallets, compared to 26% used for the construction sector (Forestry Commission, 2016).

Three quarters of the sawn softwoods that are imported into the UK are from European countries, mostly Sweden, Latvia and Finland (Forestry Commission, 2016).

Importation of wood can be reduced through improvement of silvicultural practice in Scotland and advancements of engineering techniques that allow lower-grade timber to be utilised for structural uses. There are several benefits to consuming locally-grown wood: the environmental impact would be lowered due to the reduction in transportation, the local economy would benefit from the creation of job opportunities and the supply of material would be independent of the fluctuations of the international market (Forestry Commission Scotland, 2016). In this context, it becomes fundamental to test the viability of using local timber for structures.

Scotland has gradually developed offsite solutions since the 1970s, which now account for about three quarters of new dwellings (Timbertrends, 2013; UKCES, 2013). The remaining houses adopt traditional techniques such as load-bearing masonry, generally in the form of cavity walls with internal blockwork and external brickwork or block and render. In England, the proportion of timber frame to masonry is approximately reversed, with timber frame being adopted for about one fifth of new houses (Timbertrends, 2013). Finally, in Wales and Northern Ireland, the level of adoption of timber frame has increased after the 2008 recession, reaching a market share of approximately 27% and 22%, respectively, in 2012 (Timbertrends, 2013).

The local, rainy climate in Scotland encourages the adoption of offsite construction as it allows more controlled conditions within a factory's protected environment and the erection of buildings that become weather-tight sooner during the construction process (Hairstans, 2010a).

The majority of Scottish companies delivering offsite construction are based around the Central Belt. Some of them are located in Northern Scotland, near Inverness (Smith *et al.*, 2013).

Constructors (as opposed to manufacturers of components) operate mostly in housing (both public and private), which is the main sector for many companies. Hotels and tourist accommodation are also an important share of their workload.

The UK construction industry is dominated by Small- and Medium-size Enterprises (SMEs), which account for about 95% of the sector (UKCES, 2013). The uptake of offsite activities by SMEs is slow.

Some of the reasons for this slow development are the lack of public demand (due to issues related to perception of timber construction and the phenomenon called "circle of blame"[1]) and the lack of trust in offsite methods from financial institutions, which do not view this emerging industry as well-established or as reliable as onsite construction methods (UKCES, 2013). This situation translates into difficulty obtaining mortgages and investments. Relating to this issue is the difference in cash-flows at different stages: offsite construction normally requires a substantial input of cash at the beginning, when the components must be ordered and produced, but this is mitigated by a faster pace of construction onsite, as compared to projects carried out completely onsite which require a constant influx of capital (Owen, 2007; Hairstans, 2010a).

The supply chain is also affected by high fragmentation, meaning that materials come from a diverse range of sources. This, coupled with a scarce level of internal

---

[1] See SECTION 2.6.

collaboration, results in difficulty promoting domestic production and streamlining importation and exportation routes (BIS, 2013).

Fragmentation is also reflected in the fact that many offsite projects are one-off commissions; this situation affects the ability of customers to take advantage of a shared knowledge base. In addition, the UK supply chain for offsite systems in particular is still considered relatively immature (Miles and Whitehouse, 2013).

The UK construction industry in general is affected by a lack of awareness of the possibilities of exporting materials, as noted by the Department for Business, Innovation and Skills (BIS) (2013). Exportation of offsite materials is common practice in Austria and Germany; in order to become a competitive market for both exportations and domestic demand and encourage business growth, the UK needs to increase the number of manufacturing facilities (Goulding and Arif, 2012) and address the issue of skills shortage.

2.3.3 Categorisation of offsite levels

A categorization of offsite construction has been proposed (Hairstans and Sanna, 2017) in order to understand the different types of products offered by the market.

Offsite construction offers two-dimensional elements (such as panels for walls, floors or roofs) and three-dimensional ones (also known as "volumetric construction", where whole pods are delivered to the construction site after assembly in the factory). The Scottish offsite industry offers mostly 2-D elements.

Hairstans and Sanna (2017) distinguish four categories according to the level of completeness before they reach the construction site: **subcategory 0** groups panels or pods without insulation layer and with their first skin on one side only, *e.g.,* an orientated-strand board (OSB) sheet; **subcategory 1** designates insulated panels or pods without finished linings; **subcategory 2** indicates elements which are finished on either the inside or the outside; finally, **subcategory 3** consists of panels and pods which are fully finished both internally and externally. Products belonging to subcategory 0 are the most common in the Scottish market.

Pan *et al.* (2005) and Smith *et al.* (2013) reveal that most companies in the UK produce 2-D elements (subcategories 0 to 1) and a quarter of them have started producing volumetric modules (subcategory 3).

Despite common belief, manufacturing modular construction does not necessarily require extremely-high technology (Mitchell and Hurst, 2009). In the United States, raw materials are transported manually in most cases, sometimes with a joist transport cart ("joist dealer"). Operations such as sizing raw material to obtain studs, sheathing and joists are done manually with circular, cut-off or panel saws. Similarly, simple equipment is used for nailing (manual nail-guns and pneumatic screw-drivers). Crane are often used to move subassemblies, while modules being manufactured are pushed by either a line-pusher or manually, with rollers, tracks or air pads (Mitchell and Hurst, 2009).

FIGURE 2.5 Offsite manufacturing of timber-frame panels at CCG (OSM) Ltd, Glasgow.

FIGURE 2.6 Plasterboard sheathing being added to the timber frames.

FIGURE 2.7 Insertion of mineral-wool quilts in between studs (left) and stapling of the vapour-control layer (right).

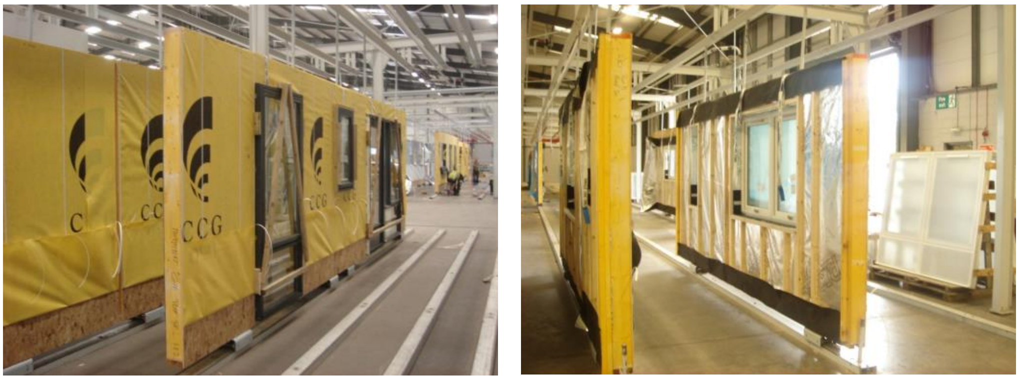

FIGURE 2.8 Panels fitted with doors and windows: the outer face is protected by a breather membrane (left); the interior side shows timber battens for a service cavity (right).

FIGURE 2.9 Panels wrapped in impermeable materials awaiting transportation to the construction site (left); positioning of the panels by crane, on site (right).

The level of automation in production processes is also an important tool to categorize offsite construction. Mitchell and Hurst (2009) have identified three levels of automation:

- manual production;
- semi-automated production;
- fully-automated production.

FIGURE 2.10 Example of manufacturing facilities with a semi-automated production process (GGC (OSM) Ltd, Glasgow).

In semi-automated factories, computer-numerical-control (CNC) routers are employed for sizing the panels and are connected to the factory's network. Thus, the operators can download the programs onto the router without leaving the workstation.

CNC machines are used to cut timber elements to length, drill holes (through which wires and pipes will be run) and notch the members. CNC machines guarantee high precision and time saving, in comparison to the equivalent manual operations.

FIGURE 2.11 Example of smaller manufacturing facilities with a manual production process (MAKAR, Inverness).

In fully-automated factories, the cut elements are transferred onto a conveyor system that temporarily stores them, until they are needed by other machinery for the next fabrication phase. Fully-automated facilities require very large capital investment, which can be very risky, due to the cyclic nature of the housing market.

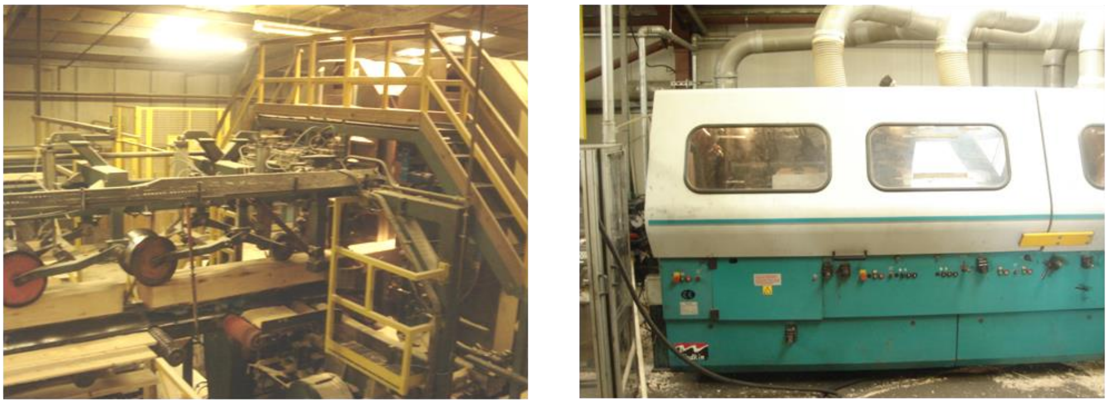

FIGURE 2.12 Example of a fully-automated sawmill (BSW Timber Ltd, Boat of Garten).

2.3.4 Advantages and disadvantages of offsite construction

There is wide agreement among scholars that, in comparison with onsite methods, offsite construction offers advantages such as lower environmental impacts, greater resource efficiency and improved waste management.

The lower environmental impacts are improved when timber is used, a natural resource that does not *generally* require as much processing as concrete or steel, and allows for reduction of onsite operations. Lower processing, in turn, translates in lower greenhouse-gas emissions or energy use. In addition, Owen (2007) and Hairstans (2010a) remind that trees contain banks of CO_2 absorbed during their growth, which might help reduce CO_2 emissions if accompanied by proper management of forests.

Related to sustainability is the issue of resource efficiency. SECTION 2.4 discusses resource management in construction in relation to waste and lists studies that demonstrate that offsite construction generates less waste. Another important consideration is speed of construction, as offsite techniques require less time due to prefabrication of components (Owen, 2007; Hairstans, 2010a). Smith *et al.* (2012) reveal that the main drivers for offsite construction are transport, plant layout to improve workflows and better design practice that lowers the production of defective parts and waste. Sustainability does not rank high amongst the advantages of offsite construction according to this study. However, some construction companies deem sustainability as one of the main reasons to adopt MMC. Skills shortage, time and cost certainty, high quality and reducing on-site duration are listed by Pan *et al.* (2005) amongst the additional incentives for switching to offsite construction. It is also believed that better working conditions outside construction sites would encourage gender diversification (Hairstans and Sanna, 2017).

However, some disadvantages of offsite construction have also been noted; for instance, it requires a new set of skills for architects and builders (Poon *et al.*, 2004; Owen, 2007; Hairstans, 2010a). As Hairstans (2010b) points out, there is a need to achieve a balance between standardisation of components and design requirements affected by the location and intended usage of a building.

Forster *et al.* (2015) argue that MMC need appropriate structural testing to avoid the mistakes incurred during the erection of post-war, prefabricated houses.

Fluctuations in the market, lack of investment and low demand constitute barriers to the growth of offsite construction (Smith *et al.*, 2013; Pan *et al.*, 2005). The higher economic costs associated with offsite construction are also reported to be one of the main obstacles to its development (Goodier and Gibb, 2007; Homes for Scotland, 2015). Ignorance about the supply chain and the fact that construction companies prefer to rely on the knowledge they already possess rather than engaging in innovation also hinder the development of offsite (Lu and Liska, 2008; Homes for Scotland, 2015).

Research carried out by the Scottish Government (2010b) identifies investment costs, poor information and inertia with regard to innovation as the main barriers for the adoption of MMC. Interestingly, an apparent discrepancy between the energy performance of a building as promised on the design stage and its actual energy performance when completed is seen as an important factor against acceptance of MMC (Scottish Government, 210b).

2.3.5 The context for research and development

Difficult times such an economic recession tend to inspire innovative thinking and the development of new solutions that have the potential to improve a company's profile in the market and justify new investment (Buildoffsite, 2015). Some of today's innovation focuses on offsite construction methods.

Lean production is very important within the context of offsite construction and is essentially concerned with the elimination of waste in all forms (Hairstans, 2010a). An in-depth understanding of the product and its manufacturing process is the first step to eliminate all the activities that do not add value to the product itself, to create processes that are more efficient.

The principles of lean are nowadays accepted in most of the industrial sectors. Lean theories lead to increased productivity and product quality. The construction industry is slower in applying these principles (Buildoffsite, 2015) in comparison to other sectors.

This is because innovation in this field tends to occur in the delivery of a particular project.

Edinburgh Napier University's Centre for Offsite Construction and Innovative Structures (COCIS) has carried out extensive research into the structural performance of wood produced in Scotland. Investigation from COCIS has included the re-engineering techniques, which allow the use of lower-grade materials, thus making the most of locally-available resources. Although manufacturers of these products are in hard competition with their international counterparts, there is scope for import substitution and for adding value to local timber.

In 2014, the Construction Scotland Innovation Centre (CSIC) was launched with the collaboration of Scottish universities, the Scottish Government (through Scottish Enterprise and Highlands and Islands Enterprise) and local businesses. Its main objective is to drive the development of innovative construction in Scotland, including offsite techniques (CSIC, 2017).

2.4 Wastage of building materials

According to the UK latest statistics (DEFRA, 2016b), 202.8 million tonnes of waste were generated in 2014, which represents an increase of 4.6% from 2012. Waste from construction and demolition as well as excavation represented a share of 59.4% in 2014, as compared to 56.2% in 2012 (see FIGURE 2.13).

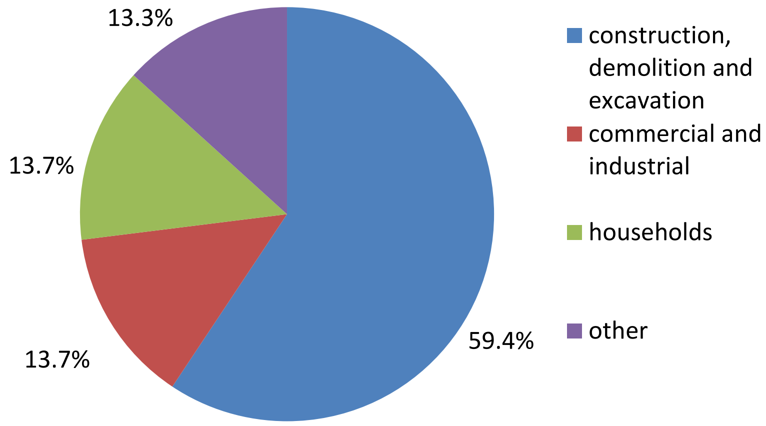

FIGURE 2.13 Waste-generation share in 2014, by sector, based on data by DEFRA (2016b).

Statistics from BRE (2016) and the Chartered Institute of Building (CIOB) (2007) confirm that the construction industry is the main source of waste in the UK. BRE forecasts a yearly waste from construction and demolition of 32%. CIOB (2007) estimates that the construction industry uses around 400 million tonnes of materials and generates 109 million tonnes of waste *per annum*.

Given the prominence of the construction industry in waste generation, this sector has become a top priority in relation to waste reduction for DEFRA and BREW (Business Resource Efficiency and Waste). Not only does waste from construction have vast environmental impacts due to emissions from incineration processes and landfill (BRE, 2016; DEFRA, 2016b), but it also has economic implications due to the issue of poor resource efficiency, which sees 13% of the approximate 400 million tonnes of materials produced or purchased by the sector each year go into skip without being used (CIOB, 2007). BRE (2008) estimates that the economic value of construction waste totals £1.2 billion a year. This issue of resource efficiency links to the LCA way of thinking, as waste should be part of an overall environmental assessment of the construction industry (BRE, 2008).

2.4.1 Waste streams

The construction industry generates waste at several stages: during the production of building components, waste resulting from demolition of existing structures for preparation of a construction site, excavation waste (*i.e.,* resulting from preparatory digging and excavation of foundation, basements and tunnels, mostly consisting in soil and stones), construction waste (any waste arising during the construction stage) and end-of-life waste (resulting from refurbishment, deconstruction and demolition). Only waste arising from the production of building components (as one of the environmental parameters of an EPD, as explained in SECTION 2.6.6) and waste generated during the construction stage as a result of over-ordering or damage (taken into consideration for bill of quantities and the LCA's sensitivity analysis) are considered in this thesis.

The waste generated during the construction stage consists of several kinds of materials. TABLE 2.3 provides a breakdown of waste by materials, according to three sources. Although these statistics differ, they all show that packaging tends to be the highest source of waste and that timber usually ranks quite highly

TABLE 2.3 Breakdown of waste by building material, according to three sources.

Material	**Bibliographical source**		
	Welsh School of Architecture (2008)	**Hurley *et al.* (2003)**	**Williams and Turner (2011)**
plasterboard and chipboard	38%	/	/
packaging	23%	26%	24%
cardboard	20%	/	/
insulation materials	10%	2%	4%
timber	4%	19%	13%
soil, masonry, bricks, rubble, asphalt, sand and stone	2%	11%	27%
plastic and rubber	3%	13%	6%
concrete	/	6%	10%
plastic and cement	/	3%	/
ceramic	/	3%	6%
metal	/	3%	5%
miscellaneous (incl. glass)	/	14%	5%
TOTAL	100%	100%	100%

The construction industry, whether offsite or onsite, purchases more materials than the amount that is incorporated into the finished building. This issue has a double environmental effect: management of waste (briefly discussed below) and effects on emissions due to the production of larger quantities of materials than needed.

Data on the percentage of each individual material that goes to waste is scarce and difficult to find. A study by Guthrie *et al.* (1999) – carried out on behalf of the Construction Industry Research and Information Association (CIRIA) – explored the material-management practices of fourteen construction sites from different sectors (including a domestic one) and offers the most co (prehensible figures to date. Reports by the Waste and Resources Action Programme (WRAP) (2008-2009) have also been useful, as they offer general estimates on waste.

2.4.2 Causes for waste

Waste is generated throughout the building project. Although some authors (Innes, 2004; Osmani *et al.*, 2008) speculate that the high amount of construction waste might be partially due to lack of resource-aware design, most authors (Bossink and Brouwers, 1996; Faniran and Caban, 1998; Poon *et al.*, 2004) agree that it is mostly generated during the construction phase.

A review of the literature shows that waste during construction is due to the following factors:

- contractual aspects and errors in communication (Keys *et al.*, 2000);
- lack of knowledge of construction techniques by designers (Chandrakanti *et al.*, 2002; Osmani *et al.*, 2008);
- changes in design (Poon *et al.*, 2004);
- procurement: ordering errors, supplier errors, mismanagement of quantities (Guthrie *et al.*, 1999; Poon *et al.*, 2004);
- damage during transportation (Guthrie *et al.*, 1999; Poon *et al.*, 2004);
- incorrect material storage and handling leading to damage (Guthrie *et al.*, 1999; Poon *et al.*, 2004; Osmani *et al.*, 2008);
- equipment malfunction (Bossink and Brouwers, 1996);

- poor craftsmanship (Chandrakanti *et al.*, 2002; Dajadian and Koch, 2014) and work practices by sub-contractors (Saunders and Wynn, 2004);
- unused materials and products (Bossink and Brouwers, 1996; Poon *et al.*, 2004);
- off-cuts (Osmani *et al.*, 2008);
- staff attitudes and culture (Teo and Loosemore, 2001; Jayamathan and Rameezdeen, 2014);
- other: weather, vandalism and theft (Poon *et al.*, 2004; Osmani *et al.*, 2008).

In terms of the research undertaken for the present cradle-to-gate study, the most significant aspects that affect waste in the production stage are damage of products due to transportation and poor storage, off-cuts and unused materials.

2.4.3 Influence of construction methods on wastage levels

Research undertaken by WRAP (2008 and 2009) demonstrates that offsite timber construction tends to generate less waste than traditional onsite construction. In a case study that analyses 37 dwellings made using semi-closed panel timber frame, WRAP (2009) observed a reduction of waste of 27.3%. This reduction was especially noticeable in waste due to design changes (from 1.32% of waste to 0.63%) and off-cuts (from 12.21% to 9.72%). Estimates by WRAP (2007) reveal the following waste-reduction ranges for MMC: 20%-40% for timber-frame systems (depending on level of prefabrication), 50%-60% for OSB SIPS and 20%-30% for composite panels.

Broadly speaking, offsite techniques grant better management of resources due to the controlled nature of workflows within factories and design specifications (WRAP, 2007, 2008 and 2009). This argument is supported, for instance, by a case study according to which Stewart Milne Timber Systems – one of the largest offsite timber-frame construction companies in the UK – has reduced waste of orientated-strand board (OSB) from 16% to 8% in the last five years. Research undertaken by Begum *et al.* (2010) and Monahan (2013) also concludes that offsite construction generates less waste.

Williams and Turner (2011) prove that small-scale construction firms tend to generate a considerable amount of waste due to working practices that disregard the economic benefits of controlling surplus of materials and lack of efficient resource-control strategies. Conversely, some authors (Saunders and Wynn, 2004; Jayamathan and

Rameezdeen, 2014) have also warned about the effects that the working practices of sub-contractors might have on the level of wastage from big companies.

2.4.4 Waste-related legislation and initiatives

Directive 2008/98/EC regulates waste produced in EU countries. This piece of legislation defines waste as "any substance or object which the holder discards, or intends or is required to discard" (§ 3.1). It also identifies special categories for "hazardous waste", "waste oils" and "biowaste".

The other major aspect of this piece of legislation is the introduction of the hierarchy of waste, which prescribes actions to avoid resorting to the solutions with the heaviest environmental impact: recycling and landfill disposal (FIGURE 2.14).

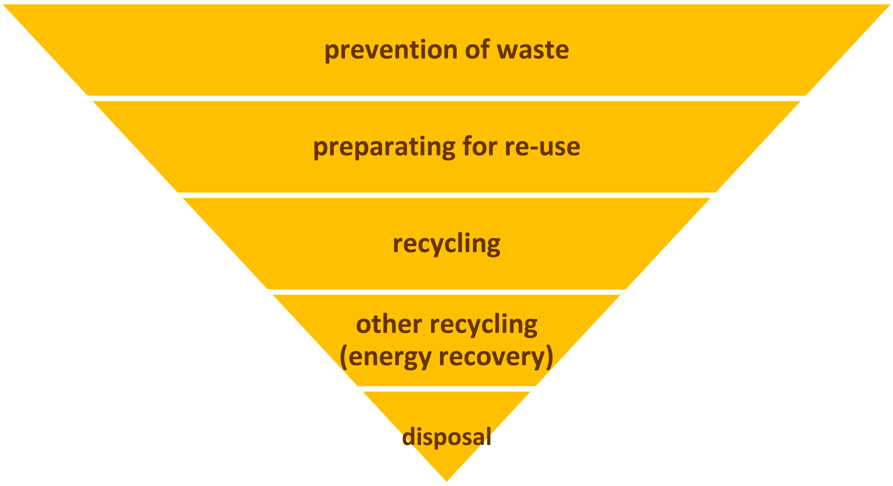

FIGURE 2.14 Waste hierarchy, according to directive 2008/98/EC.

Another important legal obligation under EU law is the European List of Waste (LoW), defined by Commission Decision 2000/532/EC. These regulations provide a classification framework for waste, which all companies must adhere to when declaring discarded material.

Directive 1999/31/EC lists the following categories of waste: municipal waste, hazardous waste, non-hazardous waste and inert waste. Consequently, EU states must be equipped with hazardous, non-hazardous and inert waste-disposal units. The following materials must not be accepted into landfill: liquid waste, flammable waste, explosive or oxidising waste, hospital and other clinical waste that is infectious and used tyres, with some exceptions.

In the UK, apart from EU legislation, the *Environmental Protection Act 1990* contains regulations which define lawful and unlawful disposal of waste.

The *Waste (Scotland) Regulations 2012* require all business to present a separate disposal collection for metal, plastic, glass, paper and card and municipal authorities must implement a ban on biodegradable waste by 2021 and provide sufficient recycling services for households.

There are several organisations that advocate the reduction of waste in the UK. Zero Waste Scotland works alongside the Scottish Government to promote reduction of waste and to increase the publication of research on waste and resource efficiency. The Waste and Resources Action Programme (WRAP) publishes research and promotes a circular economy, where waste is reduced through reutilisation and recycling. One of their three priority areas is the construction industry.

2.5 UK climate: trends and projections

Several international and national regulations that aim to reduce emissions have had an effect on UK's climate:

- the **Montreal Protocol** (effective from 1989): phasing-out of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) that deplete the stratospheric ozone;
- the **Gothenburg Protocol** (effective from 1999): control of acidification and eutrophication through reduction targets for emissions of sulphur dioxide, nitrogen oxides, volatile organic compounds and ammonia;
- the **Kyoto Protocol** (effective from 2005): control of global warming through reduction of greenhouse emissions by 2020. The **Paris Agreement** (2015) will substitute the Kyoto Protocol from 2020;
- **National Emission Ceilings Directive (NECD)** (Directive 2016/2284) (2016): setting of reduction targets for emissions of sulphur dioxide, ammonia, volatile organic compounds, nitrogen oxides and fine particulate matter in the EU. These targets should be achieved by 2030;
- the **Climate Change Act 2008**: setting of a reduction target of 80% lower than 1990 emissions for greenhouse gases in the UK.

In the UK, the National Atmospheric Emissions Inventory (NAEI) produces a yearly report on air pollutants. The UK has experienced a steady reduction of harmful emissions, especially of GHGs, sulphur and nitrogen. However, the decrease in emissions has stalled in the last decade and the emissions of ammonia have increased, meaning that completely reducing emissions to pre-1990 levels is proving difficult. It should also be noted that global emissions of GHGs are not being reduced and, consequently, global warming is still a risk.

The Climate Change Act 2008 mandates an 80% reduction of carbon emissions against 1990 levels by 2050. The Committee on Climate Change (CCC) was also established under this act.

The reduction of carbon emissions is achieved through carbon budgets that set the maximum allowed emissions in periods of five years. The current budgets are as follows (CCC, 2017):

- 1st Carbon budget (2008-12): 3,018 $MtCO_2eq$ (23% reduction achieved);
- 2nd Carbon budget (2013-17): 2,782 $MtCO_2eq$ (29% reduction achieved);
- 3rd Carbon budget (2018-22): 2,544 $MtCO_2eq$ (35% reduction by 2020);
- 4th Carbon budget (2023-27): 1,950 $MtCO_2eq$ (50% reduction by 2025);
- 5th Carbon budget (2028-32): 1,765 $MtCO_2eq$ (57% reduction by 2030).

The UK is also legally obliged to comply with the *European Union Emission Trading Scheme* that sets caps on emissions from several economic activities (Directive 2003/87/EC).

DECC (the Department for Energy and Climate Change) publishes a yearly update on energy and emissions projections, the latest available update (2015) states that the UK has achieved the 1st and the 2nd carbon budget and is projected to achieve the 3rd budget. However, the 4th budget is at risk of not being met. Projections from DECC indicate that, although the emissions of CO_2 in the UK are generally decreasing, the reduction rate if slowing down and domestic emissions are expected to rise (see FIGURE 2.15). The increase in domestic emissions of CO_2 has also been noted by the CCC (2013), which reports a 12% increase in emissions from residential dwellings, in 2012. Furthermore, the World Meteorological Organisation (WMO) reports a yearly global increase of greenhouse gases, especially CO_2 (WMO, 2016), as shown in FIGURE 2.16. These statistics describe a situation in which global emissions that contribute to climate change are far from the desired low levels.

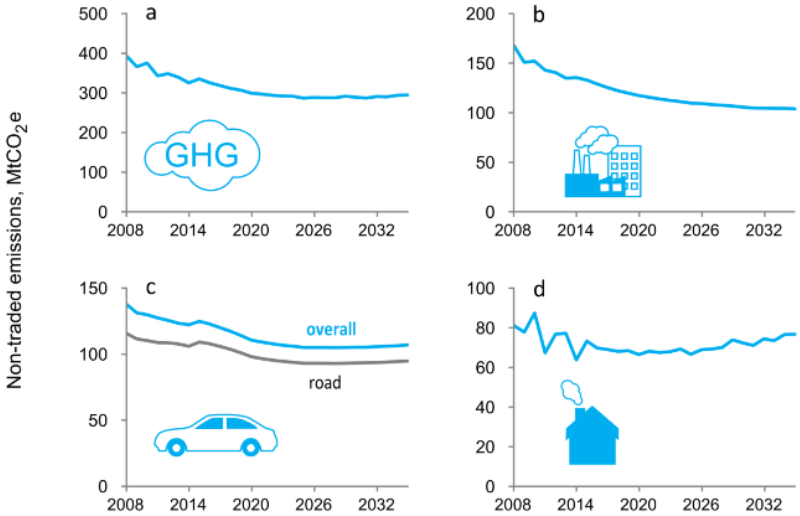

FIGURE 2.15 Predicted emissions of CO_2-eq. by economic sector, for the 2008-2035 period: a) total emissions; b) emissions from industry, services and agriculture; c) emissions from transport; d) emissions from the domestic sector. Image source: DECC, 2015.

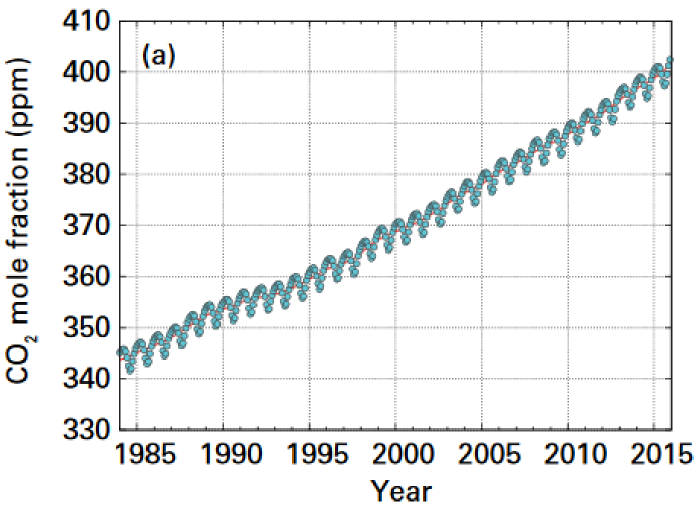

FIGURE 2.16 Global CO_2 emissions in mole fractions. Image source: WMO, 2016, p. 3.

The *UK Climate Change Risk Assessment 2012 Evidence Report* (DEFRA, 2012) lists the building sector as one of the areas of economic activity where climate change will have a great impact. According to forecasts from DEFRA (2012), extreme weather events (such as heavy rainfalls and floods) are likely to be the biggest threat to buildings in the short term (2020s); while higher temperatures and overheating are deemed the main risks for buildings in the long term (2050s and 2080s).

2.5.1 Global warming in the UK

Global warming (one of the effects of climate change) in the UK has been recorded by UKCP09 (UK Climate Projections), a tool used by the Met Office to forecast climate trends. The latest statistical release from UKCP09 (2009) estimates that all regions in the UK have experienced an increase in average annual temperatures between 1.0 and 1.7 °C, from 1961 to 2006. Eastern Scotland, where the thermal tests for this study took place, has experienced an increase of 1.34 °C for summer mean temperatures.

UKCP09 (2009) also offers predictions for potential temperature increases by the 2020s, 2050s and 2080s (see FIGURE 2.17). These predictions are based on three probability levels: 10%, 50% and 90%. This means that changes in temperature below the 10% probability level or above the 90% probability level are 10% likely, whilst the 50% probability level represents the medium range. FIGURE 2.18 offers a geographical distribution of temperature changes in the UK by the 2080s, using the aforementioned probability levels.

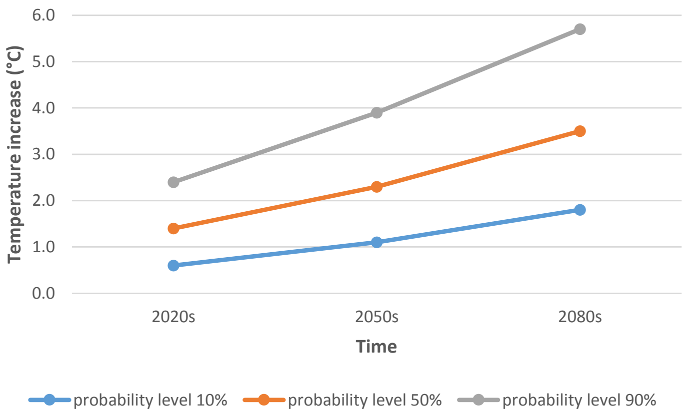

FIGURE 2.17 Temperature-increase projections with a medium level of emissions for Eastern Scotland. Data from UKCP09 (DEFRA and DECC, 2009).

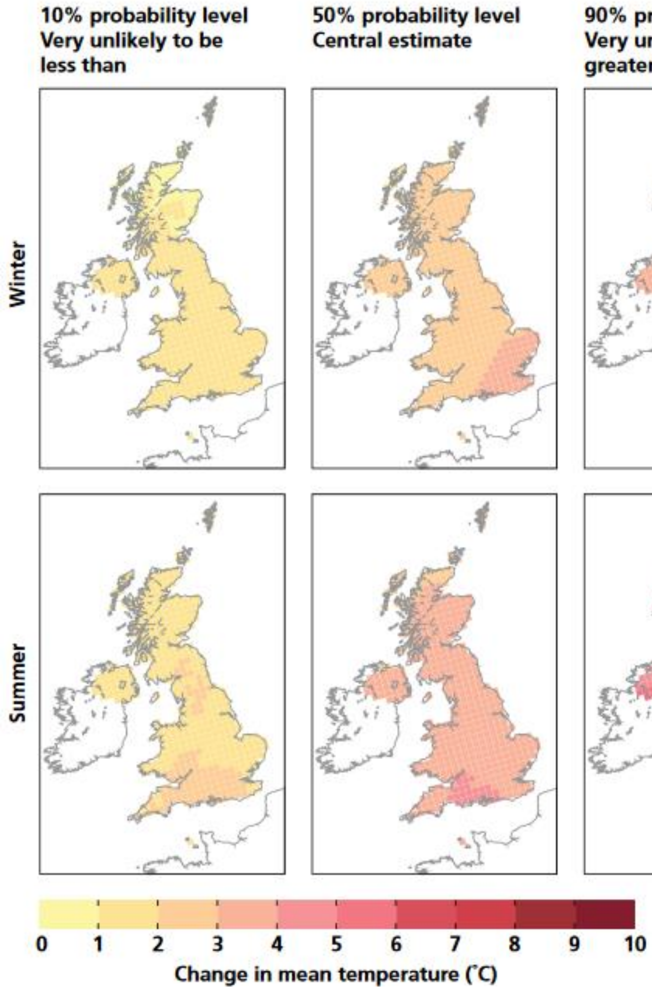

FIGURE 2.18 Estimated changes in temperature in the UK, by 2080. Image source: Jenkins et al. 2009, p. 29.

This rise in temperature translates in a need to design dwellings for warmer summers and insulate houses from hot as well as cold weather. Indeed, overheating of buildings is one of the key future long-term risks forecast by DEFRA (2012). A report by the Zero Carbon Hub (2015) raises concerns about the possibility that certain risk factors might lead to overheating during the summer months. Some of these risk factors are orientation (West-facing windows tend to experience overheating), type of properties, position of insulation layer(s) and behaviour of dwellers (especially in relation to ventilation). FIGURE 2.19 offers a visual representation of these factors.

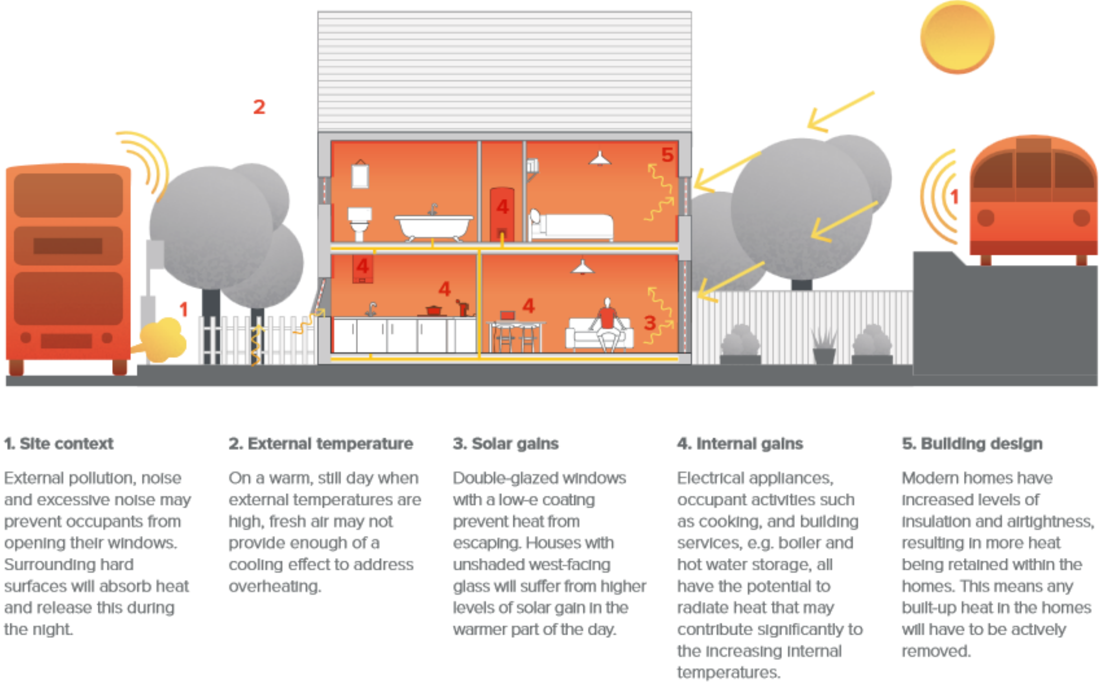

FIGURE 2.19 Causes of overheating. Image source: ZHB, 2015, p. 13.

2.5.2 Impact of solar radiation on buildings

The greenhouse effect keeps some of the energy emitted within the earth's atmosphere, rather than letting it release into space. Depletion of the stratospheric ozone layer during much of the 20th century has also had an impact on solar radiation, since the ozone layer is capable of absorbing UV (ultraviolet) light and, thus, of protecting the earth from harmful levels of UV. Although the stratospheric ozone layer is gradually recovering to pre-1980s levels, UV is expected to remain relatively high, especially in the southern hemisphere (Bais *et al.*, 2011).

A study by Tham *et al.* (2011) reveals there is going to be an increase of 100 W·h/m^2 in solar radiation in Edinburgh during the summer months, according to projections for the 2080s by UKCP09. These projections are compared to data collected from 1976 to 1992 (measured at an Edinburgh location). Solar radiation appears correlated to an increase in dry-bulb temperatures (more than 10°C) for the Edinburgh region by the 2080s. The combined increase of solar radiation (of around 20%) and temperature poses a challenge for the future design of houses.

In another study, Tham and Muneer (2011) investigate the increase of sol-air temperature (T_{sol}) in two locations, Edinburgh being one of them. Sol-air temperature is the outside air temperature that, without the effects of solar radiation, would contribute the same heat transfer through walls and roof as actual air temperature under the effect of solar radiation. Data from UKCP09 and observed local data for Edinburgh (1976-1992) were used. This study concludes that there is going to be an increase of *circa* 13°C sol-air temperature for light horizontal surfaces and 11.5°C for light vertical surfaces by the year 2080 (FIGURE 2.20).

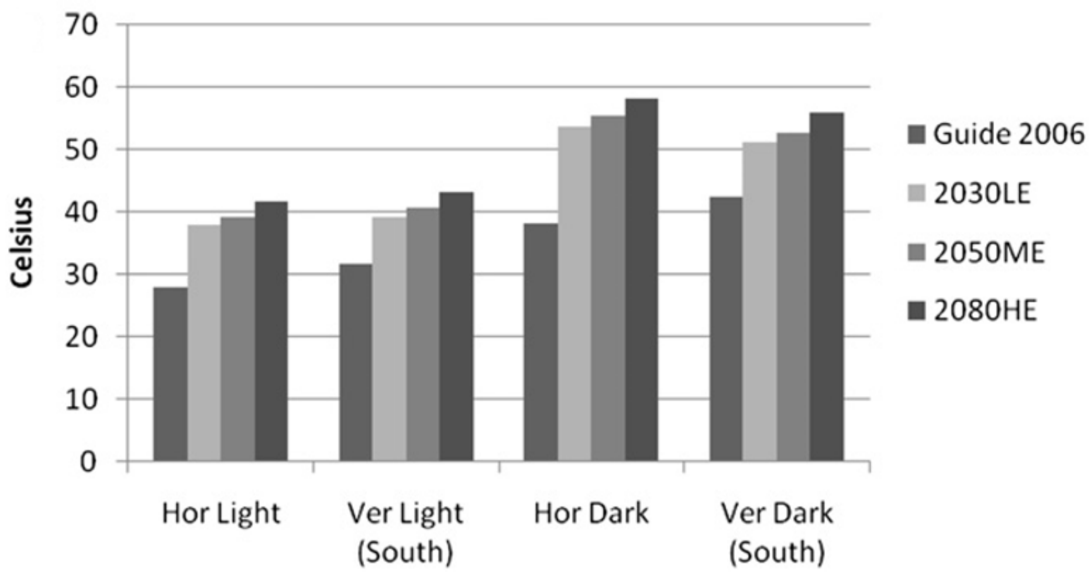

FIGURE 2.20 Sol-air temperature projections at 13:00 hours in Edinburgh. Image source: Tham and Muneer, 2011, p. 1247. "Guide 2006": CIBSE Guide A 2006; "LE": low emission; "ME": medium emission; "HE": high emission; "Hor": horizontal surface; "Ver": vertical surface.

2.6 The Life-Cycle Assessment (LCA) approach

2.6.1 Life-cycle Thinking

Life-cycle assessment (LCA) emerged as a response to an identified need to control waste produced by packaging and the realisation that resources are limited (Baumann and Tillmann, 2004; Huppes and Curran, 2012; Klöpffer and Grahl, 2014).

LCA is part of the wider life-cycle thinking (LCT), in which issues of design, cost, management and the environment are taken into consideration in relation to the whole life-span of a product. This approach relates to the need to find more sustainable production systems (UNEP and SETAC, 2016). In 2002, the United Nations Environmental Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) joined forces to launch the life-cycle initiative that promotes LCT amongst governments and industry.

Other developments in life-cycle studies (Rebitzer, 2015) advocate expanding the scope of LCA to include social and economic aspects, upstream (supply chain) and downstream (customers, services) activities, and linking sustainability management with business value (a development that was already echoed by Steger in 1995). Linnanen (1995) was the first author to propose a framework that included those aspects in a systematic way; he proposed a life-cycle management (LCM) method with three areas of influence: management and decision making of a company, engineering and product design and, finally, leadership and organization culture.

Another approach within life-cycle thinking is the inclusion of environmental factors into the design stage in what is called life-cycle design (LCD). LCD is composed of several strategies (Vezzoli and Manzini, 2008): minimisation of material and energy consumption, selection of low-impact processes and resources, optimisation and extension of a product's life span and facilitation of disassembly. Westkämper *et al.* (2000) contribute the concept of life-cycle costing (LCC), which assesses the costs of manufacturing, usage and service, and recycling and reuse.

Moreover, all stakeholders should be involved in the production process (Steger, 1995; Linnanen, 1995; Westkämper *et al.*, 2000; UNEP and SETAC, 2016). Involving different people and organisations with their own perspectives and priorities is not always straightforward, due to the influence of the so-called circle of blame (RICS, 2008; Sedlacek and Maier, 2012; Andelin *et al.*, 2015; Rauland and Newman, 2015). Applied to the construction industry, the circle of blame is a vicious circle whereby the blame on lack of widespread sustainable housing is shifted between consumers, builders, developers and investors (see FIGURE 2.21).

FIGURE 2.21 The circle of blame applied to the building industry, regarding lack of sustainability.

2.6.2 LCA principles

The early 1990s saw the birth of the first systematic life-cycle framework, proposed by the Society of Environmental Toxicology and Chemistry (SETAC) (Klöpffer and Grahl, 2014, p. 9), and early methods for the assessment of environmental impacts such as Swiss Ecopoints or the one proposed by CML,[2] which added additional layers to the analysis of emissions (Hauschild and Huijbregts, 2015). However, the first truly international standards came with the publication of ISO 14040, *Life Cycle Assessment.*

[2] CML stands for *Centrum voor Milieuwetenschappen*, the Dutch name for the University of Leiden's Institute of Environmental Sciences.

Principles and framework, in 1997 and successive documents (known as "the ISO 14040 series"), as shown in TABLE 2.4.

TABLE 2.4 The ISO 14040 series on LCA.

Standard number	Title	Date	Status
ISO 14040	Life cycle assessment – principle and framework	1997	Current: revised 2006 version
ISO 14041	Life cycle assessment – goal and scope definition and inventory analysis	1998	Withdrawn, replaced by ISO 14044
ISO 14042	Life cycle assessment – life cycle impact assessment	2000	Withdrawn, replaced by ISO 14044
ISO 14043	Life cycle assessment – life cycle interpretation	2000	Withdrawn, replaced by ISO 14044
ISO 14044	Environmental management. Life cycle assessment. Requirements and guidelines.	2006	Current
PD ISO/TR 14047	Environmental management. Life cycle assessment. Illustrative examples on how to apply ISO 14044 to impact assessment situation.	2003	Current: revised 2012 version
DD ISO/TS 14048	Environmental management. Life cycle assessment. Data documentation format.	2002	Current
PD ISO/TR 14049	Environmental management. Life cycle assessment. Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis	2002	Current: revised 2012 version

ISO 14040 defines LCA as the "compilation and evaluation of the inputs, outputs and the potential environmental factors of a product system throughout its life cycle" (BSI, 2006a, § 3.2).

LCA is based on several principles (BSI, 2006a):

- **absolute or precise environmental** impacts are **not possible** due to the use of reference units, the integration of environmental data over space and time, the inherent uncertainty in modelling of environmental impacts and the fact that some environmental impacts will happen in future;

- LCA takes a **holistic approach**, in that environmental issues are not shifted from one life-cycle stage to another or between environmental impacts (von der Assen *et al.*, 2015);
- LCA takes a **life-cycle perspective** as it takes into account "the entire life-cycle of a product, from raw-material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal" (BSI, 2006a, § 4.1.2);
- only **environmental aspects and impacts** are addressed. Economic and social aspects remain outside the remit of LCA;
- LCA has a **relative approach,** in that it is based on a functional unit;
- LCA is **iterative**: the different stages (explained below) from an LCA study inform one another, so the LCA practitioner might need to move backwards and forwards through the stages to ensure the most accurate interpretation (Hauschild and Huijbregts, 2015);
- **transparency** of LCA studies must be ensured through appropriate documentation;
- LCA aims towards **comprehensiveness** by "considering all attributes or aspects of natural environment, human health and resources" (BSI, 2016a, § 4.1.7).
- **natural science** forms the scientific basis for LCA (BSI, 2016a; Hauschild and Huijbregts, 2015).

2.6.3 Structure of an LCA

There are five stages in an LCA: definition of goal and scope, life cycle inventory analysis (LCI), life-cycle impact assessment (LCIA), interpretation and review and, finally, reporting.

Definition of goal and scope:

The **goal** of the LCA should include intended application, reasons for this study, audience and level of disclosure to the public.

The **scope** of the LCA must then be established with the following elements: product system, function of the product system, functional unit, system boundary, allocation procedures, impact categories selected, interpretation method to be used, data requirements, assumptions, limitations, initial data quality requirements, type of critical review and type and format of report.

The functional unit (FU) is not a measure of the physical product, but of the processes employed to satisfy a certain function (Vezzoli and Manzini, 2008). The services and goods needed to fulfil such a function are called "reference flows" (Jolliet *et al.*, 2016, p. 27).

Life-cycle inventory (LCI):

Jolliet *et al.* (2016, p. 47) define LCI as the quantification of "the various flows of material extractions and substance emissions crossing the system boundary". A helpful summary of the type of data to be included in LCI has been provided by Baumann and Tillman (2004, p. 103): inputs of raw materials and energy use, products, and emissions to water, air and land.

It would not be possible to determine the origin and production emissions of each component of a product system, so it is sometimes necessary to resort to generic data. The *Shonan guidance principles*, edited by Sonnemann and Vigon (2011), gives a set of rules for the creation of generic data in LCA databases. These include validity checks (completeness, plausibility, sensitivity and uncertainty, and consistency), aggregation and documentation.

There are two methods for LCI: the **process-based** and the **input-output approach** (Jolliet *et al.*, 2016). The process-based inventory analysis entails creating a flowchart of core unit processes, and listing, calculating and aggregating all according to the FU. The input/output approach includes associated flows and monetary costs outside product processes, such as banking, research, development and legal services.[3]

[3] An important distinction in LCA studies, especially applicable to the LCI phase, is that between attributional and consequential modelling. There are several definitions in the literature (Finnveden *et al.*, 2009; JRC and IES, 2010; Sonnemann *et al.*, 2011; Pomponi, 2015) for these two concepts, which can be summarised as follows: attributional LCA describes inputs and outputs that might impact the environment to and from the life-cycle of a product and its subsystems in a static way, without considering future possible changes. Consequential LCA, instead, considers how different decisions might affect the outcomes of an assessment.

Life-cycle impact assessment (LCIA)

The purpose of LCIA is to classify the emissions of raw materials into different impact categories.

Each impact category should contain the following elements (BSI, 2006a):

- category endpoints (maximum environmental damage);
- definition of a category indicator for each category endpoint;
- identification of LCI-results that can be allocated to that impact category;
- characterization model and factors.

TABLE 2.5 Classification methods within life-cycle impact assessment (LCIA)

Source	**Impact-category name**	**Sub-category names**	
Klöpffer and Grahl (2014)	general impact category (*e.g.,* greenhouse effect)	mid-point category (*e.g.,* global warming)	damage category (*e.g.,* climate change)
SETAC-Europe (1996, cited in Baumann and Tillman, 2004)	input-related categories (*e.g.,* abiotic resources)	output-related categories (*e.g.,* climate change)	
Jolliet *et al.* (2003)	impact category	mid-point category	area of protection or safeguard subject

Each emission follows a path until it reaches the *endpoint* (or maximum environmental impact): this is called the *impact pathway*.

All inventory results that have similar effects are grouped into an impact category at an intermediary level (Guinée, 2015) or **midpoint category.** The term "midpoint" reflects the fact that these results lie somewhere between the inventory result and the endpoint

In practice, this means that attributional LCAs are based on known impacts of a product system according to a functional unit; whereas consequential LCAs take into consideration changes in demand, monetary fluctuations, mitigation policies or external factors and therefore consider marginal data important. Most LCA studies favour an attributional approach. However, Suh and Yang (2014) argue that the attributional and the consequential approaches are part of a continuum within LCA and should not be considered separate methods.

category. Midpoint indicators represent the impact of an LCI result at a specific midpoint (*e.g.,* greenhouse emissions are calculated in relation to their effect on global warming).

The final step of the impact pathway can be referred to as ***areas of protection*** (Guinée, 2015), ***damage categories*** (Klöpffer and Grahl, 2014) or ***endpoint categories*** (Jolliet *et al.*, 2016), such as human health or environment. This wide variety of names to refer to the endpoint and midpoint effects results is possible due to the lack of prescription by current standards. This lack of naming conventions has also led to the incorrect classification [4] of impacts according to some author. Guinée (2015) warns that uncertainty in the results increases from the midpoint to endpoint categories, as more assumptions are made.

Once the selection of impact categories and their midpoints and endpoints categories have been finalised, the LCIA results should be assigned to an impact category (this stage is called classification). The next step is characterisation, which is defined by ISO 14044 (BSI, 2006b, § 4.4.2.4) as “the conversion of LCI results to common units and the aggregation of the converted results within the same impact category”. A common unit for all emissions is thus obtained. FIGURE 2.22 serves as an example of classification and characterisation of some common emissions.

[4] For instance, Klöpffer and Grahl (2014) highlight that some impact categories might result in two or more endpoint categories, as in the case of “ozone-layer depletion” which can have an effect on both human health (cancer) and the environment.

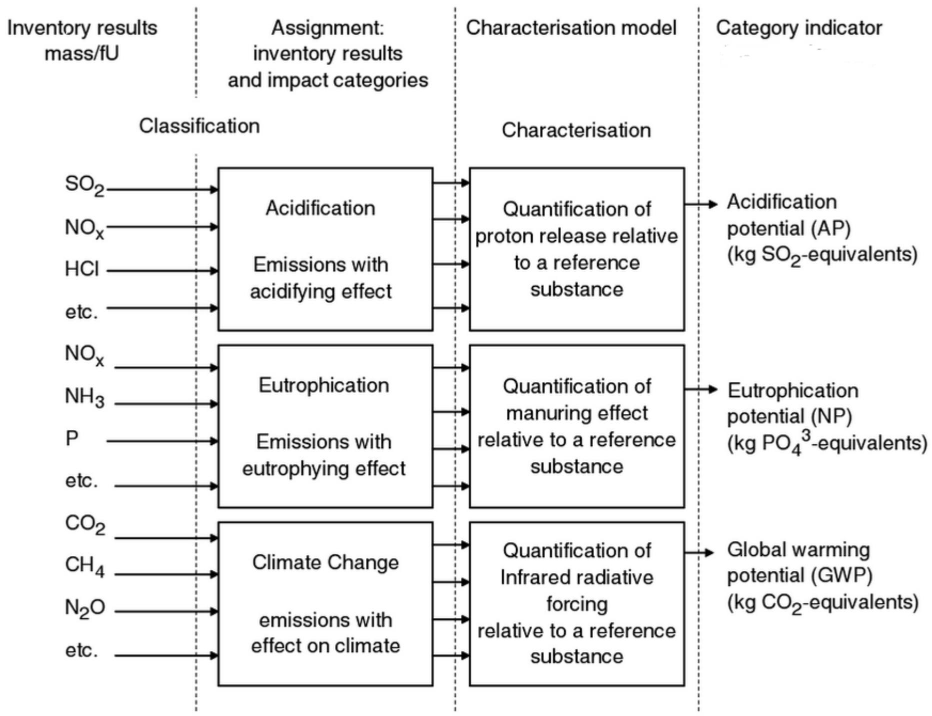

FIGURE 2.22 Example of classification and characterisation in the LCIA phase, for three impact categories: acidification, eutrophication and climate change. Image source: Klöpffer and Grahl, 2014, p. 191.

Impact categories are calculated using potential effects (*i.e.,* acidification potential, eutrophication potential, global-warming potential, *etc.*) because it is not always possible to quantify the full damaging potential of an impact (Hauschild and Huijbregts, 2015). Another important consideration is the concept of *time horizon*: emissions have different life spans; therefore, their effects change over time.

Interpretation

"The purpose of the interpretation phase is to identify the life cycle stages at which intervention can substantially reduce the environmental impacts of the systems of products" (Jolliet *et al.*, 2016, p. 149).

BS EN ISO 14044 (BSI, 2006b, § 4.5) expects interpretation to include an identification of the significant issues based on the results of the LCI and LCIA phases of LCA, an evaluation that considers completeness, sensitivity[5] and consistency checks, and conclusions, limitations, and recommendations.

Reporting and review

The results of the LCA should be reported in "an adequate form to the intended audience, addressing the data, methods and assumptions applied in the study, and the limitations thereof" (BSI, 2006a, § 6).

A report of a complete LCA (*i.e.,* including an LCIA) should contain the following parts: relationship of LCIA with LCI results, description of data quality, category endpoints to be included, and selection of impact categories, characterization model, environmental mechanisms and profile of indicator results.

A review should be carried out to ensure that the LCA offers enough quality data for interpretation and all the stages have been covered (BSI, 2006a, § 7.3).

---

[5] A **sensitivity analysis**, used in this thesis, serves the purpose of testing the effect that key assumptions and data variability have on the results of an LCA study. A sensitivity analysis is necessary in order to address uncertain input parameters or decisions for LCA studies.

According to Cellura *et al.* (2011), secondary data (mostly from well-known databases, as listed in APPENDIX I) give a degree of uncertainty to an LCA study, as the collection methods of the data might not be fully apparent. A sensitivity analysis entails analysing the results, evaluating, and implementing potential changes to the study. This should be done after the first iteration. The framework for sensitivity analysis is outlined in ISO/TR 14049, one of the technical reports that accompany ISO 14044.

The key elements to be considered during a sensitivity analysis are the functional unit, data value inside a range, system boundaries and methodological choices such as allocation and cut-off rules.

Some of the consequences of carrying out a sensitivity analysis may be the exclusion of life cycle stages, sub-systems or material flows (if they lack significance) and the inclusion of new unit processes that have been found to be significant.

A common method for sensitivity analysis is to change the data input for a selected variable by plus or minus a defined percentage (BSI, 2012, § 10.3.2). A percentage range (±%) should then be selected (BSI, 2012a): this should be within the feasible boundaries of the product system. Thus, values are calculated at a lower, a middle and an upper limit. Winiwarter and Muik (2010, p. 22) recommend using a range that contains 95% of all possible values. Jolliet *et al.* (2016) propose varying the parameters between a reasonable maximum and a reasonable minimum.

2.6.4 The CML methodology

There exists ongoing scientific debate about the benefits of selecting midpoint or endpoint categories: whilst midpoint categories are useful to identify reduction targets and measures to implement them, endpoint categories are useful to support decision-making (Kägi *et al.*, 2016). There are several available LCA methodologies, which take different approaches in their selection of impact categories. TABLE 2.6 offers an overview of the CML method, which is prescribed by EN 15804 (BSI, 2014a) for the production of Environmental Product Declarations (EPDs), as seen in SECTION 2.6.6. APPENDIX J offers a summary of other LCIA methods in order to compare them with CML, especially in relation to the selection of impact categories.

TABLE 2.6 Overview of the CML methodology for LCA.

CML methodology		
Created by	**Characteristics**	**Impact categories included**
J. Guinée and R. Heijungs (University of Leiden)	• midpoint approach • spatial reference: ○ global ○ regional (Europe) • time horizon: ○ infinite ○ 100 years for global-warming potential	• depletion of abiotic resources • depletion of biotic resources • land use • desiccation • climate change • stratospheric-ozone depletion • human toxicity • ecotoxicity • photo-oxidant formation • acidification • eutrophication • waste heat • odour • noise • ionising radiation

2.6.5 Normalization and weighting

No product is likely to outperform other products in all category impacts; this fact is likely to result in performance trade-offs (Gloria *et al.*, 2007). In 1992, Norberg-Bohm *et al.* proposed a system to calculate the importance of environmental impacts following a causal structure that started in human activities and ended in consequences to humans and the environment; this resulted in a ranking or weighting system for each environmental impact taking the following factors ("descriptors") into consideration: spatial extent, disturbance to the environment, anthropogenic flux, persistence, recurrence, population exposure, land are exposure, delay, current and future human mortality and morbidity, natural ecosystem impacts, current and future material and productivity losses, recovery period and transnational impact.

It should be noted that the priority of category affects changes over time: the Montreal Protocol (1989*)* ensured that emissions of substances that deplete the ozone decreased, therefore the focus is currently on climate change through the Kyoto Protocol (1992).

ISO 14044 allows weighting as an additional step of the LCIA after normalization and grouping. This is defined as "converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices" (BSI, 2006b, § 4.4.3.1). However, the **CML methodology strongly discourages weighting**.

This variety of methods for normalization and weighting is partly due to the co-existence (also reflected in the characterization methods seen above) of approaches that privilege either midpoint or endpoint categories. Since endpoint categories tend to rely more heavily on assumptions, any normalization of emissions and weighting based on such categories is more likely to be less objective (Guinée, 2015).

2.6.6 Environmental product declarations

2.6.6.1 Origins

The interest in the ecological impact of product systems is not limited to the scientific community, but also extends to the public. In order to improve communication of the environmental value of products, the International Standards Organisation set out the principles for environmental labelling in ISO 14020, which defines environmental labels or declarations as a "statement, symbol or graphic on a product or package label, in product literature, in technical bulletins, in advertising or in publicity, amongst other things" that "indicates the environmental aspects of a product" (BSI, 2001, § 2.1). This broad definition offers companies great freedom in the way they produce eco-labels.

However, ISO tightened the requirements by distinguishing three types of environmental labels in successive standards, as shown in TABLE 2.7.

TABLE 2.7 Types of eco-labelling according to ISO.

Eco-labels according to ISO		**ISO standard**	**Date of publication of standard**
type I	environmental labels and declarations	ISO 14024	2001
type II	self-declared environmental claims	ISO 14021	2001
type III	environmental declarations	ISO 14025	2000

The first two types (especially type II) are less regulated than type III. Ibáñez-Forés *et al.* (2015), reflecting on the concerns raised about the transparency of environmental declarations and its communicability to the general public (TEM, 2010; Directorate-General for Environment, European Commission, 2012), advocate that type-III environmental declarations are the most suitable eco-labelling tool as they allow for comparison between products and include the LCA method. This view is shared by Fet *et al.* (2006) and Zackrisson *et al.* (2008), who highlight the importance of including LCA in the production cycle as the only mechanism that can be applied to the entire production chain. Type-III environmental declarations must be verified by an independent third party and are subject to the administration of a programme operator. The overarching principle of ISO 14025 are comparability and transparency (BSI, 2010, § 5.6), which allow consumers to compare products and understand the limitations of a type-III eco label.

2.6.6.2 Application to the built environment: ISO 21930, EN 15804 and EN 15978

The first application of type-III environmental declarations to the built environment was outlined in **ISO 21930** (BSI, 2007). It is also worth noting that this is the first ISO standard in which type-III environmental declarations are called *environmental product declarations* (EPDs), a naming convention hereafter used in this study.

EPDs might take a cradle-to-gate approach (*i.e.,* until the product reaches the factory's gate, ready to be distributed) or a cradle-to-grave approach (*i.e.,* until the product reaches its end-of-life stage).

In the European Union, ISO 21930 is complemented by standard **EN 15804** (2014a), which was prepared by CEN (European Committee for Standardization) and adds more detail to the categorisation of information modules. FIGURE 2.23 lists all information modules, while FIGURE 2.24 details the processes included in the "product stage", which groups the first three information modules (A1 to A3).

Besides a *functional unit* (one of the main principles of a LCA study, as explained in SECTION 2.6.2), EN 15804 allows the use of a *declared unit* "when the precise function of the product or scenarios at the building level is not stated or is unknown" (BSI, 2014a, § 6.3.2), as in the case of cradle-to-gate EPDs.

Another European standard, **EN 15978** (BSI, 2011), sets out the principles for performing an environmental assessment in the construction industry and states that **EPDs should be used as data sources for LCA studies at the building level** (§ 1).

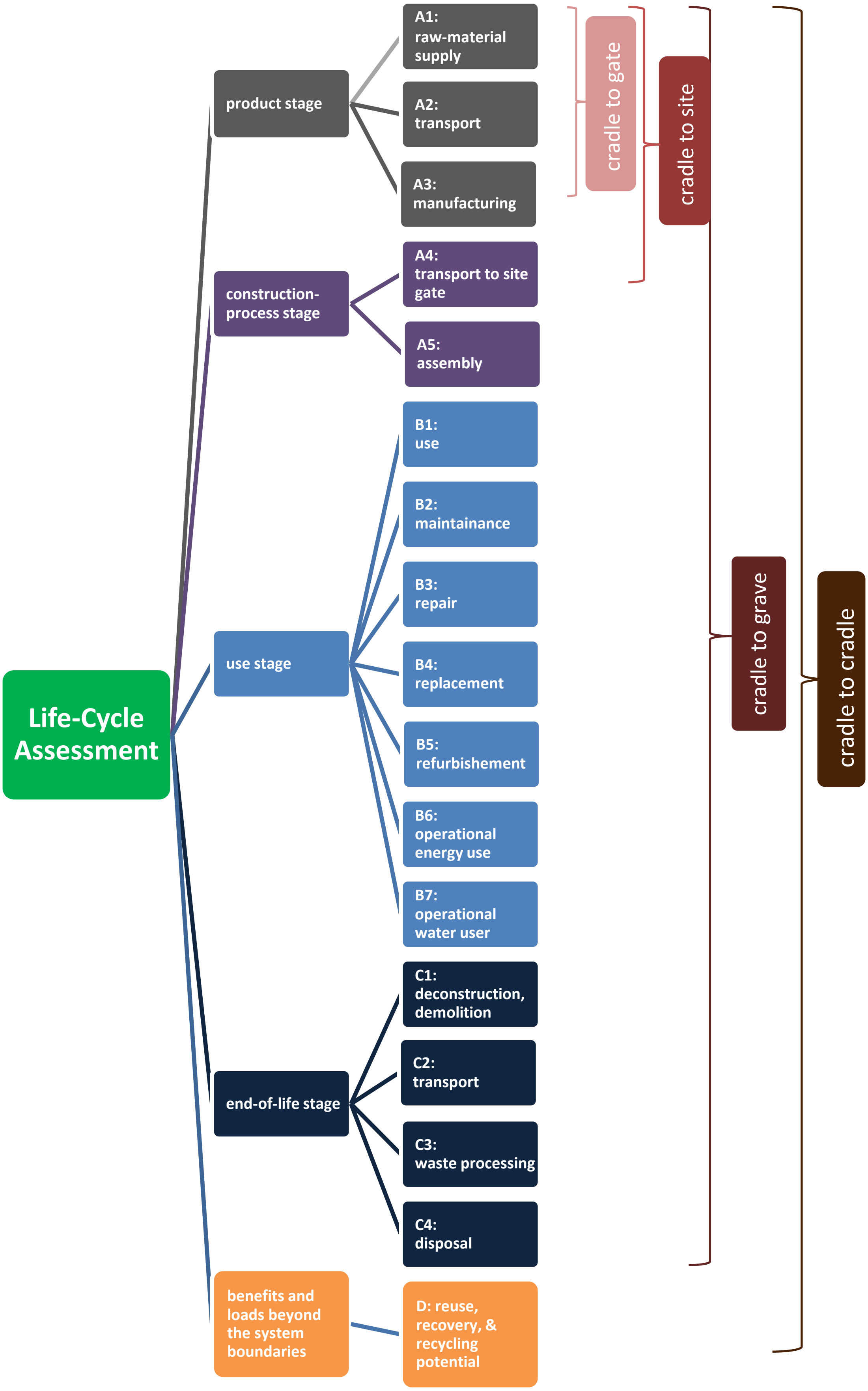

FIGURE 2.23 Information modules for an EPD, according to EN 15804 (BSI, 2014a).

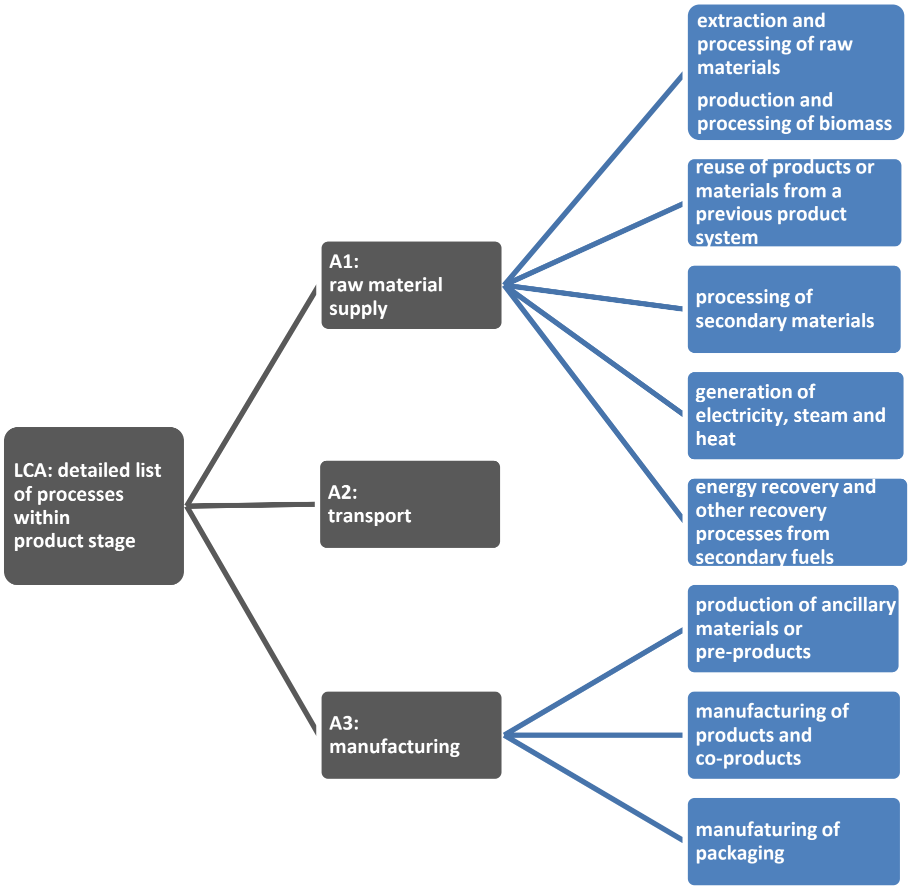

FIGURE 2.24 Processes included within the product stage of an EPD.

Recent efforts towards the harmonisation of EPDs have resulted in the creation of ECO Platform in 2013, with the aim of "coordinating the development of consistent EPD [...] programmes in Europe and stimulating the use of common implementation of the EPD methodology" (ECO Platform, 2013, p. 1). ECO Platform achieves this aim by developing a common EPD core system based on ISO 14025, a common European format[6] for EPDs and a quality-control procedure for verification (ECO Platform, 2013, p. 2).

[6] All EPDs used in this thesis belong to EPD programme holders that are part of ECO Platform (see APPENDIX I).

2.7 Environmental aspects considered in this study

2.7.1 Climate change

Definition

The earth emits infra-red radiation, but absorbs ultra-violet and visible radiation from the sun. Tuckett (2009) highlights that the exchange of energy must be balanced (*i.e.,* equal absorption and emission) for the temperature of the earth to be constant. “Primary greenhouse effect” is a phenomenon whereby naturally-occurring gases (*e.g.,* CO_2, O_3 and H_2O) keep infra-red radiation within the earth’s atmosphere, thus maintaining the average temperature of the planet (Tuckett, 2009).

However, concentrations of greenhouse gases (GHGs), especially CO_2, have increased over the last two centuries, since the advent of the Industrial Revolution. This phenomenon seems to be correlated to an increase in the average temperature of the planet (what could be called “secondary greenhouse effect”).

Apart from carbon dioxide (CO_2), the following gases also contribute to the secondary greenhouse effect (henceforth called “greenhouse effect” for simplicity): methane (CH_4), nitrous oxide (N_2O) and halocarbons (a group of gases containing fluorine, chlorine or bromine). However, it is CO_2 that has had the overall biggest impact on the rise of temperature (IPCC, 2007).

A commonly-used convention for measuring climate change is **radiative forcing**, which measures “the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism” (IPCC, 2007, p. 36). This is calculated as radiation per unit area (W/m^2). The scientific consensus (IPCC, 2007; WMO, 2014 and 2016) is that the radiative forcing caused by GHGs from human activities has a direct effect on climate change.

The building industry is one of the main sources of emissions that cause global warming. In particular, the concrete industry accounts for 7.7% of man-made CO_2 emissions (Hájek *et al.*, 2011). This is mostly due the calcination process and the burning of fossil fuels necessary to produce cement (Marinković *et al.*, 2014). TABLE 2.8 gives a summary of emissions during the production of concrete.

TABLE 2.8 Typical emissions of CO_2 and energy consumption during the production of concrete. Table source: Kjellsen et al., 2005.

Constituent	**Carbon emissions** (kg CO_2)	**Energy consumption**		
		fossil fuel (MJ)	alternative fuel (MJ)	electricity (MJ)
cement	92.3	371.8	117.0	62.4
fine aggregate	2.5	31.7	0.0	1.3
coarse aggregate	2.1	26.5	0.0	8.2
admixtures	1.5	9.1	1.3	0.4
water	0.0	0.0	0.0	0.0
transport	2.5	34.0	0.0	0.0
TOTAL	101.0	473.2	118.3	72.3

Characterisation

Global-warming potential (GWP) is the characterization factor for climate change using the model adopted by IPCC (Intergovernmental Panel on Climate Change) and CML, whereby emissions are considered in relation to their potential to cause global warming.

GHG emissions are normalised against CO_2 emissions with a time horizon of 100 years (IPCC, 2007): this is known as GWP_{100}. Other authors propose shorter time horizons such as 20 years (GWP_{20}) (Maté and Kanter, 2011) or 500 years (GWP_{500}) (UNFCC, 1995). This variability in time horizons is due to the fact that GHGs have different life spans (Tuckett, 2009).

TABLE 2.9 Overview of characterization for climate change.

Aspect	**Definition**
LCI result	greenhouse-gas emissions
characterization model	CML
category indicator	radiative forcing (W/m^2)
characterization factor	global-warming potential (GWP)
indicator result	kg CO_2-equivalent
category endpoint	years of life lost, coral reefs, crops, buildings

The unit for GWP is kg of CO_2-equivalent. TABLE 2.10 provides the values for the most common agents of global warming.

TABLE 2.10 Characterization values for most common global-warming-inducing substances, according to EN 15804.

Substance		**Characterization factor (kg CO_2-eq./kg_{gas})**
Name	**Formula**	
carbon dioxide	CO_2	1
methane	CH_4	25
nitrous oxide	N_2O	120
fluoroform (HFC-23)	CHF_3	14800

Carbon sequestration in timber and concrete

The inventory analysis may separate CO_2 as originated from fossils (*i.e.,* coal, oil, *etc.*) and minerals (lime, cement, *etc.*); additionally, CO_2 from biological sources, such as trees, should also be differentiated, because it is originated by photosynthesis first and then released again during production through incineration or aerobic degradation (Klöpffer and Grahl, 2014).

Some scientists (Lippke *et al.*, 2010; Sathre and González García, 2014) point out that wood-based products contain banks of CO_2 absorbed by the trees during growth. This phenomenon translates into negative-sign carbon emissions from wood products, because the CO_2 emitted during the production of timber is less than the CO_2 absorbed by trees. However, Lessaveur (2015) highlights the importance of measuring biogenic CO_2 emissions. This new development takes into consideration factors such as incineration of timber and the time a forest takes to grow before it can offset any global-warming potential effects originated during the production of timber. This point of view is supported by Vogtländer *et al.* (2014), who demonstrate that the benefits of carbon sequestration could only be implemented by global growth of forests and use of wood in the building industry, but that local sequestration has no effect that grants discounting CO_2 emissions from LCA studies. Eriksson *et al.* (2007) point out that forests can also become saturated and release CO_2. The *ILCD Handbook* confirms this position:

> "per default, temporary carbon storage and the equivalent delayed emissions and delayed reuse/recycling/recovery within the first 100 years from the time of the study shall not be considered quantitatively" (JRC and IES, 2010, p. 227).

Calculation methods for carbon sequestration in wood products are given in PD ISO/TR 14047 and EN 16485.

Concrete also absorbs CO_2 during its life service (Marinković *et al.*, 2014). According to Kjellsen *et al.* (2005), some of the factors that facilitate CO_2 absorption are:

- **porosity of concrete**: the higher the porosity, the higher the absorption;
- **exposure conditions**: high humidity and temperature; concentration of CO_2 in the atmosphere;
- **type of cement** or binder.

In a process called carbonation, the CO_2 absorbed by concrete reacts with calcium hydroxide $Ca(OH)_2$ and the pH of concrete is lowered (Cho *et al.*, 2016). Carbonation has a negative effect on the long-term life-span of buildings (Marinković *et al.*, 2014; Cho *et al.*, 2016), but an overall positive effect on the environment as CO_2 is absorbed. Carbonation is generally not included in the results of LCA studies (Marinković *et al.*, 2014).

2.7.2 Stratospheric-ozone depletion

Definition

Stratospheric ozone plays a vital part in protecting the earth from harmful ultra-violet radiation. In the last fifty years, the stratospheric-ozone layer has thinned mostly due to chlorofluorocarbons (CFCs) and other halocarbon emissions (Lane, 2015). In 1985, Farman *et al.* reported that Antarctica suffered an increasing reduction of ozone that resulted in a permanent stratospheric-ozone hole in spring.

In a study based on earlier discoveries by Molina and Rowland (1974), Solomon *et al.* (1986) demonstrated the relationship between CFC and stratospheric-ozone depletion. CFC is a chemical compound invented by the end of the 1920s as a safe alternative for refrigerators and aerosols. It contains chlorine, fluorine and carbon. When CFC reaches the stratospheric layer, ultraviolet rays from the sun break it down; as a consequence, atoms of chlorine are released into the stratosphere. In turn, chlorine breaks down ozone molecules (O_3) into oxygen and chlorine monoxide molecules (ClO).

The Montreal Protocol (1989) provided for the phasing-out of the production of CFCs and hydrochlorofluorocarbons (HCFCs), which also destroy the ozone. Some authors (Ravishankara *et al*., 2009; Li *et al.*, 2014), however, advocate that nitrous oxide is nowadays the dominant ozone-depleting substance and should be monitored.

It is worth noting that WMO (2006) recommends recovering and destroying banks of CFCs and halons, which are captured in products and not yet released. In theory, this would prevent future emissions to the atmosphere. This theory has wide repercussions for the construction industry as CFC banks are present in thermal-insulation foams (Paquet *et al.*, 2010), which makes their recoverability unwieldy (Ravishankara *et al*., 2009).

Stratospheric-ozone depletion is particularly harmful to human health (skin cancer), marine environments and crops (Barry and Chorley, 2010).

Characterisation

The World Meteorological Organization (WMO) (2014) has established Ozone Depletion Potential (ODP) as the most accurate method to calculate stratospheric-ozone depletion. ODP is calculated by normalising emission of substances against a unit emission of CFC-11 (trichlorofluoromethane, a type of chlorofluorocarbon) (Lane, 2015, p. 60). The main advantage of using CFC-11 as the benchmark against which the other substances are measured is that ODP values “demonstrate less sensibility to photochemical modelling errors” (WMO, 2014, p. 36). Some disadvantages have also been identified. These include the lack of certainty regarding the composition of a future atmosphere which might affect how ODPs are currently calculated (WMO, 2014). One possible solution to this issue is the inclusion of timeframe-dependent ODP (Lane, 2015).

TABLE 2.11 Overview of characterization of stratospheric-ozone depletion.

Aspect	**Definition**
LCI result	emissions of ozone-depleting gases
characterization model	CML
category indicator	depletion of stratospheric ozone
characterization factor	ozone-depletion potential (ODP)
indicator result	kg CFC11-eq.
category endpoint	illness days, marine productivity, crops

TABLE 2.12 Characterization factors for most common ODP-inducing substances according to EN 15804.

Substance		**Characterization factor (kg CFC11-eq./kg$_{gas}$)**
Name	**Formula**	
trichlorofluoromethane (CFC-11)	CC13F	1
dichlorodifluoromethane (CFC-12)	CC13F2	25
methyl chloride	CCl4	0.02
Tetrachloromethane	CCl4	1.20

Recently, WMO (2014) has recognised the importance of including non-halocarbons such as N_2O, CH_4 and CO_2 in the assessment of ODP, because CH_4 and CO_2 contribute to the regeneration of stratospheric ozone positively and N_2O negatively.

2.7.3 Acidification

Acidification

Acidification is the decrease in the pH of freshwaters, oceans and soil. Inorganic substances such as carbon dioxide, oxides of sulphur and nitrogen that are deposited by the atmosphere onto the Earth's surface are the main cause of acidification (van Zelm *et al.*, 2015, p. 164).

There are three types of acidification: **freshwater acidification** takes place when freshwater lakes or rivers are transformed into diluted acids as a consequence of acid rain, which is caused by protons resulting from the "mineralisation of nitrogen and sulphur deposition" (van Zelm *et al.*, 2015, p. 166). **Soil acidification** is caused by nitrogen and sulphur depositions from nitrogen oxides, ammonia, sulphur dioxide, pyrite and hydrogen sulfide (van Zelm *et al.*, 2015), which reduce the pH of soil. **Ocean acidification** is the pH reduction of the ocean over an extended period, as a consequence of the ocean's absorption of CO_2 from the atmosphere (Gattuso and Hansson, 2011), which increases the concentration of bicarbonate ions in seawater. While nitrogen and sulphur are the emissions that cause soil freshwater acidification, carbon dioxide is responsible for ocean acidification.

The fact that acidification affects the three distinct ecosystems listed above translates into a wide range of biodiversity loss (*e.g.,* ocean acidification is known to affect the capacity of some crustaceous to form shells (Gattuso and Hansson, 2011).

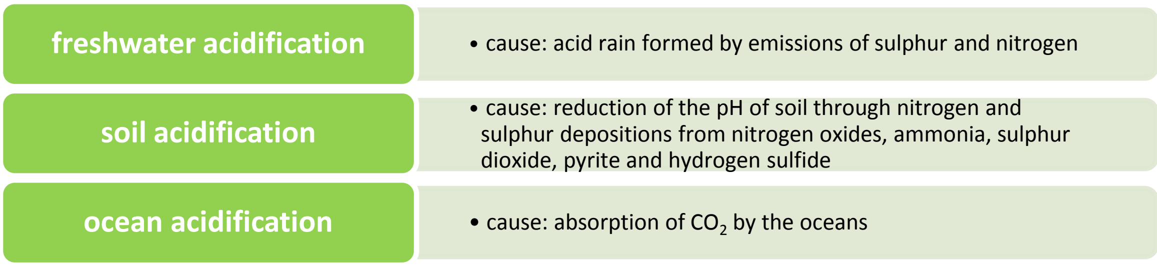

FIGURE 2.25 Types of acidification.

In the building industry, acidification is mostly caused by emissions from aggregates (Kim and Chae, 2016) and the production of metals (Marsh, 2016).

A common practice during the incineration stage of concrete production is the combustion of Bunker C (B-C) oil, bituminous coal, waste tyres, and waste plastic. This combustion causes not only CO_2 emissions, but also emissions of substances that contribute to acidification, such as ammonia and sulphuric acid (Kim and Chae, 2016).

Adhesives used in the production of timber composites, such as urea-formaldehyde (UF), contribute significantly to soil acidification as declared by several EPDs produced by Institut Bauen und Unwelt (2014) and demonstrated by studies carried out by Sathre and González García (2014).

Characterization

The reference substance against which all acidifying emissions are quantified is SO_2 (thus the unit of measurement is kg SO_2-equivalents). TABLE 2.14 gives a summary of the main substances that cause acidification.

TABLE 2.13 Overview of characterization of acidification.

Aspect	Definition
LCI result	emissions of acidifying emissions
characterization model	CML
category indicator	acidification in terrestrial and aquatic environments
characterization factor	acidification potential (AP)
indicator result	kg SO_2-eq.
category endpoint	biodiversity of forests, wood production, fish populations, materials

TABLE 2.14 Characterization factors of most common acidifying substances, according to EN 15804.

Substance		**Characterization factor (kg SO_2-eq./kg_{gas})**
Name	**Formula**	
sulphur dioxide	SO_2	1
sulphur trioxide	SO_3	0.80
nitrogen monoxide	NO	1.07
nitrogen dioxide	NO_2	0.70
Ammonia	NH_3	1.88
phosphoric acid	H_3PO_4	0.98

2.7.4 Eutrophication

Definition

Eutrophication can be defined as an over-fertilisation or excess supply of nutrients. The agents for eutrophication are plant nutrients such as phosphorus and nitrogen. Nitrogen controls growth in terrestrial environments, whereas growth in aquatic environments is controlled by phosphorus (Henderson, 2015).

Eutrophication causes biomass overgrown; waters are, as a result, deprived of oxygen through the decaying of excess plants and algae. Henderson (2015) reminds that eutrophication is a natural process, but it becomes problematic when is increased through human activities such as agriculture.

FIGURE 2.26 Effects of eutrophication on a lake's water. Image source: OpenLearn, 2017.

Eutrophication is also referred to as nutrification, hypertrophication and nutrient enrichment in EN 15804.

Petrol-based adhesives used in the production of timber composites contribute pollutant emissions to global warming, tropospheric ozone formation, acidification and eutrophication. TABLE 2.15 shows main emissions produced by common adhesives used in the timber industry.

TABLE 2.15 Emissions from commonly-used adhesives in the production of timber. Table source: Wilson, 2009, p. 134.

	UF resin (kg/kg resin)	MUF resin (kg/kg resin)	PF resin (kg/kg resin)	PRF resin (kg/kg resin)
Production output				
Resin, neat[a]	1.00	1.00	1.00	1.00
Emissions to air				
CO_2,[b] fossil (GHG)[c]	1.56E-02	2.55E-02	1.76E-02	6.85E-02
CO[b]	3.39E-05	1.30E-05	3.81E-05	1.49E-04
VOC	5.14E-05	4.94E-05	2.89E-05	3.38E-05
Particulate	2.31E-06	1.65E-06	2.31E-06	3.01E-06
Formaldehyde (HAP)[c]	7.79E-06	7.85E-06	6.69E-06	8.80E-06
Methanol (HAP)	6.08E-06	5.49E-06	3.20E-06	5.20E-06
Dimethyl ether	2.18E-05	2.26E-05	4.73E-06	
Phenol (HAP)			2.04E-06	4.16E-06
Emissions to water				
BOD	6.16E-04	6.62E-04		2.81E-03
TSS	3.66E-04	3.94E-04		1.67E-04
Solids	2.23E-04	2.39E-04		
Ammonia nitrogen	1.21E-04	1.30E-04		
Formaldehyde	7.29E-05	7.84E-05		3.32E-04
Phenol				1.14E-04
Emissions to land				
Solids	2.23E-04	5.09E-05	2.00E-04	1.65E-04

[a] Resins are liquid weight at stated solids of UF 65%, MUF 60%, PF 47%, and PRF 60%.
[b] CO_2 and CO were calculated using SimaPro and input of natural gas and propane fuel use in plant.
[c] GHG, greenhouse gas; HAP, hazardous air pollutant.
UF, urea–formaldehyde; MUF, melamine–urea–formaldehyde; PF, phenol–formaldehyde; PRF, phenol–resorcinol–formaldehyde; VOC, volatile organic compound; BOD, biological chemical demand; TSS, total suspended solids.

Greener adhesives, based on wood-based phenolic materials and phenolic-oxidising enzymes, have been successful in lowering some environmental aspects (tropospheric ozone formation and energy consumption), but have been shown to have a negative effect on eutrophication control (Sathre and González García, 2014).

Dynamites used during the extraction of minerals (iron ore and silica stone) needed for the production of concrete emit sulphur dioxide and sulphuric acid, which contribute to acidification and eutrophication (Kim and Chae, 2016).

Characterization

The impact assessment of eutrophication is rendered more complex by differences in how ecosystems interact with nutrients. This issue is reflected in the wide variety of methods proposed to assess eutrophication. However, EN 15804 (BSI, 2014a) provides for EPDs to adopt the CML model, whereby phosphate (PO_4) is the base substance against which all the others are quantified (and expressed in kg PO_4-eq.), as illustrated in TABLE 2.17.

TABLE 2.16 Overview of characterization of eutrophication.

Aspect	**Definition**
LCI result	emissions of nutrients
characterization model	CML
category indicator	increase of nitrogen and phosphorus
characterization factor	eutrophication potential (EP)
indicator result	kg PO_4-eq.
category endpoint	biodiversity, natural vegetation, algal bloom

TABLE 2.17 Characterization factors of most common eutrophication-inducing substances, according to EN 15804.

Substance		**Characterization factor (kg PO_4-eq./kg_{gas})**
Name	**Formula**	
phosphate	PO_4	1
nitrogen	N	0.42
nitrogen monoxide	NO	0.20
nitrogen dioxide	NO_2	0.70
ammonium	NH_4	0.33

2.7.5 Photochemical ozone creation

Definition

"Tropospheric ozone is a highly-oxidative compound formed in the lower atmosphere from gases […] by photochemistry driven by solar radiation" (Amann *et al.*, 2008, cited in Preiss, 2015, p. 116). A rise in tropospheric ozone is linked to well-known events such as summer smog (WMO, 2014; Preiss, 2015).

FIGURE 2.27 Tropospheric ozone (smog) over London. Image source: National Institute for Health Research, 2015.

The chemical composition of the troposphere is kept in balance as long as sufficient nitrogen oxide (NO) exists in order for NO and ozone (O_3) to react back to nitrogen dioxide (NO_2), thus maintaining optimal conditions. However, secondary photochemical reactions, aided by sun rays, with airborne emissions of carbon monoxide (CO) and volatile organic compounds (VOCs) such as ethane, acetylene or propane, cause an increase in tropospheric ozone and a decrease in NO (Preiss, 2015, p. 121).

The production of adhesives for construction is a major source of VOCs (Metzger and Eissen, 2004; Packham, 2014) as well as the production of solvents (Ioniţă *et al.*, 2009).

Characterisation

The characterization factor for tropospheric-ozone formation is photochemical ozone-creation potential (POCP) of volatile organic compounds, VOCs, as advocated by the United Nation Economic Commission for Europe (UNECE, 1991).

TABLE 2.18 Overview of characterization of photochemical ozone formation.

Aspect	Definition
LCI esult	emissions of gases that increase tropospheric ozone
Characterization model	CML
Category indicator	increase of tropospheric ozone
Characterization factor	photochemical ozone-creation potential (POCP)
Indicator result	kg ethene-eq.
Category endpoint	human health

The reference substance (against which the other substances are measured) is ethene, therefore the unit is kg ethene-equivalents, following the CML model (see TABLE 2.19 for an example of correlation of substances).

TABLE 2.19 Characterization factors of most common POCP-inducing substances according to EN 15804.

Substance		**Characterization factor (kg ethene-eq./kg$_{gas}$)**
Name	**Formula**	
Ethene	C_2H_4	1
Methane	CH_4	0.007
Propane	C_3H_8	0.42
Propene	C_3H_6	1.03
Acetylene	C_2H_2	0.17

2.7.6 Energy consumption

According to EN 15804 (BSI, 2014a, § 7.2.4), energy consumption should be divided into the categories shown in TABLE 2.20.

Eurostat (2016) classifies primary energy into raw materials and energy resources, with a further subdivision into renewable and non-renewable sources (see TABLE 2.21 for a classification of common primary-energy sources).

TABLE 2.20 Resource consumption parameters according to EN 15804.

Parameter	**Unit**
renewable primary energy	
use of renewable primary energy excluding renewable primary energy resources used as raw materials	MJ, net calorific value
use of renewable primary energy used as raw materials	MJ, net calorific value
total use of renewable energy	MJ, net calorific value
non-renewable primary energy	
use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials	MJ, net calorific value
use of non-renewable primary energy resources used as raw materials	MJ, net calorific value
total use of non-renewable primary energy resources	MJ, net calorific value

TABLE 2.21 Classification of primary energy according to Eurostat (2016).

Raw materials		Energy resources	
Renewable	**Non-renewable**	**Renewable**	**Non-renewable**
• Biomass	• mineral resources • metal ores • fossil materials	• hydropower • geothermal energy • wind energy • solar energy • biomass energy	• nuclear energy • fossil energy

2.7.7 Waste

EN 15804 (BSI, 2014a) provides for hazardous, non-hazardous and radioactive waste disposed to be reported in an EPD.

Waste should be classified following the European List of Waste (LoW), as requested by EU directive 2008/98/EC. In the UK, hazardous waste is also regulated by the Hazardous Waste (England and Wales) (Amendment) Regulations 2009 and Waste (Scotland) Regulations 2012. Commission Regulation (EU) 1357/2014 specifies a classification for hazardous waste according to its effects (TABLE 2.23).

TABLE 2.22 Waste types considered in an EPD according to EN 15804.

Type of waste	Unit
hazardous waste disposed	kg
non-hazardous waste disposed	kg
radioactive waste disposed	kg

According to data from the Department for Environment, Food and Rural Affairs (DEFRA) (2016), the construction industry is the second largest source of hazardous waste, after the commercial and industrial sector. Natural Resources Wales (2016) lists the following items as the main hazardous substances generated by the construction industry: contaminated soils (41%), bituminous mixtures (34%), asbestos waste (9%) and chemical solvents (7%).

TABLE 2.23 Types of hazardous waste according to Commission Regulation (EU) 1357/2014.

Waste type	Description
explosive	Waste which is capable by chemical reaction of producing gas at such a temperature and pressure and at such a speed as to cause damage to the surroundings.
oxidising	Waste which may, generally by providing oxygen, cause or contribute to the combustion of other materials.
flammable	Flammable liquid waste; flammable pyrophoric liquid and solid waste; flammable solid waste; flammable gaseous waste; water reactive waste; flammable aerosols, flammable self-heating waste, flammable organic peroxides and flammable self-reactive waste.
irritant	Waste which on application can cause skin irritation or damage to the eye.
specific target organ toxicity (stot)/aspiration toxicity	Waste which can cause specific target organ toxicity either from a single or repeated exposure, or which cause acute toxic effects following aspiration.
acute toxicity	Waste which can cause acute toxic effects following oral or dermal administration, or inhalation exposure.
carcinogenic	Waste which induces cancer or increases its incidence.
corrosive	Waste which on application can cause skin corrosion.
infectious	Waste containing viable micro-organisms or their toxins which are known or reliably believed to cause disease in man or other living organism.
toxic for reproduction	Waste which has adverse effects on sexual function and fertility in adult males and females, as well as developmental toxicity in the offspring
mutagenic	Waste which may cause a mutation, that is a permanent change in the amount or structure of the genetic material in a cell.
release of an acute toxic gas	Waste which releases acute toxic gases (acute toxicology 1, 2 or 3) in contact with water or an acid.
sensitising	Waste which contains one or more substances known to cause sensitising effects to the skin or the respiratory organs.
ecotoxic	Waste which presents or may present immediate or delayed risks for one or more sectors of the environment.

Non-hazardous waste generated by the building industry includes timber, packaging, insulation materials, topsoil, plastic, wet cement, empty tins and tubes, metal, food, lead piping, carpets and tantalised timber (Construction Resources and Waste Platform, 2010).

Following EU legislation (Council Directive 96/29/EURATOM), DEFRA (2011) has set a limit of 1.0 mSv/year[7], above which a substance or product is considered radioactive. The construction industry uses materials that emit gamma rays and thoron (Appleton,

[7] Milli-Sievert (ionizing-radiation unit) units per year.

2004). However, the Nuclear Decommissioning Agency (NDA, 2015) does not list the construction industry amongst sources of substantial radioactive waste.

2.8 Summary

Section 2.2 has discussed the current housing crisis in the UK due to an increase in demand coupled with a dwindling housing stock. This challenge, paired with the need to meet environmental targets, has encouraged initiatives that favour modern methods of construction (MMC).

Section 2.3 has disclosed issues that hinder the implementation of MMC, such as customers' traditional resistance to offsite construction stemming from post-war experiences, the need to understand structural and thermal performance, and a reduced supply chain operating in the UK. Nevertheless, due to the increase in demand for environmental solutions, governments, academic institutions and private initiatives have started to develop research projects around the adoption of off-site construction.

The building industry is one of the main causes of waste in the UK. There are several reasons for this, such as lack of training in new techniques, off-cuts, poor storage and excessive packaging (**Section 2.4).**

Climate change is a global issue with multiple, mid-term and long-term effects. **Section 2.5** has explored the issue of overheating of the building stock as one of its long-term effects. Overheating is caused by an increase in solar radiation, which is particularly relevant regarding the thermal performance of walls, as will be shown in the results of the thermal experiments presented in Chapter 6.

Life-cycle assessment (LCA) is a methodology that looks at a product's contribution to environmental impacts, consumption of energy and production of waste during the whole life of a product (**Section 2.6**). Since its inception in the 1990s, this method has evolved into a clearly-defined technique with different stages as described by international standards. The need to communicate the environmental impacts of a product has translated into the development of a standard for Environmental Product

Declarations (EPDs). EPDs are of great relevance to the present research, since they have been used as the major data source for the LCA carried out (presented in CHAPTER 5), as recommended by EN 15804 and EN 15978.

CML (as defined in SECTION 2.6.4) is the underlying methodology for LCA studies that follow international standards ISO 14040 and EN 15804. This methodology takes a midpoint approach, where pollutants are measured in relation to their long-term and known effects on the environment. CML is also the methodology followed in the LCA study presented in CHAPTER 5.

3 Critical review of the literature

3.1 Chapter overview

CHAPTER 3 documents the literature review that has been conducted, by articulating the most significant themes and matters that were drawn from it and that informed the design of the present research work. Hence, the content here presented constitutes a conceptual foundation for the investigation documented in the following chapters.

The two main SECTIONS, 3.2 and 3.3, mirror the two interconnected strands of this research work: the strand on life-cycle assessment of timber buildings and that on their thermal behaviour.

SECTION 3.2 revolves around the application of life-cycle assessment to the construction industry. It presents a review conducted on LCAs on housing, at the European and national level (SECTION 3.2.1). The corpus of reviewed publications and the information they disseminate form the basis upon which the present project offers a further contribution to knowledge. Particular emphasis is placed on LCAs of timber buildings considered in isolation or in comparison with others that employ different materials for their structural systems.

Then, attention is given to the few published LCAs that have accounted for wastage of building materials in the determination of environmental impacts (SECTION 3.2.2), as is done in this thesis and to the strategies that are in place today to reduce the environmental impacts of the most common building materials (SECTION 3.2.3).

SECTION 3.2.4 critically explains the most recurrent problems and limitations which characterize LCAs on buildings. Such aspects have been taken into consideration when designing the present research, so as to avoid them and to improve comparability of the findings of this study with those from other (past and future) LCAs.

Section 3.3 deals with the thermal performance of buildings. First, the mechanism governing thermal inertia is explained, in terms of cause-effect relationships and physical properties which can be used to characterize and quantify this phenomenon (Section 3.3.1). A review of the research conducted on the optimisation of wall build-ups is then presented, thus illustrating the work upon which the current study is based (SECTION 3.3.2).

3.2 Review of LCA applied to the construction industry

3.2.1 LCAs of housing

LCA has been applied to the construction industry (both buildings and civil-engineering works) since the late 1970s. LCAs of buildings are been carried out and published with increasing frequency, showing that this discipline is in rapid growth.

Over the last 20 years, in the UK, LCAs have been carried out mostly on houses, offices and commercial buildings. Fewer studies focus on educational or service buildings (*e.g.,* data centres). LCAs are being applied to both new-build and refurbishment, the latter especially for office buildings and, to a lesser extent, housing, to assess the environmental benefits of potential thermal retrofit interventions and reduce the burdens arising from space heating (houses and offices) and cooling (mostly offices).

Even though this is still a discipline in its infancy, certain changes in direction and trends can already be described. These changes concern, among other aspects, the life-cycle stages studied. In particular, the relative importance of embodied burdens and operational burdens has changed over the years, with a rising interest towards the former.

Some authors distinguish between two main types of LCA studies applied to buildings (Ortiz *et al.*, 2009):

- studies dealing with Building Material and Component Combination (BMCC);
- studies dealing with the Whole Process of Construction (WPC).

However, it must be noted that some existing studies sit between these two categories, therefore this differentiation is only indicative.

A broad review of LCA focusing on housing has been carried out, with particular attention to the UK context. However, due to these not being numerous, the research has been extended to the broader European and, in exceptional cases, overseas context.

Ding (2004) and Dixit *et al.* (2010) have analysed embodied-energy values from a variety of LCAs of residential units (in disparate countries), published between 1978 and 2000. They show that the average embodied energy for housing is 5.506 GJ/m^2 (with a standard deviation of 1.56 GJ/m^2). According to these studies, the variability of this aspect is low in comparison with that of commercial buildings (for which the average embodied energy is 9.19 GJ/m^2, with a standard deviation of 5.4 GJ/m^2). Since these studies are now at least 18 years old, value averages would be likely to be much higher, for the properties of the building envelope discussed above.

Gustavsson and Sathre (2006) have conducted an extensive, comparative study (also reported in Gustavsson *et al.*, 2006) on reinforced-concrete structures and timber structures (timber-frame panel construction) in North-European housing. They have performed numerous sensitivity analyses on all the major parameters influencing their calculations and results. These parameters concerned uncertainties and variability relating to, for instance, the growth rate of forests (affecting the calculation of carbon emissions), the amount of energy required to process raw materials (depending on their characteristics, which can vary widely), the technological processes adopted to produce cement, the type of fuels burnt, the use of recycled or primary materials such as steel. These authors have initially analysed the effect of varying each of these parameters individually on the final output obtained. Then, they have grouped the values of the parameters in different combinations, each of which is overall more advantageous for one material (concrete) or the other (wood). Their study suggests that the concrete-framed building causes a lesser environmental burden (in terms of carbon and energy) only when the LCA is performed under the (rather unlikely) combination of parameter variations that is least favourable to timber. In all the other combinations (including the ones that are moderately more advantageous for concrete), it was found that the concrete buildings would entail more energy consumption and carbon releases than the timber-built equivalent.

Nemry *et al.* (2008) have conducted an extensive study on the environmental impacts of low-rise construction across the EU-25 countries. The UK was grouped with other twelve countries[1] with a relative similar climate. The study results clearly showed that timber buildings (in comparison with other four types based on bricks or concrete) tend to offer an improvement in almost all[2] the aspects considered (PE, GWP, AP, EP, POCP, ODP). In particular, over the life-cycle of the buildings, the timber solution offers a decrease in primary energy ranging between -8% and -4% and a decrease in GWP between -12% and -4% of the brick/concrete buildings.[3] As Nemry *et al.* (2008) explain, "the other construction options [*i.e.,* non-timber options] may differ from each other, but any systematic benefit that would result is not as obvious".

Monahan and Powell (2011) have carried out a cradle-to-commissioning[4] LCA of the thermal envelope of a semi-detached house in the UK. They have analysed the results for three different constructional variations of the same dwelling and found that embodied energy and carbon amount to:

- 8.2 GJ/m^2 and 612 kg CO_2eq/m^2, respectively, for the load-bearing masonry house;
- 7.7 GJ/m^2 and 535 kg CO_2eq/m^2, for the dwelling with closed timber frame panels and heavyweight cladding;
- 5.7 GJ/m^2 and 405 kg CO_2eq/m^2, for the house with closed timber-frame panels and lightweight cladding.

Therefore, when the masonry house is compared with the two timber-frame scenarios, energy decreases[5] by 6% (HW cladding) or 30% (LW cladding), while carbon decreases by 12% (HW cladding) or 34% (LW cladding).

---

[1] Namely, Belgium, the Netherlands, Ireland, Hungary, Slovenia, Luxembourg, Germany, Slovakia, Denmark, Czech Republic, Austria and Poland.

[2] The only exception being the value of ODP of the timber building estimated at 1% more than one of the brick buildings (over the whole life cycle).

[3] Values calculated in the present study, based on the values provided in table 7.13, page 95, of the cited source.

[4] Corresponding to information modules A1 to A5 inclusive.

[5] In the cited source, the percentage difference between scenarios are, in most cases, given relative to the timber frame option, with LW cladding.

3.2.2 Accounting for building-material wastage in LCA

Building-material wastage affects the bill of quantities for a construction project and the actual amount of materials that is needed to erect a building. In other words, the real quantity of materials needed is greater than that physically incorporated in the completed building. This has been discussed in greater depth in SECTION 2.5.

While the wastage problem and its repercussions on the bill of quantities (which constitute the inventory of an LCA at the building level) affect any building, very few LCA studies have taken it into consideration.

A study presented by Gustavsson and Sathre (2006) and Gustavsson *et al.* (2006) on housing in Sweden and Finland did consider wastage of buildings materials and the bill of quantities was adjusted by multiplying the amounts incorporated in the building by appropriate wastage coefficients. Such wastage percentages were based on a previously-published survey conducted in the Swedish context. The quantities of all incorporated timber materials (solid timber and wood-based products) were increased by 10%, insulating materials by 7%, plasterboard by 10% and so on. In these referenced sources (by Gustavsson, Sathre *et al*.), the environmental burden associated with wastage is not expressed. However, since the highest wastage percentages were 10%, the percentage increase of the output must necessarily be below 10% (probably ranging, it is believed by the present author, between 5% and 10%).

Another LCA of Swedish housing (undertaken by Adalberth *et al.*, 2001) follows a similar approach to the inclusion of wastage and utilises wastage factors from a previously-published study on this topic, in the Swedish context. However, wastage coefficients are not indicated in this publication, and neither is their effect on the outputs of the study.

In the UK, Monahan and Powell (2011) have considered waste, but in a different manner (and with different objectives) than in the two studies discussed above. The total amount of waste volume produced onsite (and, with a lesser degree of precision, offsite) for the construction of one of the houses under investigation was measured (as an aggregate figure), but detailed information on the breakdown into individual materials was not available to the researchers. Such breakdown was therefore estimated based on data on typical waste mixes sourced from the literature around British construction sites. These authors explain that the carbon emissions due to the materials incorporated in a closed-panel timber frame house with timber cladding amount to 82% of the total embodied energy (in this case covering phases A1 to A5 inclusive). The percentage share of primary energy and carbon associated with the waste calculated as described above represented about 19% and 14%, respectively, of the totals[6]. These figures seem much higher than the ones that can be roughly derived or assumed from the previous, Sweden-based, studies described above. Monahan (2013) also expresses the need to further investigate the manufacturing efficiency of MMC, as opposed to on-site construction, and to explore its environmental benefits (in terms of reduced wastage and reduced associated burdens).

3.2.3 Environmental improvements in building-product manufacturing

This section deals with the enhancement of the environmental profiles of the building materials that are included in the constructional techniques under investigation.

3.2.3.1 Cement and cement-based materials

In British low-rise housing, concrete is not used as widely as in other European countries, where concrete-framed houses represent the norm. However, due to their high environmental repercussion, concrete members within a building can still play an important role within an LCA at the building level. Concrete in British homes is mostly used for foundations (reinforced or unreinforced depending upon structural/geotechnical requirements) and for ground floors in the form of suspended beam-and-block systems or ground-supported slabs. The role of concrete blocks is also significant, for both structural and cladding applications in walls). Several authors have emphasised the strategic importance of reducing foundations size (*e.g.,* Monahan, 2013 and Guardigli, 2014). This design measure, especially in single- or multiple-family houses is much interlinked with the weight of the building attributable to the façade and, consequently, the choice between heavyweight and lightweight cladding.

---

[6] These figures were calculated in the present study, based on the values reported in the original source (Monahan, 2013) in table 2-6, p. 82.

Researchers have proposed various strategies to reduce the burdens due to concrete. These strategies can be grouped into two main categories: improvement of cement and improvement of aggregate.

Cement production is responsible for the greatest contributions to the main environmental loads (PE, GWP, AP, EP and POCP) associated with concrete (Marinković *et al.*, 2014).

As far as cement is concerned, there are two main causes for its high carbon emissions: CO_2 released during the calcination process and CO_2 related to energy consumption (Habert, 2014). For the latter, the efficiency of the cement kiln is one of the aspects that can be improved: this is about designing modern kilns that can operate with lower heat consumption resulting in lower energy demand and, finally, lower carbon releases (Zabalza Bribián *et al.*, 2011; Habert, 2014). However, this mitigation strategy is weakened by the fact that it requires major technological retrofits, which entail high investment cost and long payback periods (Madlool *et al.*, 2011).

In order to reduce the carbon emitted during the calcination process, partial replacement of the raw materials is possible. Alternative materials which can be employed are (Iddon and Firth, 2013; Gustavsson and Sathre, 2006; Habert, 2014; Guardigli, 2014):

- granulated blast-furnace slag (co-produced with iron in a blast furnace);
- fly ash (a by-product from the coal power industry);
- silica fume (a by-product from the silicon-metal industry).

According to Iddon and Firth (2013), replacing 30% of the cement content with fly ash, for instance, would entail a reduction in carbon emissions of 9% for the foundations of a house and 12% for its ground-floor slab.

It is also possible to use alternative fuels for clinker production. Among these are:

- used tyres;
- sewage sludge;
- animal residues (meat and bones);

- waste oil;
- lumpy materials, *i.e.,* solid fuels obtained from industrial or municipal waste, including paper, textiles, rubber and plastics (Habert, 2014; Guardigli, 2014).

While, in theory, alternative fuels could completely replace fossil fuels, this improvement is hindered by practical limitations. For instance, conventional kilns are not compatible with all of the fuels listed above, and *ad-hoc*-designed infrastructure is needed (Habert, 2014). Other limitations include the moisture content of the alternative fuels, low calorific values and toxic substances contained in the fuel themselves, which require adequate management.

Another type of substitution is that of Ordinary Portland Cement (OPC) as a binder with cements with a lower environmental load, which are receiving growing attention within the scientific community. Some examples are (Habert, 2014):

- cements from alkali-activated alumina silicates. These materials have been used for a long time, but have obtained low market penetration;
- cements from calcium sulfoaluminate (developed in China in the 1970s). These are significantly more expensive than OPC and therefore only used in special applications;
- cements from magnesium silicates (of much more recent development than the cements listed above). These entail lower environmental impacts than OPC, but still require optimisation to become economically competitive with it.

Therefore, it can be seen that most of the strategies mentioned above are strictly interlinked with a country's level of industrialization and infrastructure, waste legislation and management. This is also why, even within Europe, each geographical region has reached different levels of material substitution.

A different approach to the problem of reducing the burden of concrete is that of addressing the impacts associated with its aggregate.

It is possible to demolish concrete and recycle it, by crushing it into aggregate (Recycled Concrete Aggregate, RCA) for new applications (Gustavsson and Sathre, 2006;

Peuportier, 2001; Marinković *et al.*, 2014). At present, RCA is used in the construction of roads or as backfilling, but can also be used to replace natural aggregate in new concrete members. RCA offers some advantages: it saves landfill space, allows for the conservation of natural aggregates [7] (Marinković *et al.*, 2014) and absorbs carbon dioxide from the atmosphere through the recarbonation process (Zabalza Bribián *et al.*, 2011). The downside of this strategy is that the production of RCA (the crushing) produces a rather high impact, and concrete made with RCA as aggregate requires a greater amount of cement. Marinković *et al.* (2014) have concluded that producing RCA (in Serbia) entails consuming about 100% more energy than crushing natural aggregate and 158% more energy than using natural, river aggregate.[8] However, these values do not significantly affect the total burdens due to concrete (because the production of aggregates remains one of the sub-processes with the lowest impacts). RCA also allows some benefits in terms of burdens other than energy use, therefore the overall benefits are less obvious to be identified.

FIGURE C.1 in APPENDIX C summarises the possible strategies that can be adopted to lower the environmental loads of concrete.

Guardigli (2014) has analysed the arguments that can be made, from industry and academia, in favour of concrete as a preferable material in comparison with less energy-intense and less polluting materials. Among these, is the durability of concrete, the fact that, in comparison with timber buildings, for instance, it is less vulnerable to moisture damage and can withstand fires or extreme events (such as hurricanes) more successfully.

It can be concluded that, at present, only a fraction of the potential improvements of concrete has been realised, due to the economic cost associated with some strategies, level of technological development of the current manufacturing infrastructure, uncertainty regarding the overall benefits of some processes under study (considering

[7] Some countries, like Sweden, have posed limitations to the maximum amount of natural aggregate that can be extracted *per annum*; as a consequence, the remainder of the aggregate must be produced by crushing natural stone or concrete reclaimed after demolition (Gustavsson and Sathre, 2006).

[8] Percentage values obtained from the figures presented in the original source (Marinković *et al.*, 2014), in section 11.3, p. 251.

burden trade-offs) and low market penetration of some alternative materials and/or processes.

As far as masonry mortars are concerned, research suggests that preferring lime over cement can lead to significant ecological improvements, especially because lime mortars absorb a greater quantity of atmospheric CO_2 while they are setting (Zabalza Bribián *et al.*, 2011).

3.2.3.2 Wood and wood-based materials

Improvement on wood or wood-based products can be implemented at several levels and following varying strategies.

The manner in which a forest is managed is key in the actual sustainability of timber as an environmentally-friendly building material. Wood is a truly renewable material only if the rate at which it is removed from forests is not less than the rate at which it is replaced by new wood: either in a natural or assisted manner, *i.e.,* through plantation forests (Buchanan and Honey, 1993), or “afforestation”.

Forest growth plays indeed a fundamental role in the energy and carbon balance of the end product (Gustavsson and Sathre, 2006; Gustavsson *et al.*, 2006). Forest growth and biogenic carbon are characterised by a high level of uncertainty, as they both depend on several variables, such as climatic conditions, soil type (Liski *et al.*, 2001). Trees grow at different rates during their lives and, as a consequence, also capture atmospheric carbon dioxide at a different rate. Old trees grow slowly and, if not harvested, they will die and decompose within the forest, re-emitting the energy and carbon stored over time (Gustavsson and Sathre, 2006). In other words, old forests reach a steady state and cease to be net absorbers of CO_2 (Buchanan and Honey, 1993). Therefore, the length of forest rotation can be adjusted in such a way to maximise carbon sequestration; this optimisation process however, is very complex to manage and extending forest rotation might even prove counterproductive (Liski *et al.*, 2001). Approximately half of dry wood (by weight) is made of carbon; however, in forest ecosystems, a significant part of the CO_2 absorbed from the atmosphere is stored in the soil. Therefore, in a managed forest, it is important to consider the overall dynamic carbon equilibrium resulting from stock in biomass and in soil (Sathre and González-García, 2014).

Other forest-management activities to affect the quality and quantity of wood include strategic selection of species, intervention on nutrients and intensification of the plantation regime. However, as Sathre and González-García (2014) observe, while intensive regimes provide a greater amount of biomass, "the return on management inputs tends to diminish as intensity increases".

Adhesives in wood-based materials, such as OSB, plywood, glulam, and particleboard are high contributors to acidification and eutrophication (Guardigli, 2014), but also global warming, POCP and toxicity (Zabalza Bribián *et al.*, 2011). They offer opportunities for improvement; in particular, conventional melamine-formaldehyde, phenol-formaldehyde and urea-formaldehyde (which are petrol-based) can be substituted with alternative, natural resins (Packham, 2014; Zabalza Bribián *et al.*, 2011). These partial or full replacements include adhesives based on lignin (Moubarik *et al.*, 2009), starch or tannins extracted from certain trees and glues of animal origin. At pilot scale, these innovative solutions have proved to be successful, in that the final products have the same properties of the ones with conventional adhesives and are more environmentally-compatible; some of these experimental products are also believed to be industrially viable, while others require further research (Sathre and González-García, 2014). An alternative route is that of reducing the use of adhesives, irrespective of their origin. While it is important to appreciate the potential improvements in the chemical production of adhesives in building products, it is also vital – for a fair evaluation – to recognise the advantages brought by them: adhesives and composites have indeed allowed partial replacement of traditional materials and offer "more efficient engineering solutions to design problems" (Packham, 2014). This holds true for adhesives in engineered-timber products that allow using lower-value elements of raw materials (*e.g.,* wood chips, or strands) and overcoming the natural limitations of the woody material (such as overcoming the anisotropic behaviour of wood in plywood and CLT, and increasing dimensional stability in these products).

Another aspect that can worsen the environmental profile of wood-based materials is the use of preservative substances. These can be grouped into two main categories: oil-borne preservatives (*e.g.,* pentachlorophenol and creosote) and water-borne ones (*e.g.,* solutions based on copper) (Lebow, 2010). The use of creosote is controlled and limited by an EU directive.[9] As explained by Sathre and González-García (2014), wood treatment entails both environmental benefits and burdens. On the one hand, preserving wood means making it more durable and therefore requiring less substitution over time and, as a consequence, requiring less forest harvest. On the other hand, preservative chemicals are toxic and pollute and, for the same reason, limit the opportunities for recycling and energy recovery during incineration. There also exist innovative treatments that are less impactful, such as acetylation, which makes timber more durable and dimensionally-stable. However, the acetylation process also has some negative repercussions on the economic sphere (it is expensive) and on the mechanical behaviour of wood, especially by making it more brittle. For such reasons, material replacement with this acetylated timber, especially for structural purposes, needs cautious consideration.

Other preservatives with limited environmental impacts are borates and furfuryl alcohol (Sathre and González-García, 2014).

Some researchers (Zabalza Bribián *et al.*, 2011) point out that energy savings could be achieved by drying wood naturally, in the open, as opposed to using kilns; in regions and seasons where outdoor climatic parameters would be good enough to do so.

FIGURE C.2 in APPENDIX C schematically summarises the improvement potentials for wood and wood-based materials discussed above.

3.2.3.3 Thermal-insulation materials

As seen in the sections above, various methods have been investigated to reduce the environmental impacts of some building materials. In the case of thermal insulators, research has focused on replacing conventional materials, rather than on lowering their impacts.

---

[9] *Commission Directive 2011/71/EU, amending Directive 98/8/EC of the European Parliament and Council to include creosote as an active substance in Annex I thereto.*

The extent of recycling, however, plays an important role in the enhancement of the environmental profile of conventional materials (for instance, the amount of recycled material present in glass-fibre products).

In the UK, as in the rest of Europe, the most widespread materials for wall insulation are polystyrene and mineral wool. Polyurethane (PUR) is also very common and entails heavy burdens for the environment. According to the environmental rating provided by Dylewski and Adamczyk (2014), the overall impact of PUR is twice as large as that of mineral wool: while global-warming, acidification and eutrophication potentials for these two options are very similar, PUR requires greater (almost double) consumption of fossil fuels and emits more than double respiratory inorganics.

According to Zabalza Bribián *et al.* (2011), there is certain inertia in the adoption of widespread insulating materials to the detriment of less impactful alternatives, which they attribute to the robust, existing commercial network (which allows for economies of scale and very competitive prices) combined with designers' "ignorance and, sometimes, scepticism" towards ecological alternatives.

Much attention has been devoted, over the last decades, to natural materials, for instance those based on flax and hemp fibres (Collet *et al.*, 2011). These alternatives have proved very effective (Dylewski and Adamczyk, 2014) generally speaking (they are durable and resistant to insect and fungal attack), thermally (they offer good thermal resistance) and environmentally (they are renewable, biodegradable, recyclable and atoxic and require low energy intensity when manufactured). The limitation of these products is of an economic nature, in that they are not competitive with typical materials that use glass or mineral fibres (Pacheco Torgal and Jalali, 2011).

A material of natural solution, which is particularly significant in the Scottish context, is the utilisation of sheep's wool. Such wool can emit up to 98% less carbon dioxide[10] than EPS or PUR (Zabalza Bribián *et al.*, 2011), which are high consumers of gas and petroleum.

[10] If final disposal occurs through incineration.

Insulation based on cellulose fibre has also received great attention from academia and the market and is now used in some housing construction systems[11] developed by the industry's "big players".

Expanded cork is a good ecological solution, thanks to cork being both a renewable and recyclable material (Pacheco Torgal and Jalali, 2011).

Other available solutions include more advanced products, such as vacuum insulation panels (VIPs), which can provide very high thermal resistance with limited thicknesses and have a long service lifespan. Numerous shortcomings, though, limit their application: they have a fixed size, which cannot be modified or adjusted on site to follow the geometry of the building, they can be easily damaged, can cause some thermal bridging through the metallic envelope (Baetens *et al.*, 2010) and are not cost-effective in comparison with commonly-used materials (Pär, 2012).

3.2.3.4 Steel

Metals are not widespread in the UK's residential sector as a main structural material, the market share of metal-framed buildings being very small. Steel and aluminium are commonly used for mechanical fixings and anchors. Steel can also be used as a reinforcement in foundations, where plain concrete is not structurally sufficient, or in concrete flexural members (in particular, beam-and-block systems for suspended ground floors).

Eco-improvement in the metal sector mostly revolves around reducing the size and relevance of the primary industry (and associated depletion of abiotic resources), to the advantage of the secondary industry, based on recycling steel, aluminium and copper (Zabalza Bribián *et al.*, 2011). There is also a problem related to globalisation, which can often mean that metals are manufactured far afield from the building location and therefore the environmental repercussion of transport (phase A4) is significant.

[11] For instance, the *Sigma System* developed by Stewart Milnes Homes.

3.2.4 Recurrent limitations and problems in published LCAs

This review and analysis of existing literature on the environmental burdens associated with housing has highlighted some recurrent problems. One of the major obstacles is the extreme difficulty in comparing results from different case studies. This is mostly due to the fact that there is little standardization in the approach taken by researchers and in the framework of their investigations. Some of these problems have also been experienced by the authors of systematic reviews of housing-related LCAs.

Every LCA is characterized by many aspects that do not present themselves often in the same combination: among these, are the goal and scope defined, the functional unit used, the LCIA method adopted (including, where applicable, the impact-rating system) and the quality and availability of the data used.

The application of LCA to the built environment is a complex, time-consuming process (Stajanca *et al.*, 2012), and requires a large amount of assumptions or modifications (Gregory and Yost, 2002).

3.2.4.1 Goal and scope

The differences in goal and scope definition are among the greatest obstacle preventing comparability between LCA studies (Khasreen *et al.*, 2009; Guardigli, 2014; Menzies *et al.*, 2007). Some LCAs tend to be excessively case-specific, therefore their findings cannot be easily utilised for, and transferred to, other building projects or studies (Rajagopalan *et al.*, 2012).

One of the problems identified within comparative studies is the way in which the different scenarios are defined. There are cases in which each scenario is characterised not only by a specific construction method (different from the other scenarios), but also by very different performance levels of the building envelope, where the differences go beyond those necessarily entailed by the techniques themselves. For instance, Iddon and Firth (2013) present four different scenarios, each with a unique construction method and U-value of the envelope. This leads to extremely different results in the estimates of carbon releases, and, as the authors themselves explain, “direct comparisons between the different construction scenarios […] cannot be drawn, as the buildings are not like-for-like with regard to thermal performance" (Iddon and Firth, 2013, p. 487).

Another aspect that often prevents direct comparison between LCAs is the different choice of functional unit. As noted by Khasreen *et al.* (2009), there have been various attempts to standardize the FU for buildings, but these have not yielded satisfactory results yet. A difference in FU often requires normalisation of the data presented in a published LCA relative to another FU, to allow for comparison between differing research projects. The same procedure aimed at "neutralising" such differences had to be followed in the current review as it had in other reviews (*e.g.,* Monahan, 2013 and Sartori and Hestnes, 2007). Some researchers disseminate their findings by normalising them in two or three different manners (*i.e.,* with respect to different parameters) within the same publication: this *modus operandi* proves very convenient and advantageous for the scientific community, as it facilitates comparison with other studies with no need to re-analyse other researchers' results for one's own purposes. An example of this attentive approach to the communication of results is the LCA study conducted by Eštoková and Porhincak (2015) on housing, who first provide the (impact) results for the whole building and then the results normalised by total area, useful area, total weight of dwelling and total volume.

3.2.4.2 Availability and quality of data

Menzies *et al.* (2007) describe the incompleteness and inadequacy of databases for a specific project and the fact that estimates on data quality and uncertainty are not often provided within the databases. In addition to this, Pomponi and Moncaster (2016) stress the fact that sensitivity and uncertainty analyses are rarely conducted by LCA practitioners in the built environment and suggest that more consideration should be paid to these important aspects. Khasreen *et al.* (2009) emphasise the importance of using quality indicators in order to strengthen the data-collection strategy and advise using the method proposed by Weidema and Wesnæs (1997).

Some authors clarify the differences between the results obtained through process-based analysis as opposed to input/output-based analysis. The former is deemed to yield more accurate and reliable results, but, in comparison with the latter, tends to underestimate the quantities studied (Dixit *et al.*, 2010). This is due to the fact that input-output analysis is more complete and can account for most direct and indirect energy inputs (Khasreen *et al.*, 2009). This method, however, has some inherent limitations and is likely to lead to erroneous results (Crawford and Treloar, 2003).

There is still a high level of uncertainty around some impact categories, since the exact effects of polluting substances is not easily quantifiable; this is particularly true of human toxicity (Adalbert, 2001).

3.2.4.3 Transparency and clarity

Lack of transparency, which characterises numerous studies, makes results incomparable (Menzies *et al.*, 2007). Some of the areas in which the present author has found very scarce transparency are the background-data resources used and the exact construction methods described. This becomes particularly problematic in comparative studies, because comparability between different buildings with different construction methods becomes unclear both within the same LCA and even more so with other LCAs available in the literature. As an example, the structural systems adopted or imagined) for the LCA case studies/scenarios are rarely described exhaustively. It is often the case that building elements are only described in terms of non-structural components (*e.g.,* the covering or internal finishes for a roof), without any clear information on the structural system or members.

Another problem leading to difficulties for the research community in understanding published LCAs lies in the misuse of technical terms, and lack of reference to the ISO and/or CEN standards terminology or codes, where these are available.[12]

The problem mentioned above is, however, interlinked with another issue: the interdisciplinary nature of LCA applied to construction. Many (if not most) of the LCA practitioners/researchers with an interest in buildings come from the environmental or chemical sciences and tend to have little knowledge of construction. This is likely to be the explanation for the lack of information given in their studies and their reliance on other professionals or sources – architects, council administrators, construction

[12] For instance, Cuéllar-Franca and Azapagic (2012) refer to the whole production stage (A1 to A5) as "construction" or "on-site construction", generating confusion with the erection of the building (*i.e.,* A5). See SECTION 2.6.6.

companies, *etc.* (Ortiz *et al.*, 2009; Cuéllar-Franca and Azapagic, 2012; Peuportier, 2001 and Asif *et al.*, 2007) – to compile the bill of quantities which constitutes the basis of any LCA at the building level. Iddon and Firth (2013) indicate the importance of multidisciplinary teams to overcome problems in LCAs that they have experienced in the course of their own research and have also observed in the literature.

3.2.4.4 Consistency in LCI

Numerous authors (*e.g.,* Sartori and Hestnes, 2007; Ibn-Mohammed *et al.*, 2013, Dixit *et al.*, 2010) point out that making comparisons between energy estimates is hindered by the fact that some authors consider primary energy (as recommended today by the standards, EN 15804), while other studies assess end-use energy; in addition exact indication on energy carriers and conversion factors are rare and the type of energy considered is not always explicitly described. Sartori and Hestnes (2007, p. 251) explain that "the same hypothetical building placed in different countries, but with similar climates, is likely to have very similar figures about end-use energy". Primary energy, instead, is measured at the natural-resource level and thus expresses the actual burden associated with the building. However, primary-energy values are severely affected by the electricity mix of each country and by the energy carriers used, for instance, for space heating. Figures describing primary energy can be 30-40% higher than those representing end-use energy (Pears, 2006) and it would be advisable for LCA practitioners to provide conversion ratios from primary to secondary energy (Menzies *et al.*, 2007).

Another problem relating to comparison of LCAs in terms of energy is posed by the different definitions (and consequent different computational procedures) encountered in literature. For instance, terms such as "embodied energy" or "low-energy" building" are used in a different way by different authors. Sartori and Hestnes (2007) suggest calling a "low-energy" building one which, in the operation phase, does not require more than 121 kWh/(m^2·year) of end-use energy or 202 kWh/(m^2·year) of primary energy.

Furthermore, lack of comparability of studies can stem from the type of inventory adopted and the method upon which it is based: process-based, input/output or hybrid analysis (Khasreen *et al.*, 2009).

3.2.4.5 Breadth and completeness of studies

The level of completeness of LCAs poses two opposite problems. On the one hand, the more processes, activities and impacts are taken into account in an LCA, the more accuracy it might be expected to provide (Menzies *et al.*, 2007). On the other hand, though, a broader study requires LCA-practitioners to have an understanding of a wider range of different issues (Rønning & Brekke, 2014) and could also result in higher likelihood of mistakes and, therefore, lower accuracy, given the time and cost constraints within which researchers operate (Treolar, 1994).

3.3 Review on the thermal performance of buildings

3.3.1 The mechanism behind thermal inertia

Thermal inertia has been identified as key parameter in the design of the building envelope, to achieve enhanced thermal comfort in interior spaces and higher energy efficiency (Kontoleon *et al.*, 2013; Mavromatidis *et al.*, 2012; Sun *et al.*, 2013) both in winter and summer, especially when combined with the correct level of insulation (Hall and Allinson, 2008; Soares *et al.*, 2013).

When an element of the building envelope works as thermal mass, it offers "inertia" against interior temperature oscillations. Thanks to its inertia, a wall will start releasing heat to the interior space a certain period after it has been heated (concept of time lag) (Mavromatidis *et al.*, 2012).

Passive systems can rely on thermal mass located either within the envelope of a building or inside the building itself. In the latter case, thermal mass can be provided by intermediate floors, internal walls or even furniture (Zhou *et al.*, 2008), which do not interact dynamically with the outdoor environment (di Perna *et al.*, 2011). This doctoral thesis, however, focuses on the building envelope and does not deal with the effects of internal thermal mass.

A building can be thought of as a complex thermodynamic system (Soares *et al.*, 2013), subject to internal and external thermal loads, whose boundaries consist in the envelope elements, with their thermo-physical characteristics (insulation and heat capacity). Among the external loads are the climatic data: solar irradiance, air temperature, wind direction and speed. The parameters at play internally, instead, are the room size, occupation rate, performed activities, air-exchange rate, internal heat sources, *etc.*

When the exterior face of a wall reaches a steady-state, the balance of the surface thermal transfer can be written as (Shi and Zhang, 2011):

$$\mathrm{q}_{solar} + \mathrm{q}_{ground} + \mathrm{q}_{sky,long} + \mathrm{q}_{ground,long} = \mathrm{q}_{net} + \mathrm{q}_{conv} + \mathrm{q}_{rad,long}$$

EQUATION 3.1

where q_{solar} is the solar energy absorbed by the outer surface, q_{ground} is the ground-reflecting solar energy absorbed by the outer surface, $q_{sky,long}$ is the sky longwave radiation energy absorbed by the outer surface, $q_{ground,long}$ is the ground longwave-radiation energy absorbed by the sky, q_{net} is the net heat gain/loss of the wall, q_{conv} is the convection heat transfer between the wall and the environment and $q_{rad,long}$ is the longwave-radiation heat transfer between the wall and the environment.

This energy balance between the outer surface of the wall and the outdoor environment is mostly influenced by heat transfer through convection (q_{conv}, in EQUATION 3.1) and solar radiation (q_{solar}) (Prager *et al.*, 2006; Krzaczek and Kowalczuk, 2011; Ling *et al.*, 2016). The natural fraction of convection depends upon the temperature gradient between the outer surface of the wall and the air near this surface; whereas the forced portion of convection is affected by the wind. Here the speed and direction of the wind relative to the wall surface play a major role in determining the magnitude of forced convection.

While, as seen above, the mechanisms of convection and radiation drive heat transfer between the outer face of the envelope and the environment, heat transfer between indoors and outdoors is dominated by conduction across the envelope and is proportional to the temperature gradient between the interior and exterior surfaces of the building element (Ling *et al.*, 2016).

The distinction is often made between *direct* and *indirect* solar gains; the former consist in the solar radiation penetrating a building directly (for instance, through its openings), the latter, instead, consist in the heat transmitted from the outer surface of the envelope to the walls. This research focuses on the effects of the envelope and, therefore, on the effects of indirect heat gains/losses.

3.3.2 Optimisation of the building envelope

In order that high energy efficiency is obtained, the envelope must be designed in such a way to attenuate the rate of heat transmission between the "environmental node" (*i.e.,* the inner surface of the envelope) and the "ambient node" (*i.e.,* the outer surface) to the greatest possible extent (Hall and Allinson, 2008). This implies minimising heat gains through the envelope during summer and heat losses during winter.

The greatest intensities of solar radiation affect walls with different orientation in a different manner throughout the year: at most latitudes of the Northern hemisphere, the highest intensity occurs on East- and West-facing walls in summer, and on South-facing walls in winter (Givoni, 1981).

The effective influence of solar radiation strongly depends on its intensity, but also on the absorptivity of the outer surface of the wall (Kontoleon and Bikas, 2007; Mavromatidis *et al.*, 2012; Prager *et al.*, 2006): this parameter measures the fraction of incident solar radiation absorbed by a surface and varies between 0 (no absorption) and 1 (maximum absorption). The lighter the colour of a façade (or roof) is, the higher its solar absorptivity becomes.

About 20% of the heat loss which happens in winter can be attributed to the longwave-radiation heat exchange between the wall and the environment (Shi and Zhang, 2011). This type of heat exchange is influenced by many variables: among these are the longwave emissivity of the outer face of the wall (Prager *et al.*, 2006; Shi and Zhang, 2011) and its orientation and climatic conditions (Ruivo *et al.*, 2013; Shi and Zhang, 2011). If the emissivity of a wall is reduced, the radiative heat losses will decrease and, consequently, the outer-surface temperature will increase and the relative proportion of heat loss due to convection will rise, as demonstrated by Prager *et al.* (2006).

As noted by Ruivo *et al.* (2013), the values of time lag (TL) and decrement factor (DF) offered for some constructions in Guide A (*Environmental Design*) by CIBSE (2006) do not take into account the dependence of these two parameters on the orientation of the walls. Such published values therefore, can just offer a rough indication of the inertia-related behaviour of the building envelope, but cannot be used in a more precise manner, due to this significant simplification.

Ma and Wang (2012) confirm the commonly-accepted concept that, generally, the lower the DF, the better the summer performance. However, they warn against the widespread belief that a longer time lag will necessarily result in better performance; they point out that, for instance, a wall with a one-period TL (*i.e.,* 24 hours) behaves similarly to a wall with zero TL, under steady periodic conditions. The ideal TL for a wall depends on the climatic conditions and on its orientation: for example, while, in very general terms, it is true that long TLs are advantageous, this is not the case for hot, humid climates, where short TLs are recommended instead (Barrios *et al.*, 2012).

This confirms the importance of understanding the ideal TL for an envelope element, taking into consideration the complexity of variables that affect this index of inertia (Barrios *et al.*, 2012). In addition, in terms of research findings, this also demonstrate how much caution is needed when trying to apply research findings relating to a certain geographical area to another having a different climate.

The colour of the external surface of a wall and its orientation affect its TL and DF (Kaşka *et al.*, 2009; Kaşka and Yumrutaş, 2008; Ruivo *et al.*, 2013; Tsilingiris, 2002; Mavromatidis *et al.*, 2012). Tsilingiris (2002) indicates that significant reductions in heat loss can be achieved by simply adjusting the absorptivity of the outer surface.

In order to achieve an efficient passive system, the thermal mass used in building constructions often needs to be associated with adequate ventilation, occurring at a suitable time and at a sufficient rate. Generally speaking, ventilation within a building can be used for three main functions: maintaining good indoor air quality, providing cooling for occupants and cooling for the thermal mass incorporated in the building (Zhou *et al.*, 2008).

In the summer, the envelope can store the heat absorbed during daytime and partially release it to the inside later, at night, when the internal heat loads are generally lower and so is the outdoor temperature, allowing for passive cooling strategies such as night ventilation (Ferrari and Zanotto, 2013). In addition, cool can be absorbed and stored at night from outdoor air, either by natural or forced convection (Zhang *et al.*, 2007). Thanks to ventilation, the building element can release cool the next day, lowering the temperature of interior air and wall surfaces and thus improving thermal comfort for the occupants (Barrios *et al.*, 2012; Zhou *et al.*, 2008; Zhang *et al.*, 2007). Numerous authors recognise the importance of ventilation as a key, and economical, parameter for a successful application of thermal inertia. While natural ventilation has to rely on window opening, mechanical ventilation can be obtained, for instance, by means of ceiling fans.

Research conducted by Sun *et al.* (2013) suggests that when the outer temperature increases, the TL increases, too. This implies that, when temperature rises from one day to the next, the maximum daily temperature occurs later (at a larger temporal distance from the outer peak). These researchers also argue that the lowest temperature occurs earlier during the day, under the same change in weather. If, instead, external temperature is steadily decreasing from one day to the next, exactly the opposite situation will present itself, with the highest interior temperature occurring earlier and the lowest one occurring later.

According to some authors (*e.g.,* Sun *et al.*, 2013; Ozel, 2013), the DF is less dependent than the TL on climatological data and orientation. The experimental study by Kaşka *et al.* (2009) seems to suggest similar results and emphasises the effect of the thermo-physical properties[13] of the building materials incorporated in a wall on its DF.

For walls with an equal build-up, the longest TL is associated with East-facing walls and the shortest TL with West-facing walls, since the combination of temperature and radiation[14] reaches its maximum value at the earliest for the East wall and at the latest for the West wall (Ozel, 2013).

Extensive research has been conducted towards optimising the location of the insulation layer within the make-up of walls and roofs, for both summer- and wintertime. Various researchers argue that if only one layer of insulation is incorporated in a wall, the overall best results are achieved when the insulation is placed on the outside (Zhou *et al.*, 2008; Ozel and Pihtili, 2007): such configuration maximises TL and minimises DF.

Zhou *et al.* (2008), for instance, have compared different wall lay-ups, each containing a single layer of insulation placed in a different location within the wall thickness (the other layers providing more thermal mass); they conclude that the best-performing walls are the ones where the insulation is located on the outer surface. Evola and Marletta (2013) have reached very similar conclusions, indicating that an insulating material placed on the internal surface of an external wall will offer short TL and high DF

[13] Especially the wall's thermal-heat capacity.

[14] Expressed, for instance, in terms of sol-air temperature.

irrespective of the thickness and density of the materials used in the remainder of the wall. Evola and Marletta (2013) have also pointed out that, when thermal mass is desired on the inner surface of a wall (for wintertime performance, for instance), the mass should not be covered by any insulation layer (not even a thin one), as this would prevent the mass from taking part in the mechanism of heat absorption and release. In other words, the forcing wave would be reflected back towards the interior space with little inertia, that is, very short TL and small DF. For a similar wall configuration (*i.e.,* with insulation layer on the outside and thermal mass on the inside), Hall and Allinson (2008) explain that the wall mitigates heat loss in wintertime, thanks to the thermal transmittance provided by the insulant, and retains elevated thermal admittance for passive indoor cooling in summertime. According to Hall and Allinson (2008), a wall with a reversed build-up (that is, internal insulation and external mass) would be ideal in cold climates in that its low thermal admittance would reduce the heating load. These conclusions seem to conflict – at least to a certain extent – with the results (some of which have been outlined above) obtained by other researchers, who have emphasized the benefits of positioning thermal mass on the inside of walls in disparate climates: from hot climates such as in Kenya and cold climates of Scandinavia.

Some studies (Asan, 2000; Ozel and Pihtili, 2007; Mavromatidis *et al.*, 2012; Al-Sanea and Zedan, 2011) suggest that even better performance (energy savings and thermal comfort) is obtained when the same wall contains multiple layers[15] of insulant: one layer on the outside, one on the inside and one in the middle of the wall. According to Ozel and Pihtili (2007), this type of build-up is the most successful one for walls of any orientation and therefore is independent of climatic conditions and can be generalised for all geographical/climatic areas. Al-Sanea and Zedan (2011) argue that, for wall build-ups having the same heat capacity, the optimal overall thickness of the insulation material is the same when there is only one layer of it or when there are three layers: therefore, according to these authors, the optimum thickness of the insulant is independent of its location within the wall.

[15] For the same overall thickness of the insulant and the same overall resistance offered by it.

The studies illustrated in Kontoleon *et al.* (2013) and Kontoleon and Bikas (2007) focus on a comparison of various wall constructions with one or two insulation layers (with the same overall thickness) and conclude that a double insulation layer is more advantageous than a single one in terms of thermal performance. However, their findings suggest that the optimisation of the TL and that of the DF lead to different wall configurations: the TL is optimised (*i.e.,* maximised) when one of the two insulation layers is placed externally and the other at the centre of the wall thickness. The DF, instead, is optimised (*i.e.,* minimised) when the two insulation layers are located at the outer and inner surfaces of the wall. Other researchers (Al Sanea and Zedan, 2001; Al Sanea *et al.*, 2012) draw similar conclusions when argue that, for walls with a single insulation layer, this layer provides better TL if placed outside, but better DF if positioned inside.

This is an example of how identifying optimal envelope solutions can be a complex process and might require the designer to privilege one thermal-performance parameter over the others, even within the same group of parameters, *e.g.,* the TL *versus* the DF within the category of properties acting as an index of thermal inertia. In other words, deciding whether the TL or DF should be privileged and the extent to which they should be maximised or minimised, respectively, is often debatable (Bond *et al.*, 2013) and needs to be treated with extreme attention.

Hall and Allinson (2008) also describe the good thermal performance achievable with walls insulated both internally and externally (with a core providing thermal mass) and describe it as the ideal solution for cold climates, thanks to its low admittance and ability to reduce the oscillations of fabric heat flux.

Build-ups with double or triple layers of insulation material, according to these researchers, offer increased time lags and reduce the propagation of heat waves. However, it could be argued that such configurations with multiple insulation layers can be very impractical from a constructional point of view.

From an economic viewpoint, a strand of research has concentrated on defining the optimum specification of the insulation layer, in terms of type and size. While increasing the insulant thickness always results in decreased heat transfer through the envelope (without a limit), there is no linear relationship between these two aspects. This means that the rate at which heat transmission drops is very high for small thicknesses of insulant, whereas it becomes much lower for substantial thicknesses (Ozel, 2012). This concept is also interlinked with another: that there is a thickness threshold beyond which increasing the amount of insulation material is no longer economical, since operational energy savings for heating and/or cooling do not compensate any more for the initial cost of the insulation layer. The economically-ideal insulation thickness depends on numerous variables: cost and conductivity of the insulating material, cost of energy for space heating/cooling, efficiency of the heating/cooling system(s), lifespan of the building and, finally, inflation and interest rates (Ozel, 2012).

One economic advantage of a thermal-energy storage (TES) system inside the envelope as a means to improve its response to climatic conditions lies in the fact that not only are heating and cooling loads reduced, but they are also shifted to off-peak times of the electric utility, when electric energy is supplied at a lower cost for the end-user (Soares *et al.*, 2013; Kontoleon *et al.*, 2013; Neeper, 1999).

Mavromatidis *et al.* (2012) have researched into the optimisation of the thermal inertia of wall construction when multilayer thermal insulation (MTI) materials are used. These are composed of multiple, highly-reflective layers alternated with polymer or ceramic layers. The reflective layers (*e.g.,* aluminium foil) significantly reduce the infra-red (longwave) radiation exchange between the wall and the external environment and enhance the inertia parameters (*i.e.,* TL and DF). The polymer or ceramic spacers, instead, have the role of reducing conductive heat transfer thanks to their low-thermal conductivity. Since, when using MTI, reduction of heat transfer mostly relies on reduction of its radiative component (as opposed to its conductive component), it can be seen that each insulating material can be selectively used to tackle one of the aspects that regulate the thermal exchange between an inner space and the environment. Mavromatidis *et al.* (2012) also explain that resorting to three layers of insulation material across a wall thickness is the optimum configuration when MTI is adopted: these findings agree with those obtained by other authors who focused on the most widespread types of insulants (*e.g.,* mineral wool, extruded or expanded polystyrene, *etc.*), as explained above.

Many researchers (*e.g.,* Ulgen, 2002; Bond *et al.*, 2013) place emphasis on the necessity to take into consideration all the factors described above to ensure that thermal comfort is provided inside a space.

3.3.3 Performance of light-weight construction

Low thermal mass (and, consequently, low thermal inertia) has been often indicated as one of the main shortcomings of light-weight construction, from the viewpoint of thermal comfort: this is because of the risk of overheating and wide temperature oscillations due to internal and external heat sources (Ling *et al.*, 2016; Soares *et al.*, 2013).

In conventional, passive, solar technology, heat-storage systems present some recurrent disadvantages, such as high economic cost, voluminous mass within the building footprint and temperature fluctuations above the desired level (Heim, 2010). Thus, much recent research has concentrated on advanced materials that can be adopted to attenuate these problems and to regulate the thermal inertia of the envelope: phase-change materials (PCMs).

When PCMs are specified for a building envelope, the necessary amount of thermal mass can either be achieved by using PCMs exclusively, or by combining these with conventional materials that have elevated storage capacity.

When PCMs are incorporated in building elements, thermal-energy storage occurs in the form of *latent heat*,[16] as opposed to *sensible heat* as happens with conventional materials (Krzaczek and Kowalczuk, 2011; Mandilaras *et al.*, 2013; Zhang *et al.*, 2007). In other words, when the thermal-energy storage is based on PCMs,[17] heat absorption and

---

[16] When PCM are subjected to a temperature increase, they change from a solid to a liquid phase: this reaction is endothermic and, as a result, PCMs absorb heat. When temperature decreases, instead, the opposite reaction from liquid to solid is exothermic and PCMs release heat (Soares *et al.*, 2013). Unlike conventional construction materials, PCMs do not have constant thermal properties, in that they exhibit varying equivalent specific heat capacity while changing phase: this poses further computational difficulties when their behaviour is modelled in thermal simulations (Ling *et al.*, 2016).

[17] The amount of PCMs to be inserted in a building requires very attentive consideration: the objective is to optimise the heat-storage capacity with the minimum possible amount of PCMs (Soares *et al.*, 2013), to reduce economic cost and constructional practicalities associated with the incorporation of PCMs. If the quantity of PCMs is overestimated,

release are caused by the storage material changing in phase and not in temperature, as would be the case with traditional materials (Heim, 2010; Soares *et al.*, 2013).

Not only do PCMs exhibit considerable heat-storage capacity, they also offer the advantage that their storage process (and their phase change) is generally almost isothermal (Trigui *et al.*, 2013; Soares *et al.*, 2013), thus offering a remarkable contribution to temperature control (Heim, 2010).

PCMs can be either organic or inorganic[18] (Trigui *et al.*, 2013) and can be incorporated into building elements in various manners,[19] such as impregnation, encapsulation or lamination.

Some authors (*e.g.,* Mandilaras *et al.*, 2013; Soares *et al.*, 2013) have identified the inclusion of PCMs into the building envelope as a viable solution to the problem of light-weight buildings having limited thermal inertia: in this scenario, indeed, exploiting latent-heat storage can compensate for the small sensible-heat storage potential. PCMs can thus be used to increase the thermo-regulator capacity of a building and to provide its users with better thermal comfort.

Ling *et al.* (2016) point out that, depending on the type of PCMs used in construction, these can also ameliorate the thermal resistance of the envelope and not just its thermal inertia.

---

there is a risk that the solidification/melting process might not reach completion and that, as a result, the thermal storage achieved is insufficient (Soares *et al.*, 2013).

[18] Inorganic PCMs are typically hydrated salts, with advantageous qualities such as having elevated energy-storage potential, being non-flammable and inexpensive; but also with important shortcomings such as being corrosive and lacking compatibility with some other construction materials and needing an adequate container (Zhang *et al.*, 2007). Organic PCMs, on the other hand, are more compatible with other materials, but are flammable and undergo changes in volume (Zhang *et al.*, 2007).

[19] For instance, porous components such as gypsum-based board, concrete or clay blocks can be submerged into hot, melted PCMs in order to absorb them; other strategies include encapsulation of PCMs or the manufacturing of products laminated with them (Heim, 2010; Zhang *et al.*, 2007; Neeper, 1999). PCM plates can be utilised as internal wall or ceiling lining, in order to store solar energy or night cool and reduce internal temperature fluctuations (Neeper, 1999; Zhou *et al.*, 2011; Mandilaras *et al.*, 2013). PCM can also be coupled with electrical or hydraulic heating systems (Trigui *et al.*, 2013; Zhou *et al.*, 2011).

However, the application of PCMs in construction still encounters some obstacles that need to be overcome before it can be considered a fully-reliable, effective and generalised strategy (Zhang *et al.*, 2007; Soares *et al.*, 2013).

It is noteworthy that, according to some authors, there are instances in which light-weight constructions can be thermally-preferable to heavy-weight ones. For Saastamoinen (1994), the former are more efficient in energy saving than the latter in buildings that are not continuously occupied and are heated intermittently during wintertime. In light-weight buildings, energy efficiency can be further ameliorated by using heat storage separated from the envelope, in the form of large central heat storage or heat-recovery systems for individual buildings (Saastamoinen, 1994).

4 Research framework

4.1 Chapter overview

This chapter illustrates the methodological principles and research design that underpin this thesis in order to meet its aims and objectives and provide an answer to the research questions articulated in the Introduction.

Section 4.2 discusses the rationale for carrying out this research and the methodologies behind the LCA study and the thermal tests. A discussion on the link between both work strands is also provided.

The types of analyses and structure for both the LCA and the thermal investigations are given in **Section 4.3**.

The current work is based on the definition of ten notional buildings, which can be interpreted as the constructional variation of the same semi-detached house. **Section 4.4** explains the layout and spatial solution of the semi-detached house and the construction method of each of the ten buildings.

Finally, **Section 4.5** describes the three scenarios which have been defined in terms of different levels of wastage of building materials during the construction process (see also background discussion on this topic, Section 2.5). As will be discussed, the extent to which such materials are wasted substantially affects the environmental impacts associated with a building.

4.2 Overarching methodology

4.2.1 Rationale

The **gaps in knowledge** illustrated in SECTION 1.3 were mainly identified by means of an extensive literature review on the environmental impact of housing in the UK (and in the wider European context) and on the issue of adaptation of the building envelope to a changing climate.

The research design was also strongly influenced by a survey in which the author participated in 2012; this was funded by the Scottish Government and aimed at reviewing the offsite sector in Scotland. The review (Smith *et al.*, 2013) looked at offsite construction from various viewpoints and allowed the present author to familiarise himself with designers and companies who deal with offsite products and techniques and to establish contacts in industry. These contacts were also used later on in the research to source useful information and expert advice that is, in most cases, unpublished and outside the remit of academic knowledge.

In particular, conducting the review of the offsite sector informed the design of this research with regard to:

- an appreciation of construction products readily-available in Scotland, especially those which are based on natural or engineered timber;
- an understanding of the building processes that lead to the realisation of buildings that employ the products referred to in the point above;
- an understanding of the available infrastructure (within the Scottish construction industry) through which building components can be manufactured and buildings erected;
- a comprehension of constructors and manufacturers' insights into the field of offsite construction, especially when it is compared to its traditional, onsite counterpart.

The methodology and methods chosen to meet the objectives of this thesis and to answer the research questions outlined in CHAPTER 1 are the ones that, through a literature review and analysis of the physical and financial resources available for this investigation, were judged most adequate.

4.2.2 Methodological foundation for the LCA study

For the understanding and estimation of the embodied environmental impacts associated with timber housing, a life-cycle assessment approach was taken, following the recommendations found both in academic literature and in the international (ISO), European (CEN) and/or national (BSI) standards. The structure and principles of LCA as a methodology have been outlined in CHAPTER 2.

This LCA study is conducted from a cradle-to-gate[1] perspective; therefore, the system boundaries considered cover the three initial phases of extraction of materials and resources, transportation of these to the factory and manufacturing of building components in the factory itself.

The LCA approach has been chosen because it is the only available methodology with a **holistic view on the environmental impacts** of a product system. Other methodologies tend to focus on specific emissions (such as studies on carbon emissions, "carbon footprints", or Environmental Impact Assessments, EIAs) and specific stages, whereas LCA investigates different stages and impacts during the life cycle of a product (see SECTION 2.6).

This comprehensive approach of LCA is enhanced by its foundation on life sciences and chemistry (BSI, 2006a; Klöpffer and Grahl, 2014; Jolliet *et al.*, 2016); this characteristic results in a **rigorous approach** whereby polluting emissions, energy consumption and waste production are all measured against the actual properties of chemical elements and their known effects on the environment. These features of LCA make it an optimal methodology to answer research questions ①, ② and ③ with appropriate scientific rigour.

[1] See SECTION 2.6.

In terms of LCA computational procedures, **replicability and transparency** (on modelling assumptions, data sources, scenario definition, *etc.*) are two of the main drivers for this study. The discipline of LCA has developed through a set of international standards (see SECTION 2.6) which have been strictly followed by the present author. Environmental Product Declarations (EPDs) have been used – as recommended by standard EN 15798 (BSI, 2011c) – as the main source of environmental information on building products. The underlying life-cycle impact assessment (LCIA) methodology is that proposed by the Dutch academic centre **CML**, which organises emissions into **midpoint impacts** (SECTIONS 2.6.2 and 2.6.4 offer more information about midpoint and endpoint approaches and CML). There is ongoing scientific debate (Baumann and Tillmann, 2004; Finnveden *et al.*, 2009; Huppes and Curran, 2012; Klöpffer and Grahl, 2014; Hauschild and Huijbregts, 2015) regarding the suitability of using midpoint or endpoint impacts;[2] however, the main benefit of using a midpoint approach is that it allows measuring known, rather than theoretical, environmental burdens. It is therefore deemed that applying the CML methodology facilitates answering research questions ①, ② and ③ by using input data that has been generated through actual measurements, rather than assumptions.

Within studies on the environmental proficiency of products or activities, transparency may be affected by the tendency to adhere to weighting systems whereby the scores for individual impacts are combined through weighted averages and, thus, yield an overall score for a product. With such weighting models, overall scores can also be used to rank alternative products, if a comparison is desired. The almost-inevitable risk of such an approach is to disregard burden trade-offs that come to light when comparing different products (building techniques, in this case)[3].

Although some LCIA methodologies allow for weighting of impacts, the LCA standards explicitly discourage it (BSI, 2006a). As pointed out by Curran (2013), LCA is as an instrument to address a wide range of environmental factors and it is not intended to give a "clear winner". The comparative LCA methodology adopted in this thesis allows

[2] APPENDIX J offers a summary of other LCIA methodology whose approach is based on midpoint impacts, endpoint impacts or both. A midpoint approach allows measuring impacts that are already known rather than likely to happen in the future.

[3] See CHAPTER 1 for research question ②.

for enhanced transparency, as it does not assign more weight to certain emissions over others and does not aim at identifying a building technique whose overall environmental performance could be simplistically defined as best.

4.2.3 Methodological foundation for the thermal study

The method for the thermal tests is described in depth within SECTION 6.3. Field tests were chosen, as these allow evaluating the thermal behaviour of building elements under real weather conditions. An approach based on theoretical simulations bears the risk of lack of transparency due to variability in methods and modelling programmes; whereas the detailed description of the tests carried out in this study enables other researchers to replicate them. In addition, the replicable and transparent nature of the tests make them applicable to other climates and locations: an important factor considering the global nature of the issue of adaptation to climate change (see CHAPTER 1). All of these characteristics correspond to the criteria that distinguish experimental methodologies according to Marcum (2013): controllability (the tests were carried out following certain controls such as the design of the walls, choice of location, timing for collection of data and equipment), reproducibility and fecundity (*i.e.,* the data from these tests can be used for further experiments and could become the basis for computer simulations).

Experimental studies on thermal inertia are rarely performed, due to time and resources limitations. The opportunity to conduct tests has allowed the author to avoid resorting to simulations.

Some scholars from the field of philosophy of science (Peck, 2004; Morrison, 2009; Parke, 2014) argue that the lines between experiments and simulations are now more blurred than ever, due to advances in computational science that allow applying very complex models to hypotheses.

Morgan (2005), however, advocates the importance of the elements of “surprise” and “confoundment” only afforded by carrying out experimental studies; in other words, data produced by experimental tests might not always correspond to established paradigms and might open the path to new theoretical frameworks and discussions. Morgan’s position harks back to Bacon’s epistemological stance, which favoured inductive reasoning[4] through tests and collection of data. Indeed, Baetu (2008) states that scientific hypotheses do not have much value if they are not accompanied by experiments.

Mayo (1996) is able to strike a balance between these two opposing views[5] by proposing a hierarchy of models of inquiry; this hierarchy bridges the gap between experiments and simulations: experimental work is based on primary questions, but it must also be followed by statistical analysis on the data collected. Analogously, the author of the present thesis acknowledges (CHAPTER 7) the value of carrying out statistical modelling to further the knowledge on thermal inertia of the building envelope.

4.2.4 Relationship between the LCA and the thermal strands of work

The relationship between experiments and simulations comes to life in this thesis thanks to the link between the LCA study (partly simulation: data from real emissions applied to notional buildings) and the thermal tests. The two research strands are connected by the concepts of mitigation of, and adaptation to, climate change (see also SECTION 1.3.3). Indeed, the walling systems tested for thermal performance correspond to three building techniques also studied under the LCA investigation; this enables comparison between the results from both studies.

Both work strands are based on the common methodological framework of inductive reasoning (see above). According to the wheel of science (FIGURE 4.1) discussed by Abbott and McKinney (2013), induction in science starts with an observation and concludes in empirical generalisations which then inform theory and hypotheses (a deductive approach, on the contrary, would start from a theory and a hypothesis that need to be tested). The author of this thesis does not present a pre-conceived hypothesis or theory, but research questions that can be answered through the LCA methodology and the thermal tests.

---

[4] Francis Bacon (1620), *Novum Organum*; aphorism XIV.

[5] Peck (2004), Morrison (2009) and Parke (2014) on the one hand; Morgan (2005) and Baetu (2008) on the other.

The findings of the tests are then discussed in relation to the theories identified in the literature review (CHAPTERS 1 and 3), which have been formulated by their respective authors following simulation- or experiment-based studies.

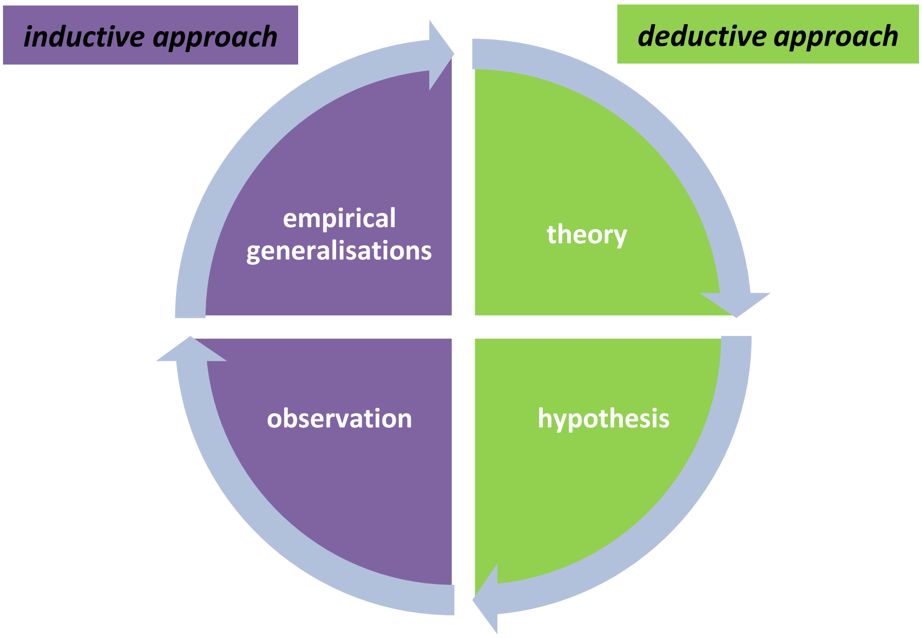

FIGURE 4.1 Wheel of science, adapted from Abbott and McKinney (2013, p. 22). Four stages in experimental science are identified. All stages are linked within a continuous circle, but the starting point varies depending on the approach: the inductive approach starts from observation and the deductive approach from theory.

4.3 Research design

Since this LCA study includes ten notional buildings and ten environmental aspects, the impact analysis forms a very extensive dataset. It has therefore been necessary to organise this body of data into a structure that was adequate to answer the research questions and suitable for the object of the investigation: the notional buildings in their constructional and typological aspects.

In order to answer research question ①, which revolves on the impacts of each building considered in isolation, a series of **contribution analyses** has been designed (and implemented in the dedicated Microsoft Office Excel file). One analysis sorts impact contributions by components' structural role and groups them into two categories: impacts from structural components and impacts from non-structural components. This analysis is fundamental, because it allows revealing the environmental burdens associated specifically with the structural system of the buildings, which, in this study, is also the principal criterion whereby the six building "families" (*i.e.,* **A**, **B**, **C**, **D**, **E** and **F**) have been defined.

There is also a contribution analysis by type of materials: here building components (and their environmental burdens) are grouped together depending on the materials that they are made from: minerals, wood-based, metals, plastics and hybrid.

A third contribution analysis – which is more complex and runs in parallel with the previous two – is that by building element. Here, impacts are divided into two main groups: those belonging to the building envelope and those belonging to the reminder of the dwelling. The envelope group includes: external walls, roof and ground floor; the non-envelope group includes strip foundations, partition walls, party walls and intermediate floors. Then, a second distinction criterion is applied to this analysis: the impact of each building element[6] is further broken down into sub-contribution by material type (following the types listed above: minerals, wood-based, *etc.*)

[6] For the definitions of building "elements" and "components" adopted in this thesis, see SECTION 4.4.

This approach to the impacts makes it possible to identify parts of the buildings that are major contributors to a certain environmental impact. Thus, it becomes possible to single out parts of the buildings that require further LCA analysis or a change in the material specification or detailing, so that their environmental burden can be reduced. In other words, an attentive consideration of the results obtained from the three different contribution analyses outlined above permits identifying critical aspects of the constructions studied and thus constitute a starting point to suggest potential material replacements and *ad-hoc* changes to the detailing solutions.

A **comparative analysis** has also been devised and carried out to compare the results of individual buildings for each environmental aspect considered. This analysis ascertains which buildings perform better than the others under each impact and allows identifying burden trade-offs (or burden shifts) between buildings. [7] Hence, this analysis is instrumental in answering research question ②.

The impact scores offered by the contribution and comparative analyses have been subjected to an **uncertainty analysis**, aimed at understanding the level of confidence associated with the scores themselves. This type of analysis has been introduced in response to the literature review on the methodological aspects of LCA: it is indeed recommended as good practice, although it is often neglected (see discussion on this issue in SECTION 3.2).

A **sensitivity analysis**[8] was also organised, in order to answer research question ③ which regards the impact of the building *processes* (as opposed to *products*) used in construction and their respective wastage rates of building materials, as explained in SECTION 2.4. The sensitivity analysis explores how changing the modelling assumptions[9] on waste made in scenario 1 affects the magnitude of the LCA results, *i.e.,* the environmental burdens foreseen.

---

[7] See glossary (APPENDIX B) for a definition of *burden trade-offs*.

[8] The structure of the sensitivity analysis will be illustrated in more detail in SECTION 4.5.

[9] Scenario 1, on purpose, does not include any wastage of materials, see SECTION 4.5.

Scenario 1 constitutes the baseline for the sensitivity analysis: first, the results of scenario 2 are compared to those of scenario 1; then, in a similar fashion, the results of scenario 3 against those of scenario 1.

Due to the difficulty encountered in determining exact wastage rates of building materials for scenarios 2 and 3 (see discussion in SECTION 2.4), the sensitivity analysis was structured in such a way to be able to contemplate a degree of variance of the parameters.

The data obtained from the thermal experiments also needed to be organised and processed in a suitable fashion to answer research questions ④ and ⑤.

A first strand of **thermal analysis** was therefore designed to identify the two inertia parameters[10] (decrement factor and time lag) of each of the external walls tested. The outputs of such analysis provide an answer to question ④.

Two sets of **regression analyses**[11] were planned and conducted to understand the significance of two factors that can affect the results obtained in the previous analysis. A regression analysis was thus performed to understand the correlation between the inertia parameters and solar energy; and another was conducted for the correlation between the same parameters and the heat capacity of the constructions. The findings from these analyses offer an answer to research question ⑤.

FIGURE 4.2 summarises the framework of this research and the analyses (outlined above) that it encompasses.

[10] The method used to process the large set of data collected during the experiments is detailed in SECTION 6.3.

[11] These regression analyses will be presented in more detail in SECTION 6.4.2.

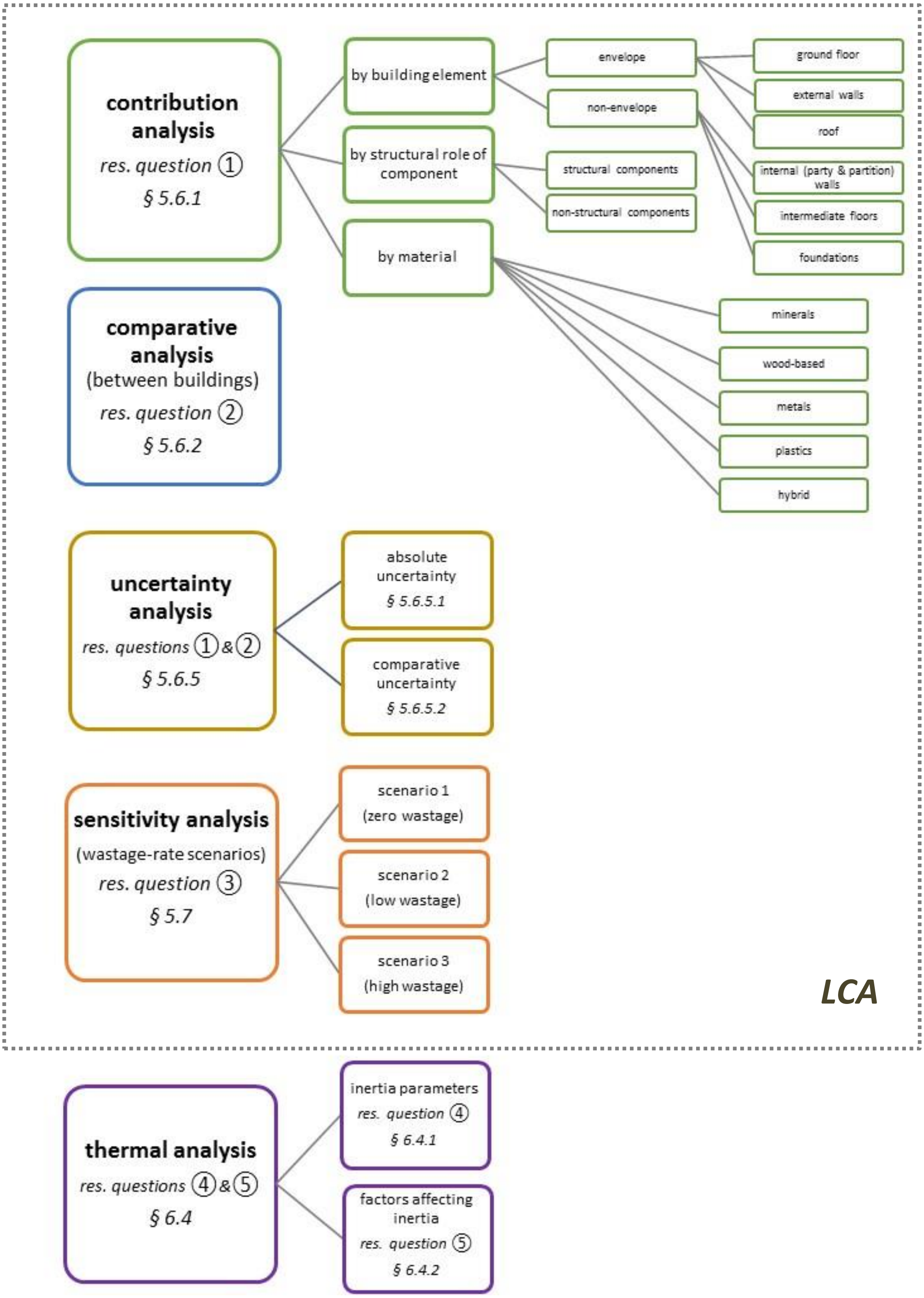

FIGURE 4.2 Structure of analyses conducted in this thesis. The box with a round dots border distinguishes analyses done within the LCA framework.

4.4 Notional buildings

Both the LCA and the thermal study presented in this thesis share a common basis: the definition of ten notional buildings.

Nine of these buildings are timber-based and have been selected to capture the variety of techniques that are available today in the Scottish residential field. These techniques include the most widespread methods (timber-frame panel construction), the second most used techniques (structural insulated panels) and methods that have attracted the attention of designers and researchers in the construction industry over the last decade, but that are still uncommon in Scotland (massive timber systems). The tenth building included in the study and used as a reference is the only non-timber building (load-bearing masonry). The thermal study has been carried out on three samples of external walls of three of the notional buildings: a closed-panel wall, a cross-laminated and a masonry wall.

4.4.1 Typological and geometric characteristics

The ten notional dwellings represent ten constructional variations of the same building type: a semi-detached house, which, as seen in SECTION 2.2, is one of the most common types in Scotland.

The house has been designed in such a way to reflect the plan layout and spatial arrangements of a typical semi-detached dwelling in Scotland, at least for the aspects that can be significant for this research, *i.e.,* the quantification of building materials for a dwelling of this type and size, that allows for an estimation of its environmental aspects.

The house consists of two full storeys and an attic. The ground floor accommodates the kitchen and living area, the first floor three bedrooms, and the attic a spare room.

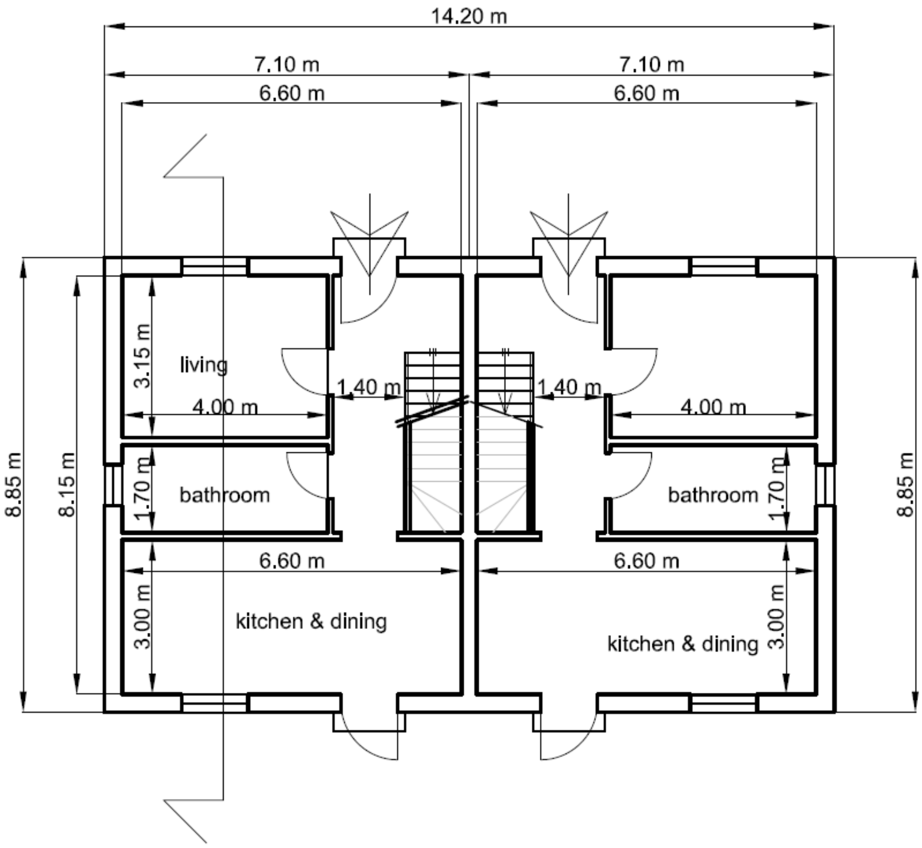

FIGURE 4.3 Semi-detached house: ground- floor plan.

All rooms on the ground floor are accessible to wheelchair-users, including kitchen (Standard 3.11) and bathroom (Standard 3.12). In addition, the living room could be easily converted into a bedroom for wheelchair-users (Standard 4.2.b). All corridors have a minimum width of 1.2 m, to allow convenient passage and provide space for manoeuvring.

The ten buildings all have the same gross *internal* floor area (hereafter, GFA): this is independent of the thickness of the external walls, which varies from building to building. The GFA has indeed been chosen as the common denominator of the notional dwellings since it allows a fair comparison between them.

The GFA is 53.7 m^2 for both the ground floor and the first floor and 28.7 m^2 for the room under the roof (attic), with a total of 136.1 m^2.

One of the advantages of the plan layout employed is that it is very similar to that of other building types: with minor adjustments,[12] indeed, then current layout would reflect a typical terraced house or detached house. Thus, the environmental impacts determined for this notional dwelling (in its ten variations) is assumed to be adequately representative of other building types of comparable dimensions.

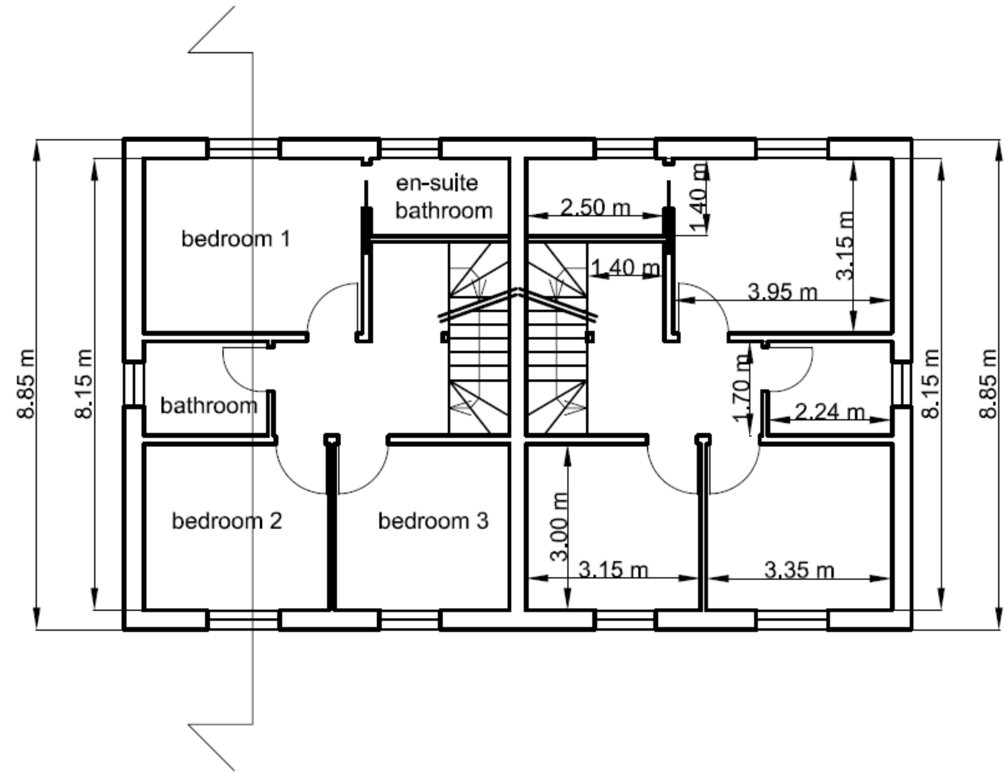

FIGURE 4.4 Semi-detached house: first-floor plan.

[12] Especially adjustments to the fenestration on the side elevation of the building. A terraced house would lose the windows on the side (where the bathrooms are); whereas a detached house could gain a window on the side of the current party wall, for the lighting of the vertical-circulation space.

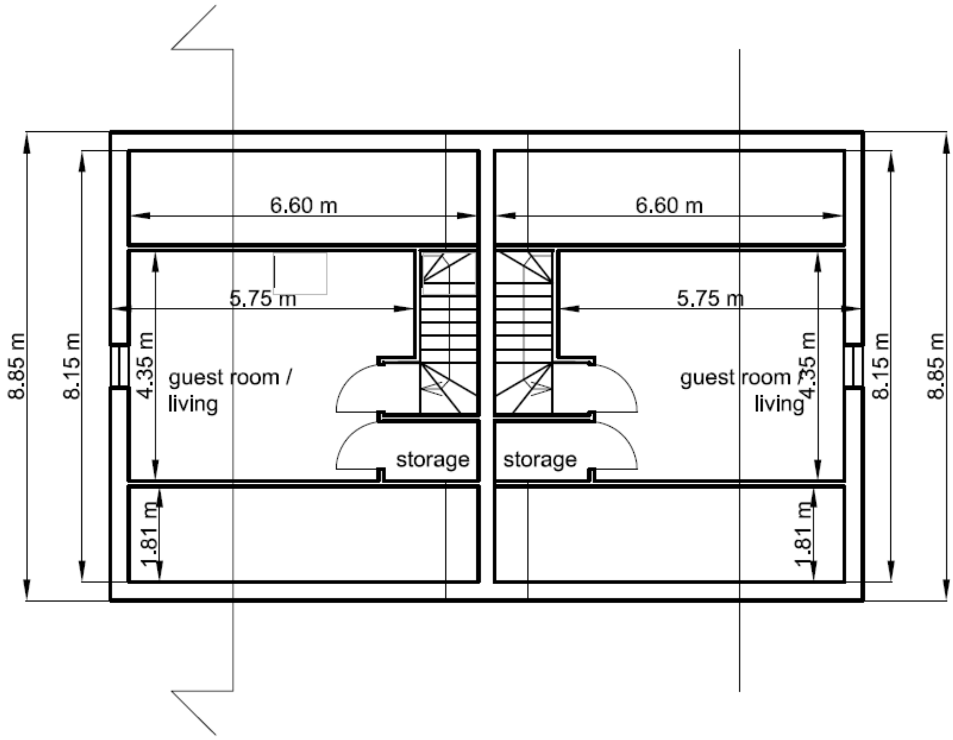

FIGURE 4.5 Semi-detached house: second-floor plan.

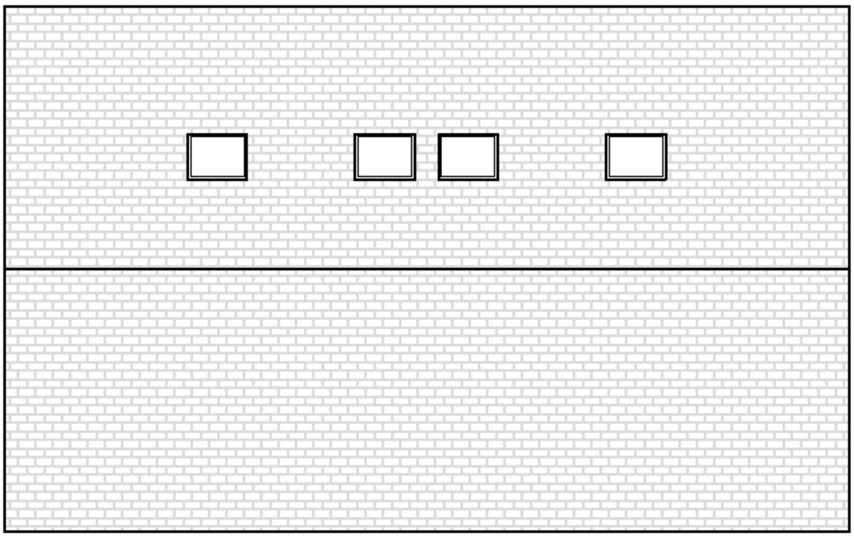

FIGURE 4.6 Semi-detached house: roof plan.

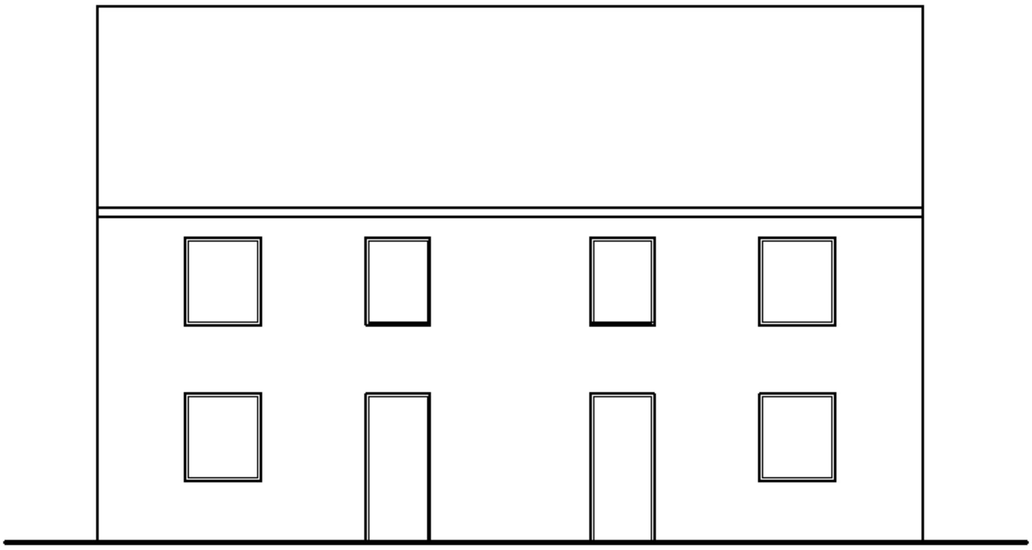

FIGURE 4.7 Semi-detached house: front elevation.

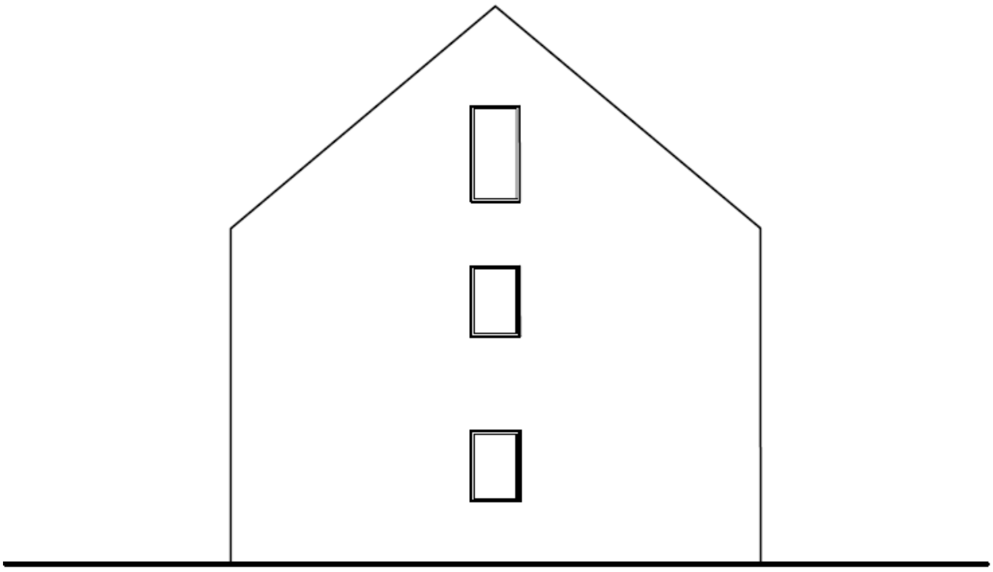

FIGURE 4.8 Semi-detached house: side elevation.

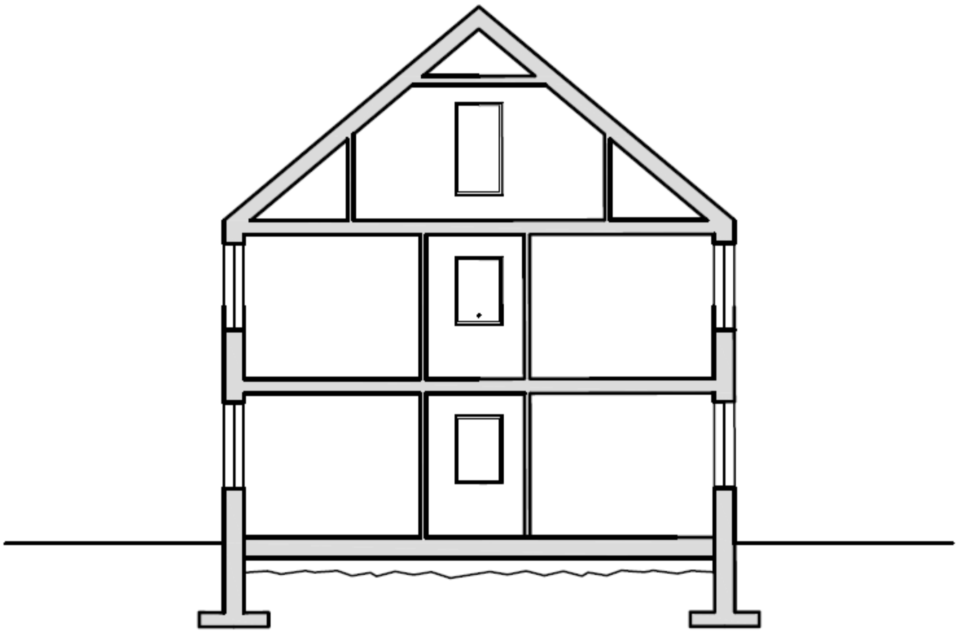

FIGURE 4.9 Semi-detached house: cross-section.

TABLE 4.1 Geometric properties for each building.

Category	Geometric property	Unit	Building									
			A	B1	B2	C1	C2	D1	D2	E1	E2	F
floor areas	footprint area	m^2	62.61	63.67	61.35	62.81	60.50	61.71	61.30	62.81	62.81	63.28
	gross internal ground-floor area	m^2	53.79	53.79	53.79	53.79	53.79	53.79	53.79	53.79	53.79	53.79
	gross internal first-floor area	m^2	53.79	53.79	53.79	53.79	53.79	53.79	53.79	53.79	53.79	53.79
	gross internal attic-floor area	m^2	28.71	28.71	28.71	28.71	28.71	28.71	28.71	28.71	28.71	28.71
	total gross internal floor area	m^2	136.29	136.29	136.29	136.29	136.29	136.29	136.29	136.29	136.29	136.29
ext. walls	area of ext. walls (solid)	m^2	124.34	128.48	126.19	124.77	122.52	121.52	120.84	123.67	123.67	124.80
	area of openings on ext. walls	m^2	19.87	19.87	19.87	19.87	19.87	19.87	19.87	19.87	19.87	19.87
	tot. area of ext. walls (solid + openings)	m^2	144.21	148.35	146.06	144.64	142.39	141.39	140.71	143.54	143.54	144.67
	thickness of ext. walls	m	0.34	0.37	0.27	0.34	0.24	0.29	0.27	0.33	0.33	0.37
	eaves height (off ground level)	m	5.56	5.68	5.68	5.56	5.56	5.46	5.45	5.51	5.51	5.56
int. walls	length of partition walls (incl. doors), ground floor	m	15.85	15.85	15.85	15.85	15.85	15.85	15.85	15.85	15.85	15.85
	length of partition walls (incl. doors), first floor	m	21.36	21.36	21.36	21.36	21.36	21.36	21.36	21.36	21.36	21.36
	length of partition walls (incl. doors), attic	m	20.13	20.13	20.13	20.13	20.13	20.13	20.13	20.13	20.13	20.13
	individual area of int. doors	m^2	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68
	cumulat. area of int. doors	m^2	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8
	thickness of int. walls	m	0.11	0.11	0.11	0.18	0.18	0.17	0.17	0.18	0.18	0.13
party wall	area	m^2	65.39	66.94	65.42	65.39	63.89	63.74	63.37	64.86	64.86	65.92
	thickness	m	0.317	0.384	0.384	0.363	0.363	0.384	0.384	0.384	0.384	0.28
ceiling heights	ceiling height, ground-floor	m	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	ceiling height, first-floor	m	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	ceiling height, attic (average)	m	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93
volumes	gross internal volume, ground floor	m^3	134.48	134.48	134.48	134.48	134.48	134.48	134.48	134.48	134.48	134.48
	gross internal volume, first floor	m^3	134.48	134.48	134.48	134.48	134.48	134.48	134.48	134.48	134.48	134.48
	gross internal volume, attic	m^3	55.41	55.41	55.41	55.41	55.41	55.41	55.41	55.41	55.41	55.41
	total gross internal volume	m^3	324.36	324.36	324.36	324.36	324.36	324.36	324.36	324.36	324.36	324.36
roof	roof area (solid)	m^2	79.73	81.12	78.08	80.00	76.98	78.56	78.02	80.00	80.00	80.60
	cumulat. rooflight area	m^2	2	2	2	2	2	2	2	2	2	2
	total roof area (solid + rooflights)	m^2	81.73	83.12	80.08	82.00	78.98	80.56	80.02	82.00	82.00	82.60
	roof slope	°	40	40	40	40	40	40	40	40	40	40

TABLE 4.2 Geometry of the internal finishes.

Building element	Storey / location	Finish type	Area m^2	Proportion of total %
walls	(inside of) ext. walls	paint	103.06	82
		ceramic tiles	22.25	18
	partition walls	paint	40.8759	82
		ceramic tiles	74.2	18
	party walls	paint	66	100
flooring	groud floor	laminated vinyl	27.19	51
		ceramic tiles	26.6	49
	first floor	carpet	46.48	86
		ceramic tiles	7.31	14
	attic	carpet	28.71	100
ceilings	groud floor	paint	53.79	100
	first floor	paint	53.79	100
	attic	paint	32.868	100

4.4.2 Functional requirements

The detailing of the dwellings has been done in such a way to meet all the most important functional requirements set by the building regulations (*i.e.,* the *Technical Handbook – Domestic*), as listed in TABLE 4.3.

TABLE 4.3 Functional requirements set by the building regulations that have informed the detailing and material specification for the notional houses.

Element group	Element	Thermal requirements: max U-value W/(m²·K)	Fire-resistance requirements		
		clause 6.2.1, TABLE 6.3 [a]	clause 2.A.3, TABLE 2.7 [a]		
wall	external wall	0.22	stability 30	integrity /	insul. /
	party wall	0.2 (if with empty cavity)	60	/	/
	partition wall	/	30 (if load-bearing)	/	/
floor	ground floor	0.18	/	/	/
	intermediate floor	/	30	/	/
roof	*n.a.*	0.15	30	/	/

Notes
a Clause of the *Technical Handbook – Domestic*.

All the external walls meet the thermal requirement[13] in terms of level of insulation and have an overall thermal transmittance (U-value) of 0.21 ± 0.005 W/(m²·K).

Since the height of the dwellings[14] is below 7.5m, the detailing has been done so as to meet the fire-safety requirements[15] of this category of houses (as provided for in clause 2.31., TABLE 2.1).

[13] Clause 2.A.3, Table 2.7 of the *Technical Handbook – Domestic*.

[14] Measured according to the rules in clause 0.7.2 of the *Technical Handbook – Domestic*.

[15] For this category, a short fire-resistance duration is specified.

All the detailing and material specification has been done following the guidance provided in the documents accompanying the *Technical Handbooks*, such as the *Accredited Construction Details (Scotland)* 2015[16] and the *Example Construction and Generic Internal Constructions.*[17]

4.4.3 Supporting structures

Although accurate structural calculations were beyond the scope of this study and were not performed, great care has been put into the pre-sizing of all structural members, in order that they are commensurate with the structural capacity of their materials and the loading configuration in which they are meant to operate.

Thus, for the purposes of this research, the sizes of all structural components are deemed to approximate adequately the sizes that would be obtained through more rigorous calculations.

Particular care has been spent for the pre-sizing of the foundations, since they contain materials that can heavily affect the environmental impacts arising from the buildings. All buildings have strip foundations, which have been sized following the recommendations provided in the *Small Buildings Structural Guidance* (Buildings Standards Division, 2010), hereafter SBSG.

The foundation walls are made with high-density concrete blocks and the footings with un-reinforced concrete of grade ST2[18] (clause 1.C.3 of SBSG). The mix[19] selected for this research consists in 255 kg of Portland cement, 1332 kg of coarse aggregate and 572 kg of fine aggregate per cubic metre of final product.

The width of the foundations is proportional to the gravitational loads that they are subjected to and vary for each building.

---

[16] Building Standards Division (2015).

[17] Building Standards Division (2011).

[18] ST2 is a standardized prescribed concrete, which is regulated by Standard BS 8500-2: 2002 (Table 10).

[19] Values recommended by the Standard for slump class S3.

It has been assumed that the buildings are constructed on an average type of ground, in terms of structural capacity and chemical conditions; namely type III, clay or sandy clay (as defined in clause 1.C.6 of SBSG), chemically non-aggressive.

For all ten buildings, the total footing width exceeds the minimum set by clauses 1.C.3 and 1.C.6 of SBSG, in order to follow good practice and ensure that the scarcement is 150mm-wide on each side, thus creating an inverted-T cross-section for the foundations.

4.4.4 Constructional aspects

The main constructional characteristics of each building are explained in the next sections. Detail drawings for each building element[20] are provided in APPENDIX F.

Some elements belong to two or more buildings: TABLE 4.4 illustrates all the elements that have been designed for this study and indicates in which of the ten buildings they are used.

[20] In this thesis, the words "building element" designate parts of a building such as a roof, floor, wall, *etc.* Smaller parts of a building are instead referred to as "building components", *e.g.,* a roof tile, a concrete block, a timber stud, *etc.* These definitions follow the terminology recommended in the international standards.

TABLE 4.4 List of all building elements, indicating the dwelling(s) in which they are employed.

Element identification			Description	Building type in which element is									
group	element	type		A	B1	B2	C1	C2	D1	D2	E1	E2	F
foundations	*n.a.*	A	strip foundations	✓									
		B1	strip foundations		✓								
		B2	strip foundations			✓							
		C1	strip foundations				✓						
		C2	strip foundations					✓					
		D1	strip foundations						✓				
		D2	strip foundations							✓			
		E1	strip foundations								✓		
		E2	strip foundations									✓	
		F	strip foundations										✓
walls	external wall	A	open TF panels	✓									
		B1	closed TF panels		✓								
		B2	closed TF panels			✓							
		C1	SIPs				✓						
		C2	SIPs					✓					
		D1	CLT panels						✓				
		D2	CLT panels							✓			
		E1	NLT panels								✓		
		E2	NLT panels									✓	
		F	struct. masonry										✓
	party wall	TF	open TF panels	✓									
		B	closed TF panels		✓	✓							
		C	SIPs				✓	✓					
		D	CLT panels						✓	✓			
		E	NLT panels								✓	✓	
		F	masonry										✓
	partition wall	TF	open TF panels	✓	✓	✓							
		C	SIPs				✓	✓					
		D	CLT panels						✓	✓			
		E	NLT panels								✓	✓	
		F	masonry										✓
floors	ground floor	TF	in-situ timber	✓			✓	✓					✓
		B	timber-frame		✓	✓							
		D1	ground-supported						✓				
		D2	CLT panels (no							✓			
		E	NLT panels								✓	✓	
	interm. floor	TF	in-situ timber	✓			✓	✓					✓
		B	timber-frame		✓	✓							
		D1	CLT panels						✓				
		D2	CLT panels (no							✓			
		E	NLT panels								✓	✓	
roof	*n.a.*	TF	timber attic	✓									✓
		B	timber-frame		✓	✓							
		C	SIPs				✓	✓					
		D	CLT panels						✓	✓			
		E	NLT panels								✓	✓	

4.4.4.1 Building A

Building **A** is based on an open-panel, timber-frame system. This means that the wall panels are fabricated offsite with the lining on one side only (generally, the exterior side) and then completed with the internal lining onsite. The insulation material consists in glass-wool quilts placed in between the timber studs and can be inserted either in the factory or onsite (see also illustrations in SECTION 2.4).

The exterior cladding of the perimeter walls of building **A** is realised with a rendered leaf of medium-density-concrete blocks.

All the floors are timber-framed and constructed onsite; the ground floor is therefore elevated.

The roof is made with a series of timber attic trusses fabricated offsite and joined onsite. The roof covering is made of interlocking concrete tiles.

The load-bearing walls rest on plain-concrete, strip foundations.

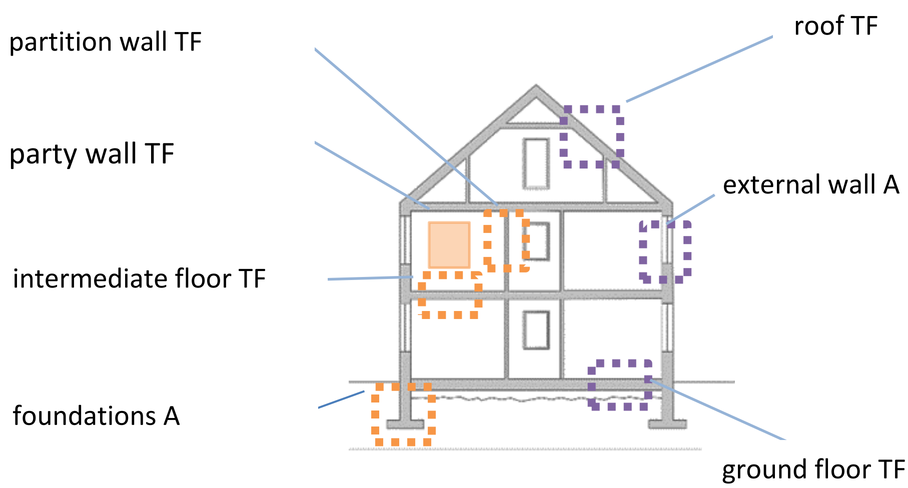

FIGURE 4.10 Elements of building A.

4.4.4.2 Buildings B1 and B2

Buildings **B1** and **B2** adopt a closed-panel timber-frame system; that is, the wall panels are fabricated in the factory, insulated and completed with internal and external linings (OSB sheets).

Due to this method of construction, the building services cannot be accommodated in the space between the wall studs (as this is no longer accessible when the panels are installed onsite): therefore, the walls of **B1** and **B2** have a service cavity on the inside (unlike the walls of **A**, which employ an *open*-panel system). The same applies to the floors of **B1** and **B2**, in which the horizontal services are run in an *ad-hoc* cavity between the top of the cassettes and the floor deck (this is not necessary in the floor system adopted in **A**, in which pipes and cables can be accommodated in the voids between the joists). For these reasons (*i.e.,* for the construction of the service cavities), a closed-panel system requires more use of timber-based materials than its open-panel counterpart.

The exterior cladding consists in rendered blockwork for **B1** (as for building **A**) and render on cement board for **B2**. Therefore, the main difference between **B1** and **B2** lies in the heavy-weight or light-weight solution adopted for the perimeter walls.

All the floors (including the ground floor) are made of prefabricated timber cassettes and so is the roof.

Since the weight exerted by the external walls differs largely, building **B1** has wider foundation footing than **B2**.

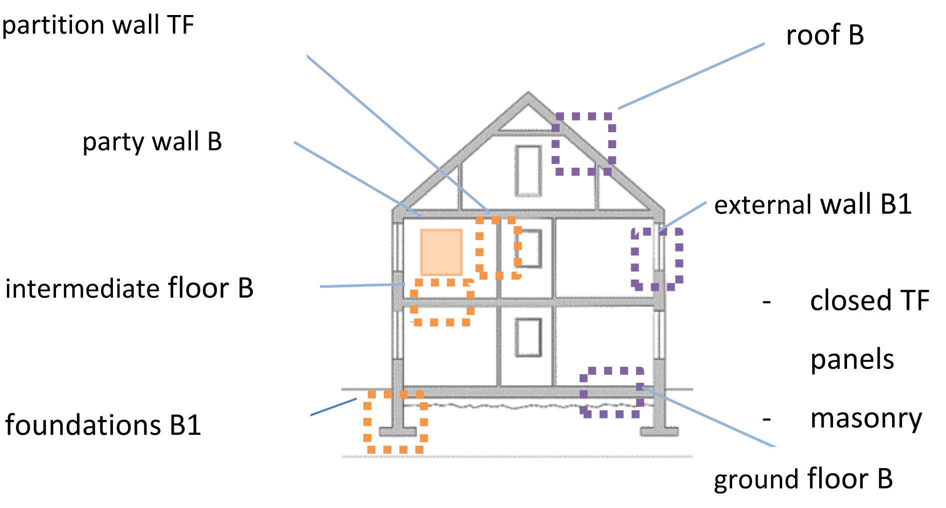

FIGURE 4.11 Elements of building B1.

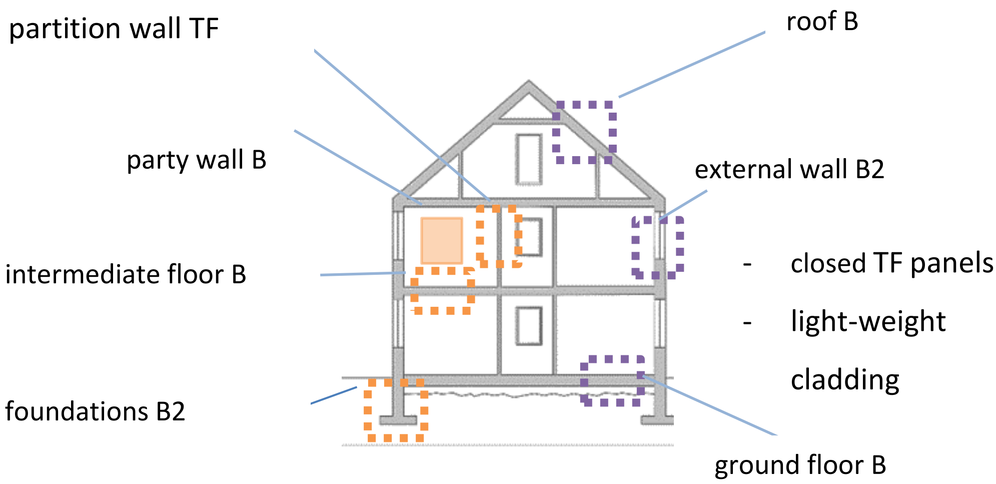

FIGURE 4.12 Elements of building B2.

4.4.4.3 Buildings C1 and C2

Buildings **C1** and **C2** use structural insulated panels for both internal and external walls.

Similarly to buildings **B1** and **B2**, the difference between these two options is in the external cladding of the perimeter walls: rendered blockwork for **C1** (as seen for **A** and **B1**) and render on cement board for **C2**.

All the floors are timber-framed and use the same system as the one described for building **A**.

The roof is made with SIPs reinforced by means of timber splines with a solid cross-section.

The sizes of the foundation footings vary accordingly to the magnitude of the gravitational loads transmitted by the walls.

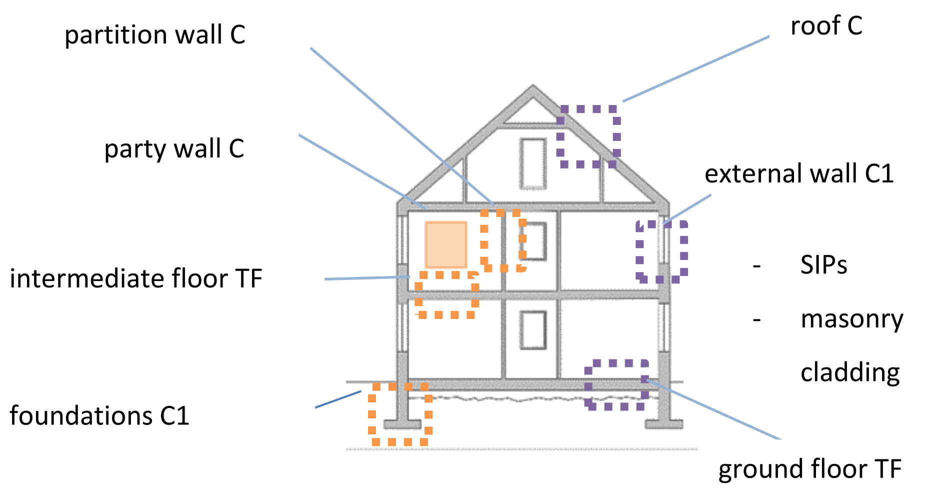

FIGURE 4.13 Elements of building C1.

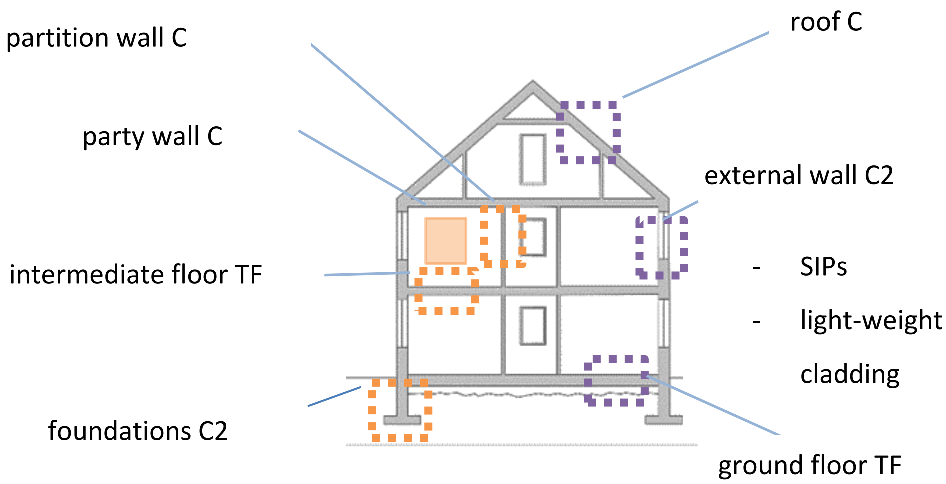

FIGURE 4.14 Elements of building C2.

4.4.4.4 Buildings D1 and D2

Buildings **D1** and **D2** are based on cross-laminated-timber panel solutions, used for external and internal walls, most of the floors and the roof.

The differences between **D1** and **D2** are as follows:

- the external cladding of **D1** is render on cement board (as in **B2** and **C2**), whereas the external cladding of **D2** is made of timber boards;
- the ground floor of **D1** consists in a concrete slab directly supported by the soil, while that of **D2** is a suspended CLT floor;
- the intermediate floors of **D1** have a cement:lime screed on top of CLT panels, while the floors of **D2** use a dry solution with no screed.

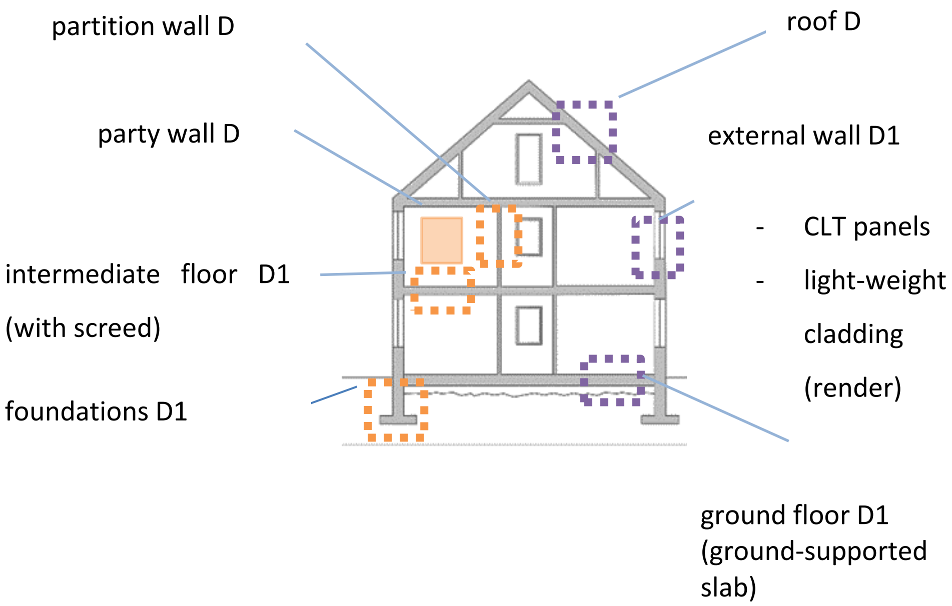

FIGURE 4.15 Elements of building D1.

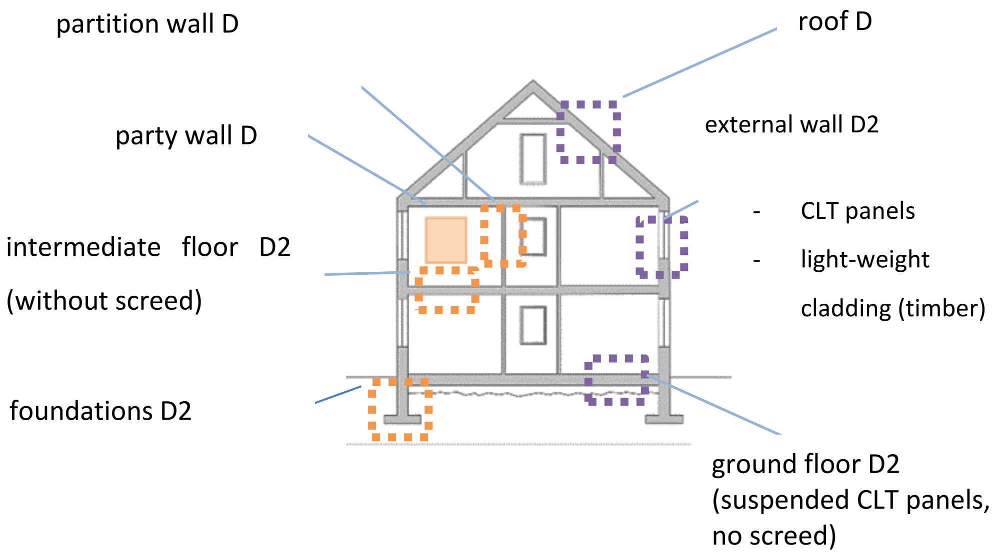

FIGURE 4.16 Elements of building D2.

4.4.4.5 Buildings E1 and E2

Buildings **E1** and **E2** employ nail-laminated-timber panels for all the structural elements: external and internal walls, all floors and the roof. The NLT panels are sheathed with a layer of OSB, which improves their racking and bending structural capacity.

One of the advantages of nail-lamination is that, once the timber planks have been nailed together, the natural defects of the woody material in each of them has very little effect on the overall structural behaviour of the NLT panels (Hairstans and Sanna, 2017).

Furthermore, NLT panels can achieve overall good structural capacity even when timber with moderate (as opposed to high) density, strength and rigidity is used (Sanna *et al.*, 2012). This aspect makes NLT products compatible with timber from Scottish and Welsh forests, which is often of lower grade, owing to the climatic conditions in which the trees grow (see SECTION 2.3). Another aspect of this system is that the manufacture of NLT panels does not require highly-skilled operatives, which becomes especially advantageous in the context of skill shortage in construction.

For the reasons above, the nail-lamination process has attracted the attention of researchers and designers in Scotland over the last decade and has been at the centre of collaborative research projects that led to the construction of houses with novel NLT solutions (Sanna *et al.*, 2012).

The floors of dwellings **E1** and **E2** do not include a screed, so are completely made of timber.

The sole distinction between the two alternatives lies in the external cladding of the perimeter walls: **E1** is clad with render on board (as **B2**, **C2** and **D1**), while **E2** is clad with wooden boards (as **D2**). Thus, all external walls adopt a light-weight cladding solution (as is the case for houses **D1** and **D2**).

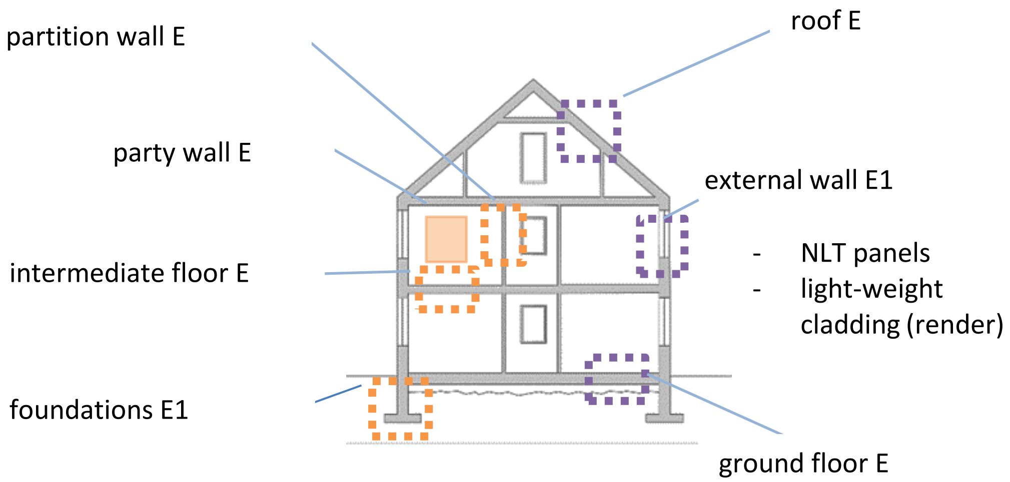

FIGURE 4.17 Elements of building E1.

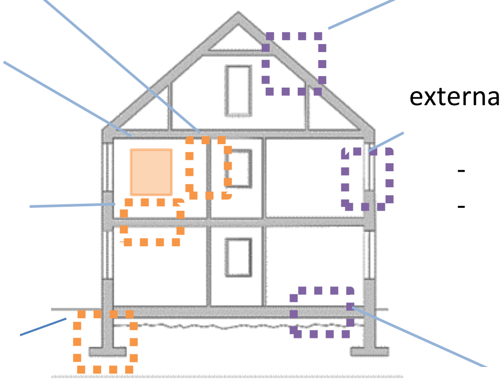

FIGURE 4.18 Elements of building E2.

4.4.4.6 Building F

Building **F** is the only non-timber building investigated in this study: its walls adopt a more "traditional" load-bearing masonry system.

The external walls consist of two skins: the inner skin is the load-bearing one and constructed with high-density blocks (which also provide these elements with high thermal capacity). The outer leaf is made with rendered, medium-density-concrete blocks (as in buildings **A**, **B1** and **C1**).

The internal walls are made of blockwork, too.

The floors are exactly the same as in buildings **A**, **C1** and **C2**: timber-framed and constructed onsite. The roof is the same as in building **A** (timber frame).

Building **F** is the one with the widest foundation footings (and the heaviest external walls).

4.4.4.7 Common characteristics

All dwellings are modelled to have the same finishes, which have been chosen from materials that are commonly used in main-stream dwellings. The floors and walls of the kitchen and bathrooms are finished in ceramic tiles; all the other internal walls are painted. The living area has PVC flooring, while the bedrooms have carpet flooring. The roofs are covered in interlocking concrete tiles.

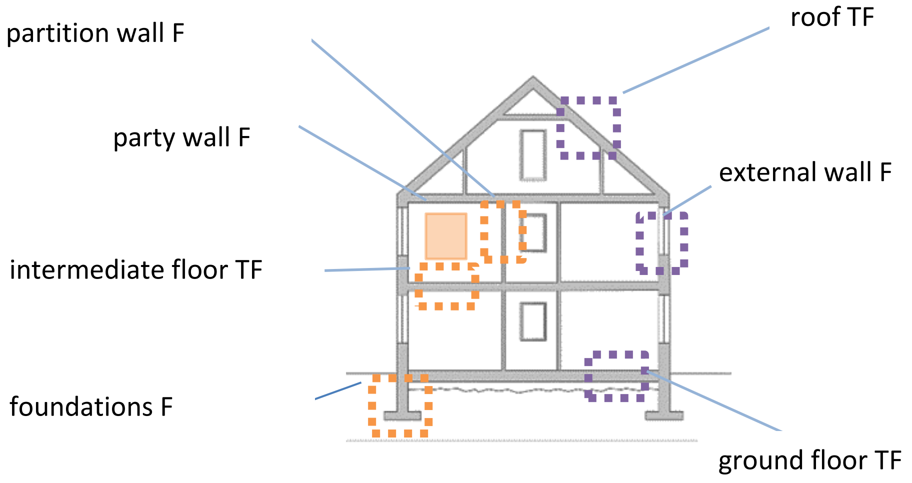

FIGURE 4.19 Elements of building F.

4.5 Definition of wastage scenarios

When a life-cycle assessment is carried out at the building level, the inventory consists in a bill of quantities (BoQ) that specifies the amount of all the materials that have been included in the study, depending on its scope, boundary conditions and desired level of accuracy and completeness.

In this LCA, three scenarios have been defined, each characterised by specific BoQs for all ten of the notional buildings examined.

It is important to stress that the inclusion of these scenarios into the LCA does not constitute a study of the "end-of-life stage" (modules C1-C4) or "benefits and loads beyond the system boundary" (module D: reuse and recycling) as defined in Standard BS EN 15804. Nor does it constitute a study of the construction stage, *i.e.,* modules A4 and A5 in the same standard (see SECTION 2.6.6). Therefore, building-material wastage is only considered in its repercussions on the amounts of the bills of quantities, which are the base for the LCA and, in turn, have repercussions on the environmental impacts.

TABLE 4.5 Wastage rates of building materials, for offsite and onsite operations.

building component		offsite construction		onsite construction	
category	item	wastage rate [a]	uncertainty [b]	wastage rate [a]	uncertainty [b]
wood-based	softwood components (excl. cladding)	1.5%	± 0.5%	10.0%	± 2.5%
	softwood cladding	1.5%	± 0.5%	10.0%	± 2.5%
	CLT panels	1.0%	± 0.5%	n.a.	n.a.
	OSB-3 sheathing	2.5%	± 0.5%	10.0%	± 2.5%
	chipboard decking	1.5%	± 0.5%	10.0%	± 2.5%
	wood-fibre thermal insul.	7.5%	± 0.8%	20.0%	± 5.0%
minerals	cement & lime blocklaying or screed mortar	n.a.	n.a.	7.5%	± 1.0%
	cement & lime rendering mortar	n.a.	n.a.	7.5%	± 1.0%
	cement board	n.a.	n.a.	7.5%	± 1.0%
	Portland cement (for concrete)	n.a.	n.a.	7.5%	± 1.0%
	aggregrate	n.a.	n.a.	5.0%	± 1.0%
	HD concrete blocks	n.a.	n.a.	5.0%	± 1.0%
	MD concrete blocks	n.a.	n.a.	5.0%	± 1.0%
	concrete roof tiles	n.a.	n.a.	10.0%	± 2.0%
	ceramic wall/floor tiles	n.a.	n.a.	10.0%	± 2.0%
	gypsum plasterboard	n.a.	n.a.	5.0%	± 1.5%
	glass-fibre acoustic insul.	1.5%	± 0.5%	9.0%	± 2.5%
	glass-fibre thermal insul.	1.5%	± 0.5%	9.0%	± 2.5%
metals	galvanised steel	n.a.	n.a.	5.0%	± 1.0%
plastics	PP & HDPE breather membrane	5.0%	± 1.0%	8.0%	± 1.5%
	LDPE vapour barrier	5.0%	± 1.0%	8.0%	± 1.5%
	LDPE damp-proof course	5.0%	± 1.0%	8.0%	± 1.5%
	LDPE damp-proof membrane	5.0%	± 1.0%	8.0%	± 1.5%
	PVC flooring	n.a.	n.a.	5.0%	± 1.0%
	PUR insulation	7.5%	± 0.8%	20.0%	± 5.0%
other / hybrid	undercoat paint	n.a.	n.a.	5.0%	± 1.0%
	internal paint	n.a.	n.a.	5.0%	± 1.0%
	external paint	n.a.	n.a.	5.0%	± 1.0%
	carpet flooring	n.a.	n.a.	5.0%	± 1.0%
Notes					
a	In this study, the wastage rate is intended as: $\frac{material\ purchased - material\ incorporated}{material\ incorporated} = \frac{material\ wasted}{material\ incorporated}$				
b	This uncertainty value to be added to the wastage rate (upper bound) or deducted from it (lower bound).				

4.5.1 Scenario 1, baseline (zero-wastage)

Scenario 1 represents the ideal situation in which there is no wastage of building materials at all during the construction process. Therefore, the BoQs of this scenario only account for the materials that would be physically incorporated in the finished buildings if they were constructed by accurately following the detail drawings and specifications provided in this study.

4.5.2 Scenario 2 (low wastage)

Scenario 2 represents a more realistic situation, in which there is a degree of wastage of building materials, although minimal. This scenario could thus be representative of segments of the construction industry where builders and suppliers adopt modern methods of construction and promote ethos among their employees and/or enforce internal policies aimed at reducing the amount of wastage, in order to minimise the economic and environmental costs associated with them.

TABLE 4.6 Summary of the modelling assumptions made regarding the way in which openings (for doors, windows or rooflights) are formed inside wall or roof panels, across the three different wastage scenarios. In scenario 1 (zero wastage), no material for the openings is included in the calculations.

Notional buildings	**Type of panelised system**	**Technique to create openings in panels**		
		Scenario 1 ***Zero wastage***	**Scenario 2** ***Low wastage***	**Scenario 3** ***High wastage***
C1 and C2	structural insulated panels	*n.a. (no material for the openings is included in the calculations)*	openings are post-formed (cut away from assembled panels)	openings are post-formed (cut away from assembled panels)
D1 and D2	cross-laminated-timber panels	*n.a. (no material for the openings is included in the calculations)*	openings are pre-formed (in the press)	openings are post-formed (after panels have been fabricated in the press)
E1 and E2	nail-laminated-timber panels	*n.a. (no material for the openings is included in the calculations)*	openings are pre-formed (before nailing of the planks)	openings are pre-formed (before nailing of the planks)

It is assumed that most of the insulating layers are pre-inserted into the wall and roof panels in the factory for all buildings, apart from building **F** (for which the insulation layers are installed on site).

As regards the CLT buildings (**D1** and **D2**), it is assumed that the openings needed in the massive timber walls (for windows and internal and external doors) are pre-formed in the press used to fabricate the panels. Therefore, no material has to be removed to create the apertures once the panel has been manufactured, with a resulting saving of timber and glue. Although pre-forming the openings in CLT panels does not require advanced machinery or highly-skilled operatives, it is not common practice among CLT manufacturers.

A different assumption is made for the apertures in the SIP walls: here, it is assumed that the apertures are cut after the fabrication of the panels, since doing otherwise is even less common than in the CLT case.

Similarly to **D1** and **D2**, but for different reasons, it is assumed that the openings in the nail-laminated-timber walls (buildings **E1** and **E2**) are pre-formed. This modelling choice is in line with another assumption: that the wood planks are connected by means of steel nails, which preclude the possibility of portions being removed from the panels once they have been fabricated. This is because steel nails would damage the cutting machinery, therefore this option is only available when aluminium nails are used.

Thus, the BoQ of Scenario 2 presents quantities of materials that are affected by their specific wastage rates. Since it is very difficult to determine the wastage coefficients with precision, due to lack of in-depth literature on the subject,[21] a wastage interval has been defined for each material, characterised by a central value with an upper bound and a lower bound symmetrically placed around it. An analogous procedure to follow when dealing with variance of model parameters and defining their intervals is suggested, *inter alia*, in PD ISO/TR 14049:2012 (§ B.3.3) and BS EN ISO 14044:2006 (§ 10.3.3.3).

[21] As explained in SECTION 2.5.

4.5.3 Scenario 3 (high wastage)

Scenario 3 depicts a construction setting in which the wastage of materials is much higher than in Scenario 2: it is therefore representative of a combination of the two following aspects:

- the companies (contractors and sub-contractors) involved in the construction process do not have very rigorous policies or working practices in regard to minimising materials;
- the extent of offsite manufacturing is lower than in Scenario 2, with more construction operations performed on site, resulting in increased levels of wastage.

As for scenario 2, the wastage levels of scenario 3 are expressed by means of intervals whose amplitude is derived from the estimates found in literature and expert judgment offered by senior managers from construction companies.

For all buildings, with the exception of **B1**, **B2**, **C1** and **C2**, most of the insulating materials (rigid boards or quilts) are assumed to be installed on site. This corresponds to subcategory 0 of the offsite categorisation.

In Scenario 3, it is assumed that the openings in the CLT panels (specified for houses **D1** and **D2**) are cut away after the construction of the panels. This is, at present, the most recurrent practice and entails a high wastage level of "virgin" CLT material (which is generally disposed of, as it is difficult to be repurposed).

TABLE 6.7 shows the wastage coefficients adopted in the model, sorted by type of fabrication (whether onsite or offsite) and not by scenario. This is because both scenarios 2 and 3 can contain some materials/components that are constructed partly onsite and partly offsite. Thus, the BoQs of these two scenarios contain quantities that are determined by various combinations of materials and wastage coefficients referring either to onsite or offsite production activities.

4.5.4 Quantities of building materials

FIGURE 4.20 presents a summary of the mass of materials incorporated in each building, within wastage scenario 1.

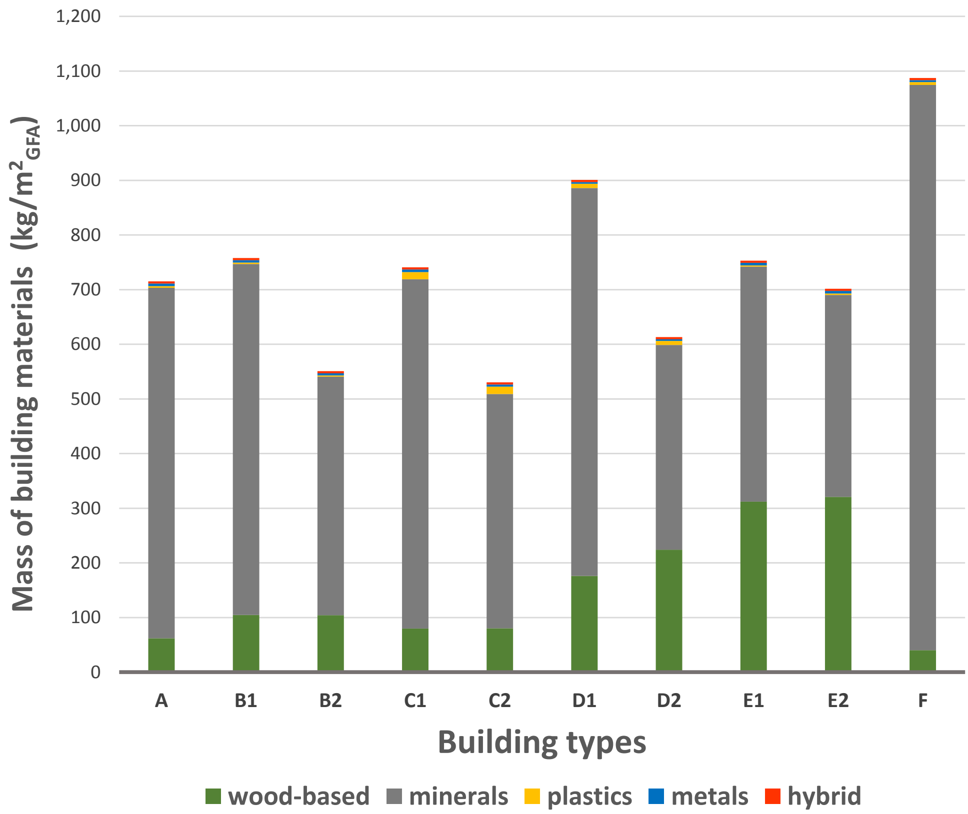

FIGURE 4.20 Mass of materials incorporated in each dwelling (per unit floor area): breakdown by material type.

The bill of quantities for building **A** (covering all three wastage scenarios) is given below as an example. The bills of quantities for the other buildings can be found in APPENDIX H.

TABLE 4.7 Bill of quantities for building A.

category	item	scenario 1 (baseline, zero wastage)	scenario 2 (low wastage)						scenario 3 (high wastage)					
			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)	35.23	35.65	1%	35.85	2%	36.05	2%	35.65	1%	35.85	2%	36.05	2%
	softwood cladding	/	/	/	/	/	/	/	/	/	/	/	/	/
	CLT panels	/	/	/	/	/	/	/	/	/	/	/	/	/
	OSB-3 sheathing	11.95	12.19	2%	12.25	3%	12.31	3%	12.85	8%	13.14	10%	13.44	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	26.54	28.27	7%	28.53	8%	28.80	9%	28.27	7%	28.53	8%	28.80	9%
	cement & lime rendering mortar	29.50	31.42	6%	31.71	8%	32.01	9%	31.42	6%	31.71	8%	32.01	9%
	cement board	/	/	/	/	/	/	/	/	/	/	/	/	/
	Portland cement (for concrete)	22.27	23.72	7%	23.94	8%	24.16	9%	23.72	7%	23.94	8%	24.16	9%
	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	132.29	137.58	4%	138.90	5%	140.23	6%	137.58	4%	138.90	5%	140.23	6%
	concrete roof tiles	23.59	25.48	8%	25.95	10%	26.42	12%	25.48	8%	25.95	10%	26.42	12%
	ceramic wall/floor tiles	37.04	40.00	8%	40.75	10%	41.49	12%	40.00	8%	40.75	10%	41.49	12%
	gypsum plasterboard	54.27	56.17	4%	56.99	5%	57.80	6%	56.17	4%	56.99	5%	57.80	6%
	glass-fibre acoustic insul.	1.05	1.09	3%	1.10	4%	1.11	6%	1.12	6%	1.15	9%	1.17	12%
	glass-fibre thermal insul.	8.49	8.58	1%	8.62	1%	8.66	2%	9.05	7%	9.26	9%	9.47	12%
metals	galvanised steel	4.91	5.10	4%	5.15	5%	5.20	6%	5.10	4%	5.15	5%	5.20	6%
plastics	PP & HDPE breather membrane	0.22	0.23	7%	0.23	8%	0.24	9%	0.23	7%	0.23	8%	0.24	9%
	LDPE vapour barrier	0.22	0.23	7%	0.23	8%	0.24	10%	0.23	7%	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	0.73	0.83	15%	0.87	20%	0.91	25%	0.83	15%	0.87	20%	0.91	25%
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	0.43	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: $\frac{Quantity_{scen3} - Quantity_{scen1}}{Quantity_{scen1}}$

5 LCA study on environmental performance of constructional techniques

5.1 Chapter overview

This chapter presents the doctoral research undertaken on the environmental burdens associated with timber-based constructional techniques applied to small residential buildings.

Sections 5.2 and 5.3 describe the goal and scope of this environmental study, respectively.

Section 5.4 offers an outline of the methods employed for this LCA, while **Section 5.5** explains its limitations.

In **Section 5.6**, the results of the LCA are presented for scenario 1 (*i.e.,* the scenario that does not account for wastage of building materials) and their reliability is estimated and discussed. Here, the answers to research questions ① and ② (articulated in Chapter 1) are provided.

In **Section 5.7**, research question ③ is answered and the results of wastage scenarios 2 and 3 are compared with those of scenario 1 (the baseline). This sensitivity analysis accounts for the problem of wastage in the construction industry and explores how it affects the environmental cost of residential buildings.

Lastly, a summary of the LCA findings can be found in **Section 5.8.**

5.2 Goal of the study

The goal of this study is to better understand the environmental burdens arising from the erection of small residential buildings that employ different timber-based modern methods of construction. Such environmental loads are also considered in comparison with a more traditional, masonry alternative.

The underlying research questions for this study have already been articulated in SECTION 1.3.3 and the notional buildings that have been defined to represent the various constructional methods have been presented in SECTION 4.4.

5.3 Scope of the study

5.3.1 Type of LCA

The study presented in this chapter is an attributional LCA of ten different semi-detached houses, each corresponding to a different constructional solution (as described in depth in SECTION 4.4). The LCA model at the building level has been created using process-based data at the building component/material level, sourced from the literature.

The framework of this LCA follows the general guidelines offered by ISO and EN standards (in particular, standard BS EN 15978:2011, §1) and the methodological approach they recommend.

The LCIA methodology underpinning this study is that devised by CML[1] and embraced by the standards mentioned above.

5.3.2 Product system

The product system under investigation consists in all the construction materials of the ten notional houses and includes:

- elements of the building envelope (ground floor, external walls and roof);
- foundations and internal elements (intermediate floors, interior walls and party walls).

The building components and materials assessed environmentally are those of the full build-up, including interior and exterior finishes.

The following items are instead outside the scope of this study and therefore excluded from the LCA model:

- building services;
- fittings and appliances;
- windows and doors;

[1] This was discussed in depth in SECTION 2.6.4.

- furniture;
- garden and landscaping elements.

5.3.3 Functional unit

The functional unit (FU) adopted in this LCA model is 1 square metre of gross internal floor area (as described in SECTION 4.4.1) and hereafter abbreviated as 1 m^2_{GFA}.

This unit has been chosen following the recommendations encountered during the literature review on similar LCAs performed at the building level. One of the main advantages offered by this FU is that it facilitates comparison with the results of previous and future studies in the same field, in that it is less affected by the building size than is the case when the whole building is chosen as the FU.

5.3.4 System boundaries

This LCA model is based on cradle-to-gate system boundaries. According to the terminology of the international standards (in particular, EN 15804, which has been discussed in SECTION 2.6.6), this corresponds to the first three life-cycle modules:

- A1, material extraction;
- A2, transportation of materials to the manufacturing site;
- A3, manufacturing of the building components/materials.

Since the main data sources used (EPDs) do not always provide the environmental coefficients for modules A1, A2 and A3 individually and offer instead aggregated data[2] (*i.e.,* A1-A3), the impacts in this study are presented in aggregated form, too, within the boundaries specified.

[2] For further details, see SECTION 2.6.6.

5.3.5 Environmental aspects and LCIA methodology

This study covers various environmental aspects, which can be grouped into three main[3] categories:

- **environmental impacts**. This category includes five aspects:
  - climate change, estimated in terms of global-warming potential computed in two different manners, that is, both neglecting biogenic carbon sequestration and accounting for it;
  - stratospheric-ozone depletion;
  - acidification;
  - eutrophication;
  - photochemical ozone creation (in the troposphere);
- consumption of **primary energy**, with a distinction between:
  - renewable primary energy;
  - non-renewable primary energy;
- production of **waste**, of the following classes:
  - non-hazardous waste;
  - hazardous waste;
  - radioactive waste.

[3] A description of these environmental aspects and the ways in which they can be quantified is provided in SECTION 2.10.

5.4 LCA modelling method

5.4.1 Data sources

The main type of data sources used in this research is environmental product declarations, as recommended by the guidelines from the European Union and standard BS EN 15978:2011 (§ 1).

The main aspects of an EPD, including its minimum content, its structure, the process through which it is compiled and validated by a third party and the international standards to which it must adhere have already been dealt with in SECTION 2.6.6.

Two different types of EPDs have been used in this thesis:

- **specific EPDs**, which describe the environmental impacts of a single product (or a small group of similar products) manufactured by one company;
- **generic EPDs** on a category of products manufactured by a variety of companies, at the national or European level. These EPDs are therefore representative of the average environmental credentials of a given building product and are generally commissioned and owned by a consortium of companies or an industry association. Examples of this type of EPDs include:
  - the EPD on UK average Portland Cement,[4] owned by the Mineral Products Association (MPA) UK. This document is based on data collated from numerous production sites across the country.
  - the EPD on polyurethane insulation boards,[5] owned by PU Europe, the Federation of the European Rigid Polyurethane Foam Associations. Members of the Federation constitute 90% of this market segment and use similar production techniques.

[4] Inventory code 203 in the present study. More information is provided in APPENDIX G.

[5] Inventory code 106 in the present study. For more details, see APPENDIX G.

One of the advantages of using EPDs as data sources for the LCA of buildings is that they allow simplifying the LCA process itself (Hoxha *et al.*, 2016, Bayer *et al.*, 2010 from Hoxha *et al.*, 2016).

A detailed inventory of the EPDs used in the present research project and a summary of the properties of the building components that they are based on is provided in APPENDIX G.

The average quality[6] of the data sourced from these EPDs was generally deemed very good or satisfactory.

Since all EPDs used include carbon sequestration in the determination of GWP coefficients, and it was considered useful to also offer an estimation of GWP excluding this phenomenon, an alternative source has been found in the Bath Inventory of Carbon and Energy (ICE), developed by Geoff Hammond and Craig Jones at the University of Bath.

More detailed considerations on the quality and reliability of the data used in this study from both EPDs and ICE are presented in SECTION 5.6.5.

5.4.2 LCI and model assumptions

5.4.2.1 Life-cycle inventories

An LCA at the building level generally has an inventory that is a bill of quantities like the ones typically compiled for the construction of a building.

The structure of the bills of quantities of the ten notional buildings under investigation has already been described in SECTION 4.4: as explained there, three scenarios have been modelled, each corresponding to a different level of wastage of building materials, which results in different quantifications of the materials in the bills. The sensitivity analysis connected to the variation of environmental impacts due to variations in the bills of quantities is presented in SECTION 5.7.

[6] Quality intended both in absolute terms (i.e. not in relation to this LCA study) and for the purposes and scope of this study.

5.4.2.2 Modelling process and computational tools

The LCA model has been created in an *ad-hoc* series of spreadsheets in Excel (version 2013) by Microsoft Inc., which contain most of the calculations, inventory of input data and outputs in tabular and graphic form.

Some of the analytical calculations to study the propagation of uncertainty in input data through the model have been performed in Mathcad (v.15.0) by PTC Inc..

5.4.3 Data quality and uncertainty analysis

5.4.3.1 Propagation of uncertainty through LCAs

Uncertainty arises from the fact that measured values do not match true values: an error is therefore the difference between a measured value and a true one. Since true values cannot be exactly measured, one cannot exclude the possibility of error and the uncertainty associated with measured values. This problem of uncertainty also applies to LCA studies (Ciroth *et al.*, 2004) and their quantitative data (*e.g.,* material flows, processes, *etc.*)

If LCA calculations are based on data that is characterised by some uncertainty, the latter propagates through the system and affects all the subsequent steps of the LCA process: intermediate results (such as inventories) and final results (Ciroth *et al.*, 2004). Uncertainty in the final outcomes, however, cannot be easily foreseen, since one or both of the following two situations might occur:

- the small uncertainty of an input results in considerable uncertainty of the output(s);
- the uncertainties of different inputs counteract one other.

Uncertainty in the field of LCA has great importance for stakeholders who base their decisions on the results of a specific LCA: if the uncertainty of such results is not estimated and communicated, the decision-maker might be led in the wrong direction (Ross *et al.*, 2002).

Therefore, in order to make informed decisions based on an LCA, both environmental impacts and their associated uncertainties should be estimated and transparently presented.

However, most LCAs still do not include any estimation of the reliability of their results; this is also true for most LCAs concerned with the construction industry: while they focus on the minimisation of the environmental impacts of buildings and the development and use of new materials, little effort is put into assessing the uncertainty accompanying the LCA outcomes (Hoxha *et al.*, 2016).

Ciroth *et al.* (2010) explain the problem of uncertainty assessment in LCA as an "input-output box" consisting of three sub-problems (which also correspond to three different steps):

1 estimation of uncertainty in input data;

2 estimation of uncertainty propagation through LCA calculations;

3 estimation of uncertainty in the outputs (*i.e.,* the results of the LCA calculations) and interpretation of these outputs with their uncertainty.

In an LCA, uncertainty in the outcomes might arise from the combined effects of the following factors (Clavreul *et al.*, 2012; Heijungs *et al.*, 2005):

- the use of unrepresentative datasets;
- inherent data variability;
- modelling assumptions that do not perfectly match realistic situations.

The following TABLE lists the publications in which the methods for uncertainty estimation applied in this thesis are presented by the researchers who devised them.

TABLE 5.1 Main academic sources describing the methods applied in this study for the estimation of data quality and uncertainty.

Topic	**References** [a]
uncertainty in LCAs and theory of error propagation	Weidema and Wesnæs, 1996 Weidema, 1998 MacLeod *et al.*, 2002 Ciroth *et al.*, 2004 Heijungs and Frischknecht, 2005 Jolliet *et al.*, 2016 (chapter 2)
pedigree matrix: criteria to determine data-quality indicators	Weidema and Wesnæs, 1996 Weidema *et al.*, 1998 Weidema *et al.*, 2013 (p. 76) Ciroth *et. al.*, 2013
uncertainty factors for lognormal distributions (to be used in conjunction with the pedigree matrix)	Frischknecht *et al.*, 2004 Ciroth *et al.*, 2013 Jolliet *et al.*, 2016 (chapter 2)
analytical method for the quantitative estimation of uncertainty	MacLeod *et al.*, 2002 Ciroth *et al.*, 2004 Hong *et al.*, 2010 (including online supplementary material)
Notes a In chronological order	

5.4.3.2 Assessment of input-data quality

A **pedigree matrix** can be compiled, which depicts the quality of all the parameters used in the determination of the environmental impacts.

The matrix is based on six criteria against which each parameter is assessed and described:

- **reliability**. This aspect depends on whether the data values are based on measurements or assumptions and how rigorously they have been verified;
- **completeness**. This depends on the proportion of the production sites included in the data quantification to the total of the existing sites for the considered market;
- **temporal correlation**. This criterion is based on the temporal difference between the time when the data was collected and the time when the LCA based on it is performed;

- **geographical correlation**. This depends on whether the data refers to an area close to, or distant from, the area under investigation;
- **further technological correlation**. This aspect is based on whether the data comes from manufacturers who use processes and materials similar to, or different from, those under study;
- **sample size**. This relates to the number of measurements on which the data values are based.

For each of these criteria, a score is attributed to the parameter under assessment, ranging from 1 to 5; 1 means very high quality, whereas 5 is the default score and indicates the lowest quality level.

For any combination of the six criteria and the five scores, a description is provided by the authors of the method: this explains the quality that corresponds to each score and thus provides guidance to the researchers who adopt this technique.

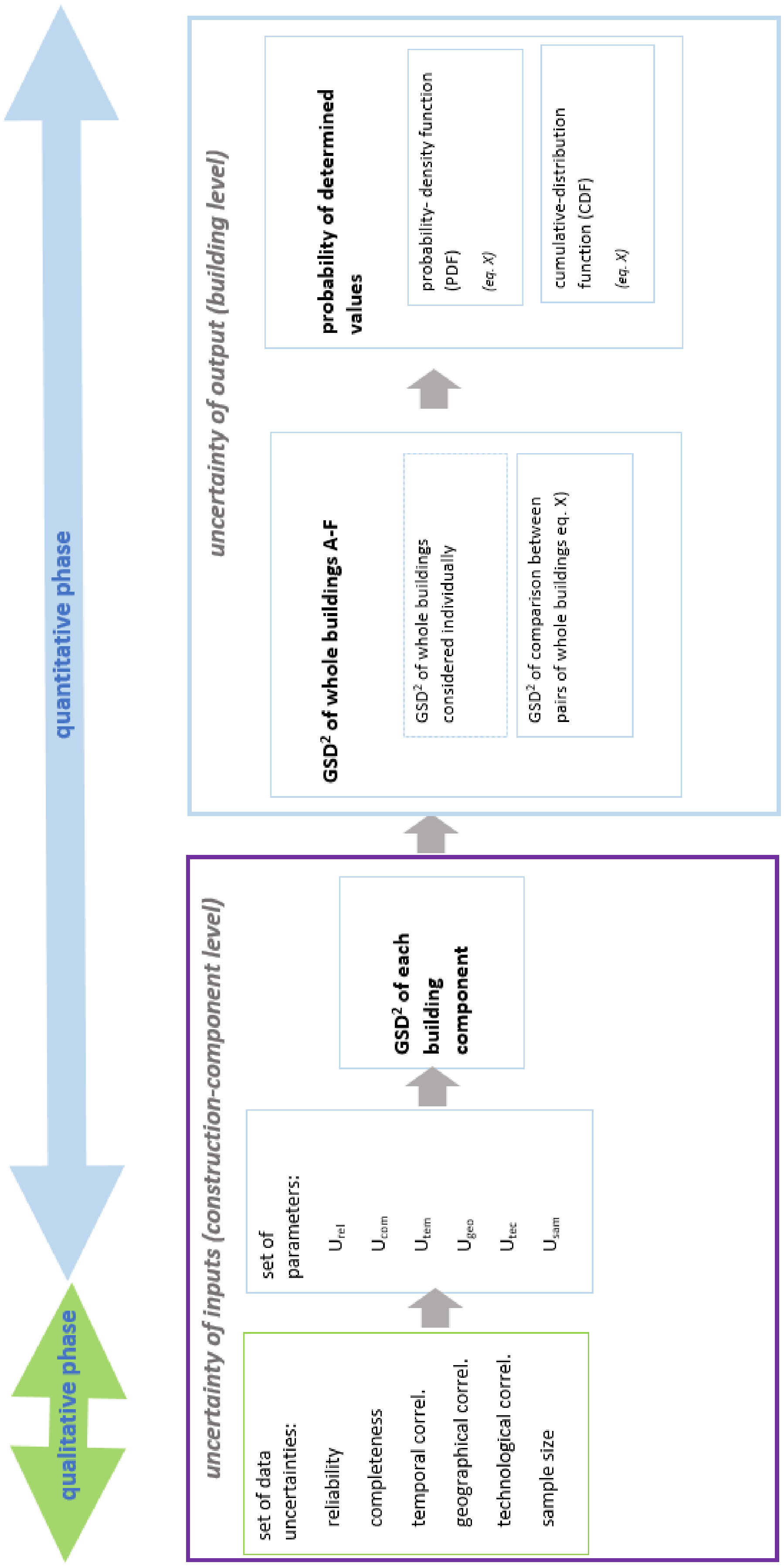

FIGURE 5.1 Semi-quantitative method for the estimation of uncertainty in LCA results

TABLE 5.2 Pedigree matrix used for uncertainty calculations, based on Ciroth et al., 2016.

Quality indicator	Reliability		Completeness		Temporal correlation		Geographical correlation		Further technological correlation		Sample size	
	description	U_{rel}	description	U_{com}	description	U_{tem}	description	U_{geo}	description	U_{tec}	description	U_{sam}
1	verified data based on measurements	1.00	representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	1.00	less than 3 years of difference to the time period of the data set	1.00	data from area under study	1.00	data from entrepises, processes, and materials under study	1.00	>100, continuous measurement	1.00
2	verified data partially based on assumptions or non-verified data based on measurements	1.05	reprensentative data from >50% of the sites relevant to for the market considered, over an adequate period to even out normal fluctuations	1.02	less than 6 years of difference to the time period of the data set	1.03	average data from larger area in which the area under study is included	1.01	data from processes and materials under study (i.e. identical technology), but from different enterprises	1.10	>20	1.02
3	non-verified data partially based on qualified estimates	1.10	representative data from only some sites (<50%) relevant for the market considred or from >50% of sites, but from shorter periods	1.05	less than 10 years of difference to the time period of the data set	1.10	data from area with similar production conditions	1.02	data from processes and materials under study, but from different technology	1.20	>10	1.05
4	qualified estimate (e.g. by industrial expert)	1.20	representative data from only one site relevant for the market considered or from some sites, but from shorter periods	1.10	less than 15 years of difference to the time period of the data set	1.20	data from area with slightly similar production conditions	1.05	data on related processes and materials	1.50	≥3	1.10
5	non-qualified estimate	1.50	representativeness unknown or data from small number of sites and from shorter periods	1.20	age of data unknown or more than 15 years of difference to the time period of data set	1.50	data from unknown area of distinctly different area	1.10	data on related processes on laboratory scale or from different tehcnology	2.00	unknown	1.20

Abbreviations

com	completeness	U	uncertainty
geo	geographical	var.	variance
Q.I.	quality indicator		

Notes

a source for calculation excluding carbon sequestration

It is worth noticing that analysis of the data used in an LCA under a set of criteria very similar to the one provided above is also recommended by BS EN ISO 14044:2006 (§

B.3.4). The Standard refers to this type of analysis as "consistency check" and presents it in a form that appears briefer and simplified in comparison with the procedure followed here.

Once the pedigree matrix has been completed qualitatively, it is possible to take this estimation process further by assigning an uncertainty factor to each parameter and each aspect.

The contribution of all uncertainty factors is accounted for in EQUATION 5.1, which provides a value of the overall uncertainty for each parameter considered. When it is assumed that the uncertainty follows a lognormal distribution, this overall indicator is expressed in terms of the square of a geometric standard deviation (GSD^2) and offers a measure of the variance of each parameter assessed. TABLES N.1, N.2 and N.3 in APPENDIX N list all these GSD^2 values. Using the GSD^2 as a measure of dispersion is particularly useful for lognormally-distributed variables, as it can be used to define their 95%-confidence intervals.

$$GSD^2 = \exp\left(\sqrt{(ln(U_{rel}))^2 + (ln(U_{com}))^2 + (ln(U_{tem}))^2 + \left(ln(U_{geo})\right)^2 + (ln(U_{tec}))^2 + (ln(U_{sam}))^2}\right)$$

EQUATION 5.1

where U_{rel} is the uncertainty factor of reliability, U_{com} is the uncertainty factor of completeness, U_{tem} is the uncertainty factor of temporal correlation, U_{geo} is the uncertainty factor of geographical correlation, U_{tec} is the uncertainty factor of further technological correlation and U_{sam} is the uncertainty factor of sample size.

5.4.3.3 Assessment of output-data quality

Methodological approaches to the quantification of uncertainty

In LCAs, the most common approach to the quantification of uncertainty is a **stochastic process** known as **Monte Carlo**. A Monte Carlo simulation consists of numerous iterations: in each iteration, random values are assigned to all of the parameters used for the calculation of the environmental impacts, within their individual confidence intervals. Each run of the simulation therefore uses a different combination of values for the parameters and yields a different output result. After a sufficiently-large number of runs, the output values obtained from each iteration are averaged and thus yield the final result. The underpinning principle in the Monte Carlo approach is the law of large numbers, according to which the mean of the results obtained from a big number of trials is close to the expected value: indeed, the more trials are performed, the closer the mean becomes to the expected value. Therefore, depending on the complexity of the LCA study and the number of parameters that it includes, the number of iterations required to obtain accurate results might be of the order of one thousand or ten thousand.

Monte Carlo simulations entail some problems of varying nature: they are computationally-intensive and do not offer information on which parameters mostly contribute to the overall uncertainty associated with the LCA results. The latter aspect thus poses a problem of transparency in the computational procedure, which limits the utility of this type of mathematical tool.

In order to overcome these limitations of the Monte Carlo approach, analytical methods have been proposed as an alternative.

The method adopted in this study

Introduction

The **analytical method** adopted in this thesis is based on Taylor series expansion. This method has been progressively developed by several authors over the last 30 years (Hong *et al.*, 2010). Morgan and Herion (1990) first proposed a Taylor series for uncertainty propagation; then MacLeod *et al.* (2002) adapted it to multimedia fate model and, after that, some scholars used this method for the quantification of uncertainty of impact assessments. Ciroth *et al.* (2004) further developed the method so as to quantify uncertainty propagation in LCAs: they compared their newly-devised method to the most established Monte Carlo simulations and realised that it can be applied successfully[7] to LCAs in which the relative input uncertainty is low or medium.

[7] With results in good agreement with those obtained through the Monte Carlo procedure.

In particular:

- when the relative input uncertainty is low, the method by Ciroth *et al.* (2004) can be applied with a first-order Taylor series;
- when the relative input uncertainty is medium, this method needs to be applied with a higher-order Taylor series;
- when the relative input uncertainty is high, the analytical method does not show good agreement with Monte Carlo results and should not be applied.

Hong *et al.* (2010) have further developed this method in order to enable scenario comparison and have illustrated it by means of an example based on a comparative LCA where different scenarios for the same product system (the manufacturing of a mechanical piece in the automobile industry) are studied individually and then compared.

The researchers who have devised this method (Hong *et al.*, 2010) have also validated their results against those of a Monte Carlo simulation and demonstrated that they exhibit a satisfactory level of agreement.

Advantages

The main advantages of this analytical approach by Hong *et al.* (2010) are as follows (Jolliet *et al.*, 2016):

- it is a good compromise between accuracy of the results and complexity of the mathematical formulation of the problem;
- from a computational point of view, it is less intensive than a Monte Carlo simulation;
- it is transparent, in that it allows LCA practitioners to identify the contribution to uncertainty of individual parameters (which, as mentioned above, is not possible, or at least not automatic or straightforward, with a Monte Carlo simulation).

In both Monte Carlo and analytical methods, the LCA practitioner might decide to reduce the complexity of the uncertainty-estimation process by identifying *a priori* which parameters to include in this estimation, based on expert judgement. From the point of view of computational effort, this practice is particularly advantageous in the context of complex LCAs, which often have numerous parameters. Thus, the study of uncertainty propagation is limited to the parameters that have been selected. However, such an approach might compromise the accuracy of uncertainty estimation if the preliminary selection of parameters is erroneous and the significance of some parameters has been underestimated.

When discussing the reliability of an LCA's results, it is important to remember that, as noted by Ciroth *et al.* (2004), the true values of the errors in the LCA and the corresponding uncertainties are not directly measurable: therefore, they can only be estimated (but not exactly calculated).

Recently, Hoxha *et al.* (2016) have taken an approach to the quantification of uncertainty in the results analogous to the one taken in this thesis, when they have conducted an LCA at the building level (as opposed to the individual building-material or component level). These authors have adopted, indeed, a similar analytical method, which is also based on Taylor series expansion and analysis of variance.

Estimation procedure for absolute uncertainty

Once the GSD^2 of each parameter has been estimated, it is possible to determine how uncertainty propagates from the inputs (*i.e.,* the parameters used to assess the environmental impacts included in an LCA) to the outputs (*i.e.,* the calculated environmental impacts).

Under the assumption that all input parameters are independent from one another, the uncertainty of the output is described by EQUATION 5.2 (Hong *et al.*, 2010; MacLeod *et al.*, 2002):

$$(lnGSD_y)^2 = S_1^2(lnGSD_{x1})^2 + S_2^2(lnGSD_{x2})^2 + \ldots + S_n^2(lnGSD_{xn})^2$$
$$= \sum_{i=1}^{n} S_i^2(lnGSD_{xi})^2$$

EQUATION 5.2

where GSD_y designates the geometric standard deviation of the output.

It follows from EQUATION 5.2 that GSD_y^2 (*i.e.,* the square of the geometric standard deviation of the output) can be determined as:

$$GSD_y^2 = e^{2\left(\sqrt{S_1^2(lnGSD_{x1})^2+S_2^2(lnGSD_{x2})^2+...+S_n^2(lnGSD_{xn})^2}\right)} = e^{2\left(\sqrt{\sum_{i=1}^{n} S_i^2(lnGSD_{xi})^2}\right)}$$

EQUATION 5.3

Therefore, GSD_y has the following formulation:

$$GSD_y = e^{\sqrt{S_1^2(lnGSD_{x1})^2+S_2^2(lnGSD_{x2})^2+...+S_n^2(lnGSD_{xn})^2}} = e^{\sum_{i=1}^{n} S_i^2(lnGSD_{xi})^2}$$

EQUATION 5.4

The "sensitivity", S_i, of a material or process *i* can be calculated as (Jolliet *et al.*, 2016, p. 197; Hong *et al.*, 2010b):

$$S_i = \frac{I_i}{I_{tot}}$$

EQUATION 5.5

where I_i is the impact of the i^{th} material/process and I_{tot} is the total impact of the system (in the case of this thesis, a building).

It can be seen from EQUATIONS 5.3 and 5.4 that the uncertainty contribution of each parameter (x_i) is influenced by the combined effect of two measures:

- the geometric standard deviation of the parameter, GSD_{xi}, which in this thesis is calculated with the pedigree-matrix method. This is an inherent property of the data used in the LCA, and does not depend on the system.
- the relative sensitivity (S_i) of the model output to this parameter.

Neither of the measures above can be considered in isolation when one wishes to identify the dominant sources of uncertainty in the model output GSD_y: only the combination of these two aspects of parameter x_i determines its effective influence on the output's uncertainty (Hong *et al.*, 2010; Bisinella *et al.*, 2016). Since this interaction between the two measures is difficult to predict before the uncertainty-estimation process is performed, the identification of key input parameters and the exclusion of the remaining parameters from the estimation process[8] should never be done *a priori* (Bisinella *et al.*, 2016).

It is assumed that the deterministic value[9] of any impact whose uncertainty is being investigated corresponds to the arithmetic mean, $\bar{x}$, of the distribution for this impact (*i.e.,* the distribution of variable *X*).

The mean of the natural logarithm of *x*, ξ, can be defined as:

$$\xi = \ln(\bar{x}) - \frac{(\ln(GSD^2))^2}{8}$$

EQUATION 5.6

The geometric mean of *x, μ*, can be expressed as a function of the mean of the logarithm of *x* (*i.e.*, ξ, defined in EQUATION 5.6) or as a function of the arithmetic mean of *x*, $\bar{x}$:

$$\mu = \exp(\xi) = exp\left(\ln(\bar{x}) - \frac{(\ln(GSD^2))^2}{8}\right)$$

EQUATION 5.7

The standard deviation (σ) of the natural logarithm of *x* can be defined as a function of *GSD*:

$$\sigma = \ln(GSD)$$

EQUATION 5.8

[8] Such selection of parameters is generally carried out so as to reduce model complexity and computational time when estimating the uncertainty of the final LCA outcomes.

[9] The deterministic value is the impact value obtained through the LCA study (and is independent of the estimation of uncertainty).

It is useful to use a probability-density function[10] (PDF) to study the absolute uncertainty associated with an (absolute) LCA result. A PDF can be parametrised by means of a pair of parameters from those defined above:

- a location parameter: either μ (geometric mean of *x*) or ξ (mean of *ln(x)*);
- a dispersion parameter: σ (standard deviation of *ln(x)*).

The PDF is therefore a function of *x*, which can be written in terms of μ and σ as in EQUATION 5.9:

$$PDF(x;\mu,\sigma) = \begin{cases} \frac{1}{x \cdot \sigma\sqrt{2\pi}} exp\left(-\frac{(\ln(x) - \ln(\mu))^2}{2\sigma^2}\right) & for\ x > 0 \\ 0 & for\ x \leq 0 \end{cases}$$

EQUATION 5.9

By substituting $\ln(\mu) = \xi$ into EQUATION 5.9, the PDF can be re-formulated in terms of ξ and σ. The PDF is then represented as (Heijungs and Frischknecht, 2005):

$$PDF(x;\xi,\sigma) = \begin{cases} \frac{1}{x \cdot \sigma\sqrt{2\pi}} exp\left(-\frac{(\ln(x) - \xi)^2}{2\sigma^2}\right) & for\ x > 0 \\ 0 & for\ x \leq 0 \end{cases}$$

EQUATION 5.10

In a lognormal distribution, the 95% confidence interval can be expressed in terms of GSD^2 and μ: the lower bound (corresponding to the 2.5th percentile) is $\frac{\mu}{GSD^2}$, while the upper bound (corresponding to the 97.5th percentile) is $\mu \cdot GSD^2$. Therefore, the 95% confidence interval can be written as:

$$P\left(\frac{\mu}{GSD^2} < x < \mu \cdot GSD^2\right) = 0.95 = 95\%$$

EQUATION 5.11

---

[10] The probability-density function is also referred to as "probability density" (Dekking *et al.*, 2005, p. 56) or "probability-distribution function" by some authors.

Once the PDF of a continuous random variable (*X*) has been defined, its primitive function can also be defined, *i.e.*, the cumulative-distribution function[11] (CDF). When the CDF is calculated at a point *b*, its relation with the PDF can be written as (Dekking *et al.*, 2005, p. 59):

$$CDF(b) = \int_{-\infty}^{b} PDF(x)dx$$

EQUATION 5.12

This also means that the following relationship holds between a PDF and a CDF (for all *x*-values where the PDF is continuous):

$$PDF(x) = \frac{d}{dx} CDF(x)$$

EQUATION 5.13

The CDF is a probability and, as such, varies between 0 and 1. It can be expressed as (Dekking *et al.*, 2005, p. 44):

$$CDF(a) = P(X \leq a) \quad for \ -\infty < a < \infty$$

EQUATION 5.14

Estimation procedure for comparative uncertainty

Estimating comparative uncertainty requires a more complex formulation than that seen in the previous SECTION for absolute uncertainty. This is due to the fact that, when comparing two objects (two product systems, two scenarios or, as in the case of this study, two buildings), one must treat differently the contributions to uncertainty arising from:

- independent parameters (*i.e.,* parameters which are only present in one object);

[11] The cumulative-distribution function can also be referred to as "distribution function" by some authors (Dekking *et al.*, 2005, p. 44).

- common parameters (*i.e.,* parameters present in both objects).

For common parameters, it is necessary to estimate their covariance.

EQUATION 5.15 explains the relationship of the geometric standard deviation of the I_X/I_F distribution for this study (*i.e.,* the distribution of the ratio between the impact value of building **X**[12] and that of building **F**) with the geometric standard deviation of each building and the covariance between the two buildings[13] (Hong *et al.*, 2010):

$$(lnGSD_{X/F})^2 = (lnGSD_X)^2 + (lnGSD_F)^2 - 2Cov[\ln(Inp_X), \ln(Inp_F)]$$

EQUATION 5.15

where Inp_X and Inp_F are the sampled inputs of buildings **X** and **F**, respectively.

Hong *et al.* (2010) have demonstrated that $(lnGSD_{X/F})^2$ can also be expressed as the summation of the individual contributions coming from independent and common parameters, under the assumption that the two building options **X** and **F** are positively correlated:

$$(lnGSD_{X/F})^2 = \sum_{i=1}^{l} S_{Xi}^2 (lnGSD_{Xi})^2 + \sum_{j=l+1}^{m} S_{Fj}^2 (lnGSD_{Fj})^2 + \sum_{k=m+1}^{n} (S_{Xk}^2 - S_{Fk}^2)(lnGSD_{Zk})^2$$

EQUATION 5.16

where:

X indicates any of the nine buildings from **A** to **E2**;

S_X and GSD_X are the sensitivities and the geometric standard deviations, respectively, of the independent processes x_i of buildings **A** to **E2** (with 1 ≤ i ≤ l);

S_F and GSD_F are the sensitivities and the geometric standard deviations, respectively, of the independent processes x_j of building **F** (with l+1 ≤ j ≤ m);

---

[12] Building **X** is any timber building, from **A** to **E2**.

[13] Here, the nomenclature and symbol system has been considerably changed from that used in the cited sources. In the sources, the comparison is expressed in terms of two generic scenarios A and B, whereas here it has been contextualised and expressed as a comparison between any timber building from **A** to **E2**, indicated with **X**, and masonry building **F**.

S_{Xk} and S_{Fk} are the sensitivities of the common parameters x_k of buildings **A**-**E2** and **F**, respectively (with m+1 ≤ k ≤ n);

GSD_{Zk} is the geometric standard deviation of common parameters x_k for buildings **A**-**E2** and **F**.

It can be noted that the contribution of the common parameters (the third summation in EQUATION 5.16) is a function of the difference in sensitivity between buildings **X** and **F** $(S_{Xk}^2 - S_{Fk}^2)$.

From EQUATION 5.16, it is possible to make term $GSD^2{}_{X/F}$ explicit:

$$GSD_{X/F}^2 = exp\left(2 \cdot \sqrt{\sum_{i=1}^{l} S_{Xi}^2 (lnGSD_{Xi})^2 + \sum_{j=l+1}^{m} S_{Fj}^2 (lnGSD_{Fj})^2 + \sum_{k=m+1}^{n} (S_{Xk}^2 - S_{Fk}^2)(lnGSD_{Zk})^2}\right)$$

EQUATION 5.17

In LCA practice, it is important to be able to describe the degree of reliability of comparative statements. In the context of this thesis, it is useful to indicate the level of confidence with which it can be stated that the impact (I_X) of building **X** (*i.e.,* any building from **A** to **E2**) is less than the impact (I_F) of reference building **F**, *i.e.,* the probability that $I_X<I_F$. For a lognormal distribution, this statistic is calculated as the probability that $\frac{I_X}{I_F} < 1$, since the ratio of two lognormal distributions[14] is also lognormal. Such probability can be determined by integrating the relevant PDF ($PDF_{I_X/I_F}(x)$) between 0 and 1:

$$P\left(\frac{I_X}{I_F} < 1\right) = \int_0^1 PDF_{I_X/I_F}(x)\, dx$$

EQUATION 5.18

[14] The difference between two lognormal distributions, instead, is not lognormal. Therefore, for this type of distributions, one cannot assess the probability that I_X is less than I_F by studying the probability that their difference is less than zero, i.e. $P(I_X - I_F) < 0$ (this is generally done, for instance, with normal distributions).

A cumulative-density function $CDF_{I_X/I_F}(x)$ can also be introduced to determine this probability. It is defined as:

$$CDF_{I_X/I_F}(x) = \int PDF_{I_X/I_F}(x)\,dx$$

EQUATION 5.19

The probability that the ratio between the two impacts is less than 1, *i.e.,* $P\left(\frac{I_X}{I_F} < 1\right)$, can also be obtained by calculating CDF(x) at x=1:

$$P\left(\frac{I_X}{I_F} < 1\right) = CDF_{I_X/I_F}(1)$$

EQUATION 5.20

5.5 Limitations of the study

One limitation of this study lies in its system boundaries, *i.e.,* the cradle-to-gate approach. For this reason (as also suggested in CHAPTER 7), it would be beneficial, in future, to extend the model in order to include other life-cycle stages, such as construction, maintenance and replacement.

Another major limitation is correlated to the sources that were readily-available for input parameters (*i.e.,* impact coefficients). Only one up-to-date and relevant EPD was found for medium-density concrete blocks and only one for high-density blocks. Since the impacts associated with these components heavily affect the comparison between the reference building (masonry, **F**) and all the timber buildings, it would have been useful to check the environmental characteristics of analogous products from other manufacturers or to adopt a generic EPD, containing average values for concrete blocks, based on data collected from multiple producers.

In other words, if more sources had been available at the time in which this LCA was planned and carried out, it would have been possible to perform an *ad-hoc* sensitivity analysis and check the consequences of considering analogous masonry products from other manufacturers.

Thus, the interpretation of the impact results presented in this study should take the above into consideration.

Disadvantages and limitations of uncertainty analysis

The main limitation of the method adopted in this thesis and described in SECTION 5.4 is that its mathematical formulation excludes negative environmental impacts arising from avoided burdens. As seen at the beginning of this chapter, negative emissions are obtained when determining the global-warming potential of wood-based materials. In some cases, the large amount of timber incorporated in a building can even lead to a negative overall GWP. Therefore, this method cannot be applied to the assessment of uncertainty associated with GWP that accounts for carbon sequestration.

However, in this thesis, the method is applied to the reliability of the determined GWP impacts that exclude carbon sequestration (and are therefore always positive).

Overall, the inherent limitation of this method and its repercussion on the present study have been deemed outweighed by its numerous advantages.

5.6 Results: impact analysis for wastage scenario 1

5.6.1 Results by building family and contribution analysis

This section illustrates the results of the cradle-to-gate LCA performed, for each of the six building "families" (*i.e.*, **A** to **F**). In the discussion of the impact scores obtained, the building components that carry the highest burdens are identified (through a contribution analysis[15]), in order to indicate areas or aspects of the buildings that prove most critical and for which the greatest efforts should be spent towards environmental improvement. Thus, the present section addresses **research question ①**.

For the sake of brevity, the illustrations in the following sections offer the outputs of the contribution analysis in concise form: more detailed information, both in graphic and tabulated form, can be found in APPENDICES L and M.

5.6.1.1 Building A

In the cradle-to-gate phase, building **A** (open-panel timber frame) causes a GWP (excluding biogenic carbon sequestration) of 154 kg CO_2-eq/m^2_{GFA} , which is attributable in almost equal proportions to the envelope (51%) and the remaining elements of the building (49%), see FIGURE 5.2 (bar chart in the top right quarter). This is explained by the fact that the envelope and non-envelope components contain a similar amount of minerals, which are the materials that emit most carbon: Portland cement in the foundations (12% of the total $GWP_{excl.seq.}$), concrete blocks in the façade and foundations (14%), mineral-wool thermal insulation in the envelope (12%).

If carbon sequestration is included in the quantification of the GWP, then these emissions are estimated at only 38.5 kg CO_2-eq/m^2_{GFA}, thanks to wood-based materials subtracting 90 kg CO_2-eq/m^2_{GFA} from the atmosphere.

The contribution analyses show that as many as three impact categories – acidification, eutrophication and photochemical ozone creation – are strongly affected by plastic

[15] The manner in which the contribution analysis has been designed and structured has been explained in SECTION 4.3.

components,[16] such as damp-proof course, damp-proof membrane and, especially, vapour barrier. Plastic components alone, indeed, contribute 90%, 66% and 92% of the total scores for AP, EP and POCP, respectively (see set of bar charts at the bottom of FIGURE 5.2). Thus, these three impacts are dominated by non-structural constituents of the building envelope and it is here that a viable environmental improvement should be identified.

As regards EP, hybrid components (paint, carpet, *etc.*) also play a noticeable role and contribute 19% of the total.

Building **A** requires 1.92 GJ/m^2_{GFA} of non-renewable primary energy. In terms of contribution analysis, the divide between structural and non-structural components is noticeable, with the former accounting for 25% of non-renewable PE and the latter for 75% of it. This is explained by the fact that the greatest contributors are mineral-based,[17] non-structural components, such as ceramic wall and floor tiles (19% of the total) and gypsum plasterboard (13%).

The production of hazardous waste amounts to 0.32 kg/m^2_{GFA} and its great majority (98%) is attributable to the minerals contained in non-structural components and almost equally divided between the envelope and the remainder of the house.[18]

The production of radioactive waste is 0.026 kg/m^2_{GFA} and due to both structural and non-structural mineral-based components, such as ceramic tiles (19%), medium-density concrete blocks (12%) and high-density concrete blocks (15%).

[16] SECTION 5.6.2 will explain how the role of plastic in building **A** (and also **B1** to **C2**) plays an important role in the comparison with the masonry building.

[17] The share of non-renewable PE consumed by all the mineral-based components together is 68% of the total for building **A**.

[18] This is because gypsum plasterboard (which causes 60% of hazardous waste) appears in similar proportions in the envelope and in the internal elements of the dwelling.

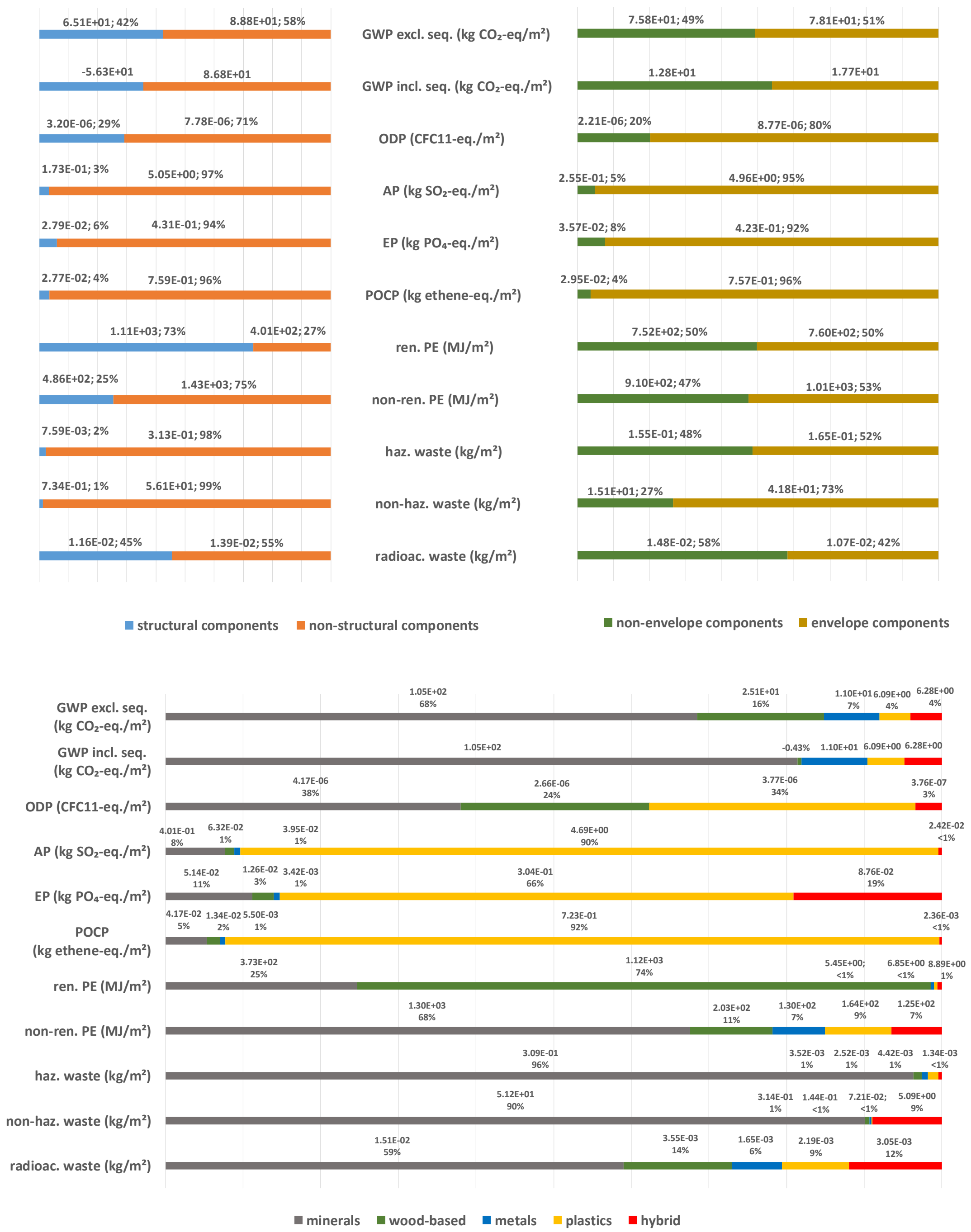

FIGURE 5.2 Summary of contribution analysis for building A. Breakdown by components' structural role (top left), location inside/outside the envelope (top right) and material (bottom).

5.6.1.2 Buildings B1 and B2

There are only two differences between houses **B1** and **B2**: the type of cladding for the external walls (heavy-weight in **B1**, light-weight in **B2**) and, consequently, the width of the strip foundations[19] (wider in **B1** than in **B2**). It is therefore interesting to check the environmental advantages or disadvantages that these differences entail.

The estimated $GWP_{excl.seq.}$ values for buildings **B1** and **B2** are 166 and 158 kg CO_2-eq/m^2_{GFA}, respectively; which corresponds to a relative change of about -5% when the heavy-weight cladding of **B1** is replaced with the light-weight cladding of **B2** (TABLE 5.3 shows the contributions of the external walls and foundations). In both **B1** and **B2**, minerals are, by far, the greatest contributors to $GWP_{excl.seq.}$ and cause *circa* 63-64% of the totals (see FIGURES 5.3 and 5.4).

TABLE 5.3 Global-warming potential (excl. sequestration) of B1 and B2: contributions of the two elements that vary between these two houses (i.e., external walls and foundations). All the other elements do not vary and thus have the same impacts in both buildings.

Building element	**$GWP_{excl.seq.}$** kg CO_2-eq/m^2_{GFA}		
	building B1	**building B2**	**change from B1 to B2**
external walls	42.6	42.4	-0.20
foundations	23.1	16.5	-6.60
total	**65.7**	**58.9**	**-6.80**

A negligible difference is instead noticed between **B1** and **B2**, in terms of consumption of non-renewable primary energy, which is assessed at *ca*. 2.1 GJ/m^2_{GFA} for both buildings. While the light-weight cladding of **B2** is *per se* more energy-intense than the heavy-weight cladding of **B1**,[20] this difference is counterbalanced[21] by the greater

[19] See building description in SECTION 4.4.

[20] Different results would probably have been obtained if a gypsum-based render-carrier board had been specified for **B2**, instead of the current cement-based board.

[21] In house **B1**, the non-renewable energy required for the external walls (which include concrete blocks and block-laying mortar) is 0.53 GJ/m^2_{GFA} and the energy for the strip foundations 0.13 GJ/m^2_{GFA}: this yields a total of 0.66 GJ/m^2_{GFA}. In house **B2**, instead, the energy consumed by the external walls (including the cement-based, render-carrier board) is 0.58 GJ/m^2_{GFA} and the energy for the foundations is 0.091 GJ/m^2_{GFA}, for a total of 0.67 GJ/m^2_{GFA} (very similar to the amount obtained above for option **B1**).

energy consumption of the wider foundations in **B1** (TABLE 5.4 summarises these gains and losses in terms of PE).

TABLE 5.4 Non-renewable primary energy in B1 and B2: contributions of the two elements that vary between these two houses (i.e., external walls and foundations). All the other elements do not vary and thus have the same impacts in both buildings.

Building element	**Non-renewable primary energy** GJ/m^2_{GFA}		
	building B1	**building B2**	**change from B1 to B2**
external walls	0.53	0.58	+0.05
foundations	0.13	0.09	-0.04
total	**0.66**	**0.67**	**+0.01**

When biogenic carbon is taken into account in GWP assessment, the overall carbon emissions are negative for both buildings: -23.6 and -30.8 kg CO_2-eq/m^2_{GFA} for **B1** and **B2**, respectively. This means that the materials in house **B2** sequester 31% more carbon from the atmosphere than those in **B1**.

In both **B1** and **B2**, contribution analysis for acidification, eutrophication and photochemical ozone creation reveals a very similar trend to that discussed for building **A** (see SECTION 5.6.1.1), with the largest contributors being plastic components.

An equal amount of hazardous waste is associated with both buildings and estimated at *ca.* 0.3 kg/m^2_{GFA}, with 96% of this impact arising from minerals. The quantity of radioactive waste for both **B1** and **B2** is assessed at approx. 0.03 kg/m^2_{GFA}.

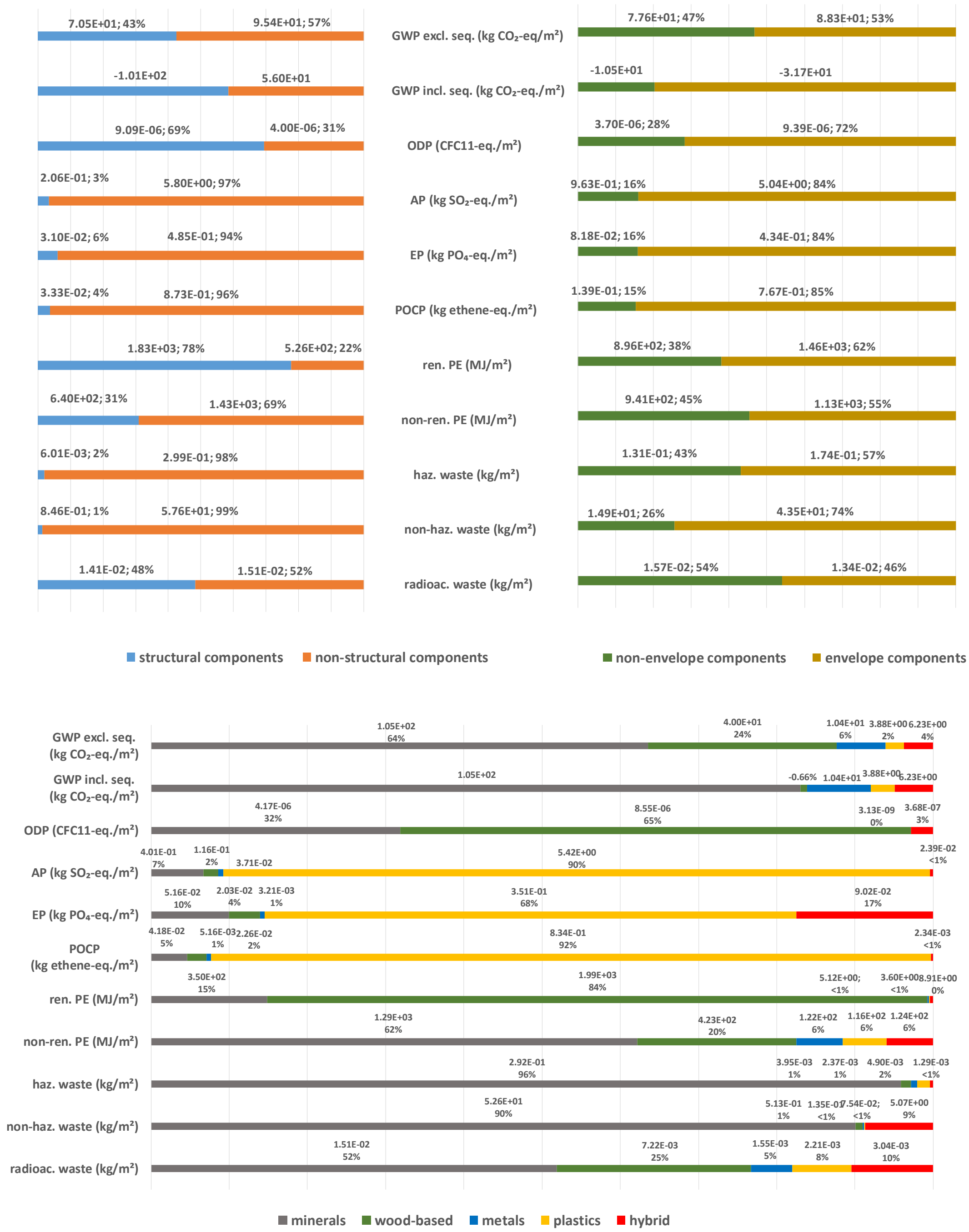

FIGURE 5.3 Summary of contribution analysis for building B1. Breakdown by components' structural role (top left), location inside/outside the envelope (top right) and material (bottom).

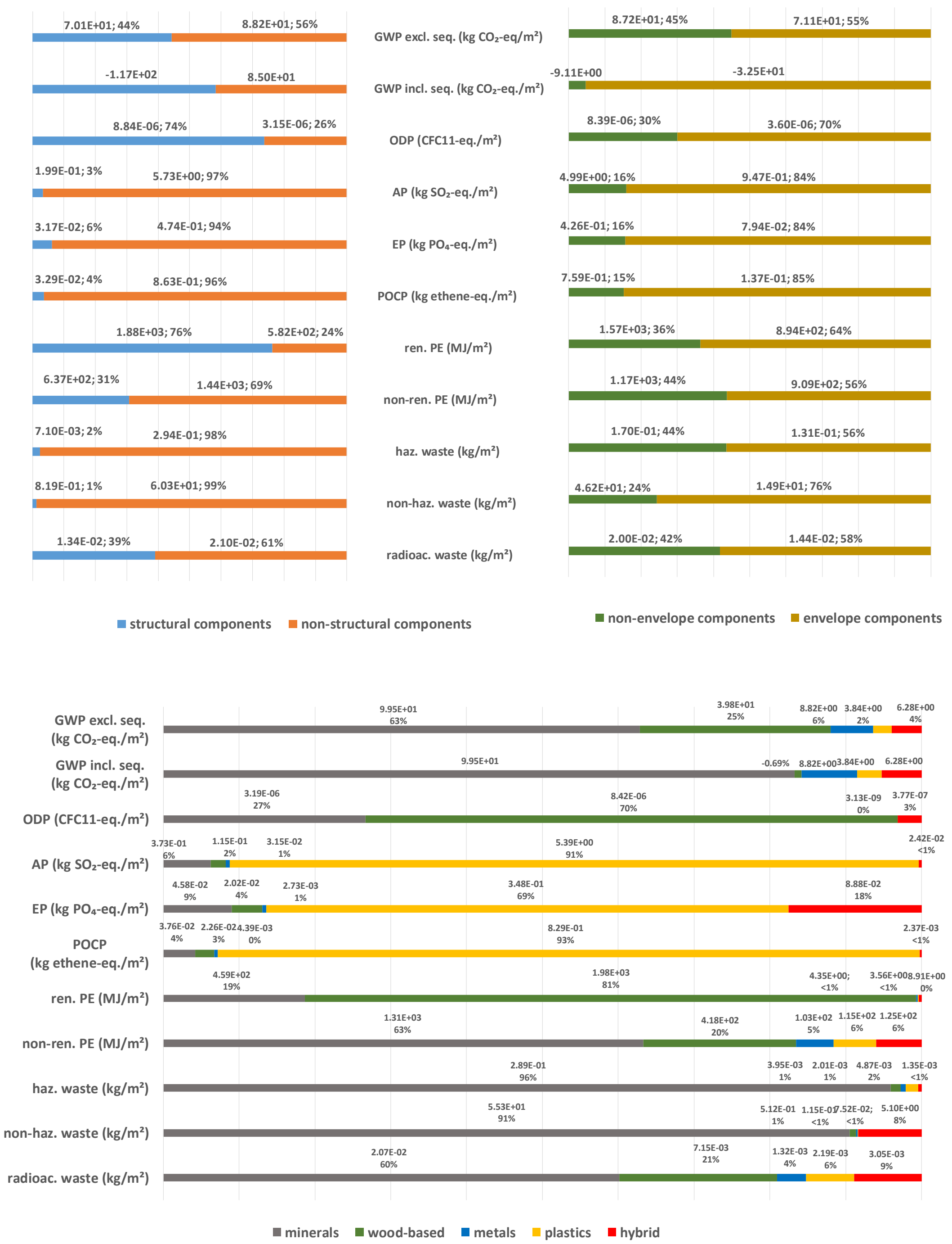

FIGURE 5.4 Summary of contribution analysis for building B2. Breakdown by components' structural role (top left), location inside/outside the envelope (top right) and material (bottom).

5.6.1.3 Buildings C1 and C2

The GWP (excluding sequestration of carbon) amounts to 184 and 176 kg CO_2-eq/m^2_{GFA} for buildings **C1** and **C2**, respectively: this corresponds to a decrease of 4.4% from building **C1** to **C2**. This relative change[22] stems from the different type of external wall cladding (blockwork in **C1** *versus* render on board in **C2**) and associated foundations (wider in **C1**, narrower in **C2**). TABLE 5.5 shows the individual contributions of these elements in both dwellings.

TABLE 5.5 Global-warming potential (excl. sequestration) of C1 and C2: contributions of the two elements that vary between these two houses (i.e., external walls and foundations). All the other elements do not vary and thus have the same impacts in both buildings.

Building element	**$GWP_{excl.seq.}$** kg CO_2-eq/m^2_{GFA}		
	building C1	**building C2**	**change from C1 to C2**
external walls	45.9	45.8	-0.10
foundations	23.5	16.0	-7.50
total	**69.4**	**61.8**	**-7.60**

If carbon sequestration is accounted for, the estimate of $GWP_{incl.seq.}$ amounts to 41 and 32 kg CO_2-eq/m^2_{GFA} for **C1** and **C2**, respectively. Within this impact category, the shift from heavy-weight cladding to light-weight cladding results in a more evident drop of emissions, equal to 22%. All environmental aspects considered, this is the greatest relative change that can be noticed between options **C1** and **C2**.

Similarly to what has been observed in SECTION 5.6.1.2 for the two closed-panel buildings (*i.e.,* **B1** and **B2**), houses **C1** and **C2** require almost the same amount of renewable primary energy (estimated at about 2.0 GJ/m^2_{GFA}) and non-renewable primary energy (2.7 GJ /m^2_{GFA}). This means that the shift from heavy-weight to light-weight cladding (with its repercussions on the foundations) entails negligible differences in overall energy demand. The reason lies in the fact that the energy saved in buildings **C2** thanks to its smaller foundations is counterbalanced by an equal increase in the energy

[22] A similar differential was observed for the $GWP_{excl.seq.}$ of houses **B1** and **B2** in SECTION 5.6.1.2.

embodied in its light-weight cladding (see TABLE 5.6). The light-weight cladding of **C2** is indeed slightly more energy-intensive than the blockwork in **C1**.

TABLE 5.6 Non-renewable primary energy in buildings C1 and C2: contributions of the two varying elements (i.e., external walls and foundations). All the other elements do not vary between C1 and C2 and thus have the same impacts.

Building element	**Non-renewable primary energy** GJ/m^2_{GFA}		
	building C1	**building C2**	**change from C1 to C2**
external walls	0.66	0.72	+0.06
foundations	0.13	0.09	-0.04
total	**0.79**	**0.81**	**+0.02**

The ozone-depletion potential is minimal and estimated at about $7 \cdot 10^{-5}$ kg CFC-11-eq/m^2_{GFA} for both houses.

The acidification, eutrophication and photochemical-ozone-creation results[23] do not show any significant differences between **C1** and **C2**. For all three of these impact categories (AP, EP and POCP), the great majority (>90%) of contributions come from the building envelope, and, in particular from plastic-based components (see FIGURES 5.5 and 5.6).

Hazardous waste is also very similar in **C1** and **C2** (about 0.27 kg/m^2_{GFA}); whereas a difference can be observed in the estimated production[24] of radioactive waste, to the advantage of **C1**.

[23] For *both* **C1** and **C2**, these impacts amount to approximately: 5.2 kg SO_2-eq/m^2_{GFA} for AP, 0.5 kg PO_4-eq/m^2_{GFA} for EP and 0.8 kg ethene-eq/m^2_{GFA} for POCP.

[24] While the absolute amount is small in both cases, building **C2** produces 17% more radioactive waste than building **C1** (owing to the type of external cladding).

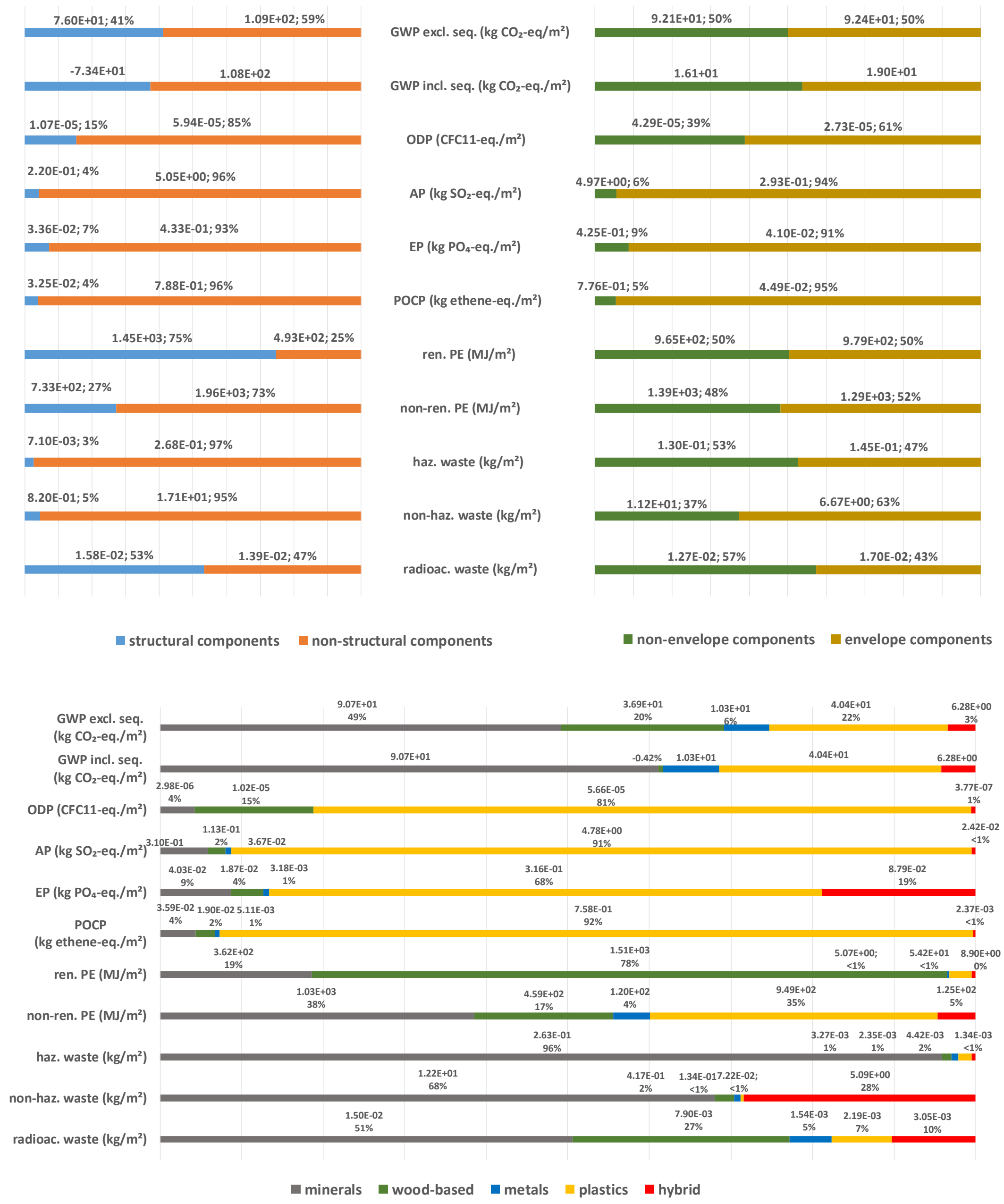

FIGURE 5.5 Summary of contribution analysis for building C1. Breakdown by components' structural role (top left), location inside/outside the envelope (top right) and material (bottom).

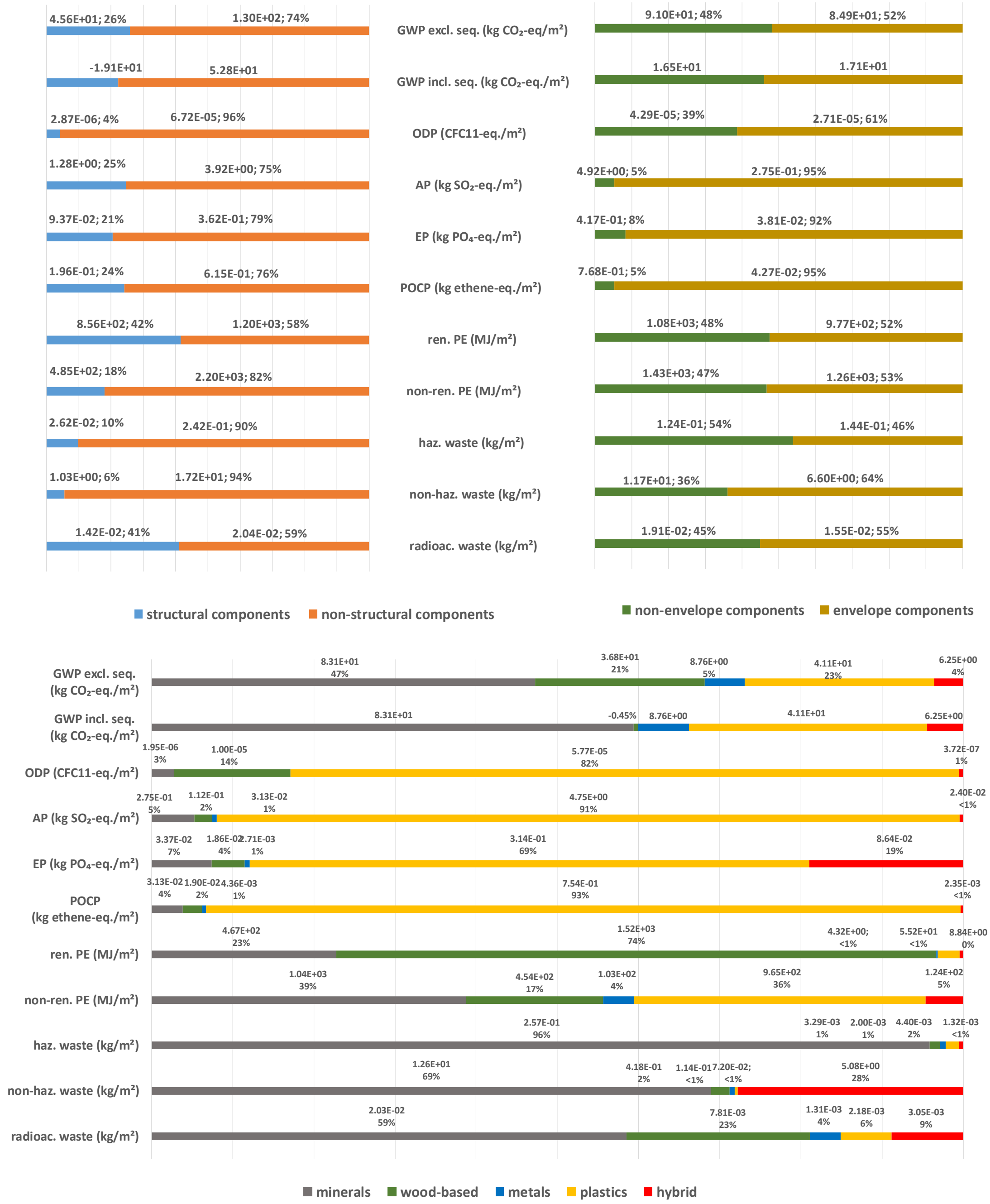

FIGURE 5.6 Summary of contribution analysis for building C2. Breakdown by components' structural role (top left), location inside/outside the envelope (top right) and material (bottom).

5.6.1.4 Buildings D1 and D2

The cradle-to-gate assessment suggests that the $GWP_{excl.seq.}$ values of buildings **D1** and **D2** are 289 and 276 kg CO_2-eq/m^2_{GFA}, respectively: thus, there is a reduction of 4.5% when changing from option **D1** to **D2**. This difference is mostly due to the greater quantity of minerals present in the construction of the ground-floor and intermediate floors of **D1** in comparison[25] with **D2**. Minerals, indeed, generate 103 kg CO_2-eq/m^2_{GFA} in house **D1** and *ca.* half as much (58.7 kg CO_2-eq/m^2_{GFA}) in **D2** (FIGURES 5.9 and 5.10).

Timber accounts for 53% of the total $GWP_{excl.seq.}$ of building **D1** and for as much as 67% of **D2**'s total (in **D2**, the floor constructions contain more timber); see FIGURES 5.9 and 5.10 for a full breakdown into material types. These impacts are strongly dominated by CLT and the other wood-based materials contribute marginally to $GWP_{excl.seq.}$ (see proportions in FIGURES 5.7 and 5.8).

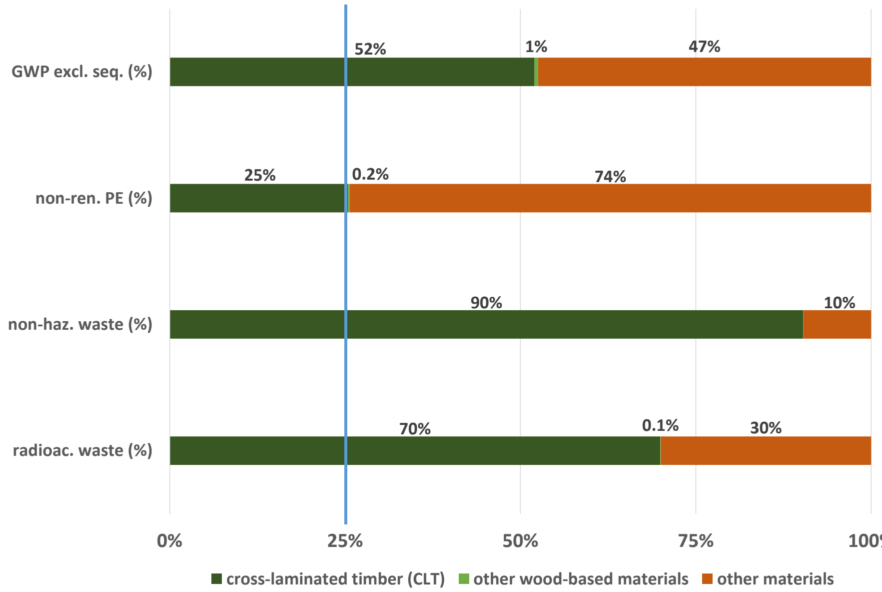

FIGURE 5.7 Contribution analysis for building D1, showing the impact categories in which CLT alone contributes more than 25% of the total.

When carbon sequestration is included in the determination of GWP impacts, the difference between buildings **D1** and **D2** appears much greater than in the $GWP_{excl.seq.}$. The $GWP_{incl.seq.}$ of **D1** corresponds to -164 kg CO_2-eq/m^2_{GFA} and that of **D2** to -276 kg

[25] See amounts of different building materials in FIGURE 4.20.

CO_2-eq/m^2_{GFA}. This means that the amount of carbon sequestered by the materials incorporated in house **D2** is about 1.7 times as large as that sequestered in house **D1**.

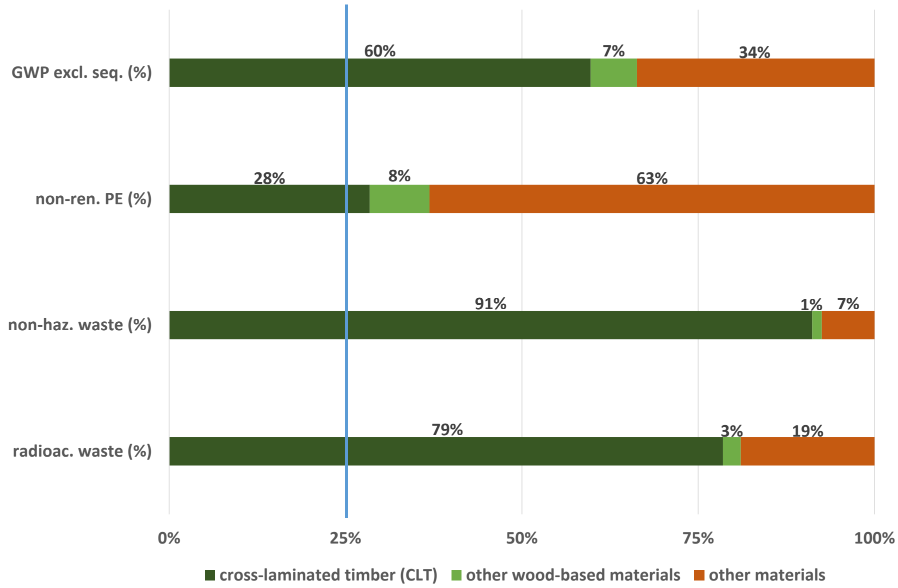

FIGURE 5.8 Contribution analysis for building D2, showing the impact categories in which CLT alone contributes more than 25% of the total.

Polluting emissions responsible for acidification,[26] eutrophication[27] and photochemical creation of ozone[28] are all approx. 9-15% lower in building **D2** than in **D1**. These percentage changes are affected by the difference in mineral content, but also by the difference in amount of plastic. **D1**, indeed, contains more plastic than **D2**: this dissimilarity is mostly due to the presence, in the intermediate floors of **D1**, of plastic membranes acting as a separation layer between screed and timber panels. The intermediate floors in **D2** do not include a screed, therefore less plastic is needed.

In terms of renewable primary energy, building **D1** shows a value of 4.60 GJ /m^2_{GFA}, which increases by 17% in option **D2**. This can be explained by the larger quantity of

[26] The AP of **D2** is 12% lower than that of **D1**. One of the main factors towards this result consists in minerals causing 0.29 kg SO_2-eq/m^2_{GFA} in **D1** and 0.21 in **D2** (compare FIGURES 5.9 and 5.10).

[27] The EP of **D2** is 9% lower than that of **D1**.

[28] The POCP of **D2** is 15% lower than that of **D1**.

timber incorporated in house **D2**, which entails a greater amount of primary energy from raw materials.

The estimation of non-renewable primary energy, instead, yields a value of 2.39 GJ /m^2_{GFA} for dwelling **D1**, and 2.35 GJ /m^2_{GFA} for **D2**, which corresponds to a 2% drop.[29]

The results of hazardous-waste production show that while building **D1** generates 0.27 kg/m^2_{GFA}, building **D2** exhibits an 11% increase, with a production of 0.30 kg/m^2_{GFA} of hazardous substances: this is especially caused by the manufacturing of a larger volume of wood-based materials in **D2**, as has been explained above when discussing other environmental impacts.

The production of radioactive waste for house **D1** is almost 0.1 kg/m^2_{GFA}; that for **D2** is slightly smaller.

To conclude, the greatest advantages offered by **D2** (more CLT-intense) in comparison with **D1** (more cement-intense) are $GWP_{excl.seq.}$, AP and POCP (*ca.* 5%, 12% and 15% less than in **D1**, respectively). Conversely, **D2** proves an unfavourable choice in terms of hazardous and non-hazardous waste (both types *ca.* 10% greater than in **D1**).

[29] This relative change originates from the fact that, while option **D2** requires more energy for the manufacturing of CLT and three types of wood-based materials that are not used in **D1** (namely, OSB, softwood for exterior wall cladding and chipboard), building **D1** has a higher energy demand for its larger quantity of minerals (in particular, mortars for screed and rendering). The increase in energy needed for minerals in **D1** slightly exceeds that of building **D2** for wood; hence, the above-mentioned -2% change from option **D1** to **D2**.

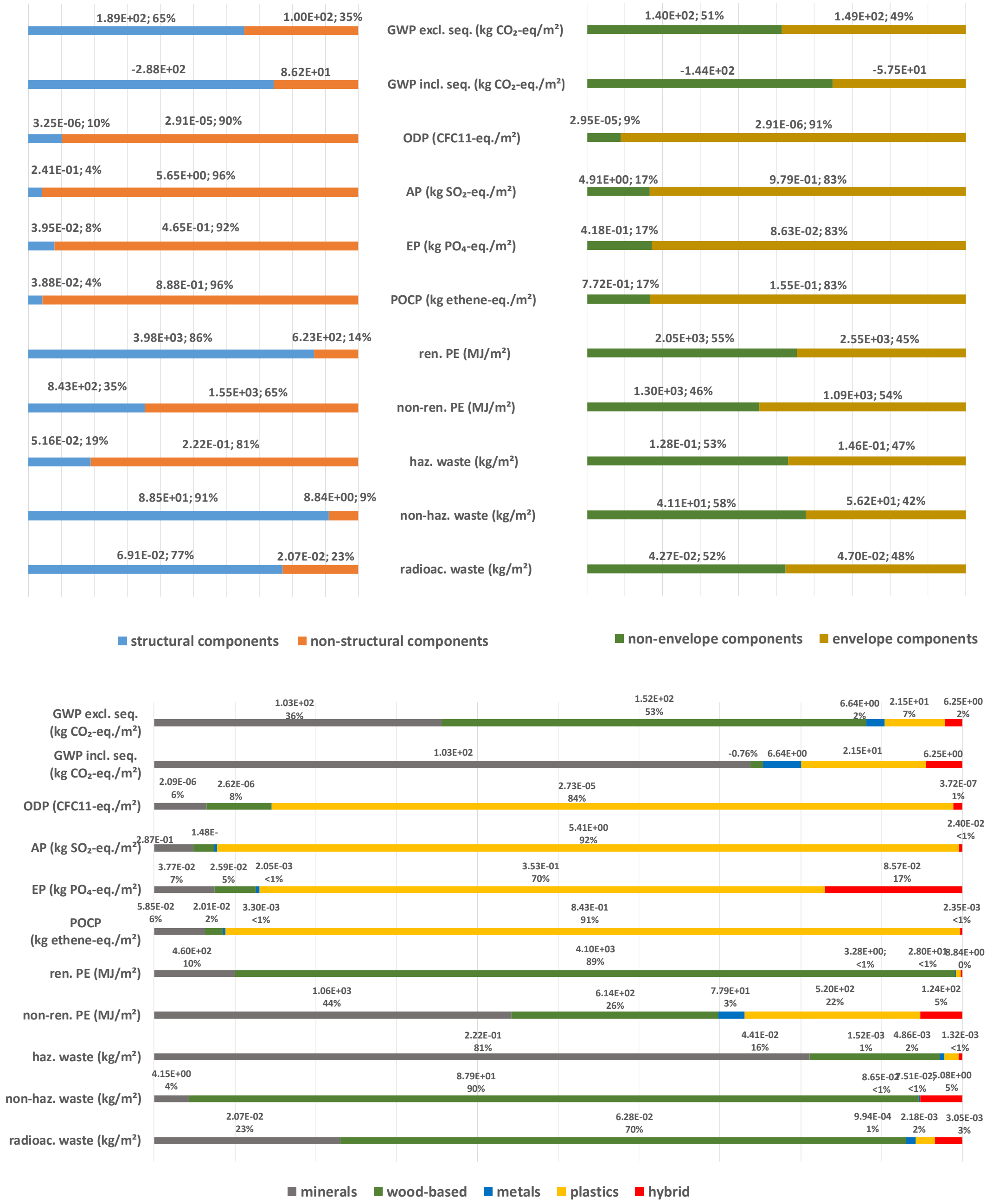

FIGURE 5.9 Summary of contribution analysis for building D1. Breakdown by components' structural role (top left), location inside/outside the envelope (top right) and material (bottom).

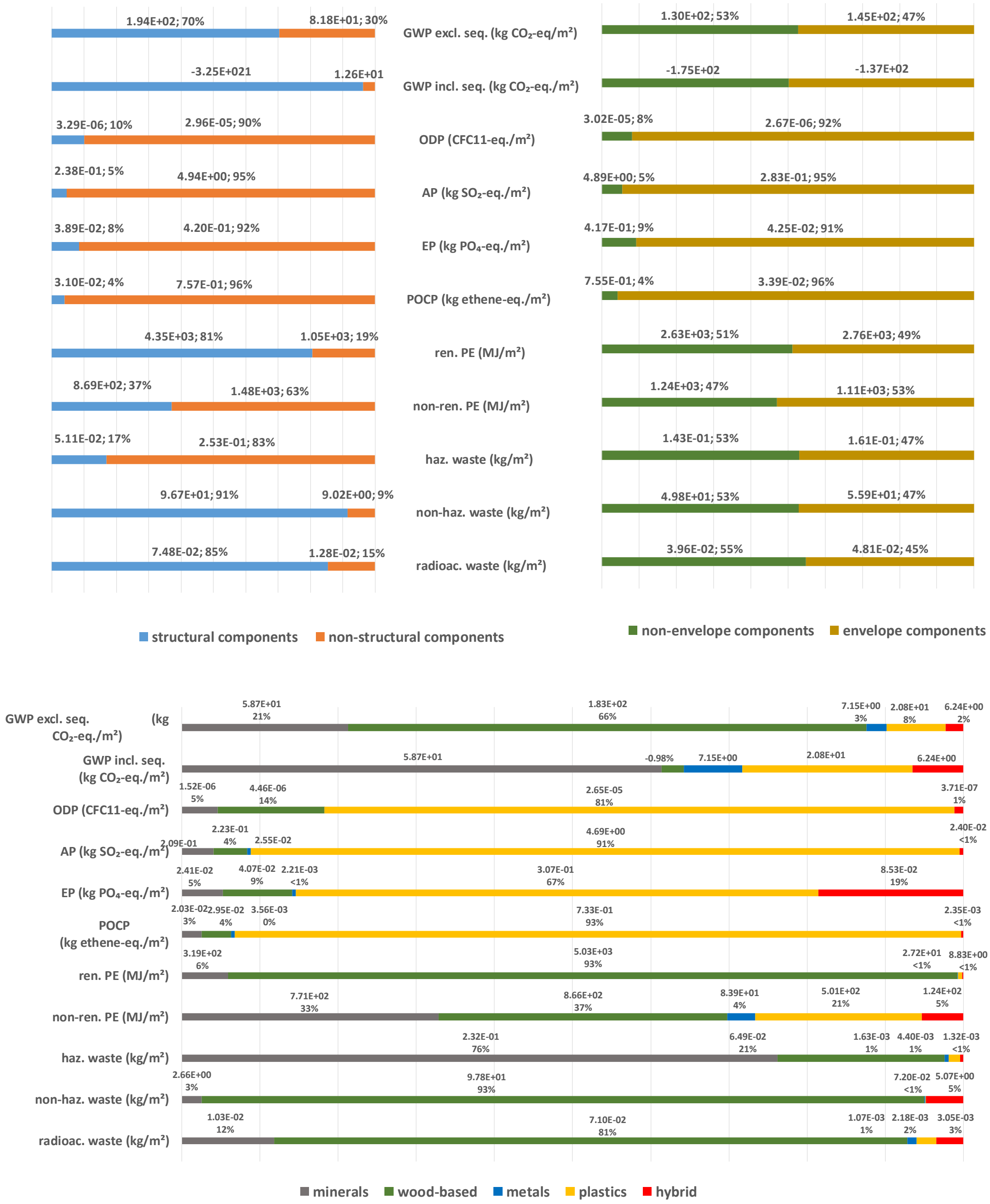

FIGURE 5.10 Summary of contribution analysis for building D2. Breakdown by components' structural role (top left), location inside/outside the envelope (top right) and material (bottom).

5.6.1.5 Buildings E1 and E2

Since buildings **E1** and **E2** differ only in the materials of the external wall cladding (*i.e.,* render on board for **E1** and timber boards for **E2**), the impact differences that can be observed are all attributable to this specific part of the buildings.

The estimated $GWP_{excl.seq.}$ amounts to 216 and 195 kg CO_2-eq/m^2_{GFA}, for buildings **E1** and **E2** respectively; this drop of *ca.* 10% from **E1** to **E2** is mostly due to **E1** incorporating more minerals in the façade. Indeed, the minerals in **E1** (which include the rendering mortar and its cement-based carrier board) are responsible for 79.6 kg of carbon emissions per unit floor area, whereas the minerals in **E2** produce 57.4 kg/m^2_{GFA} of the same emissions[30] (see FIGURES 5.11 and 5.12).

As seen for the other building families in the previous sections, accounting for sequestration of carbon towards the overall GWP leads to a wider gap between these two design options. The $GWP_{incl.seq.}$ totals -366 and -436 kg CO_2-eq/m^2_{GFA}, for houses **E1** and **E2** respectively, which means a -19% change from **E1** to **E2**.[31]

The assessment of impacts such as acidification, eutrophication and photochemical ozone creation all yield similar results for **E1** and **E2**,[32] with variations between the two below 2%.

Building **E2** requires a slightly-larger amount of renewable primary energy, due to the energy (as raw materials) embodied in its wooden cladding: the construction of building **E1** consumes 6.68 GJ/m^2_{GFA}, whereas **E2** consumes 6.75 GJ/m^2_{GFA}.

As regards the estimated consumption of non-renewable primary energy, an opposite trend can be observed: 2.30 and 2.17 GJ/m^2_{GFA} are consumed for houses **E1** and **E2**,

---

[30] While the additional timber present in **E2** (*i.e.,* cladding boards) produces some more carbon emissions, this increase is much less than that due to the increase of minerals.

[31] This $GWP_{incl.seq.}$ result is attributable to the combined effect of the avoided burdens in **E2**, namely: the avoided burden of minerals-related carbon emissions in **E2** with respect to **E1** (*i.e.,* minerals in the cladding); the avoided burden of carbon subtracted from the atmosphere due to the extra amount of timber incorporated in the exterior-wall construction of **E2**.

[32] In *both* buildings, the polluting emissions per unit area are *ca.*: 5.3 kg SO_2-eq/m^2_{GFA} for AP, 0.48 kg PO_4-eq /m^2_{GFA} for EP and 0.83 kg ethene-eq/m^2_{GFA} for POCP.

respectively (with a resulting change of -6% from **E1** to **E2**). This difference is explained by the greater amount of energy needed for the manufacturing of the mineral-based cladding components of dwelling **E1**.

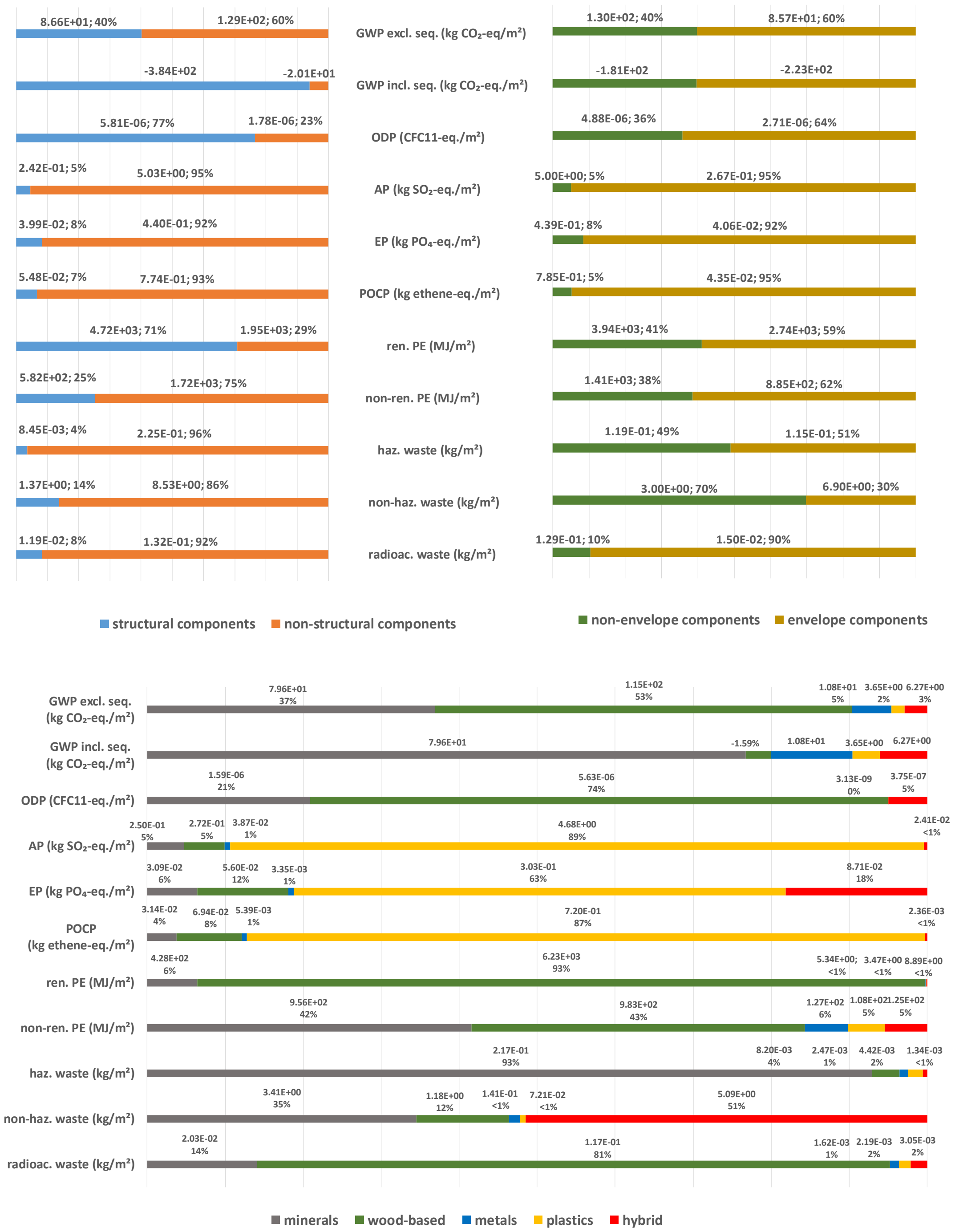

FIGURE 5.11 Summary of contribution analysis for building E1. Breakdown by components' structural role (top left), location inside/outside the envelope (top right) and material (bottom).

In terms of waste production arising from the manufacturing of building components, house **E1** is accountable for 0.23 kg/m$^2_{GFA}$ of hazardous substances (which increase by 4% in house **E2**) and 0.14 kg/m$^2_{GFA}$ of radioactive materials (which decrease by 7% in **E2**, thanks to its smaller quantity of minerals).

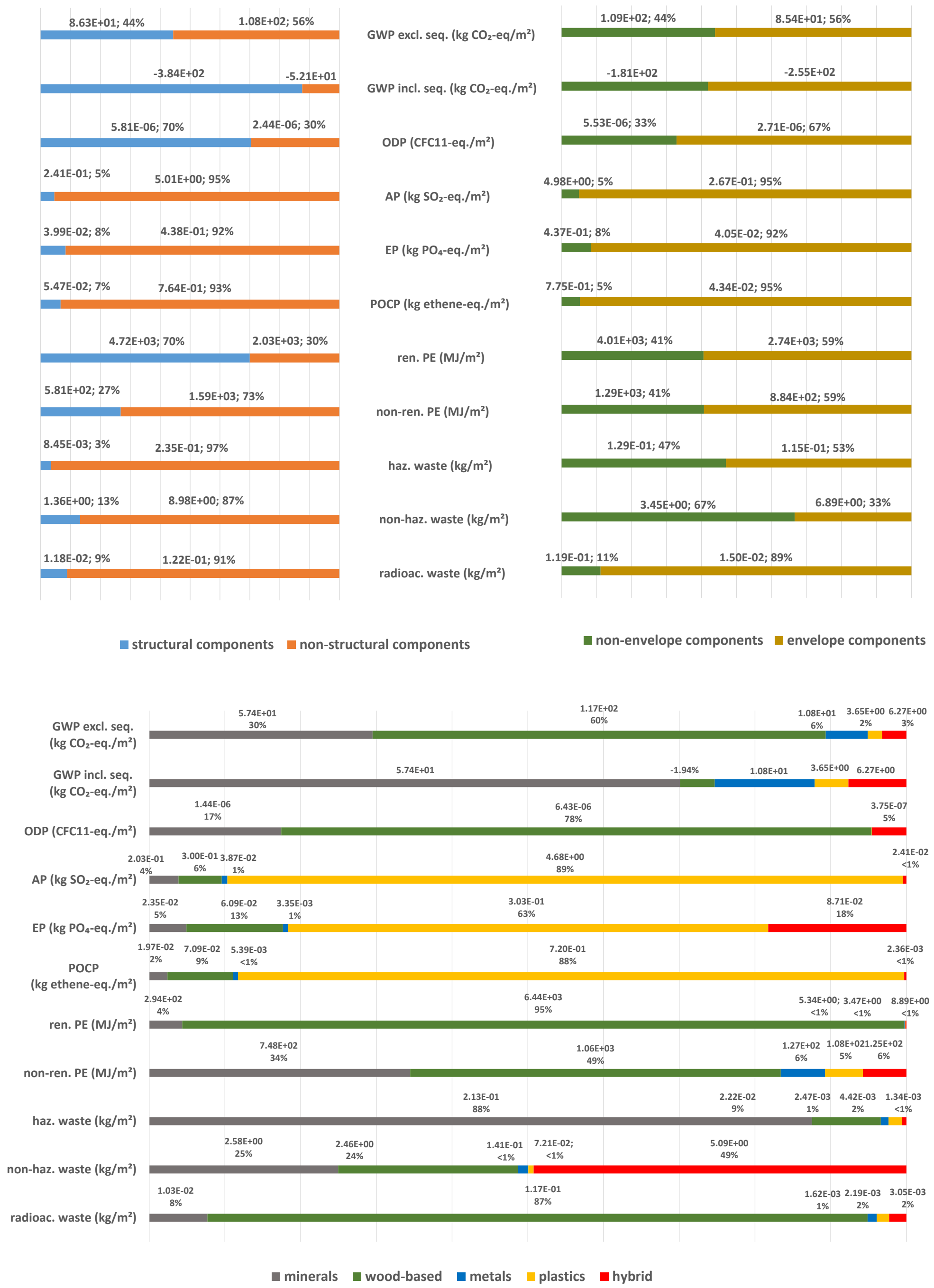

FIGURE 5.12 Summary of contribution analysis for building E2. Breakdown by components' structural role (top left), location inside/outside the envelope (top right) and material (bottom).

5.6.1.6 Building F

The cradle-to-gate $GWP_{excl.seq.}$ of building **F** amounts to 171 kg CO_2-eq/m^2_{GFA}, and arises in almost equal proportions both from structural (51%) and non-structural (49%) components and from materials inside (48%) and outside (52%) the envelope (FIGURE 5.13). This is explained by the fact that as much as 73% of $GWP_{excl.seq.}$ emissions are associated with the minerals of this building, which are very similarly split between exterior and interior walls (and, therefore, envelope and non-envelope components) and load-bearing and cladding (*i.e.,* structural and non-structural) concrete blocks. The relatively-wide foundation footings of house **F** contribute 14% of the overall $GWP_{excl.seq.}$.

The total $GWP_{incl.seq.}$ for this dwelling is positive in sign (unlike most of the other buildings discussed above) and equal to +94.4 kg CO_2-eq/m^2_{GFA}; this is due to the avoided burden of wood-based materials (-58 kg CO_2-eq/m^2_{GFA}) not being sufficiently large to counterbalance the positive emissions from the other types of materials, and, in particular, from the noticeable amount of minerals incorporated in the envelope and in the foundations.

The acidification potential is estimated at 4.4 kg SO_2-eq/m^2_{GFA}; the eutrophication potential at 0.42 kg PO_4-eq/m^2_{GFA} and the tropospheric-ozone-creation potential (POCP) at 0.67 kg ethene-eq/m^2_{GFA}. For all these impacts, the external walls alone contribute between 50% and 60% of the totals; the ground-floor also plays an important role, with contributions varying between 18% and 27% of the totals. This contribution profile is strongly correlated to the amount of plastic contained in the external walls, roof and ground-floor: vapour barriers and waterproofing membranes, but also polyurethane thermal insulation.

Renewable primary energy[33] is consumed at a rate of 1.04 GJ/m^2_{GFA}; its non-renewable counterpart, instead, is used at a rate of 1.96 GJ/m^2_{GFA}: it can therefore be seen that the requirement for non-renewable energy is almost twice as much as that from renewable sources.

---

[33] A large amount (65%) of renewable PE comes from the timber products constituting the structure of the trussed roof and the timber-framed floors. A smaller, yet significant, proportion (32%) of this type of energy is employed for the manufacturing of mineral-based products (see FIGURE 5.13).

About 66% of the consumption of non-renewable primary energy is attributable to minerals, with the remaining proportion being especially dominated by plastic (see FIGURE 5.13).

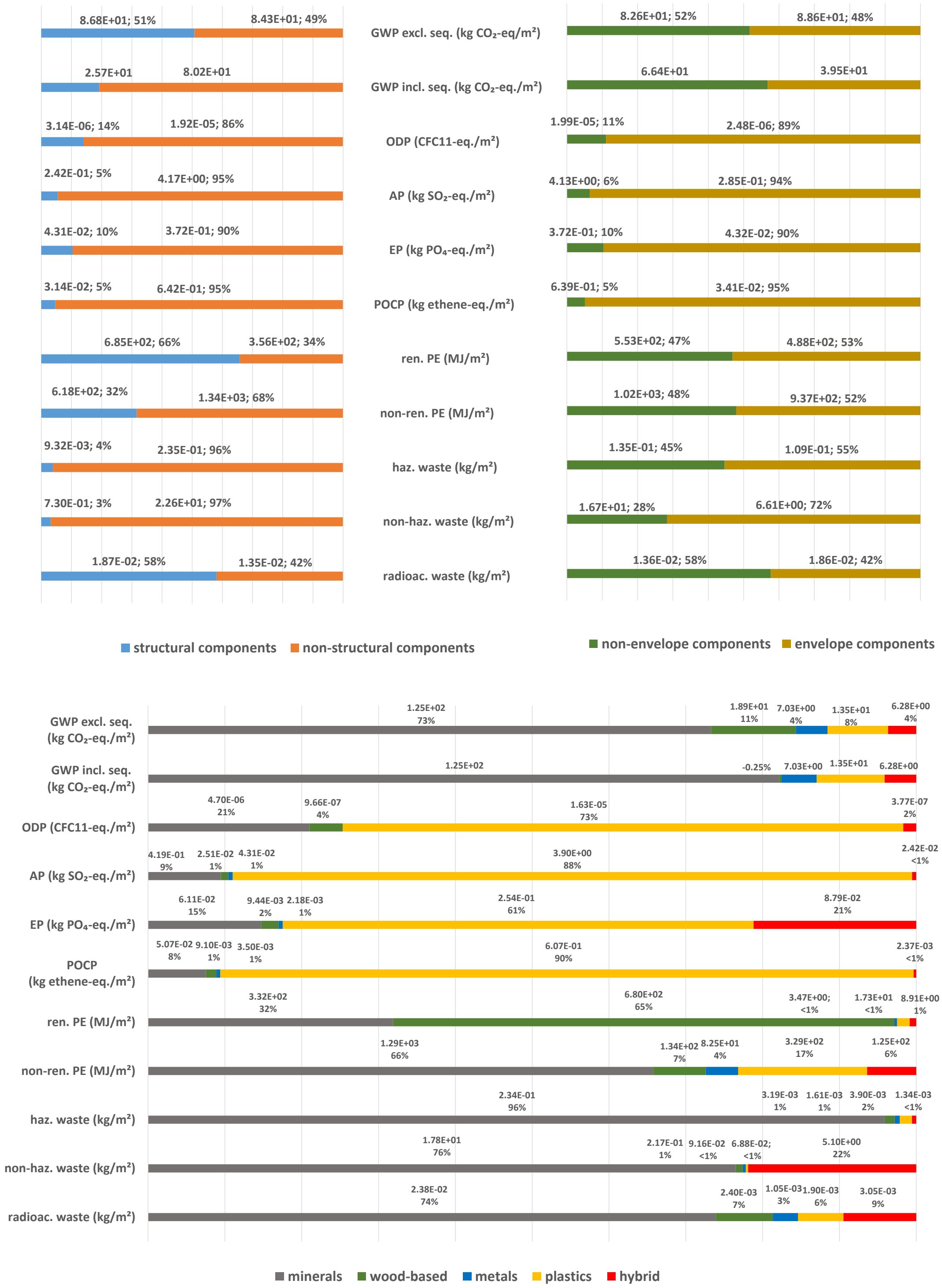

FIGURE 5.13 Summary of contribution analysis for building F. Breakdown by components' structural role (top left), location inside/outside the envelope (top right) and material (bottom).

Waste production for the cradle-to-gate stages is assessed at 0.24 kg/m^2_{GFA} of hazardous materials and a very small amount (0.03 kg/m^2_{GFA}) of radioactive substances: both these impacts mostly arise from mineral-based components.

5.6.2 Comparative results and trade-off analysis

This section offers an answer to **research question ②**, by explaining how the ten notional buildings compare within the impact categories embraced in this LCA, and, in particular, by providing a comparison between each of the timber houses and the masonry house (**F**), here used as a reference. This comparative approach allows for the identification of burden trade-offs between the buildings assessed.

5.6.2.1 Global warming

Global-warming potential excluding carbon sequestration

The $GWP_{excl.seq.}$ of buildings **D1** and **D2** (cross-laminated timber) is the highest across the houses considered in this LCA and is estimated at 289 and 276 kg CO_2-eq/m^2_{GFA}, respectively. In comparative terms[34] (FIGURE 5.14), these emissions of **D1** and **D2** are, respectively, 69% and 61% more than that of **F** (which equals 171 kg CO_2-eq/m^2_{GFA}). This is due to the large amount of massive, wood panels: the manufacturing process of CLT entails very high carbon-equivalent emissions.[35] In addition, it is worth noticing that **D1** is the only dwelling with a ground-floor directly supported by the soil; this results in a larger amount of minerals than in the other ground-floors, which are all timber-constructed and suspended from the soil.

Buildings **E1** and **E2** show large $GWP_{excl.seq.}$, too. This is partly due to the very large amount of materials incorporated in these houses with massive, NLT panels for most

---

[34] Relative differences between each of the timber buildings (**X**) and the masonry building (**F**) are calculated as follows (and expressed in percentage terms): $(Impact_X - Impact_F) / Impact_F$.

[35] See further discussion in SECTION 5.6.3.

elements: walls, roof and floors; partly it is also due to the high carbon emissions arising from the type of insulating material used, based on wood fibres.[36]

The $GWP_{excl.seq.}$ estimates for buildings **C1** and **C2** are 8% and 3 %, respectively, more than that for **F**.

The three buildings adopting timber-frame systems (**A**, **B1** and **B2**) show the lowest carbon emissions: in particular, building **A** (open-panel system) is expected to produce the lowest emissions (154 kg CO_2-eq/m^2_{GFA}), equal to 10% less than **F**.

It is worth noticing that opting for light-weight cladding (as in houses **B2** and **C2**) instead of heavy-weight cladding (as in houses **B1** and **C1**) does not necessarily offer the advantages that one might expect, if, as is the case with these notional buildings, the light-weight cladding makes use of carbon-intense materials such as cement-based render carriers. This has already been discussed in SECTION 5.6.1.

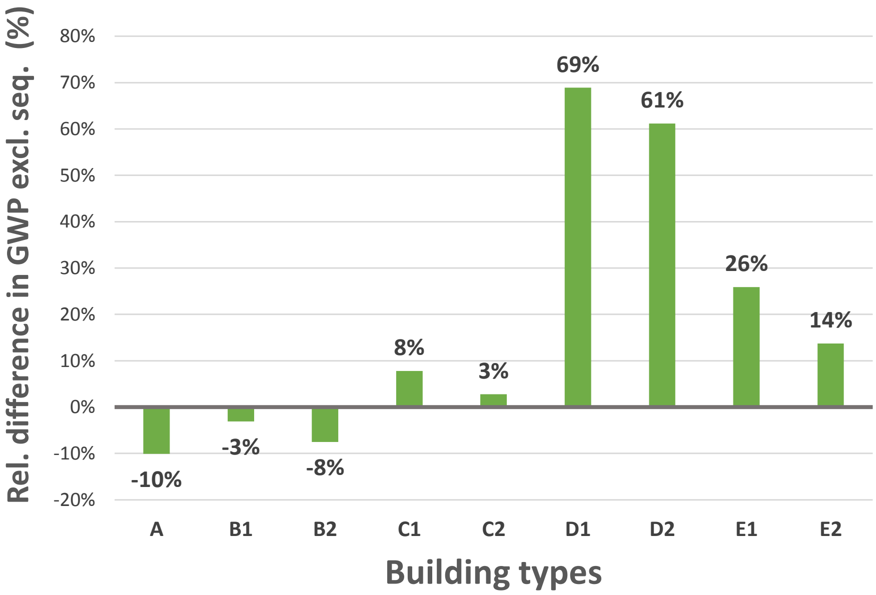

FIGURE 5.14 Global-warming potential (excluding carbon sequestration): results normalised with respect to building F (relative differences, see FOOTNOTE 34).

36 More details can be found in SECTION 5.6.4.

Global-warming potential including carbon sequestration

When biogenic carbon sequestration is accounted for in the computation of GWP, the results discussed above are inverted. Within this method, indeed, the buildings using massive-timber panels are the ones showing the best performance:

- buildings **D1** and **D2** achieve more significant negative emissions, with estimates at -164 and -276 kg CO_2-eq/m^2_{GFA}, respectively. This corresponds to as much as 274% and 393% less than **F**[37] (FIGURE 5.15);
- buildings **E1** and **E2** reach even smaller impact values, with their $GWP_{incl.seq.}$ expected to total -366 and -436 kg CO_2-eq/m^2_{GFA}, respectively. This is equivalent to 488% and 562%, respectively, less than **F**.

The noticeable difference between the impacts of building **D2** (CLT) and the two NLT buildings might appear surprising, considering that the overall amount of timber-based materials they all incorporate is roughly equal. This is because **E1** and **E2** employ a vast quantity of softwood, which, in comparison with CLT, subtracts more carbon from the atmosphere (per unit volume of wood). This is due to the combined effect of two processes: cross-lamination of timber boards and production of structural glue.

While building **A** still shows positive overall emissions of carbon-equivalents, the other two timber-framed buildings[38] (**B1** and **B2**) achieve negative overall emissions, since they incorporate a larger amount of wood than does **A**.

[37] Since building **F** contains a smaller amount of timber than all the other buildings, it shows a more limited difference between the results of $GWP_{excl.seq.}$ and $GWP_{incl.seq.}$(with the latter remaining positive in sign).

[38] The $GWP_{incl.seq.}$ values of **B1** and **B2** are -24 and -31 CO_2-eq/m^2_{GFA}, respectively.

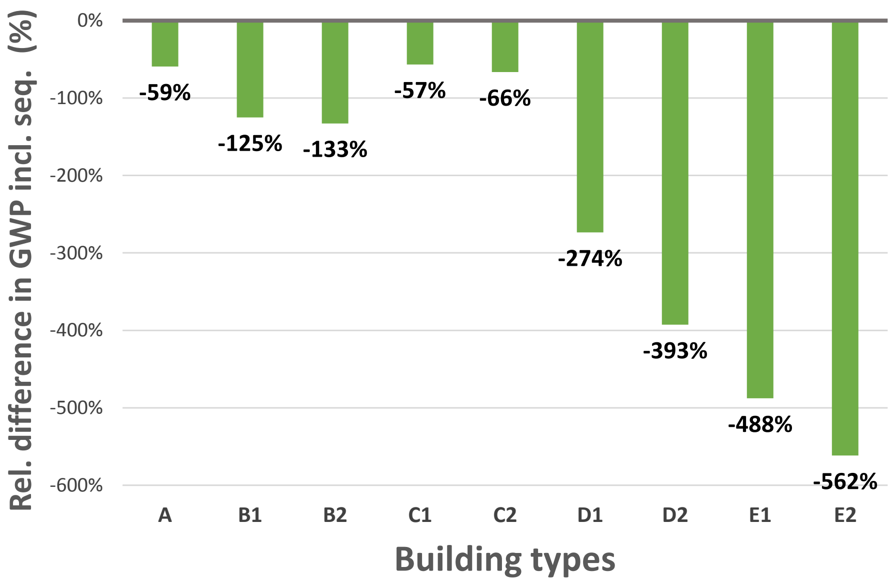

FIGURE 5.15 Global-warming potential (including carbon sequestration): results normalised with respect to building F (relative differences).

5.6.2.2 Acidification, eutrophication and photochemical ozone creation

Since, in this study, the emissions responsible for acidification, eutrophication and photochemical ozone creation are mostly caused by components made of low-density polyethylene (LDPE), variations in such impact categories are commensurate with fluctuations in the amount of this plastic material incorporated in the ten buildings (see FIGURE 5.16).

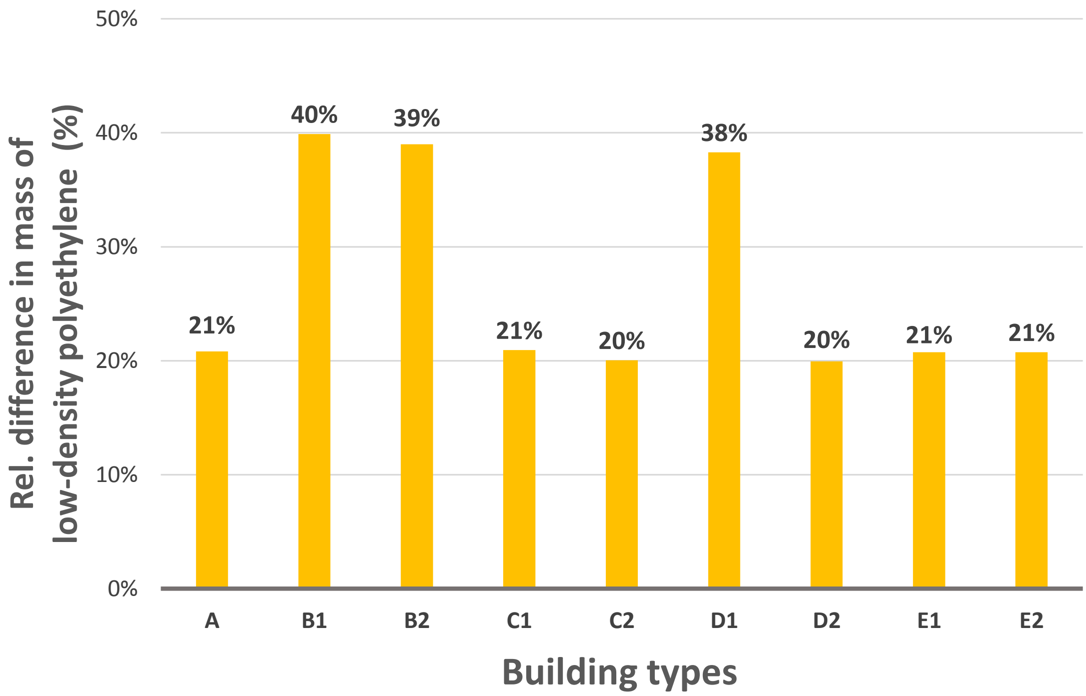

FIGURE 5.16 Mass of low-density polyethylene (LDPE) incorporated in each timber building: results normalised with respect to building F (relative differences).

For these reasons, building **F** shows the lowest AP, EP and POCP results: its double-leaf masonry walls do not require protection[39] from moisture, therefore the amount of LDPE membranes (vapour barriers and breather membranes) is smaller than in the timber-built dwellings.[40]

[39] Penetration of water vapour from the inside is not as problematic as in timber buildings. Similarly, rainwater penetration (from the outside) is impeded by the outer leaf and poses fewer challenges for the inner leaf, which is also made of blockwork.

[40] It is worth noticing, though, that the *overall* amount of plastic materials (*i.e.*, the sum of *all* types of plastic, not only LDPE) is much greater in building **F** than it is in **A**, **B1** and **B2**, due to **F** having PUR boards in the external walls (this can be seen in FIGURE 4.20, and in the bills of quantities in APPENDIX H). PUR, however, has much lower AP, EP and POCP coefficients per unit mass than LDPE: this results in a small amount of LDPE being much more impactful than a high amount of PUR, under these three categories.

The results for the **acidification** potential show that **F** is accountable for 4.42 kg SO_2-eq/m^2_{GFA}. The buildings with the highest AP are **B1**, **B2** and **D1**, with values around 6 kg SO_2-eq/m^2_{GFA}, which is equivalent to *ca.* 35% more than **F** (see FIGURE 5.17).

Buildings **A**, **C1**, **C2**, **D2**, **E1** and **E2** all show comparable emissions of acidifying substances, in the region of 5.2-5.3 kg SO_2-eq/m^2_{GFA}, that is, approximately 17-19% more than **F**.

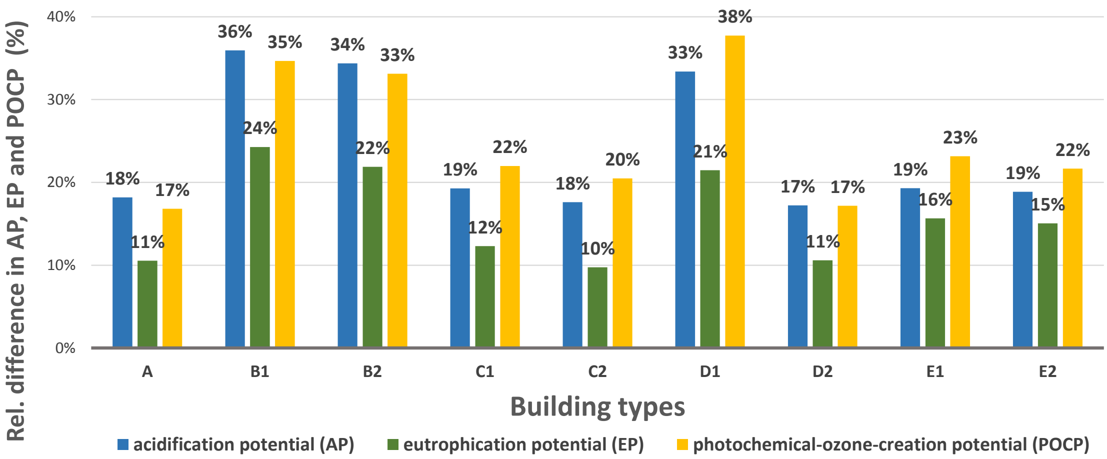

FIGURE 5.17 Acidification, eutrophication and photochemical-ozone-creation potentials: results normalised with respect to building F (relative differences).

The **eutrophication**-potential figures[41] show slightly lesser variation than is the case with the acidification potential: here the estimated value for **F** is 0.42 kg PO_4-eq/m^2_{GFA}, and the other buildings range between 10% and 24% more than **F** (see FIGURE 5.17).

The expected **photochemical creation of ozone** for building **F** is 0.67 kg ethene-eq/m^2_{GFA}. The peak value for this impact (assessed at 0.93 kg ethene-eq/m^2_{GFA}, or 38% more than **F**) is reached in building **D1**, where the effect of plastic cumulates with that of a higher content in minerals (see FIGURE 5.17). Similar values to **D1** have been obtained for the two closed-panel timber dwellings, **B1** and **B2**. Finally, there is narrow

[41] In all timber-based buildings (**A** to **E2**), the greatest contributors of eutrophying substances are plastic-based materials (responsible for roughly 65-70% of the totals) and hybrid materials (accountable for *ca.* 15-20% of the totals), with the other types of materials giving much smaller contributions (generally <10% of the totals). Instead, in building **F**, which has the highest content of minerals, the relative contribution of minerals themselves to EP is estimated at 15% of the total.

variation in POCP results between the remaining houses (**A**, **C1**, **C2**, **D2**, **E1** and **E2**), which all emit approximately 17% to 23% more than **F**.

5.6.2.3 Ozone depletion

The results for the ozone-depletion potential appear minimal for all of the ten houses assessed. This suggests that the manufacturing processes adopted for the building components specified in the design of the notional buildings are successful in minimising the emissions of chlorofluorocarbons.

However, with the above in mind, it can be observed that the CFC11-eq emissions associated with buildings **C1** and **C2** are by far the largest (FIGURE 5.18), because of the vast quantity of polyurethane contained in the SIPs forming their external and internal walls and roofs. A certain amount of chlorofluorocarbons is indeed emitted during the production of the blowing agents used for polyurethane foam.[42]

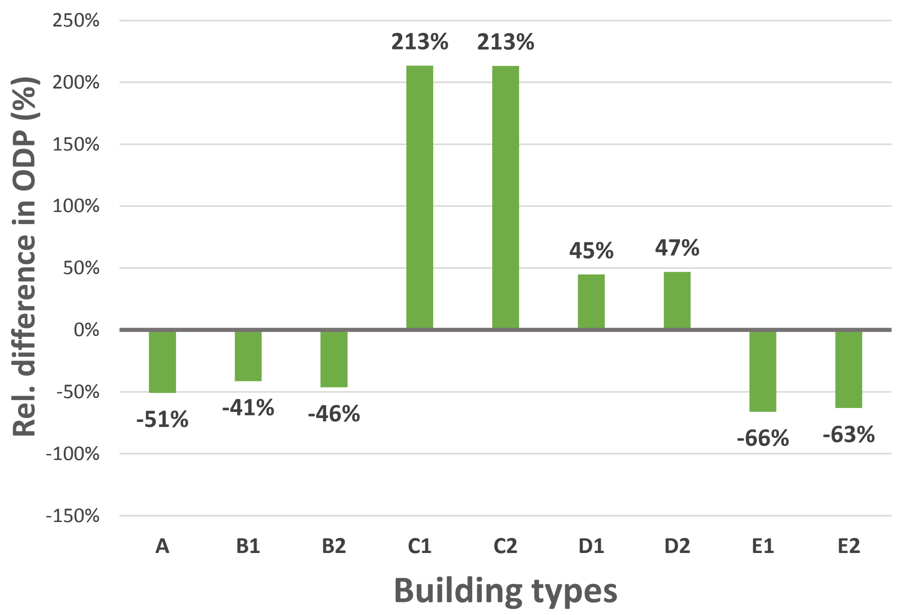

FIGURE 5.18 Ozone-depletion potential: results normalised with respect to building F (relative differences).

[42] Institut Bauen und Umwelt (IBU), 2014b.

5.6.2.4 Energy consumption

Renewable primary energy

When the amount of renewable primary energy needed for the cradle-to-gate stages of each house is analysed, one can observe that it is commensurate with the volume of wood incorporated in the constructions. This is due to the component of energy as raw materials being very high for wood-based products.

The assessment reveals that building **F** has the lowest renewable PE requirements, with a comparatively-modest figure of 1.04 GJ/m^2_{GFA}, in line with its low content of wood.

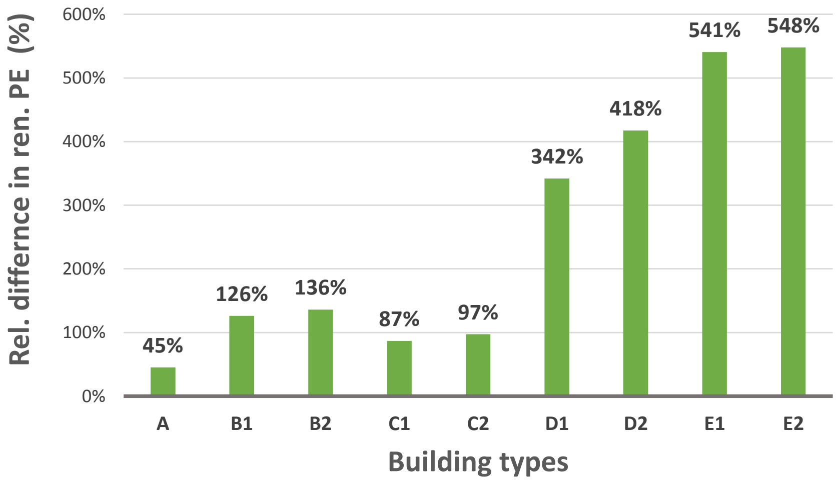

FIGURE 5.19 Consumption of renewable primary energy: results normalised with respect to building F (relative differences).

Dwellings **E1** and **E2** show the greatest requirements of renewable primary energy, which, for both cases, are in the region of 6.7 GJ/m^2_{GFA}, that is, *circa* 545% more than **F** (FIGURE 5.19).

Buildings **D1** and **D2** contain a similar quantity of structural timber (for the massive wall, floor and roof panels) to **E1** and **E2**, but the latter also have wood-fibre insulating materials, resulting in an overall larger amount of wood. Therefore, buildings **D1** and **D2** show requirements[43] of this type of energy below those for **E1** and **E2**. The consumption of renewable PE for the three timber-frame buildings (**A** to **B2**) and the SIP buildings (**C1** and **C2**) oscillates between 1.5 and 2.5 GJ/m^2_{GFA}.

Non-renewable primary energy

The values describing the consumption of non-renewable PE for the ten buildings studied show a very different pattern from those regarding its renewable counterpart. There is much less variation between buildings here than it is the case for non-renewable energy.

The non-renewable PE result for building **F** is among the lowest of all buildings, with a figure[44] of 1.96 GJ/m^2_{GFA}. This value might seem surprisingly low, but is explained by the fact that the concrete blocks forming the load-bearing leaf and the cladding leaf of the walls are environmentally-enhanced and thus require a relatively small amount of energy to be manufactured.[45]

The non-renewable-PE consumption of all dwellings ranges between 1.92 GJ/m^2_{GFA} (house **A**) and 2.69 GJ/m^2_{GFA} (houses **C1** and **C2**); these two limit values correspond to changes of -2% and +37% relative to **F**, respectively (FIGURE 5.20). It is worth noticing that building **A** is the only one that consumes less energy than **F**,[46] though by a very small margin.

---

[43] In particular, the renewable PE for D2 amounts to 5.39 GJ/m^2_{GFA}, followed by the PE for D1, estimated at 4.60 GJ/m^2_{GFA} (since D1, unlike D2, does not use timber for the structure of the ground-floor).

[44] The medium-density blocks used for the internal walls and the cladding leaf of the external walls are responsible for a consumption of 0.28 GJ/m^2_{GFA} (corresponding to 15% of **F**'s total), while the high-density blocks used on the inner side of the external walls and for the foundations consume 0.12 GJ/m^2_{GFA} (equivalent to 6% of the total).

[45] This is also in line with the measures that today can be taken to improve the sustainability of concrete-based building products, as discussed in SECTION 3.2.3.

[46] Contribution analysis by structural role of the components reveals that the load-bearing structure of **F** (which includes blockwork for the walls and timber frame for the floors and roof) causes a non-renewable-energy consumption of 0.62 GJ/m^2_{GFA} (*i.e.,* 32% of the total). It can be useful to compare these figures with those for building

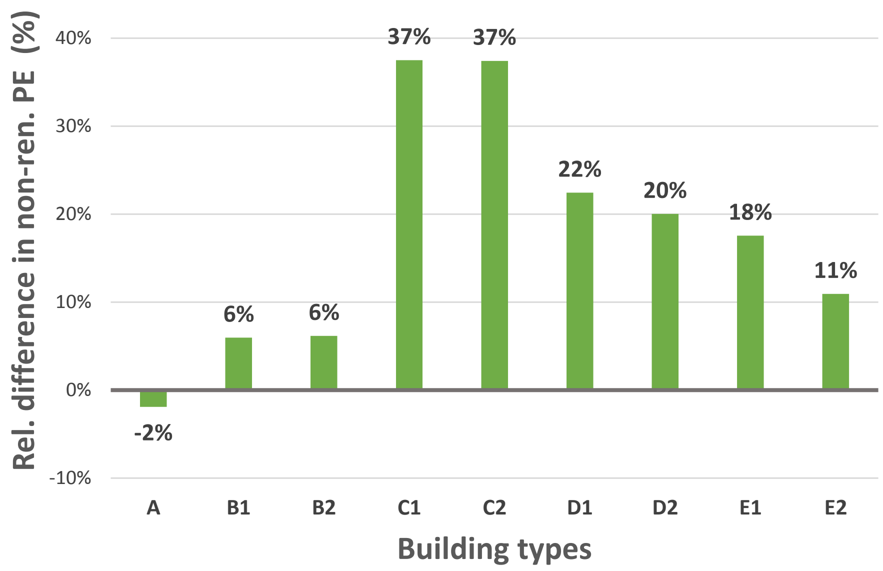

FIGURE 5.20 Consumption of non-renewable primary energy: results normalised with respect to building F (relative differences).

The reason why the lowest value is achieved by building **A** is mainly that its open-panel timber-frame system requires a comparatively-small amount of materials to be incorporated in the build-ups.[47]

Buildings **C1** and **C2**[48] entail a high non-renewable PE consumption, due to the manufacturing process of the structural insulated panels, which is energy-intensive.

A, which employs a different structural solution for all wall types, but exactly the same system for roof and floors. It can then be seen that the structural components of house **A** require 0.49 GJ/m^2_{GFA} (25% of **A**'s total consumption). Thus, there is a difference of 0.13 GJ/m^2_{GFA} between the structures of **A** and **F**, to the advantage of the former. However, this saving is counterbalanced by an almost-equal difference in the energy consumed for the non-structural components (greater in **A** than in **F**), leading to a very similar overall non-renewable-energy consumption for these two design options.

[47] For instance, the services are accommodated behind the internal lining of the open wall panels, thus there is no service cavity (unlike in the other timber-constructed buildings); a similar situation occurs with the floors of house **A**, which require a "slimmer" construction than those of buildings **B1**, **B2**, **D1**, **D2**, **E1** and **E2**.

[48] In **C1** and **C2**, indeed, thermal insulation alone (comprising mostly PUR and smaller amounts of mineral wool) is responsible for 34% of the total use of non-renewable PE (with a contribution of 0.90 and 0.92 GJ/m^2_{GFA} in **C1** and **C2**, respectively). See SECTION 5.6.4 for an in-depth discussion on the role of insulants.

5.6.2.5 Waste production

Hazardous waste

The production of hazardous waste for building **F** is evaluated at 0.24 kg/m^2_{GFA}: the same value is also envisaged for **E2**. Building **E1** is the only one to generate less waste than **F**, with a relative change of -4% (from **F** to **E1**), see FIGURE 5.21. All the remaining buildings exceed the values of **F**, with **A** showing the highest burden, estimated at 31% more than **F** (0.32 kg/m^2_{GFA}, in absolute terms).

The building components that entail the greatest contribution to this environmental burden are those based on minerals; principally, concrete roof tiles, gypsum plasterboard and mineral-wool thermal insulation. While roof tiles and plasterboard are incorporated in all of the notional buildings and in comparable quantities, mineral wool is predominantly utilised in open- and closed-panel timber-frame houses: this fact explains why **A**, **B1** and **B2** produce the largest amounts of hazardous waste. Building **D2** also causes a comparatively-elevated amount of this type of waste: here the reason lies in the large amount of CLT, which contributes 16% of the total burden for this dwelling.

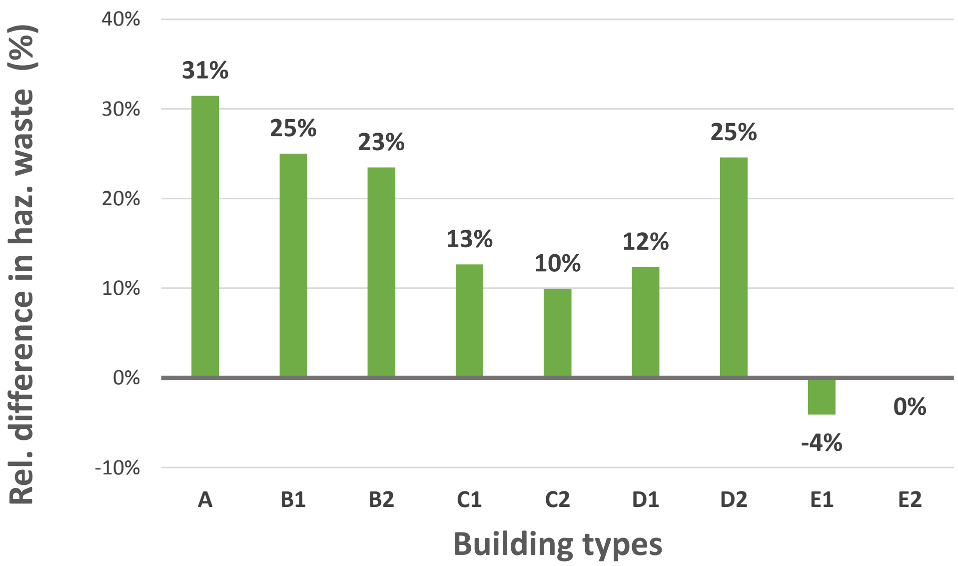

FIGURE 5.21 Hazardous waste disposed: results normalised with respect to building F (relative differences).

Non-hazardous waste

The buildings associated with the largest production of non-hazardous waste are **D1** and **D2**, with a burden of 97 and 106 kg/m$^2_{GFA}$, respectively. These values correspond to an increase of above 300% with respect to house **F** (FIGURE 5.22), which produces 23 kg/m$^2_{GFA}$. This is the consequence of the manufacturing of cross-laminated timber, which accounts for about 90% of the totals of both **D1** and **D2**.

The timber-frame buildings (**A**, **B1** and **B2**) entail a similar production of this type of waste, estimated at around 60 kg/m$^2_{GFA}$., *i.e.,* 144% to 162% more than **F**. This finding is explained by the industrial process through which mineral wool is produced: approximately 85% of the waste of these three dwellings comes indeed from this insulant.

The remaining buildings (**C1**, **C2**, **E1** and **E2**) all produce less non-hazardous waste than **F**, in absolute quantities below 18 kg/m$^2_{GFA}$.

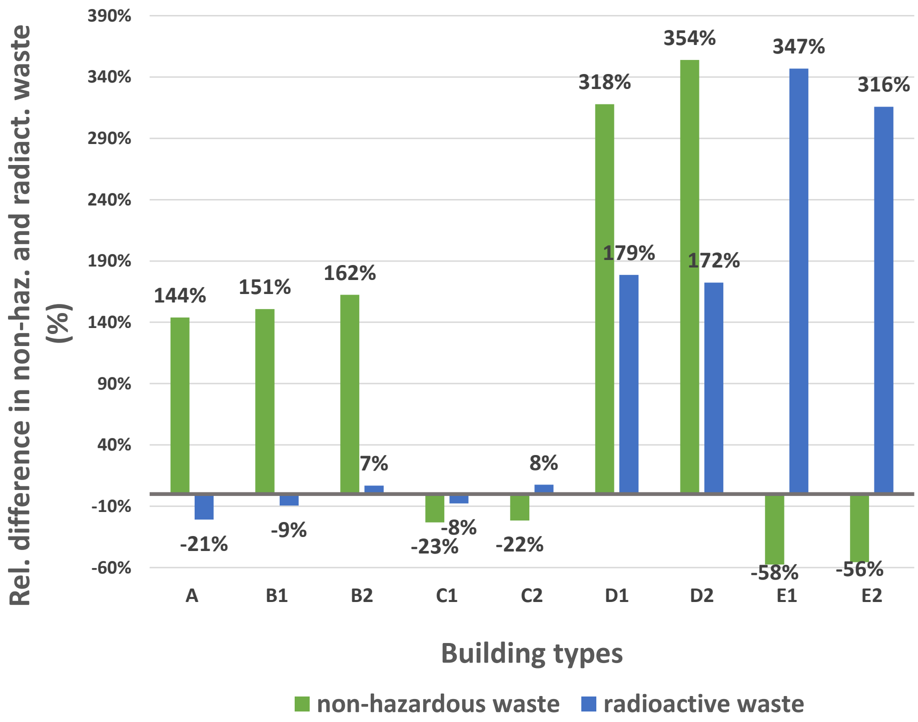

FIGURE 5.22 Non-hazardous and radioactive waste disposed: results normalised with respect to building F (relative differences).

Radioactive waste

The amount of radioactive waste produced differs widely from building to building.

House **F** is accountable for production of 0.03 kg/m^2_{GFA} and the timber-frame and SIP houses show relatively-small variations around this value.

Results for buildings **D1** and **D2**, instead, show an increase of above 170% relative to **F**, owing to the production of their CLT panels (which account for more than 69% of the total in both **D1** and **D2**).

Finally, houses **E1** and **E2** exhibit an even more substantial increase from **F** (above 300%), leading to radioactive-waste production of 0.14 kg/m^2_{GFA} (**E1**) and 0.13 kg/m^2_{GFA} (**E2**). This is due to the fabrication process of wood-fibre insulation boards (see SECTION 5.6.4).

5.6.3 Impacts of wood-based components

This section looks into the environmental burdens associated with the manufacturing of the timber-based products specified for the ten notional buildings and allows a better understanding of the impact results (discussed in SECTIONS 5.6.1 AND 5.6.2) for which such products were significant contributors. Thus, cause-effect links between the results at the building level and those at the product level are here explained.

The production of building components that are based on wood or wood by-products, such as chips or strands, consumes elevated amounts of primary energy[49] for **heat provision**. The number and type of activities requiring thermal energy vary from product to product and according to the manufacturing process[50] implemented; such activities can include the boiling of fibres, the drying of raw or preliminary materials and the subsequent drying of pressed products (*i.e.*, mats, sheets, boards, *etc.*). Since a large proportion of this energy requirement comes from non-renewable sources, these fabrication stages are responsible for high environmental burdens. Moreover, the burning of fuels for drying processes is responsible for the majority of the emissions causing global warming, acidification and eutrophication arising from the timber products under discussion.

Operating the **infrastructure at the factory** requires further electrical energy, but generally significantly less than the heating processes mentioned above.

An additional problem of wood-based components lies in the use of (generally synthetic) **adhesives** to bind chips, strands or lamellas and **additives** to improve the performance of finished products.[51] Although the amount[52] of these "ancillary" substances is very low in comparison with that of the base material[53] (wood), their contributions to the overall environmental costs in the cradle-to-gate phase is generally very high. The

[49] IBU, 2014a; IBU, 2014e; IBU, 2016a.

[50] For example, wood-fibre insulation boards can be produced through a "dry" or a "wet" process (IBU, 2014a; IBU, 2016a).

[51] For instance, to retard the spread of flames or make the final product hydrophobic.

[52] By both mass and volume.

[53] For instance, the adhesives used in the wood-fibre insulation boards specified for buildings `E1` and `E2` constitute 6% of the mass of the finished product (IBU, 2016a).

production of the (structural or non-structural) adhesives used for the formation of wood-fibre insulation boards or mats[54], OSB[55] or chipboard[56] sheets or CLT[57] panels is, indeed, extremely energy-intensive. FIGURE 5.24 summarises the non-renewable energy consumed for each notional building and shows the contributions of both structural and non-structural timber components. Production of glues and additives also entails important polluting emissions: their setting process dominates, for instance, the POCP[58] of timber products.

For most wood-based products, the extraction stage of raw materials (module[59] A1) is usually not as burden-intensive as the manufacturing stage in the factory. The transportation stage (from the extraction site(s) to the factory, module A2) is typically negligible (often accountable[60] for less than 1% of the production stage, A1-A3). Thus, it can be concluded that most of the cradle-to-gate impacts are dominated by the processes that occur at the factory (module A3).

SECTION 5.6.4 will examine the primary energy used, and the carbon emitted, to manufacture wood-fibre boards, in comparison with the other insulating materials used in the notional dwellings.

In the present LCA study, the buildings which produce the largest amounts of radioactive waste are the nail-laminated-timber houses, **E1** and **E2**. As can be seen in FIGURE 5.25, this burden arises from non-structural, wood-based products: these are mostly the wood-fibre insulation boards incorporated in the envelope. The reason lies primarily in

---

[54] Among the adhesives and additives frequently employed for wood-fibre insulation are: phenolic resins, polyurethane (PUR), polyurea, paraffin, sodium silicate as binding agents and for hydrophobic treatment; aluminium sulphate as flame retardant; plastic bi-component fibres, *e.g.,* polyethylene (PE) and polypropylene (PP). The use of formaldehyde has been gradually reduced over the last decades (IBU, 2014a; IBU, 2016a).

[55] Polyurethane (PUR) resin, based on methylene diphenyl diisocyanate (MDI) – or polymeric methylene diphenyl diisocyanate (PMDI) – *circa* 3% by weight of the finished product (IBU, 2014d).

[56] Urea formaldehyde (UF) and melamine resin, amounting to *circa* 9% of the finished product's weight (IBU, 2016d).

[57] Adhesives often used for the manufacture of CLT panels (main surfaces, finger joints and lateral edges) are: polyurethane (PUR), melamine urea formaldehyde (MUF) and emulsion polymer isocyanate (EPI) (IBU, 2012a; Wood for Good, 2013b; IBU, 2014f).

[58] The setting of adhesives and additives can cause more than 40% or 50% of the total POCP in the A1-A3 life-cycle phases (IBU, 2014a; IBU, 2016a).

[59] An explanation of the information modules defined by standard EN 15804 has been provided in SECTION 2.6.6.

[60] IBU, 2014a; IBU, 2016a; IBU, 2012a; Wood for Good, 2013b; IBU, 2014f.

the energy mix used to operate the factory (module A3), which includes a high percentage of energy generated in nuclear-power plants (IBU, 2014a; IBU, 2016a). Therefore, it is fair to say that such radioactive-waste production is not intrinsic to the manufacturing method of this insulation product *per se*; rather, it depends on upstream processes and the type of energy that is consumed. In addition, the energy mix (especially its nuclear portion) can vary widely from country to country within Europe.

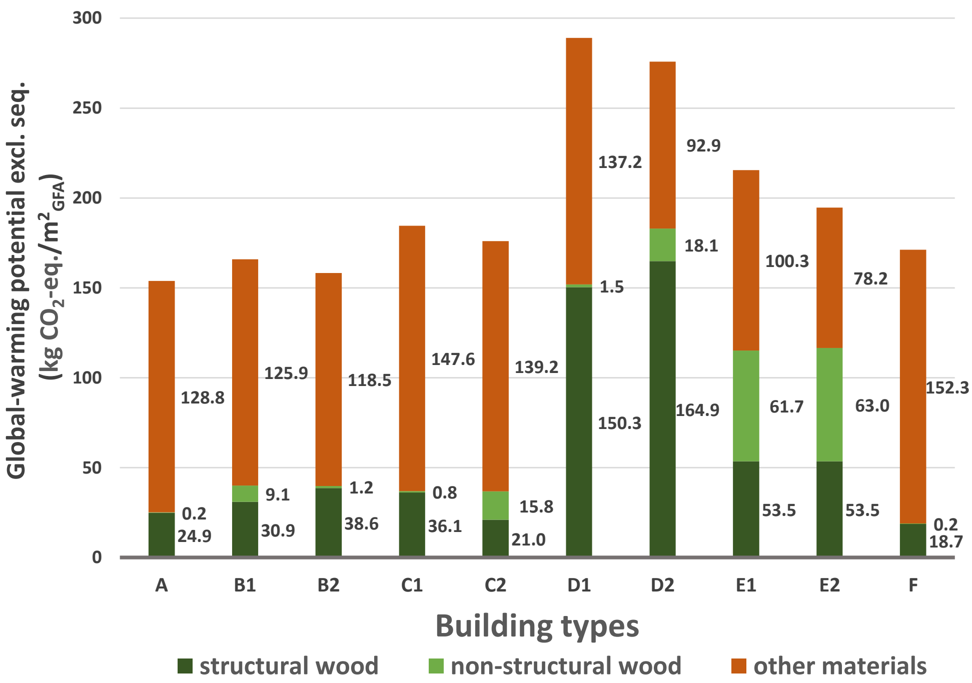

FIGURE 5.23 Global-warming potential (excluding sequestration) of all buildings. Contribution analysis focussing on structural and non-structural wood-based components.

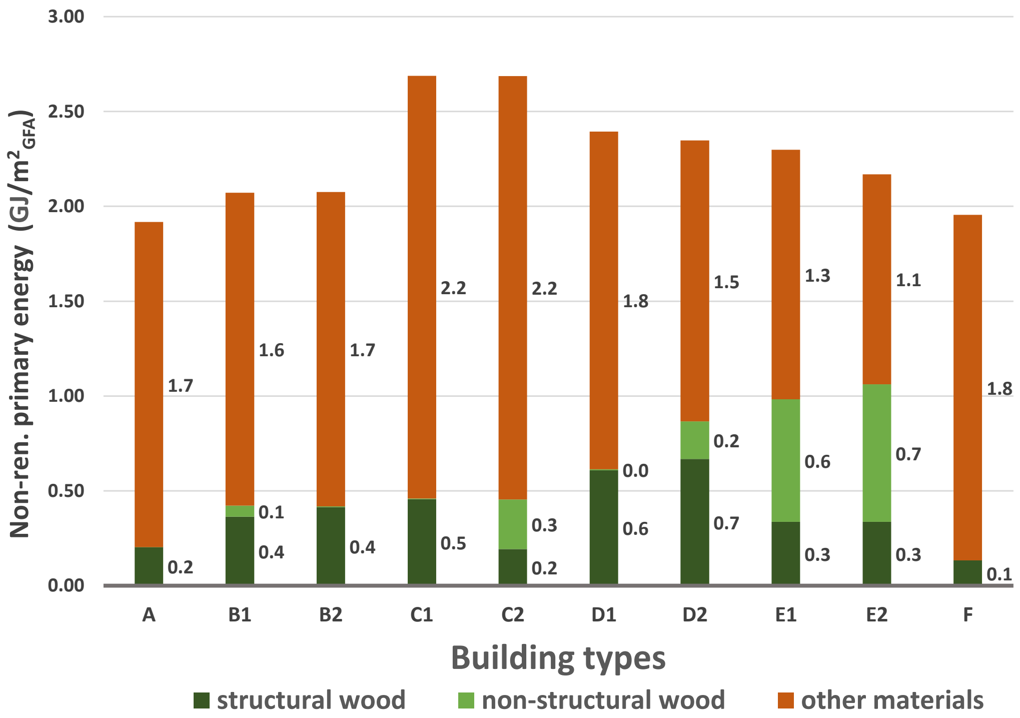

FIGURE 5.24 Consumption of non-renewable primary energy for all buildings. Contribution analysis focussing on structural and non-structural wood-based components.

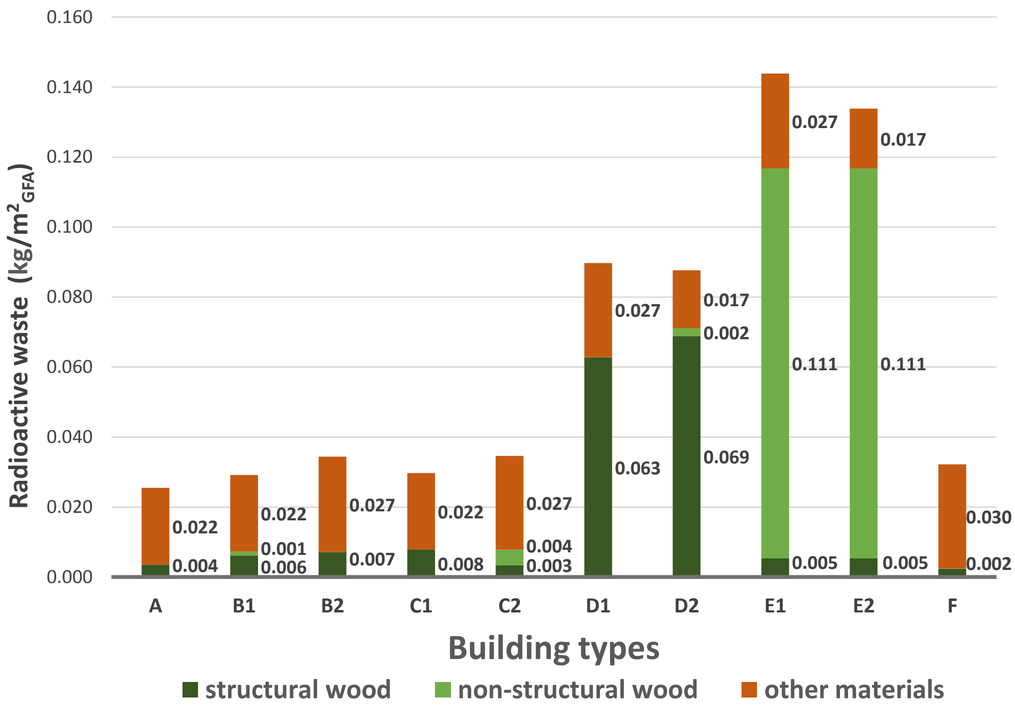

FIGURE 5.25 Production of radioactive waste for all buildings. Contribution analysis focussing on structural and non-structural wood-based components.

The results for the two CLT buildings (discussed in SECTIONS 5.6.1 and 5.6.2) have shown that they are responsible for elevated environmental costs and are outperformed by the masonry dwelling in all impact categories, except for $GWP_{incl.seq.}$.

Houses **D1** and **D2** also tend to compare unfavourably with most of the other timber buildings under a large number of impacts. This is particularly true for global warming (excluding sequestration) and non-hazardous waste, where **D1** and **D2** show the highest impacts among the nine timber dwellings.

In **D1** and **D2**, CLT panels constitute the vast majority not only of structural timber, but also of all wood-based products together: the amount of non-structural timber is indeed minimal. Thus, the proportion of impacts due to "structural wood" in FIGURES 5.23 to 5.25 is attributable to the production of CLT panels. Non-renewable primary energy is consumed especially to harvest and dry wood and to produce adhesives (IBU, 2012a; Wood for Good, 2013b; IBU, 2014f). Many polluting emissions, including those causing global warming, derive from combustion of wood and diesel.

5.6.4 Impacts of insulating components

This section revolves around the impacts of the thermal-insulation materials adopted in the notional buildings and provides information on the manufacturing processes that are accountable for the largest shares of such impacts.

Since, across all countries within the European Union, thermal standards set by building regulations have become much more stringent in the last two decades, understanding the cradle-to-gate impacts of thermal insulation has become gradually more important.

An increase in insulant quantity will necessarily cause an increase in its associated impacts, unless improvements in the manufacturing processes come into play and counteract this trend.

Since wood-fibre boards have a much higher thermal conductivity than the insulants used in the other notional buildings (namely, mineral wool and polyurethane), a noticeable amount of this particular insulant is needed to reach a U-value compliant with building regulations.

FIGURE 5.26 shows the carbon emissions and energy consumption associated with the amount of insulant needed to provide a surface of 1 m^2 with the same level of thermal resistance (here set as 1 $m^2 \cdot K/W$). This graph includes the three types of insulants used in the notional buildings: mineral wool, polyurethane and wood fibre. Wood fibre proves very impactful in terms of global warming (excluding sequestration) and, though to a lesser extent, non-renewable primary energy. In both these impact categories, mineral wool appears to be the best-performing material, followed by polyurethane.

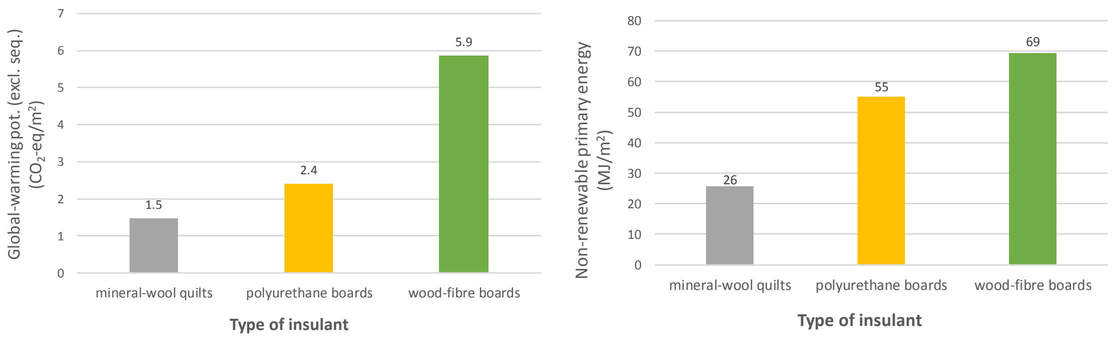

FIGURE 5.26 Global-warming potential excluding sequestration (left) and non-renewable primary energy (right) associated with the amount of insulant needed to provide a 1-m² surface with a thermal resistance of 1 m²·K/W. Comparison between the three types of insulating products used in the notional buildings.

When the insulating materials are no longer considered in isolation, but in the context of all ten notional buildings, comparison becomes more complex. The reason for this is twofold: firstly, these materials are sometimes used in combination within the same dwelling; secondly, the amount of insulants needed to reach the desired U-value will depend not only on their intrinsic thermal properties, but also on the properties of all the other materials included in the constructions (which vary widely from dwelling to dwelling).

Thermally speaking, the massive-timber techniques (**D1** to **E2**) benefit from the large quantities of timber inside their build-ups and from their moderate insulating properties. The remaining notional buildings, instead, rely more heavily on the thermal contributions of their insulating components, because all the other materials are very dense and only marginally contribute to overall thermal resistance.

Since, in an LCA perspective, the main purpose of thermal insulation is that of reducing the amount of fuel burnt for space heating or cooling, and its associated calorific value (*i.e.,* primary energy) and carbon emissions, it becomes particularly meaningful to check these two environmental aspects.[61]

[61] If, in future, a thermal study were to be conducted on the notional buildings to assess the operational energy and carbon needed to provide thermal comfort throughout a year, the present cradle-to-gate assessment would constitute a basis for comparison between embodied and operational costs.

Across the ten notional buildings, the $GWP_{excl.seq.}$ of the insulants incorporated in the envelope ranges between 16 and 47 kg CO_2-eq/m^2_{GFA}, for buildings **B1** and **E1**/**E2**, respectively (see FIGURE 5.27). In relative terms, the impacts of the insulants alone range between 6% (**D1** and **D2**) and 24% (**E2**) of the total $GWP_{excl.seq.}$ of their respective buildings (FIGURE 5.28). This is a wide variation and shows that the insulants are major contributors only in buildings **E1** and **E2** and, though to a lesser extent, **C1** and **C2**.

The above-mentioned advantage of massive-timber techniques (in reaching an adequate U-value) remains therefore evident only for buildings **D1** and **D2**, and much less obvious in **E1** and **E2**, whose wood-based insulation layer causes very high carbon emissions (despite the moderate contributions of massive panels to the U-values of the building envelope). Conversely, in the buildings where insulation is predominantly achieved with polyurethane (**C1** to **D2**, and **F**) or mineral wool (**A** to **B2**), the insulants emit much less carbon than in **E1** and **E2** (see FIGURE 5.27).

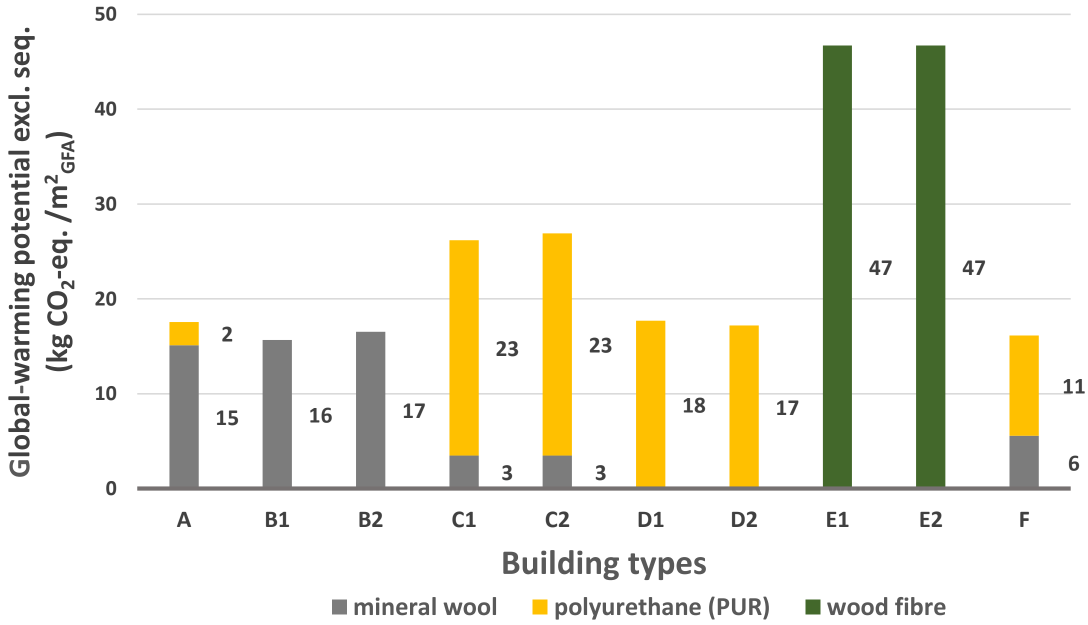

FIGURE 5.27 Global-warming potential (excluding sequestration) arising from the thermal insulants incorporated in the building envelopes of the ten notional houses. Results normalised per unit floor area.

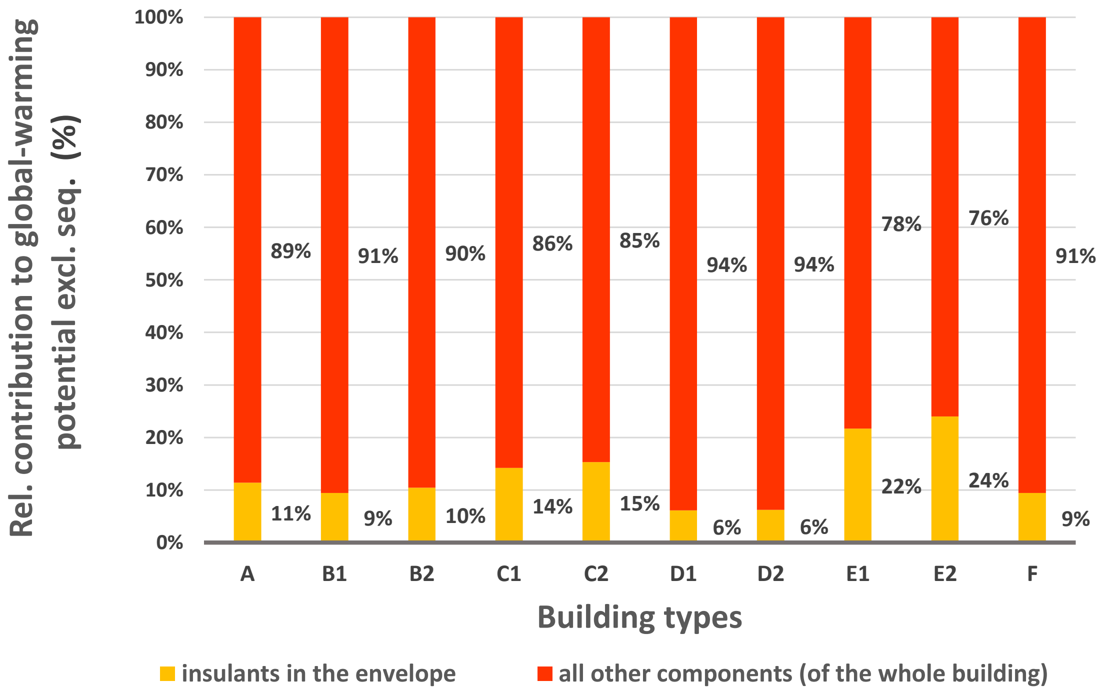

FIGURE 5.28 Global-warming potential (excluding sequestration). For each dwelling, the graph shows the percentage shares of the thermal insulants incorporated in its envelope and of all the other components (of the whole building).

In terms of non-renewable energy consumed for thermal insulation, analysis shows that this varies between 273 and 598 MJ/m^2_{GFA}, for dwellings **B1** and **C2**, respectively. Thus, energy results follow a slightly-different pattern from that previously discussed for carbon, with the insulating layers of the SIP buildings (**C1** and **C2**) proving the most energy-intensive and immediately followed by those of the NLT dwellings (**E1** and **E2**).

It is noteworthy that the energy requirements for the insulation of the SIP buildings are so high as to cause them to have the largest energy consumption amongst the notional buildings studied here.

In conclusion, the choice of specifying insulants made from a natural and renewable material such as timber, which can also include proportions of recycled resource and by-products of the wider timber industry, can entail unanticipated disadvantages in terms of global warming and primary energy. It was seen that the problem lies in the fabrication process of such products and in their *ancillary* constituents (as opposed to their *base* constituents). Furthermore, the impacts of individual wood products can be so high that they propagate to the building-level LCA impacts, as revealed by the contribution analysis illustrated in SECTION 5.6.3. These unexpectedly-high burdens invalidate the assumption – rather widespread in the construction industry, among designers, developers and their clients – that timber-based products should necessarily be preferred to their mainstream counterparts based on minerals (*e.g.,* glass or stone fibre) or plastics (*e.g.,* polyurethane, expanded or extruded polystyrene).

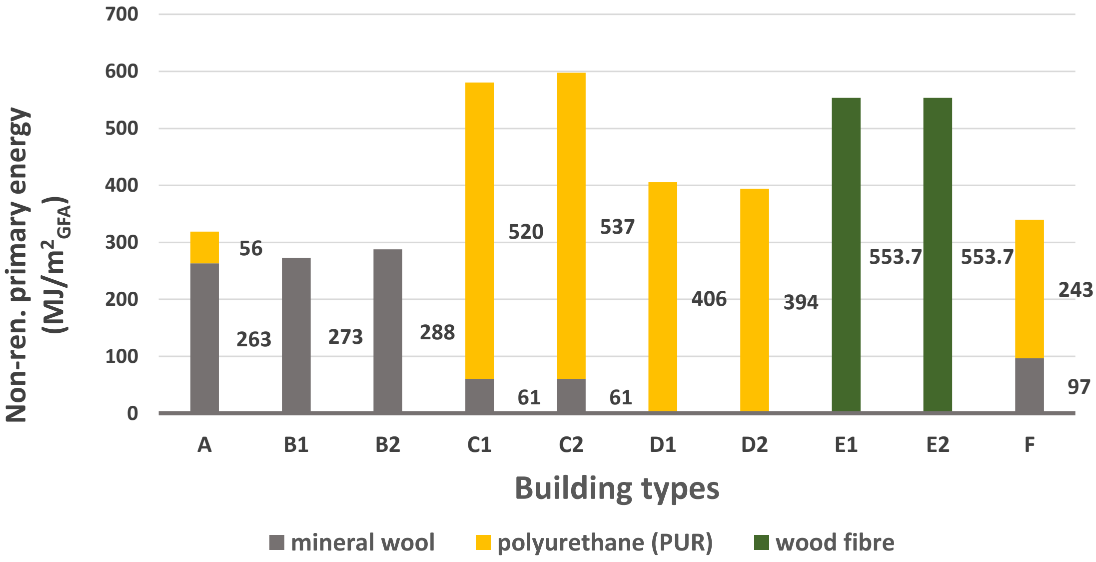

FIGURE 5.29 Non-renewable primary energy consumed for the insulants incorporated in the building envelopes of the ten notional houses. Results normalised per unit floor area.

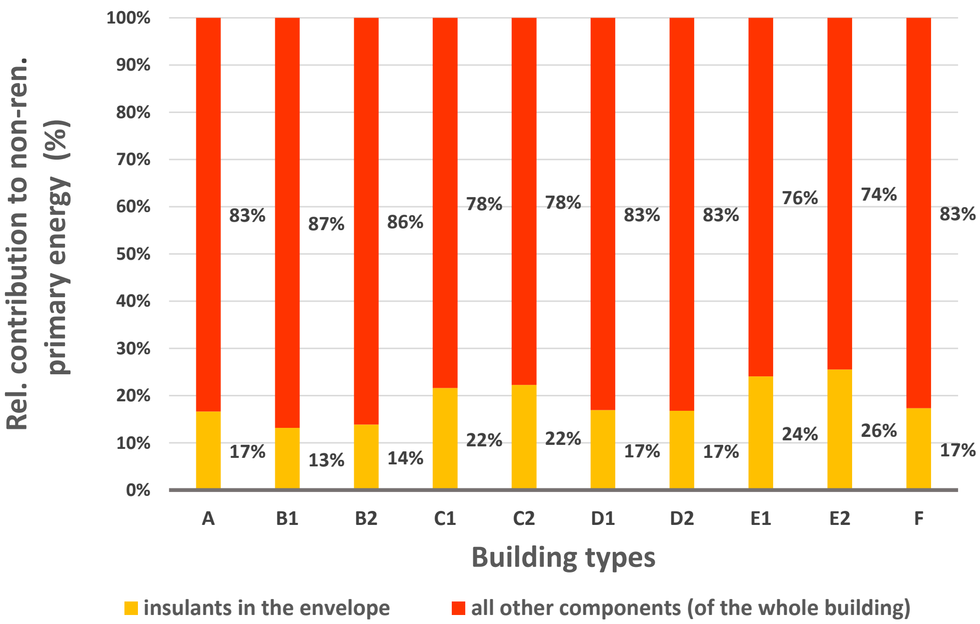

FIGURE 5.30 Non-renewable primary energy. For each dwelling, the graph shows the percentage shares of the thermal insulants incorporated in its envelope and of all the other components (of the whole building).

5.6.5 Results of uncertainty analysis

5.6.5.1 Results of absolute-uncertainty analysis

As explained in SECTION 5.4.3, the squared geometric standard deviation (GSD^2) of the output uncertainty can be used as a measure of reliability for the impact values obtained through the LCA. Since the input parameters (*i.e.,* the impact coefficients) used to determine the environmental loads of the notional buildings come, on average, from sources that have low uncertainties, the uncertainty of the outputs is very low, too.

The bar charts in FIGURES 5.31 and 5.32 refer to buildings **A** and **B1**, respectively, and show the GSD^2-values of the uncertainty for all impact categories (the equivalent graphs for the other buildings can be found in APPENDIX O). In most buildings, the GSD^2 assumes extremely-low values, which range between 1.0 (the lowest achievable value, signifying zero uncertainty) and 1.2.

It is worthwhile noticing that the GSD^2 relating to the output uncertainty of the $GWP_{excl.seq.}$ tends to be among the lowest ones, despite the fact that, for this impact, the coefficients used have been obtained from the sources with the highest uncertainty embraced in this LCA.[62]

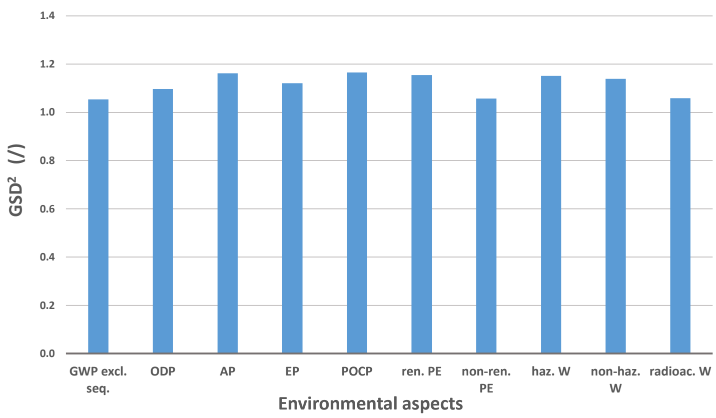

FIGURE 5.31 Estimated absolute uncertainties relating to the impact results of building A, expressed in terms of squared geometric standard deviations, GSD^2 (i.e., variance).

[62] This is because timber products alone, in comparison with all the other incorporated materials together, are generally responsible for little percentage contributions to the total $GWP_{excl.seq.}$ (exceptions to this trend have been discussed in SECTION 5.6.3). This demonstrates that the intrinsic, high uncertainty of an input (in this case, an impact coefficient for a timber product) only marginally propagates to the uncertainty of the output if the former is employed in the LCA calculations for small relative contributions to the total impact under consideration.

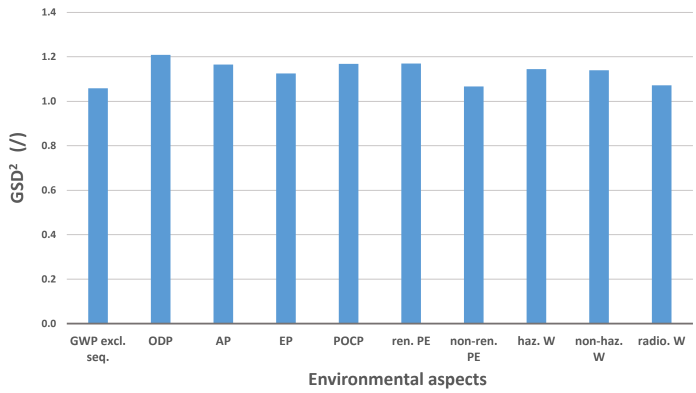

FIGURE 5.32 Estimated absolute uncertainties relating to the impact results of building B1, expressed in terms of squared geometric standard deviations, GSD² (i.e., variance).

5.6.5.2 Results of comparative-uncertainty analysis

An *ad-hoc* uncertainty analysis has been carried out to evaluate the level of confidence with which the impact of any timber building can be said to be greater or less than that of the masonry reference (**F**). The outcomes of this analysis thus accompany the comparative impact results already presented (SECTION 5.6.2), by adding a reflection on their reliability.

The results of this uncertainty assessment have shown that it is almost always possible to state with a high degree of certainty whether the timber buildings perform better or worse than the masonry one. While APPENDIX O contains all the charts that visually illustrate these results, the present section only contains the ones illustrating the highest, yet generally very low, uncertainties identified.

Global-warming potential excluding sequestration

The comparisons between most of the timber buildings and the reference building (**F**) in terms of global-warming potential excluding sequestration, lead to very reliable results.

Only two exceptions can be singled out: there is a little margin of uncertainty regarding the comparison between **B1** and **F** and, above all, between **C2** and **F** (*i.e.,* there is 16% probability that **C2** emits less carbon than **F** see FIGURES 5.33 and 5.33b). The uncertainty associated with the assessment of **C2** *versus* **F** derives mostly from input-uncertainty on minerals (leading to 53% of the total output uncertainty), wooden-based materials (29%) and plastic (18%), as can be seen in the graph on the right-hand side of FIGURE 5.33.

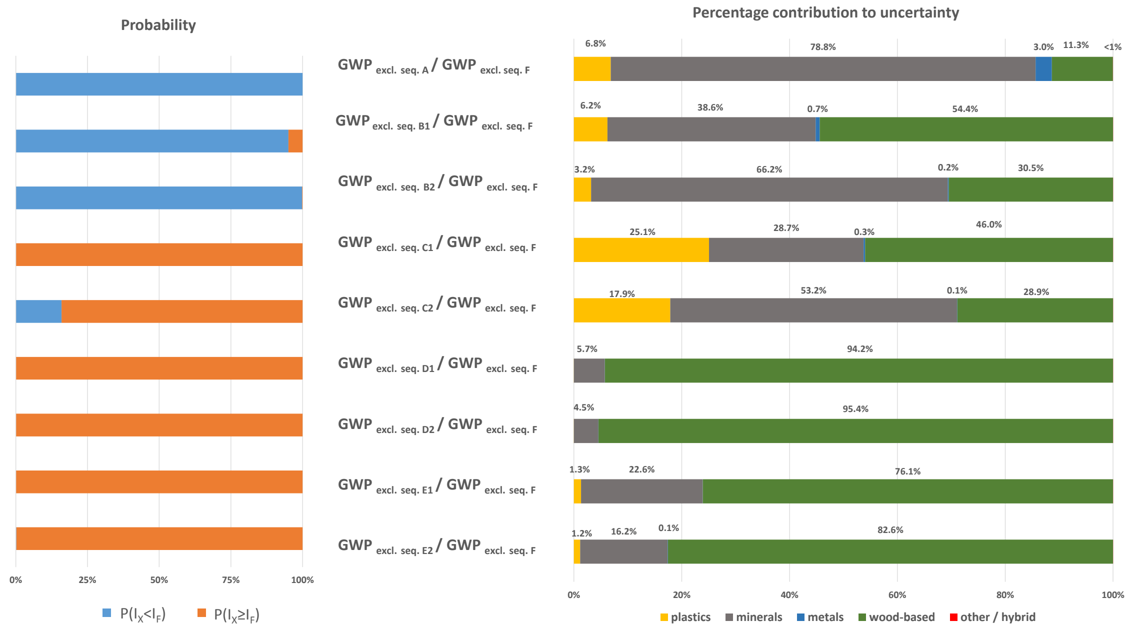

FIGURE 5.33 Estimated uncertainties associated with the comparisons of timber buildings with reference building F, for GWP (excluding sequestration). Indication of probability (left) and relative contribution to uncertainty (right). See also FIGURE 5.33b.

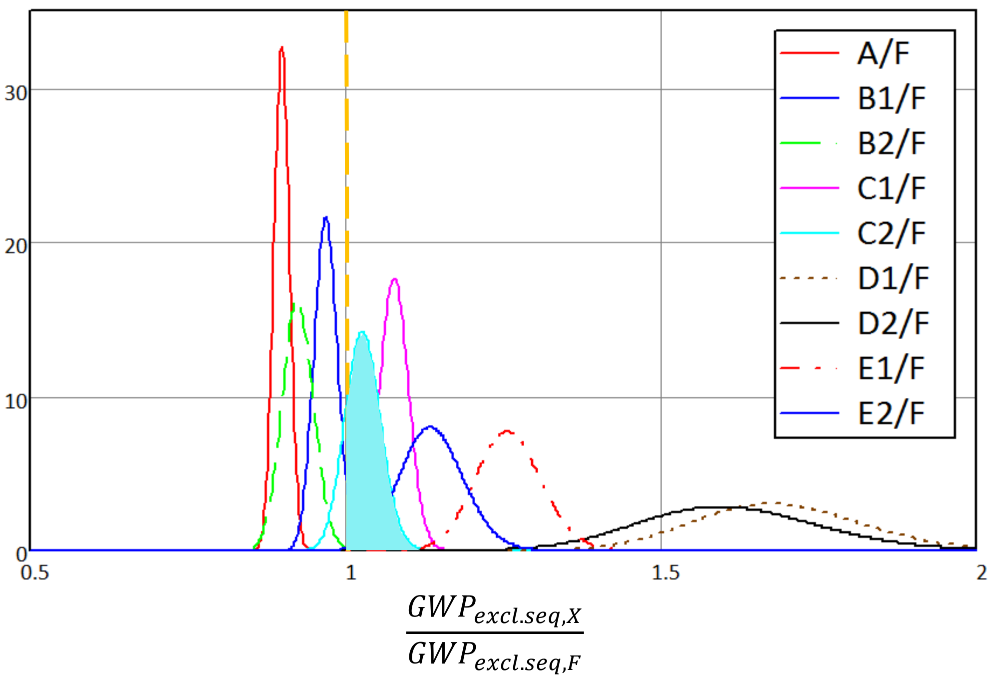

FIGURE 5.33b Comparative uncertainty with regard to GWP excluding sequestration. Probability-density functions representing the ratio between the $GWP_{excl.seq.}$ of each timber building (X) and that of the masonry building (F). It can be noted that the curve for C2 is the one that straddles vertical line x=1 the most evidently. The comparison between C2 and F is indeed the one with the lowest certainty: there is 84% probability that C2's $GWP_{excl.seq.}$ is greater than F's (such probability is geometrically represented by the area of the shaded region, bounded by the curve for C2 and line x=1). See methodological discussion on uncertainty estimation in SECTION 5.4.3.

Hazardous waste

The estimation of the uncertainty relating to hazardous waste (FIGURE 5.34) has revealed that:

- it is extremely likely that dwellings **A** to **D2** produce more hazardous waste than **F**;
- it is extremely likely that dwelling **E1** produces less hazardous waste than **F**;
- high uncertainty is associated with the comparison between **E2** and **F**: there is almost equal probability (≈50%) that **E2** produces more hazardous waste than **F** or that the opposite is true. The greatest contributions to this uncertainty stem in equal measure from wood-based materials and minerals. In order to better understand this uncertainty, it is useful to recall that the hazardous waste of buildings **E2** and **F** were both estimated at 0.24 kg/m^2_{GFA}; thus, any level of uncertainty (or numerical variation) around this result would lead one building to be either better or worse than the other in this impact category.

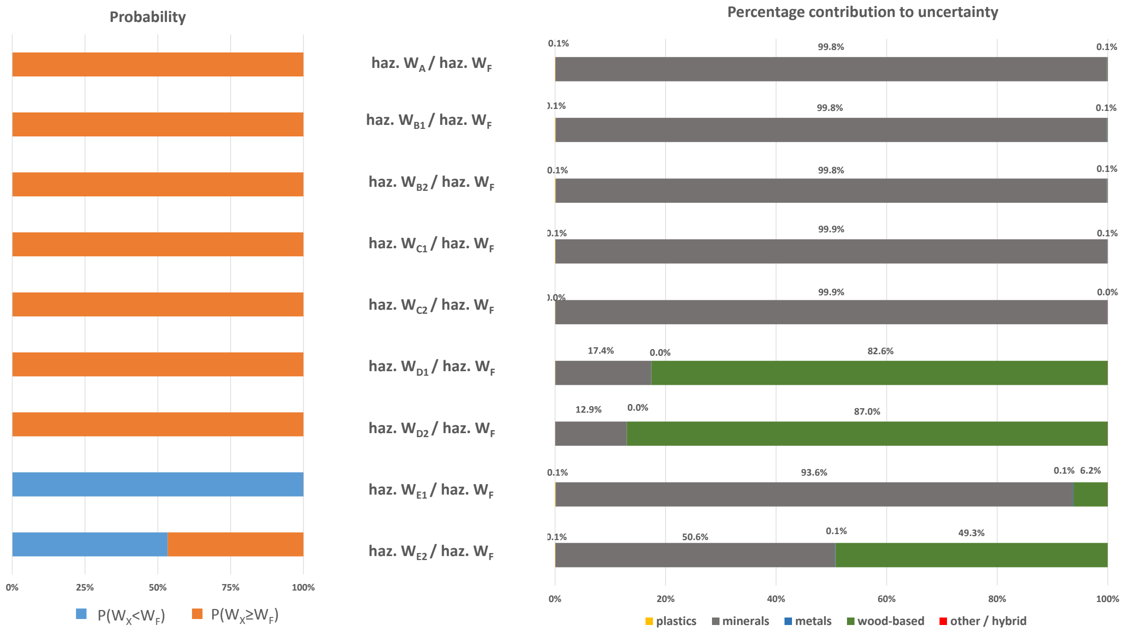

FIGURE 5.34 Estimated uncertainties associated with the comparisons of timber buildings with reference building F, for hazardous waste. Indication of probability (left) and relative contribution to uncertainty (right).

Radioactive waste

While a comparative statement regarding radioactive waste (FIGURE 5.35) can be made with a high degree of confidence for most buildings, there is a (small) margin of uncertainty regarding:

- the comparison between **B2** and **F**;
- the comparison between **C2** and **F**.

In both the above cases, it is, however, more probable that the reference building produces less radioactive waste than the two timber houses.

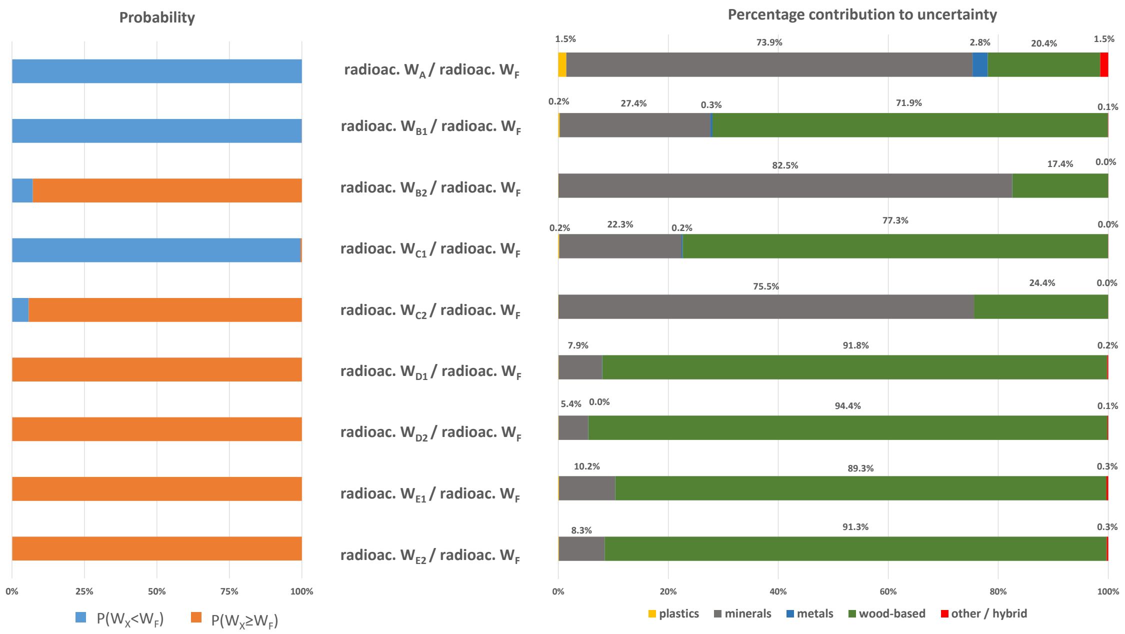

FIGURE 5.35 Estimated uncertainties associated with the comparisons of timber buildings with reference building F, for radioactive waste. Indication of probability (left) and relative contribution to uncertainty (right).

5.7 Results: sensitivity analysis for wastage scenarios 2 and 3

The present section discusses the findings obtained through the sensitivity analysis based on the wastage scenarios defined in SECTION 4.5. By illustrating the environmental repercussions of the construction processes that are implemented, this section formulates an answer to **research question ③**.

5.7.1 Global warming

5.7.1.1 Global-warming potential excluding sequestration

When the global-warming potential excluding carbon sequestration is analysed, it becomes apparent that the shift from scenario 1 (zero wastage) to scenario 2 (low wastage) entails a relative increase of about 5% for the timber-frame buildings (**A**, **B1** and **B2**) and for the nail-laminated buildings (**E1** and **E2**) – see FIGURE 5.36. This is due especially to the wastage of softwood and thermal-insulation materials, which, for scenario 2, is associated with offsite operations.

The increases in $GWP_{excl.seq.}$ for the CLT buildings (**D1** and **D2**) in scenario 2 are the lowest ones. This is due to the modelling assumption that, in scenario 2, the openings in the CLT panels are pre-formed and many operations are conducted off-site, which results in relatively-minor process differences between scenarios 1 and 2.

The two SIP buildings, **C1** and **C2**, are associated with the highest percentage increase in scenario 2: this is because of the wastage arising from the creation of window/door openings in wall and roof panels. Since such apertures are assumed to be cut away from their SIP panel after this has been formed, a larger amount of OSB and PUR foam is required. This results in both **C1** and **C2** showing an increase in carbon emissions of about 8%.

The increase in $GWP_{excl.seq.}$ from scenario 1 to scenario 2 is estimated at 7% for the masonry building (**F**): this change is determined by the on-site wastage of concrete blocks, mortar for rendering and block-laying, and polyurethane foam.

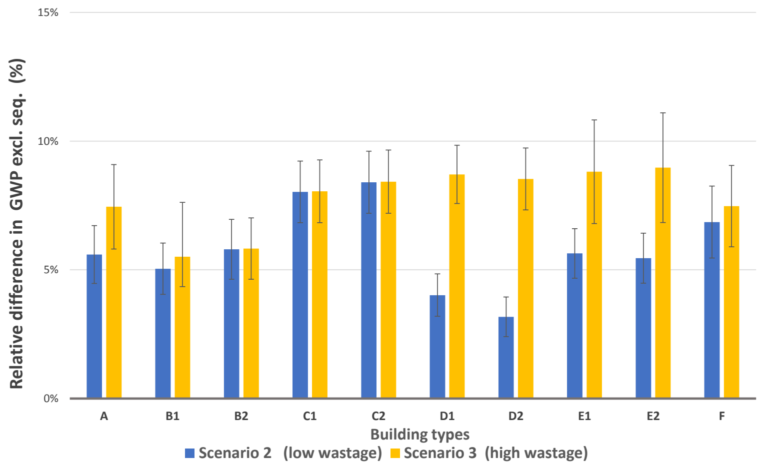

FIGURE 5.36 Comparison of scenarios 2 and 3 with the baseline (scenario 1): global-warming potential excluding sequestration (relative differences).

When scenario 3 is compared with scenario 1, most buildings show similar results to those discussed above (between scenarios 2 and 1), with the exception of the two CLT-based dwellings, which exhibit a much higher increase. The $GWP_{excl.seq.}$ in scenario 3 rises by 9% in both **D1** and **D2**: this is due to the scenario-3 assumption that openings are removed from a CLT panel only after it has been formed in the press, with a consequent high wastage of CLT offcuts.

Buildings **E1** and **E2** follow a similar pattern to that just described for **D1** and **D2**. This, however, is not related to the openings, but to the high amount of wastage of wood-fibre insulation that occurs in scenario 3, where this insulant is assumed to be installed on-site. More precisely, there is a 20% increase in consumption of wood-fibre insulant (by mass) from scenario 1 to scenario 3, due to on-site wastage, for both **E1** and **E2**.

5.7.1.2 Global-warming potential including sequestration

The $GWP_{incl.seq.}$ rises significantly from scenario 1 to both scenarios 2 and 3 in the buildings with heavy-weight cladding (**A**, **B1** and **F**). This is due to the increase of onsite wastage of the materials needed to erect the outer masonry skins of the perimeter walls.

It might seem surprising at first sight that, in all three of these buildings (**A**, **B1** and **F**) scenario 3 (high wastage) shows a more modest increase in carbon emissions than scenario 2 (low-wastage). This is the consequence of the higher amount of timber used in scenario 3 (than in scenario 2), which entails more substantial negative emissions corresponding to the larger volume of carbon sequestered from the atmosphere.

The high wastage rates of scenario 3 in comparison with the baseline lead to an overall better result for the timber-intensive dwellings (**D1**, **D2**, **E1** and **E2**). In **D1** and **D2**, the percentage change from the baseline to scenario 3 is estimated at -8% in $GWP_{incl.seq.}$, thanks to the augmented carbon sequestration outweighing the positive emissions that arise from the increased quantities of other materials, such as insulants.

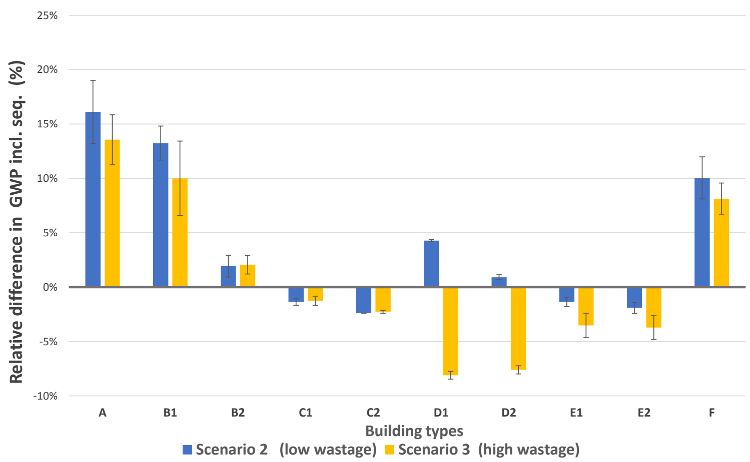

FIGURE 5.37 Comparison of scenarios 2 and 3 with the baseline (scenario 1): global-warming potential including sequestration (relative differences).

5.7.2 Acidification, eutrophication and photochemical ozone creation

In SECTION 5.6.2, it was seen that the acidification, eutrophication and ozone creation potentials in scenario 1 are all dominated by one type of plastic (polyethylene). Thus, the relative increases from scenario 1 to both scenarios 2 and 3 are strongly affected by wastage of this material.

As regards acidification, the scenario comparison yields rather homogeneous results across buildings, and for both scenarios 2 and 3 (see FIGURE 5.38). Accounting for material wastage in the LCA model shows an average increase of *circa* 8% with respect to the baseline. This reflects the increases of low-density polyethylene in scenarios 2 and 3 (relative to scenario 1) being very similar.

However, it has to be kept in mind that these are relative results and describe the increase in AP for each building considered in isolation, and that the absolute impacts (in terms of acidifying emissions) corresponding to these relative changes vary from building to building, as discussed in SECTION 5.6.2. The scenario-related changes in emissions, expressed in terms of kg SO_2-eq/m^2_{GFA}, can be found in APPENDIX P.

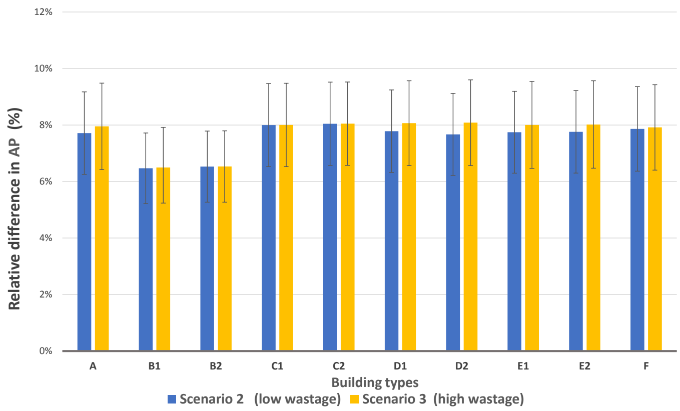

FIGURE 5.38 Comparison of scenarios 2 and 3 with the baseline (scenario 1): acidification potential (relative differences).

Analysis of the eutrophication results obtained for scenarios 2 and 3 reveals percentage changes between 6% and 8% from the baseline, for all buildings (see FIGURE 5.39).

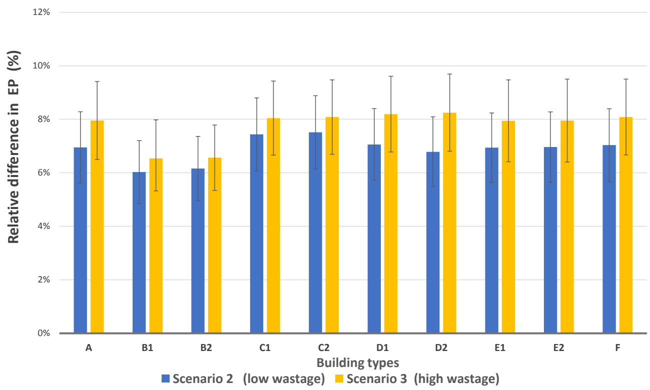

FIGURE 5.39 Comparison of scenarios 2 and 3 with the baseline (scenario 1): eutrophication potential (relative differences).

As concerns photochemical ozone creation, the wastage of polyethylene yields an average rise of approx. 7% and 8% for scenario 2 and scenario 3, respectively (see FIGURE 5.40).

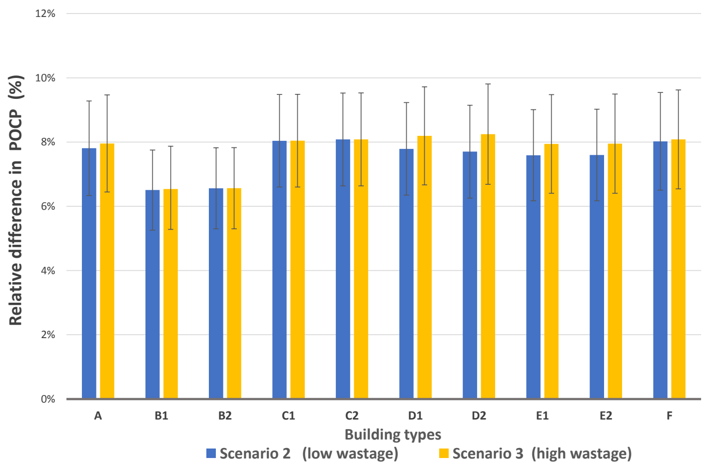

FIGURE 5.40 Comparison of scenarios 2 and 3 with the baseline (scenario 1): photochemical-ozone-creation potential (relative differences).

5.7.3 Ozone depletion

As previously noted (SECTION 5.6.2.3), all the buildings included in the study cause marginal emissions responsible for ozone depletion.

However, the sensitivity analysis shows that there is a sizeable percentage increase (around 16-18%) in scenario 2 and scenario 3 (with respect to the baseline) for the buildings that incorporate large amounts of polyurethane insulation boards: **D1**, **D2** and **F** (see FIGURE 5.41).

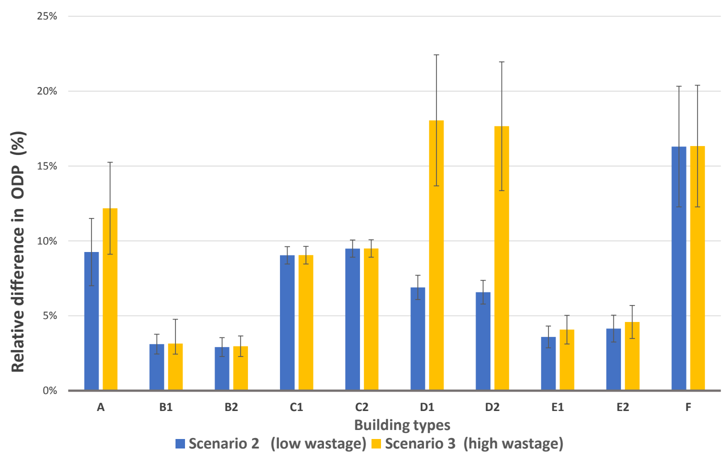

FIGURE 5.41 Comparison of scenarios 2 and 3 with the baseline (scenario 1): ozone-depletion potential (relative differences).

5.7.4 Energy consumption

5.7.4.1 Renewable primary energy

The increase of renewable primary energy observed when comparing scenarios 2 and 3 with scenario 1 is strongly affected by the portion of primary energy as raw materials (as opposed to energy carriers). Therefore, the amount of timber characterising each scenario plays an important role for this environmental aspect.

Scenario 3 is characterised by a significant rise in renewable PE from the baseline in the following buildings (see FIGURE 5.42):

- buildings **C1** and **C2**, with a 10% increase from scenario 1, due to the portions of panels removed for doors and windows (overproduction of OSB skins for these offcuts);
- buildings **D1** and **D2** (as a consequence of the extra CLT produced, and then wasted, for the window and door openings in the wall panels);
- buildings **E1** and **E2** (NLT systems), with a 6% rise, which reflects the increase in wood for the structural panels and for wood-fibre insulation.

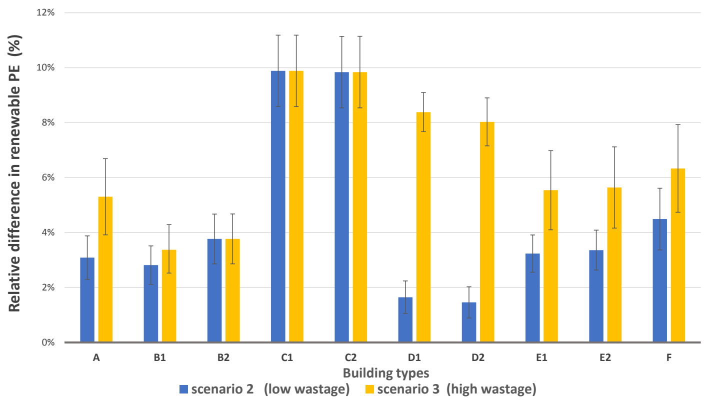

FIGURE 5.42 Comparison of scenarios 2 and 3 with the baseline (scenario 1): renewable primary energy (relative differences).

5.7.4.2 Non-renewable primary energy

Within the least-favourable scenario (*i.e.,* scenario 3), non-renewable primary energy is estimated to grow by 8-10% for most buildings (**A**, **C1**, **C2**, **D1**, **D2**, **E1**, **E2** and **F**). The common denominator behind these results is the energy consumed to produce the wasted portion of thermal insulation, which is not contemplated in scenario 1.

Another important factor for increased energy use lies in the extra quantity of structural materials such as OSB (especially for dwellings **C1** and **C2**) and CLT (for dwellings **D1** and **D2**).

Finally, it is worth noticing that these results are also affected by a building component that is present in all the buildings studied: ceramic tiles. These are subjected to high wastage rates because they are installed *onsite*, rather than *offsite*, and their manufacture is energy-intensive.

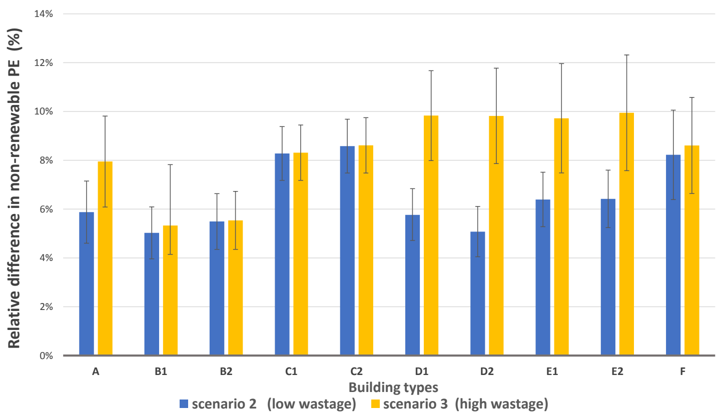

FIGURE 5.43 Comparison of scenarios 2 and 3 with the baseline (scenario 1): non-renewable primary energy (relative differences).

5.7.5 Waste production

5.7.5.1 Hazardous waste

The analysis of hazardous waste shows homogeneous results across the notional buildings, since the increase relative to the baseline is mostly due to materials that are common to all houses and are subjected to the wastage ratios of onsite operations: concrete roof tiles and gypsum plasterboard. Accounting for material-wastage thus leads to an average change of around 5% for scenario 2 and 6% for scenario 3 (see FIGURE 5.44).

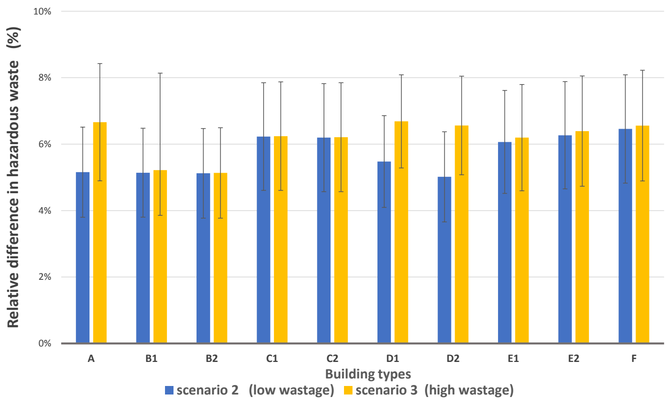

FIGURE 5.44 Comparison of scenarios 2 and 3 with the baseline (scenario 1): hazardous waste (relative differences).

5.7.5.2 Non-hazardous waste

The extra production of non-hazardous waste associated with the assumptions of scenarios 2 and 3 shows a great differentiation across the ten buildings and between the two scenarios (see FIGURE 5.45).

The most evident increase of this type of burden is that of scenario 3, with many buildings reaching a relative change of about +8% (**A**, **C1**, **C2**, **D1**, **D2** and **F**).

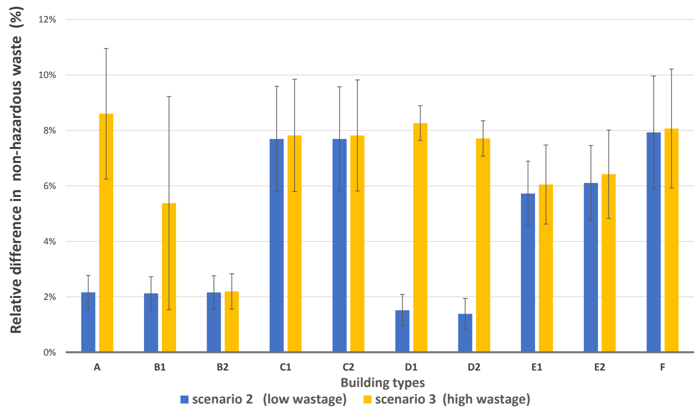

FIGURE 5.45 Comparison of scenarios 2 and 3 with the baseline (scenario 1): non-hazardous waste (relative differences).

5.7.5.3 Radioactive waste

As mentioned in the discussion of scenario-1 results, radioactive waste is only produced in little quantities in all buildings.

The sensitivity analysis of scenario 3, however, shows noticeable intensification of radioactive-waste production for buildings **E1** and **E2**, due to the increase in wood-fibre insulation, which is the material accountable for the greatest contribution (above 80% of the total) to this burden (see also SECTION 5.6.4, *Impacts of insulating components*, on this issue).

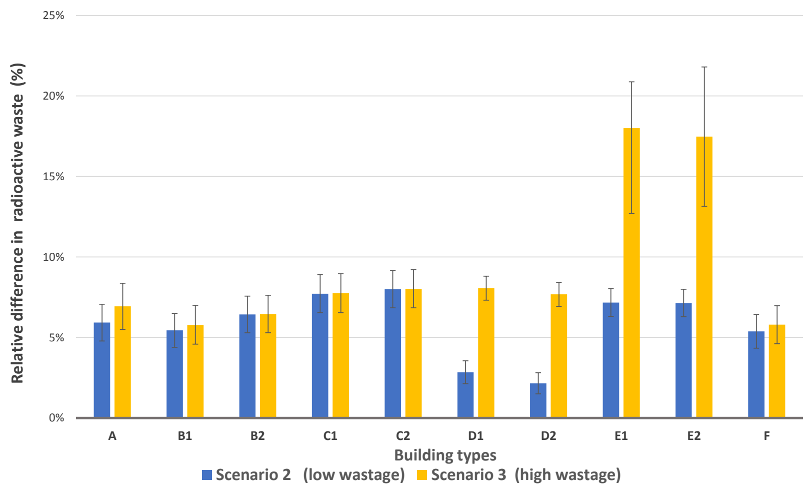

FIGURE 5.46 Comparison of scenarios 2 and 3 with the baseline (scenario 1): radioactive waste (relative differences).

5.8 Summary of findings

The key points from the performed life-cycle assessment can be summarised as follows:

a) when **wood-fibre board** is specified for thermal insulation, a very large amount of this material is needed to obtain a U-value compliant with current building regulations. This might lead to unexpected (*i.e.,* higher-than-envisaged) impact results, especially due to the types of adhesives that are used for the bonding of the fibres;

b) a **light-weight cladding system** does not necessarily offer ample advantages in comparison with heavier systems based on blockwork. More precisely, the materials specified in this study for the light-weight (yet cement-intense) cladding of notional houses **B2** and **C2** do not show any substantial overall improvement on the blockwork alternatives of **B1** and **C1**;

c) thanks to recent advancements in the manufacture of **concrete-based products** (such as blocks), some of these can have environmental loads significantly lower than one might expect; therefore, specification of these components requires great attention, especially when considering alternatives such as timber products or systems;

d) commonly-used internal and external **finishes and coverings** (which are often considered negligible in published LCAs) can give substantial contributions to some impacts; for instance, ceramic wall/floor tiles contribute largely to radioactive waste and non-renewable primary energy, as do concrete roof tiles to hazardous waste;

e) when assessing the impact of timber-constructed buildings (both in absolute and in comparison with non-timber buildings), the **method used to estimate climate change** through global-warming potential is likely to lead to completely-different results depending on weather biogenic carbon sequestration is included in the calculations or not;

f) when **global-warming potential excluding biogenic carbon sequestration** is considered, results suggest that:

- the timber-frame buildings show a better performance than the masonry building; this is particularly true of the open-panel system, which emits about 10% less carbon than the masonry dwelling;
- the massive-timber buildings (and especially those employing CLT panels) compare very unfavourably with the masonry building and might cause around 60-70% more carbon emissions than masonry;

g) when **global-warming potential including carbon sequestration** is considered, this study shows that all timber buildings compare well with the masonry building, with massive-timber systems showing a -600% change in carbon emissions with respect to the masonry house;

h) timber buildings tend to incorporate a greater amount of components (such as vapour barriers) made from low-density polyethylene (LDPE) than masonry buildings: this leads to increased environmental burdens such as acidification, eutrophication and photochemical ozone creation (*i.e.,* tropospheric ozone). This, considered along with the results in point f), leads to the identification of an important **burden trade-off** between timber-frame buildings and masonry buildings: the former cause less carbon emissions (excluding sequestration) than the latter, but more acidifying, eutrophying and ozone-creating emissions.

i) with the sole exception of the open-panel, timber-frame dwelling, all the timber buildings consume more **non-renewable primary energy** than the masonry one. In particular, the SIP houses involve, by far, the highest consumption of energy, with an increase of 37% relative to their masonry counterpart;

j) the propagation of **uncertainty** from input parameters to output results has been estimated through an analytical method. This process has shown that there is, on average, a high level of confidence associated with the results obtained, both in terms of buildings studied in isolation and in comparison. Therefore, for most of the environmental aspects embraced in this LCA, comparative statements involving the timber buildings considered each at a time in comparison with the reference building (**`F`**, masonry) can be made with an elevated degree of confidence and do not require further analysis;

k) the **scenario analysis** has revealed the environmental consequences of material wastage in construction and the benefits associated with deciding to perform certain building operations offsite rather than onsite (since opting for offsite entails lower wastage rates). In particular, the following findings are worth noticing when scenario 2 (low wastage and more prefabrication) and scenario 3 (high wastage and less prefabrication) are compared with the baseline (*i.e.,* scenario 1, zero-wastage):

- global-warming potential (excluding sequestration) rises, on average, by 5% in scenario 2 and 8% in scenario 3;
- global-warming potential (including sequestration) shows an improvement for both the massive-timber systems studied (based on nail-lamination and cross-lamination);
- in both scenarios 2 and 3, there is an increase in the potentials for acidification, eutrophication and photochemical ozone creation of *circa* 6-8% in all buildings;
- non-renewable energy rises in most buildings by 4-7% in scenario 2 and 8-10% in scenario 3.

Points a) - e) above relate to research question ① (as defined in CHAPTER 1), points f) - j) to question ② and point k) to question ③.

Index - chapters 1 to 5

A

B

C

D

E

F

G

H

I

K

L

M

S

T

U

V

W