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Downsizing and the use of timber as embodied carbon reduction strategies for new-build housing: A partial life cycle assessment

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A B S T R A C T

The 2050 decarbonization goals coupled with the growing housing shortage in Europe intensify the pressure on new-build dwellings to enhance their energy performance. Beyond a zero operational energy, the focus has shifted towards reducing embodied carbon (EC). Against this backdrop, this study investigates the simultaneous impact of downsizing and the use of timber in new-build dwellings, EC reduction strategies seldom explored concurrently. Through partial life cycle assessments, three scenarios are modelled: the Small, Medium, and Large House, with two construction variations for each, comparing a modular timber design to a conventional concrete alternative. Designs are based on dwellings built in Almere, the Netherlands. Data is extracted from the Swiss Ecoinvent database using the TOTEM tool and the static −1/+1 approach for biogenic carbon accounting is adopted. Results show a total EC ranging from 42,608 to 70,384 kgCO_2eq for the timber designs versus 54,681 to 91,270 kgCO_2eq for their concrete counterparts. Findings suggest that the relationship between house size and EC is sublinear whereby a house twice the size entails less than twice the EC emissions. Only the simultaneous implementation of downsizing and the use of timber achieved 53% carbon savings. The discussion explores implications of outcomes across academic, industry and policy perspectives, challenges in implementing smaller timber dwellings, and study limitations and future research. Beyond its empirical contribution, this paper offers a practical contribution with its hierarchical data analysis approach covering building, element and component. This approach can be implemented by researchers and practitioners alike to inform their design process.

1. Introduction

In 2022, the global building sector accounted for over 30% of the final energy consumption, making it a significant contributor to climate change [1]. The impact is notably more accentuated in Europe where the building sector represents 40% of the region's energy demand [2]. Being a significant contributor is also an indication of where change is most needed. The Intergovernmental Panel on Climate Change (IPCC) has consistently highlighted, with high confidence, the potential for significant greenhouse gas (GHG) emissions reduction within the built environment to achieve the 2050 decarbonization goals [3]. However, recent reports, such as the Global Status report for buildings and construction by the United Nations Environment Programme (UNEP), reveal a widening gap between the observed performance of the building stock and the desired pathway towards a zero-carbon target in 2050 [4]. This is further corroborated by the International Energy Agency (IEA) in its own report on buildings, which categorizes the current status as 'not on track'. Therefore, given the pressing nature of climate change and the concerning trends emphasized by the UNEP and the IEA, there is an urgent need for more rapid change within the built environment to realign with the 2050 decarbonization goals [1].

Given that the residential sector constitutes 75% of the European building stock and that housing was demonstrated to be responsible for 22% of a European household's carbon footprint [5], it is safe to say that housing is in itself a pivotal contributor to climate change in the European context [6]. Even more so considering that Europe is witnessing an increase in the total number of households, primarily composed of one to two persons, leading to an increase in housing demand [7]. This highlights another growing gap, this time between housing demand and housing supply [8]. Indeed, many European countries are facing a growing housing shortage [9] necessitating the construction of new-build dwellings to address this pressing issue. Thus, the housing sector's dominance in Europe, coupled with a growing housing shortage, presents a dual challenge. On the one hand, there is an urgent need for the built environment to expedite its transition toward a net-zero emissions scenario to combat climate change [1] and, on the other

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hand, future housing needs render the generation of added emissions inevitable. Overall, this amplifies the pressure on new-build dwellings to enhance their energy efficiency performance.

1.1. Research background

When it comes to improving the energy performance of the built environment, the political focus has been on decreasing energy demand throughout a dwelling's operation phase [10]. The European Energy Performance of Buildings Directive (EPBD) was a key catalyst with the launch of NZEB: Nearly Zero-Energy Building, back in 2010 [11]. Conformingly, research has focused on investigating the reduction of a dwelling's operational energy (OE) [12] and a zero OE performance is now enforced by building regulations in several European countries. However, a dwelling's environmental impact is not restricted to its use stage but also includes GHG emissions released from the production, construction, and end-of-life stages, known as embodied energy (EE). As such, characterizing a dwelling as zero-energy based on its OE alone becomes inaccurate from a life cycle perspective. Even more so since it is argued that there is a trade-off between OE and EE [12] and that emissions saved throughout the use stage are partly, if not totally, off-set by emissions released in the initial stages due to the need for extra building materials and technical systems [13]. Indeed, theoretically, with a zero OE performance, EE makes up 100% of a dwelling's carbon footprint [14]. It becomes the sole source of GHG emissions, hence, the most significant and influential one [13]. In practice, this translates into the increase of the share of EE with the decrease of OE [15,16], reaching 90% in extreme cases [13]. This was designated as the 'carbon spike' effect indicating the high carbon investment at the initial stages of a life cycle, a relatively shorter amount of time, risking the dwelling's overall consumption budget [12,17]. This increasing contribution of EE is reinforced further when taking into account the future possibilities of the decarbonization of the energy grids [13,18,19]. Hence, the normalization of a zero OE performance through building regulations significantly increased the relevance of EE [19,20]. This has forced a shift of the political focus. What had been previously under-addressed amongst mitigation strategies has now regained traction. The reduction of EE has reached the top priority level of several international environmental programs [2,4,21] and it is necessary for research to follow suit and focus on investigating strategies to reduce a dwelling's EE.

While research on EE has received less attention than OE, the exploration of embodied carbon (EC) reduction strategies is not new [4,15,22]. Existing studies have predominantly assessed the use of low-carbon materials through life cycle assessments (LCA) [23], with timber being the most frequently studied material choice [12,24–28]. However, the lack of comparability of outcomes was identified as one of the most significant barriers hindering the field's growth [10,19,20,29–31]. For instance, reported carbon reduction outcomes from the use of timber vary from 10% [18], to surpassing 50 % [26,32]. Discrepancies between outcomes are a result of significant variations of study characteristics, scope definitions, LCA databases, the biogenic carbon accounting approach, and the lack of transparency around study assumptions and modelling choices [13,20,33]. Variations in study characteristics include differences in building types, size, geographic locations, structures, construction materials, and building services rendering any attempt at a comparison invalid [13,20,29]. Variations in scope definitions are attributed to the system boundaries leading to the exclusion/inclusion of life cycle stages increasing the complexity of such comparisons [20,34]. Limited system boundaries often lead to truncation errors whereby a dwelling's total EE is underestimated [18]. Additionally, each implementation of LCA entails a level of uncertainty around EC estimations due to various assumptions made. Known examples concern the assumptions made around carbon storage accounting and end-of-life scenarios from the use of timber [19,20]. Lastly, a lack of transparency obstructs the proper understanding of study outcomes and/or their verification and replication [10,20]. Therefore, due to the lack of comparability of existing LCA studies, there is no general consensus on the extent of the effectiveness of EC reduction strategies. Transparency is key and there is a need for clear reporting of the decision making process to better grasp the impact of such decisions on overall results.

In light of the urgency of climate action, it is argued that reducing EE through the use of low-carbon materials alone is insufficient. Unlike OE, embodied emissions in a dwelling cannot be reduced once measures are implemented. Also, the implementation of any further measures automatically causes a further increase in the dwelling's EE regardless of its potential benefits [10]. This aspect of permanence that is peculiar to EE led to the call for the prioritization of the Sufficiency strategy promoting the avoidance of the demand for energy and materials over a building's life cycle [35–37]. Within the housing sector, sufficiency translates into building less by downsizing dwellings [36,38]. Research investigating the impact of downsizing on a dwelling's EC remains limited [39]. Existing studies agree that larger houses tend to have a higher energy consumption including EC [15,40–44], but diverge on the nature of this relationship, the definition of house size, and the reporting of outcomes. Findings concerning the relationship between house size and EC are contradictory and the correlation between them was demonstrated to be either super-linear [42,45], or sublinear [46].[1] House size was either determined based on number of extra rooms in relation to the household size [42] or based on square meter of floor area [16,45,46]. Studies are often geographically located in contexts where the average house size investigated is considerably large reaching up to 328 m^2 in the U.S. and 246 m^2 in Australia [42,45,46]. This leads to outcomes that are not directly relatable to contexts like Europe where the average house size is known to be smaller and concepts such as the 'Tiny House' are being implemented [47]. Lastly, when reporting outcomes, larger dwellings appear to be more energy efficient per square meter and smaller dwellings, with the lowest total emissions, have the highest emissions per square meter [16,46,48]. Therefore, not only is there a need to investigate the impact of house size on EC to promote downsizing, but there is also a need to clarify the nature of this correlation and to bring smaller dwellings into the discussion.

1.2. Research gaps

These disparities in previous studies highlight the need to address several research gaps. First and foremost, while there are studies exploring the use of timber in housing as an EC reduction strategy, and others investigating the material impact of downsizing dwellings, these studies are typically conducted in isolation. Currently, there is a notable absence of research that examines the implementation of both strategies in tandem. Second, the lack of comparability of existing LCA studies investigating the use of timber in housing entails a lack of consensus on the extent of its effectiveness as an EC reduction strategy. This calls for more rigorous practices when implementing LCA methodology and reporting LCA outcomes and an increased transparency throughout for a better interpretation of results. Third, apart from the need to add to the restricted body of knowledge investigating downsizing as an EC reduction strategy, there is a need to address the contradictory findings regarding the nature of the relationship between house size and EC and investigate the impact of downsizing at the lower end of the range to reach outcomes that are more representative of the European context.

[1] A linear correlation entails a 1:1 ratio. A house with double the size entails double the EC. A super-linear correlation exceeds a 1:1 ratio. A size with double the size entails more than double the EC. A sublinear correlation is less than a 1:1 ratio. A house with double the size entails less than double the EC.

1.3. Research questions and objectives

To fill the identified gaps, this study aims to provide a detailed and thorough partial LCA that answers to the following main research question: *What is the impact of downsizing and the use of timber on the embodied carbon of a new-build dwelling?* In addressing this main research question, the following research sub-questions are addressed: (1) To what extent does the use of timber, in comparison to traditional construction materials, contribute to the EC reduction of new-build dwellings? (2) To what extent does downsizing contribute to the EC reduction of new-build dwellings? (3) What is the nature of the relationship between house size and EC? (4) What is the combined impact of downsizing and the use of timber on the EC reduction of new-build dwellings? In answering the research questions, the specific objectives of this research are as follows: (a) to assess the EC of actual houses as case studies to reach outcomes that better reflect the European context and are more relatable to real-life especially when it comes to investigating the correlation between house size and EC, (b) to quantify EC savings from downsizing and the use of timber as individual EC reduction strategies, (c) to demonstrate the benefits of the simultaneous implementation of both strategies by emphasizing the additional savings of implementing them together, and (d) to maximize transparency with a clear documentation of the decision making process underlying study outcomes.

2. Material and methods

2.1. Case study description

In the Netherlands, the average house size is around 106 m^2 [49] and Tiny houses are known to be between 15 and 50 m^2 [47]. Based on this range of dwelling sizes, this paper defines a small house to have a net floor area (NFA) of up to and including 50 m^2. A medium sized house has a NFA between 50 and 100 m^2 exclusively, and a large house has a NFA of 100 m^2 and above. In accordance with this definition of house sizes, this study focuses on three distinct detached dwellings located in Almere, the Netherlands. These houses have respective net floor areas (NFAs) of 45, 76, and 104 square meters, collectively representing the small, medium, and large categories within the spectrum of *smaller* house sizes. As such, every dwelling size is referred to as a scenario: the "Small House" (45 m^2), the "Medium House" (76 m^2), and the "Large House" scenario (104 m^2). Fig. 1 provides a description of each dwelling scenario with a render showing the exterior of the dwelling, a simplified floor plan and a list of the main dwelling characteristics.

The dwellings investigated were built as part of the project entitled Housing 4.0 Energy: Affordable & Sustainable Housing through Digitization (H4.0E) funded by Interreg North-West Europe [50]. Dwellings from the H4.0E project were selected due to their alignment with sustainability principles crucial for achieving the 2050 decarbonization goals, particularly in their use of sustainable building materials. All H4.0E dwellings follow 'Wikihouse', an open access design concept created to encourage self-building by providing digitally produced timber frame kits to be assembled on site [51]. With the exception of the dwellings' foundations, structural building elements such as beams and columns are made by assembling Multiplex wood panels. It is this uniformity in the dwellings' structural design that distinguishes this case study. Since the dwellings only vary in size, hence material quantities, selecting this case study offers a unique opportunity to reach tangible outcomes that are more reflective of the actual impact of downsizing in a real-life setting. This comes in contrast to prior studies that gauge the impact of downsizing through a theoretical multiplication of house size [46]. In this way, examining H4.0E dwellings allows to provide insights that bridge the gap between theoretical models and the practical implementation of downsizing.

2.2. Research process

This study uses the Belgian based Tool to Optimize the Total Environmental Impact of Materials (TOTEM) for the EC analysis[2] [52]. TOTEM was selected for its accessibility as a free online tool, increasing the potential for study replication. It also taps into the Ecoinvent database [53] with a specific focus on the European/Belgian context which aligns well with the Dutch setting. Fig. 2 provides a visual representation of this study's research process according to the following consecutive steps: data collection, data extraction as per the TOTEM taxonomy, data input following the TOTEM library, data output, data processing and visualization, finally leading to the optimized design.[3] Initially, data was collected in the form of bill of quantities, architectural drawings, architectural details and additional information provided by architects and engineers involved in the H4.0E project for the detailed composition of the dwellings. TOTEM adopts a hierarchical structure that divides a building into four levels: building, element, component, and material, referred to as the TOTEM taxonomy. Subsequently, the data extracted from the H4.0E project had to be transformed to match the TOTEM taxonomy to allow data input. The three main functional units for data entry are: square meters (m^2) for plane surfaces (roof, walls, floors, windows), linear meter (m) for structural elements (beams) and individual piece for other elements (doors) [52].

TOTEM also provides access to a library that includes predefined building elements and components. This feature grants users the flexibility to model a dwelling either by utilizing predefined building elements or by creating custom building elements using predefined building components. More importantly, this feature not only reduces the need for assumptions regarding material types and quantities but also becomes a means to verify that no element, component, or material have been overlooked. In this study, following data extraction, data input consisted of composing building elements by finding a match between the details provided by bill of quantities, architectural drawings, and architectural details and the predefined building components and materials provided by the TOTEM library. In that way, the TOTEM library enhances the precision and reliability of the data input as it serves as a cross-reference and validation of dwelling designs in addition to an initial confirmation by project architects and engineers. Fig. 3 presents the data that was inputted into TOTEM through section drawings showing the detailed composition of the timber dwellings' main building elements.

Next, in terms of data output, TOTEM provides results at the building, the building element and the building component levels, thus allowing the analysis to go across different levels of detail, from the aggregated to the specific. Then, in terms of data processing and visualization, on an aggregated level results pertaining to the building allowed situating the study outcomes in existing literature. On a more specific level, results pertaining to the building elements guided primary design choices related to the main materials of the building frame. Results pertaining to the building components informed secondary design choices including the choice of flooring, roofing and coating among others. Finally, the knowledge gained from the data processing and visualization allowed the revisiting and refining of the dwelling designs. Based on the newly acquired insights, an optimized design was modelled to demonstrate further EC reductions.

[2] The methods underlying TOTEM abide by the European standards relevant to the assessment of the environmental performance of buildings and building products. These include the standard for sustainability of construction works, environmental product declarations (EN 15804 + A2 and TR 15941), assessment of environmental performance of buildings (EN 15978), and the framework for assessment of buildings and civil engineering works (EN 15643).

[3] Refer to Appendix A for a detailed step-by-step guide outlining the study's research process.

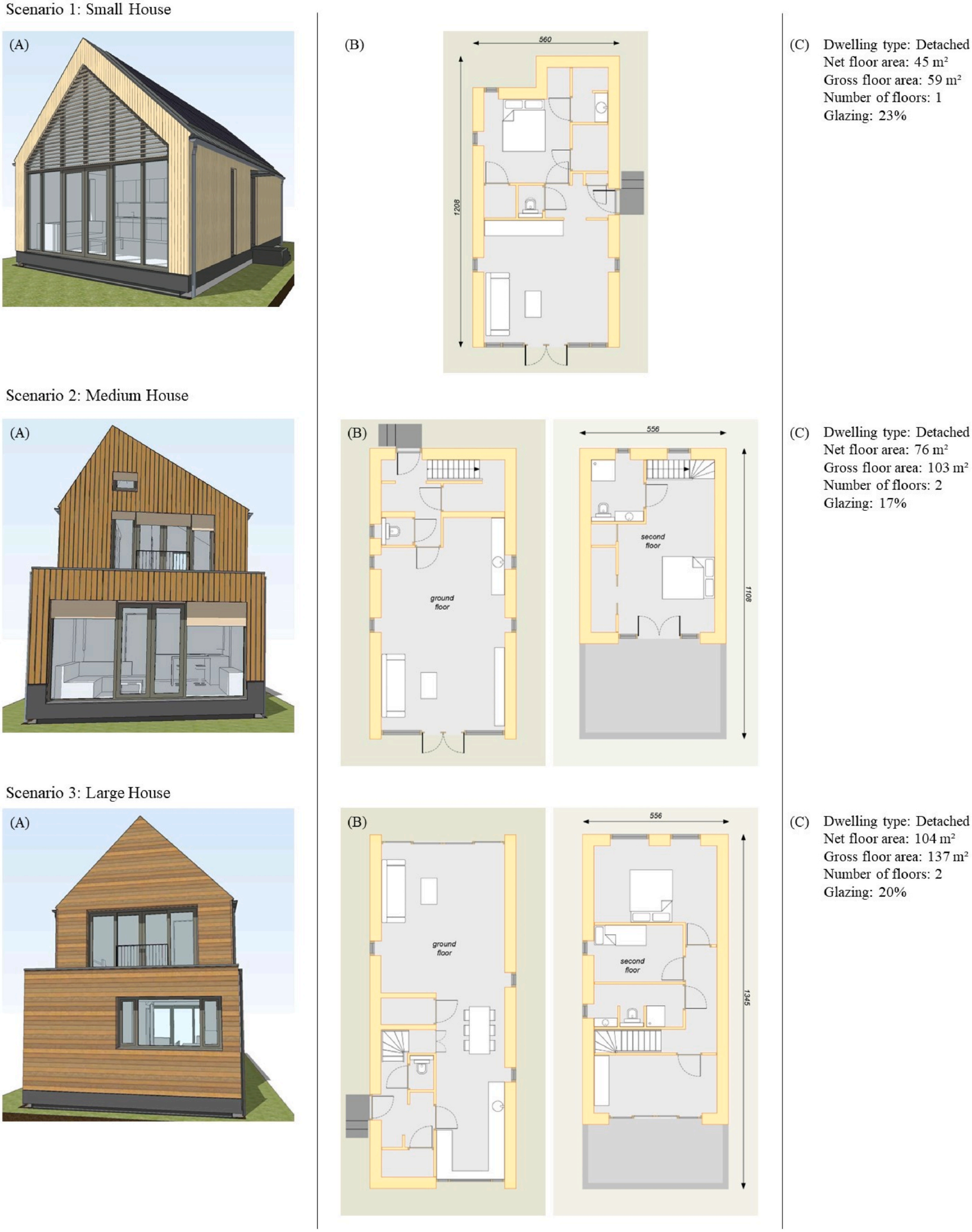


Fig. 1. Characteristics of study scenarios (A) Dwelling exterior (B) Floor plans (C) Main dwelling characteristics.

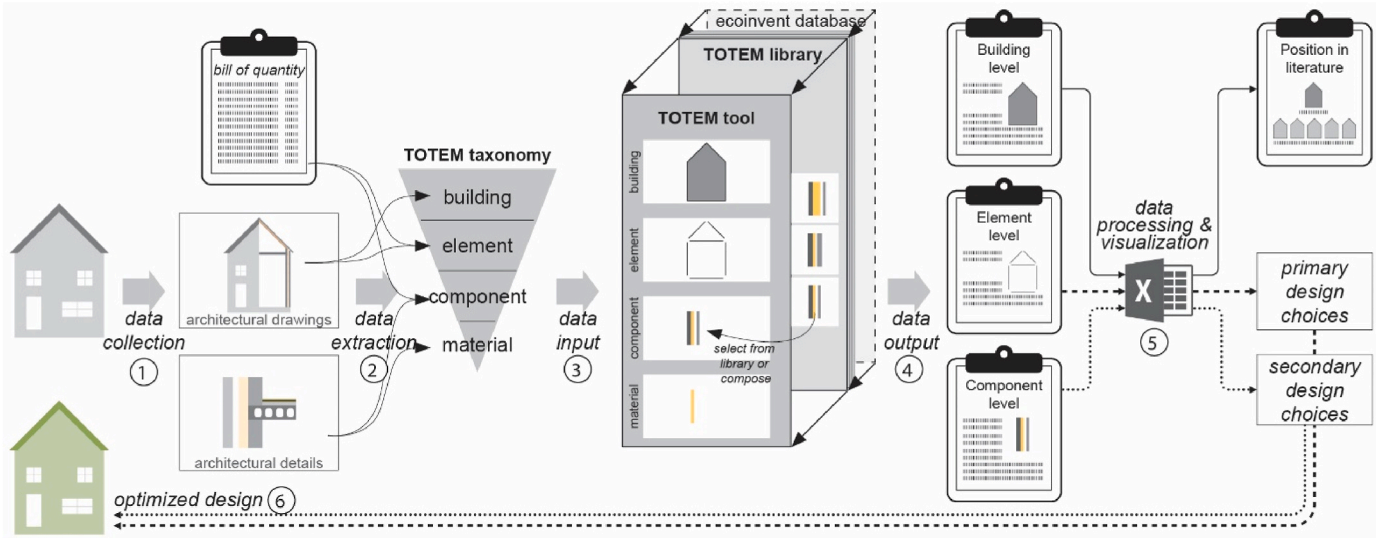


Fig. 2. Visualization of the research process.

2.3. Baseline design

To investigate the impact of timber as the main building material, there is a need for a benchmark or reference dwelling incorporating conventional building materials and construction methods. For this purpose, a theoretical baseline was created with concrete, both pre-stressed and cast in-situ, and limestone blocks and bricks as the main building materials. Concrete was chosen as the base for the alternative construction variation considering it remains the standard go-to building material in the sector [12]. The detailed baseline designs were tailored to the Dutch context based on the input of practitioners within the H4.0E project. These baseline designs will serve as the control group to draw comparisons when quantifying the EC reductions from downsizing and the use of timber. Fig. 4 provides section drawings showing the detailed composition of the baseline dwellings' main building elements. It is worth noting that the thermal performance of the H4.0E building envelope, represented in the timber dwellings, surpasses Dutch standards. This was maintained the same when designing the building envelope of the baseline alternatives.[4] Thus, overall two construction variations were assessed: the timber-based (H4.0E) construction and the concrete-based baseline as the conventional alternative, resulting in six different models. In each scenario, the timber design and the baseline alternative have the same floor space and the engineering integrity of the house was preserved in each variation.

2.4. Research scope

The physical system boundary of a dwelling is associated with the different materials, components and elements that make up the dwelling [18]. It is composed of its structural elements and building services including renewable energy technologies. Table 1 lists the building elements included and excluded from this study's physical system boundary. This study incorporates all building materials, components and elements related to the construction of the dwellings considering structural elements can be responsible for up to 50% of the initial EC and 20% of the whole life cycle carbon [19]. Including sanitary elements and furniture is not common practice in LCA studies and were excluded from this investigation in an effort to increase the comparability of outcomes. Due to uncertainties around the estimation of EC values and assumptions on the maintenance, replacement, and end-of-life of building services and renewable technologies, these were also excluded from this study. Additionally, it should be highlighted that larger dwelling sizes require additional fittings and furniture [54]. Including such elements would accentuate the EC savings of smaller dwellings and excluding them indicates that this study's outcomes are conservative.

A dwelling's temporal system boundary is linked to its service life and includes the different modules of a LCA as defined in the standards [18]. It ranges between 30 and 100 years, with the most common estimated service life (ESL) duration varying between 50 and 60 years. Although the average lifespan of a dwelling is more than 60 years, it is known that severe renovations will be required after this period. As such, the ESL of choice in this study is assumed to be 60 years [52]. In terms of LCA modules, Fig. 5 illustrates the different temporal system boundaries as per the life cycle modules of the European standard EN15978:2011 [14]. Modules highlighted in green are the ones included in this investigation. To focus on material impact, OE use related modules B1, B6 and B7 were considered beyond the scope of this study and were assessed separately.[7] Since repair activities are user-specific and no default scenarios are readily available [52], module B3 was excluded from the temporal system boundary of this study. Considering, the focus of this investigation is new-build and with a service life of 60 years, refurbishment activities (B5) also fall outside of the scope. Lastly, following the European standard cut-off, module D is considered beyond the scope of this study.

2.5. Study assumptions

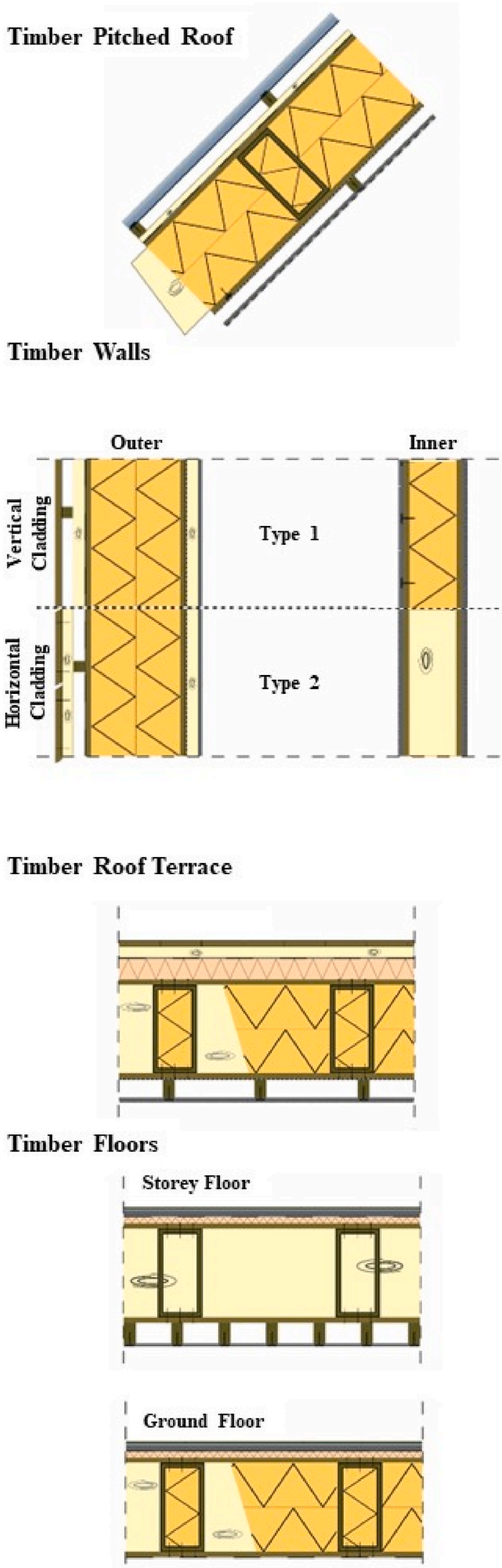
Central to achieving transparency is a clear communication of the main study assumptions. The main assumptions abided by through the use of TOTEM are listed herein [52].

[4] A known advantage to timber construction is the use of the added space within the building frame to enhance the thermal performance of the building envelope. Expectedly, maintaining the same thermal performance in the concrete-based baseline designs resulted in unusual dimensions due to an increased insulation thickness added to a solid building frame. These occurrences are highlighted in orange in Fig. 4.

[5] This study's detailed material inventory can be found in the supplementary data.

[6] This study's detailed material inventory can be found in the supplementary data.

[7] H4.0 E dwellings were designed to have a (near) zero OE and as part of the H4.0 E project, the OE use of the dwellings was monitored. Refer to Appendix B for more information on the OE performance of the dwellings.



Timber Pitched Roof – U-value = 0.11 W/m^{2}K

(1) Galvanised Steel | Corrugated Sheet – screwed	(0.6 mm)
(2) Softwood | Battens – nailed, untreated	(50 mm)
(3) Softwood | Battens – nailed, untreated, c.t.c. 450 mm	(47x22 mm)
(4) EPDM | Proofing Membrane – partially glued	(1.2 mm)
(5) Plywood | Board – nailed	(18 mm)
(6) Glass Wool | Blanket – between beams	(300 mm)
(7) Plywood | Board – nailed	(18 mm)
(8) PP-LDPE | Proofing Sheet – stapled	(0.22 mm)
(9) Softwood | Battens – nailed, untreated	(63 mm)
(10) Gypsum Fibre | Board – screwed, with joint filler	(18 mm)
(11) Traditional Plaster | Thick Coating – by machine	(7 mm)

Timber Outer Walls (Types 1&2) – U-value = 0.11 W/m^{2}K

(1) Larch | Planks – nailed, untreated	(22 mm)
(2) Softwood | Battens – screwed, untreated, c.t.c. 600 mm	(38x38 mm)
(3) PE | Proofing Membrane – stapled	(0.2 mm)
(4) Plywood | Board – nailed	(18 mm)
(5) Glass Wool | Blanket – between beams	(300 mm)
(6) Plywood | Board – nailed	(18 mm)
(7) PP-PE | Proofing Membrane – taped	(0.22 mm)
(8) Softwood | Battens – screwed, untreated c.t.c. 600 mm	(63 mm)
(9) Gypsum Fibre | Board – screwed, with joint filler	(12.5 mm)
(10) Acrylic Paint | Film Coating	(-)

Timber Inner Wall | Type 1 – U-value = 0.2 W/m^{2}K

(1) Glazed Ceramic | Rigid Tiles – glued on board	(200x200x9mm)
(2) Gypsum Fibre | Board – screwed with joint filler	(12.5 mm)
(3) Plywood | Board – screwed on softwood	(18 mm)
(4) Glass Wool | Blanket – between beams	(150 mm)
(5) Plywood | Board – screwed	(18 mm)
(6) Gypsum Fibre | Board – screwed with joint filler	(12.5 mm)
(7) Acrylic Paint | Film Coating	(-)

Timber Inner Wall | Type 2 – U-value = 1.53 W/m^{2}K

(1) Acrylic Paint | Thin film	(-)
(2) Plywood | Board – screwed	(18 mm)
(3) Cavity (support beam drawn)	(64 mm)
(4) Plywood | Board – screwed	(18 mm)
(5) Acrylic Paint | Film Coating	(-)

Timber Roof Terrace – U-value = 0.09 W/m^{2}K

(1) Hardwood | Planks – screwed, treated	(140x20 mm)
(2) Softwood | Supporting Battens	(40 mm)
(3) EPDM | Proofing Membrane – partially glued	(1.2 mm)
(4) Stone Wool | Board – loose laid (fixed on inclination)	(40/100 mm)
(5) Plywood | Board – nailed	(18 mm)
(6) Glass Wool | Blanket – between beams	(300 mm)
(7) Plywood | Board – nailed	(18 mm)
(8) PP-LDPE | Proofing Sheet – stapled	(0.22 mm)
(9) Softwood | Battens – nailed, untreated	(63 mm)
(10) Gypsum Fibre | Board – screwed, with joint filler	(18 mm)
(11) Traditional Plaster | Thick Coating – by machine	(7 mm)

Timber Storey Floor – U-value = 0.65 W/m^{2}K

(1) Laminate | Parquet – with XPS underlayment	(7+6 mm)
(2) Gypsum Fibre | Board – with slots for floor heating*	(18 mm)
(3) PE | Proofing Membrane	(0.2 mm)
(4) EPS | Board – upon floor slab	(20 mm)
(5) Plywood | Board – nailed	(18 mm)
(6) Cavity (cross beams drawn)	(300 mm)
(7) Plywood | Board – nailed	(18 mm)
(8) Softwood | Joists & Beams – nailed, treated, uncontaminated	(70 mm)
(9) Gypsum Fibre | Board – screwed with joint filler	(10 mm)

**heating system and slots are not drawn*

Timber Ground Floor – U-value = 0.11 W/m^{2}K

(1) Laminate | Parquet – with XPS underlayment	(7+6 mm)
(2) Gypsum Fibre | Board – with slots for floor heating*	(18 mm)
(3) PE | Proofing Membrane	(0.2 mm)
(4) EPS | Board – upon floor slab	(20 mm)
(5) Plywood | Board – nailed	(18 mm)
(6) Glass Wool | Blanket – between beams	(300 mm)
(7) Plywood | Board – nailed	(18 mm)
(8) PE | Cavity Membrane (water barrier) – taped	(0.6 mm)

**heating system and slots are not drawn*

Fig. 3. Detailed composition of main building elements under the timber design.[5]

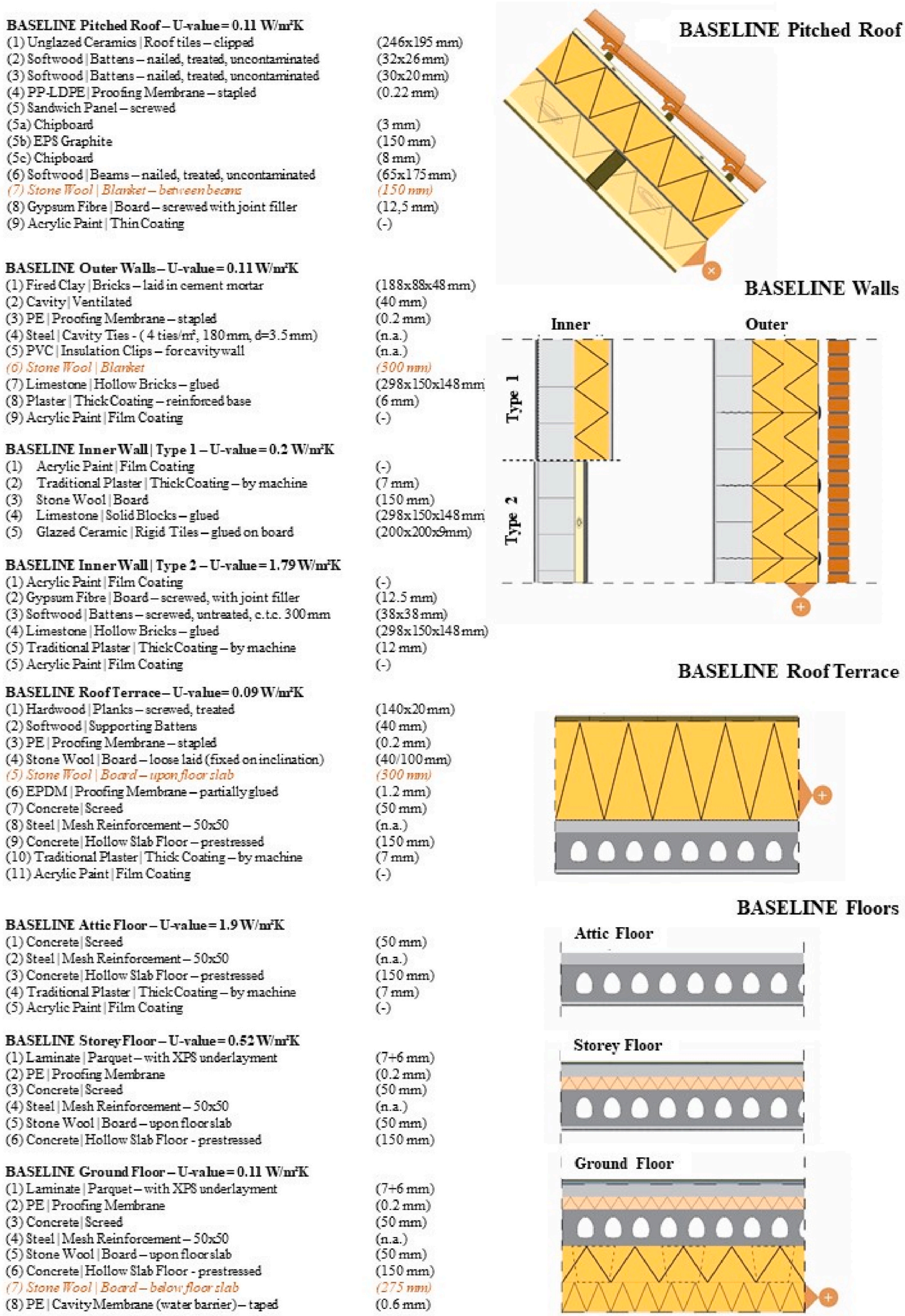


Fig. 4. Detailed composition of main building elements under the baseline design .[6]

Table 1
Building elements included and excluded from the study's physical system boundary.

Building Elements Included		Building Elements Excluded
Excavation	Storey Floor	Building Services
Foundations	Attic Floor	Renewable Technologies (PV panels)
Building Frame	Stairs	Bathroom Fittings
Structural Columns/ Beams	Pitched Roof	Kitchen Fittings
External Walls	Roof Terrace	Furniture
Internal Walls	Windows	
Ground Floor	External/Inside Doors	

- The static −1/+1 approach for biogenic carbon is adopted where a negative value of carbon emissions is assigned in the product stage of the biomaterial and is cancelled out by the equivalent positive value in its end-of-life[8] stage, mostly through incineration, making the carbon balance neutral from the whole life cycle perspective. The impact from the incineration of construction and demolition waste is allocated in its entirety to the material being incinerated.
- Maintenance and replacement scenarios are based on the type and function of every building element. Elements that serve the safety or comfort of the residents undergo maintenance/replacement interventions regardless of the expected service life of the dwelling. Elements that serve aesthetic reasons only undergo interventions when the remaining service life of the dwelling is equal to or exceeds half of the original frequency time of the intervention.[9]
- The carbonation of concrete was not integrated in the EC calculations because of its expected negligible impact within the lifespan considered [19].

3. Results

3.1. Total embodied carbon outcomes at the building level

The key metric focused on in this paper is the global warming potential (GWP) and the EC dioxide equivalent (CO_{2eq}) is used to capture it [18]. Table 2 provides the total life cycle EC in kilograms of CO_2 equivalent (kgCO_2eq) for every scenario over an ESL of 60 years. For the timber scenario, results reveal a total EC of 42,608 kgCO_2eq for the 'Small House', 52,883 kgCO_2eq for the 'Medium House', and 70,384 kgCO_2eq for the 'Large House'. These outcomes confirm previous findings underlining the fact that a larger dwelling inevitably has a higher EC due to a bigger floor area and the need for more construction materials [13,15,40]. The scaling of outcomes through the use of a spatial functional unit leads to a change in order where the 'Small House' timber scenario has the highest EC of 722 kgCO_2eq per square meter (kgCO_2eq/m^2), the 'Medium House' 512 kgCO_2eq/m^2, and the 'Large House' 514 kgCO_2eq/m^2. This is a direct manifestation of how this plays in favour of larger dwellings by masking the differences between the total impact of the dwellings as brought to attention in previous studies [16,55]. In that way, this study echoes previous research findings stating that solely measuring EC per spatial functional unit is not enough as it inadequately captures the actual environmental impact of the dwelling and additional metrics are necessary for a more accurate representation [46,48]. Additionally, when comparing construction alternatives,

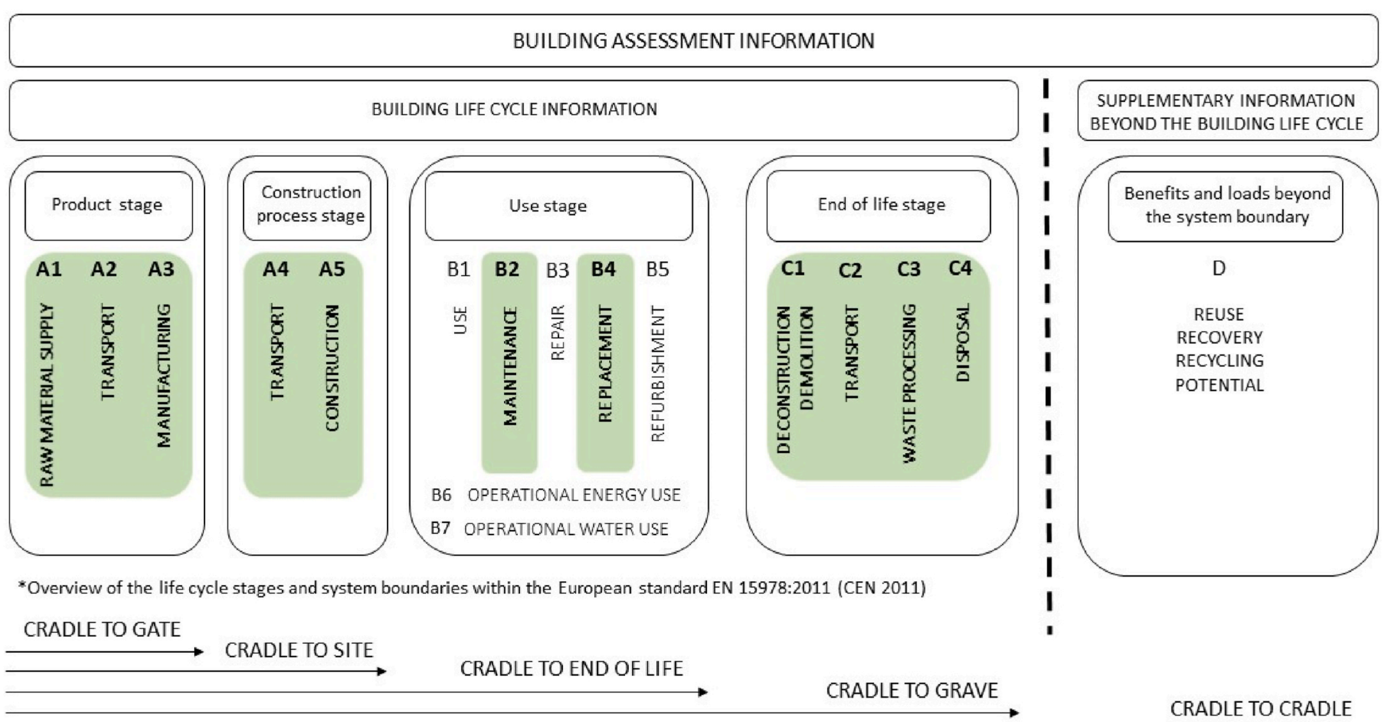


Fig. 5. EN 15978 Life cycle stages modules within different temporal system boundaries.

[8] Refer to Appendix C, Figure C.1. for end-of-life scenarios per building material/component.

[9] Refer to Study Inventory in the supplementary materials for more information on the ESLs per individual building complement within all building elements included in the study.

Table 2
Total life cycle material impact of H4.0 E dwellings and their baseline alternatives.

Scenario	Small House		Medium House		Large House	
Partial life cycle embodied carbon	Timber (Model 1)	Baseline (Model 2)	Timber (Model 3)	Baseline (Model 4)	Timber (Model 5)	Baseline (Model 6)
Total Outcome ($kgCO_2eq$)	42,608	54,681	52,883	69,725	70,384	91,270
Outcome per spatial FU ($kgCO_2eq/m^2$)	722	927	512	675	514	666

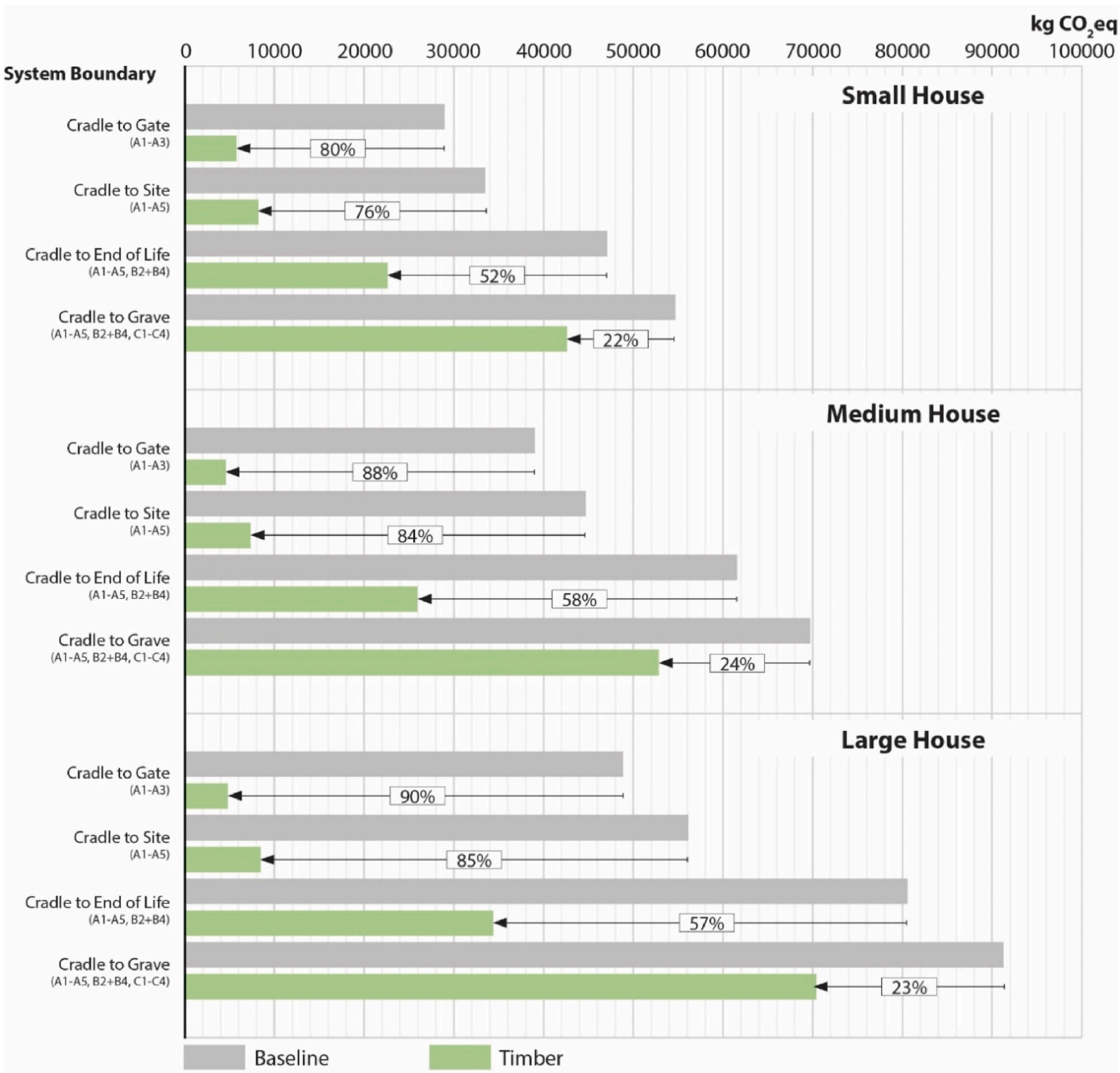


Fig. 6. Total embodied carbon reductions per temporal system boundary.

Table 2 also shows that all three timber models (Models 1, 3, and 5) achieve an EC that is lower than their baseline counterparts (Models 2, 4, and 6). This echoes the unanimity of previous studies around the better performance of timber as a construction material [12,24–28].

Fig. 6 shows EC reductions achieved from cradle to gate, cradle to site, cradle to end-of-life and cradle to grave. When comparing timber to baseline designs, a recurrent pattern reveals itself whereby achieved EC reductions start off considerably high from cradle to site, varying between 80 and 90%, to slowly being reduced to 22–24% from cradle to grave. This demonstrates that the production of building materials used to represent a dominating share of life cycle emissions. However, with the use of timber as the main building material, this initial carbon spike is tempered and the production of a timber dwelling is up to 90% less carbon intensive than the production of a concrete dwelling. Instead, another carbon spike occurs throughout the end-of-life of a dwelling where a significant amount of reductions are offset. This can be attributed to the choice of the static carbon storage accounting model (−1/+1) where a zero biogenic carbon balance is assumed over the life cycle of the material. This translates into timber structures having a greater amount of carbon emissions in their end-of-life stage due to the assumption of incineration as the end-of-life scenario, as brought to attention in earlier work [28]. In that way, this gradual presentation of outcomes confirms the importance of exploring different biogenic accounting methods and end-of-life scenarios for timber, as was highlighted in previous studies [19,24,32], to better represent its benefits as a fractional reduction in these stages would have a large reduction effect on the total EC of timber dwellings.

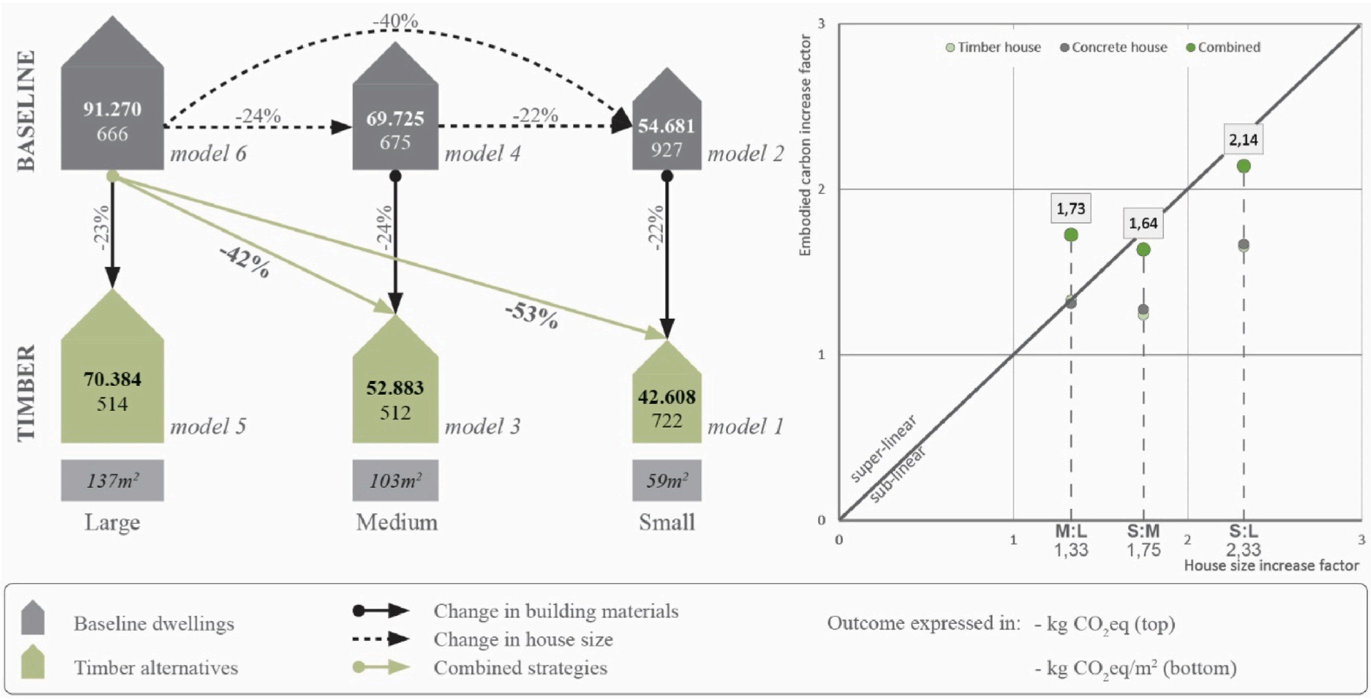


Fig. 7. Embodied carbon reductions per strategy and the relationship between house size and embodied carbon.

3.1.1. Embodied carbon reductions from downsizing and the use of timber

Fig. 7 shows the EC reductions from the implementation of downsizing and the use of timber and provides a visual representation of the relationship between house size and EC. The comparison of outcomes between timber designs and their baseline alternatives within each scenario traces reductions strictly from a change in building materials. Accordingly, using timber as the main construction material resulted in EC reductions varying between 22 and 24%. The comparison of outcomes between baseline designs alone traces reductions resulting strictly from a change in house size. As such, downsizing resulted in EC reductions varying between 22 and 40%. By comparing the large baseline house, Model 6[10], and the timber dwelling designs, Models 1 and 3, the simultaneous reductions from both downsizing and the use of timber can be traced. Overall, only the implementation of both strategies together achieves the highest EC reduction with 42% for the Medium House and 53% for the Small House scenario. All reduction percentages exceed the TOTEM significance threshold of 20% thus ruling out potential changes in outcomes due to uncertainties around the assumptions made [52].

3.1.2. The relationship between house size and embodied carbon

Contrary to what was suggested in prior work, this study's findings indicate that the nature of the relationship between house size and EC cannot be considered super-linear [45]. In comparing the timber dwellings, the Large House (GFA: 137 m^2) is 2.33 times bigger than the Small House (GFA: 59 m^2). However, it consumes 1.65 times more EC. Likewise, the Medium House (GFA: 103 m^2) is 1.75 times bigger than the Small House and consumes 1.24 times more EC. In comparing the concrete dwellings, outcomes are similar with the Large House consuming 1.67 time more and the Medium House consuming 1.26 times more than the Small House. Only the outcomes between the Large and Medium House scenarios suggest a linear relationship between house size and EC considering the former consumes 1.33 more EC for timber and 1.3 times more EC for concrete. Overall, results are more inclined towards indicating a sublinear relationship between house size and EC, aligning with the conclusion drawn by Stephan and Crawford [46]. Only when timber and downsizing strategies are implemented simultaneously, results suggest either a super-linear or a linear relationship seeing as the ratio of EC emissions of a large concrete house and a medium timber house is 1.73 which exceeds the ratio of dwellings sizes (1.33) and the ratio of EC emissions of a large concrete house and a small timber house is 2.14 which is almost as much as the ratio of their sizes (2.33) as can be seen on Fig. 7. In practice, these results indicate that architectural details render the relationship between house size and EC emissions more complex and that having a smaller living space comes at the cost of a disproportional decrease in EC depending on the architectural design choices made. Downsizing alone is not enough and the simultaneous implementation of EC strategies is necessary to increase the chances of achieving at least a linear decrease of EC emissions. More importantly, the results suggest there being an optimal point beyond which further reductions in dwelling size may not result in the equivalent significant reductions in EC emissions.

3.2. Embodied carbon outcomes at the building element level

Fig. 8 shows the impact share of every building element on total EC outcomes and the impact share of these building elements within each life cycle module. On the one hand, this presentation of outcomes reveals that the building envelope wields significant influence on EC outcomes. In the timber-based designs, the pitched roof, ground floor and external walls are important contributors taking up altogether 48–56% of the dwellings' total footprint. In the concrete-based baselines, the external walls and ground floor are dominating taking up 41–46% of their total impact. Such variations in the impact shares of main building elements between a timber-based dwelling and its baseline have been identified in previous work where the roof and the foundations were the most impactful building elements in a timber dwelling versus external walls and floors in its masonry counterpart [56]. Differences in the ranking of building elements per dwelling can be attributed to the differences in overall architectural designs such as the surface area of the pitched roof or the glazing (refer to Fig. 1). That is to say that, in terms of architectural design choices, these results underscore the importance of primary design choices related to the design and

[10] Model 6 was considered the reference since it better represents the conventional dwelling design and the average dwelling size.

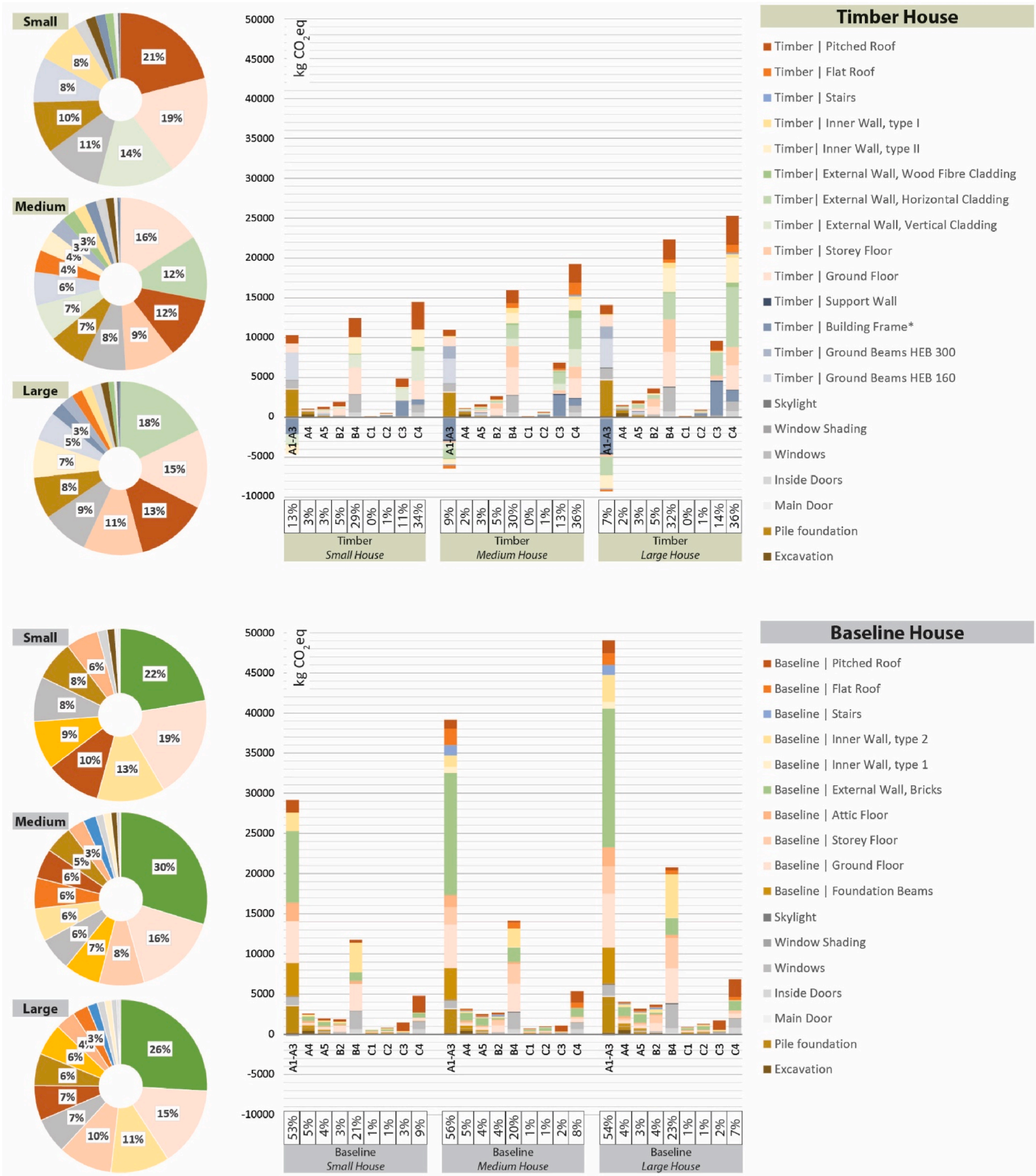


Fig. 8. Embodied carbon outcomes per building element and per life cycle module.

composition of the building frame by manifesting their significant impact on a dwelling's total EC footprint, a finding that is consistent with previous investigations [30,57,58].

On the other hand, when looking into life cycle modules, outcomes reiterate the significant impact of the biogenic accounting approach adopted considering the disposal module C4 is dominated by building elements made of timber with higher end-of-life emissions. Whereas production modules A1 to A3 are controlled by building elements made of concrete, most of which is assumed to be recycled in its end-of-life [28]. More importantly, for both designs, the results reveal replacement module B4 as a significant contributor to the dwellings' EC footprint with a share of 20%–32%. This has been flagged by previous studies stressing on the importance of accounting for the maintenance and/or replacement of building elements throughout the building's service life [42]. This confirms previous research findings demonstrating that larger dwellings do require more upkeep seeing as the share of EC emissions coming from Module B4 increases with the size of the dwelling in both construction alternatives [42]. Additionally, doors, windows and skylights, elements that are not always included in LCA studies, were revealed to be amongst the important contributors, in addition to main building elements such as ground floor, external walls, and pitched roof as was also highlighted by Resch et al. (2020) [30]. This is a direct manifestation of how the exclusion of such elements can lead to truncation errors and the underestimation of a dwelling's total EC footprint.

3.3. Embodied carbon outcomes at the building component level

Fig. 9[11] displays the shares of EC contributions at the building component level for the main elements of both construction variations. The ESL of every building component is also indicated. This presentation of outcomes reveals that finishing components are major contributors in both the timber and the concrete construction variations. In the dwelling floors, parquet laminate, a common choice of flooring in the Netherlands, accounted for the majority of the EC reaching 74% of the total impact of the floors in the timber dwelling and ranging from 59% to 67% in the baseline design. In the pitched roof, galvanized steel was chosen as the finishing of the timber dwellings in the H4.0E project and amounted to 77% of the building element's total EC. This finding resonates with observations made by Ximenes et al. where roofing also emerged as the building component with the largest impact within the roof element (2013) [32] and Taylor et al. who demonstrated significant differences in material impact between different roofing variations (2023) [55]. In the walls, although not dominant, acrylic paint is responsible for a considerable share of total EC and becomes even more significant when considering its cumulative share in all building elements. Following the same reasoning, insulation (EPS board and glass wool blanket insulation) becomes another design choice with significant EC consequences considering it is also a recurrent component in several building elements of the dwelling. A different choice of insulation could reduce the material impact of the dwelling while maintaining a similar thermal performance,[12] as was highlighted by Petrovic et al. (2019) [31]. Additionally, finishing components tend to have shorter service lives than the structural and insulating components. Galvanized steel roofing has a service life of 30 years, parquet laminate flooring 15 years, and acrylic paint coating 10 years. Considering this study includes maintenance and replacement modules in its analysis and taking into account the ESL of 60 years for the entire dwelling, this leads to having several rounds of maintenance/replacement. In this light, the importance of the choice of finishing materials is highlighted when it has often been overlooked in the past since accounting for finishing is not common practice in LCA studies [26]. Overall, by demonstrating their aggregated significant impact on a dwelling's total EC footprint, the presentation of outcomes at the building component level allowed the identification of highly carbon intensive secondary design choices outside of the primary design choices, confirming the conclusion reached by Petrovic et al. (2023) [59]. Practically, these outcomes emphasize the need for well-informed decisions at every stage of the design process, even when accommodating user preferences, particularly concerning choices related to flooring, roofing, coatings, and insulation types to ensure more effective and sustainable outcomes.

[11] For the purpose of conciseness, results reported in this section are restricted to the Medium House scenario.

[12] Refer to Appendix C, Figure C2 that traces the carbon intensity of different insulation types versus their thermal performance (R-value).

3.4. Optimized design

The hierarchical structure of outcomes allowed the identification of most carbon intensive building elements and components. Changes with the highest potential of decreasing the EC of the dwellings were identified. Accordingly, a better performing scenario was modelled to numerically gauge the corresponding reductions. Modifications consist of substituting finishing materials with natural based alternatives. This includes changing the galvanized steel roofing to local slating, the parquet laminate flooring to hardwood flooring and eliminating all acrylic paint coatings. The glass wool insulation layers were also substituted with cellulose insulation and, when applicable, rigid insulation such as EPS was replaced with wood based rigid insulation. Table 3 presents the outcomes of the optimized design modelled based on the Medium House scenario. In comparison to the timber design, these changes resulted in an overall 29% additional reduction in EC emissions, surpassing the 20% significance threshold. This outcome confirms the importance of accounting for secondary design choices in a LCA and doing so at an early design stage to prevent countering savings. While this optimized design achieves higher EC savings, this study recognizes that its implementation in practice is not as straightforward. For instance, in the case of the H4.0E project, residents opted for glass wool instead of cellulose insulation to decrease their costs. That is to say that material choices, which are dependent on user preferences, are in turn determined by external factors including the affordability, availability and established norms around natural based materials.

3.5. Situating study outcomes in existing literature

Table 4 enumerates relevant previous studies by listing their EC outcomes in a decreasing order and distinguishing location, building type, floor area, ESL, EC reduction percentage from the use of timber (TR), life cycle modules, biogenic carbon, and used database(s). The studies were searched through the databases of the Delft University of Technology Library [60] and Web of Science [61], using the following keywords: (Timber OR Wood) AND (Housing OR House* OR Dwelling*) AND (Life cycle assessment OR LCA OR Embodied Carbon OR Life cycle analysis). The initial screening was done through scanning titles and keywords followed by reading abstracts. Priority was given to studies that had a similar research goal which is to investigate the use of timber as an EC reduction strategy compared to more conventional building materials in new-build construction. As per this research goal, articles that did not include timber as a main construction material were excluded. Articles that did not include housing at all, be it in the form of individual dwellings or residential buildings, were excluded. Articles that solely focused on existing buildings/dwellings and the material

[13] The last search was performed on the 5th of January 2024.

[14] The definition of floor area varies per study and can designate the heated floor area (HFA), the net floor area (NFA), or the gross floor area (GFA).

[15] Abbreviation TR for reduction percentage from the use of timber.

[16] Life cycle modules are specified as per the EN 15978 standard.

[17] When biogenic carbon was not addressed at all in the reference studies it was assumed to be excluded from the analysis and also entered as a 'No' in the table.

[18] Reference studies tap into a wide range of databases including private LCA datasets, publicly available datasets, previous research outcomes, published EC reports, environmental product declarations (EPD), and European and global averages. Specific examples cited are Ecoinvent, Building Product Life Cycle Inventory, Inventory of Carbon and Energy (ICE), Environmental Performance in Construction, Integrated Carbon Metrics Embodied Carbon Life Cycle Inventory, and Building Construction Information Service among others.

[19] Literature reviews and benchmark studies cover variable locations, building types, floor areas, and ESLs, which is denoted by the letter 'V' in the table.

[20] When studies tap into several databases, the occurrence is designated as 'Mixed'.

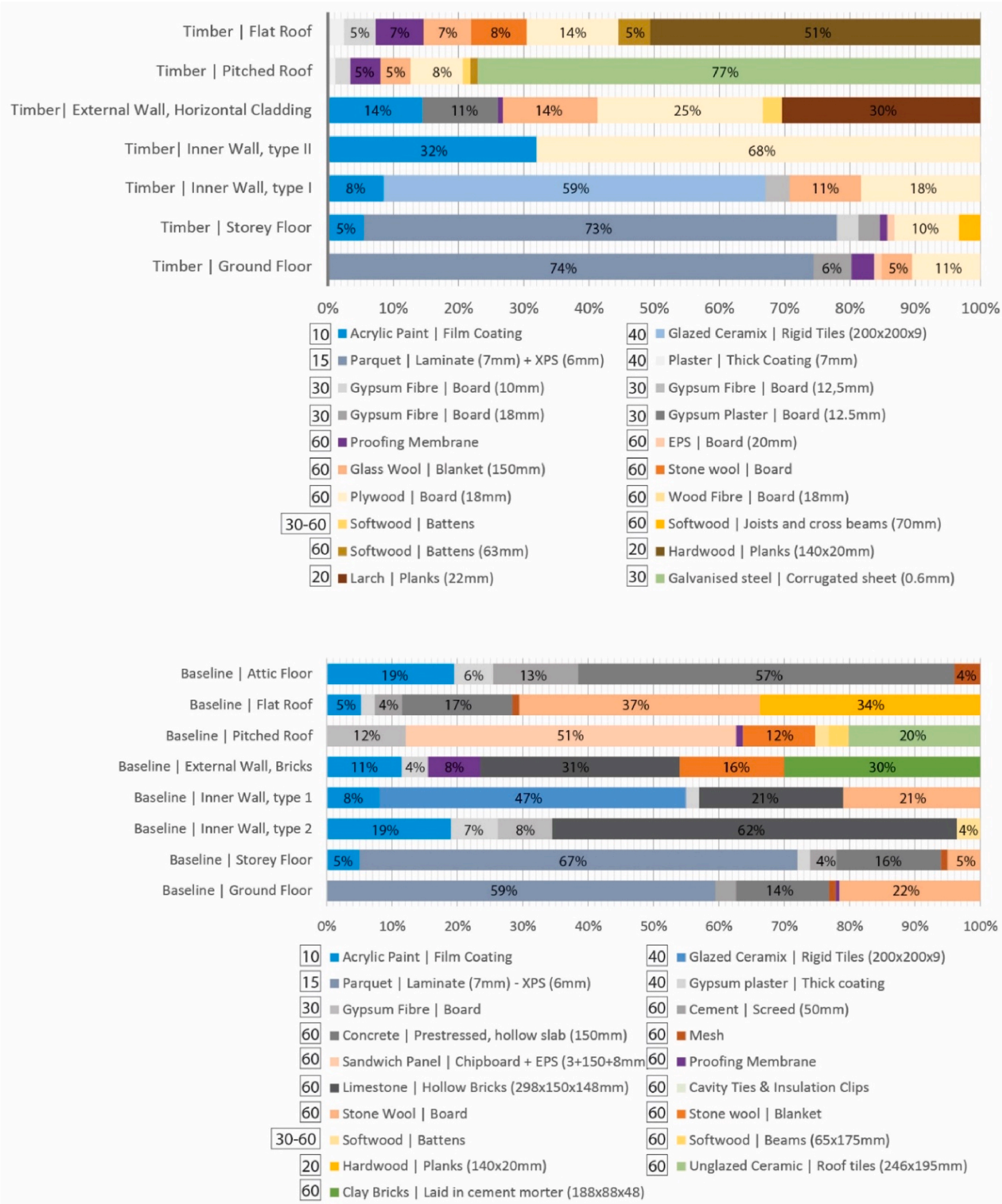


Fig. 9. Material impact per building component in the main building elements of the Medium House scenario in the timber and baseline construction variations. Numbers in squares are the estimated service life of the components within each element.

Table 3
Embodied carbon material impacts per medium dwelling scenario.

Life cycle embodied carbon		Medium House - Baseline	Medium House – Timber	Medium House – Optimized
Stage	Module			
Production	A1-A3	377	41	−69
Transport to site	A4	31	11	12
Construction and Installation	A5	24	16	13
Maintenance	B2	26	26	24
Replacement	B4	137	158	63
Deconstruction/ Demolition	C1	6.7	1.1	1.1
Transport end-of-life	C2	10	4.8	5.3
Waste Processing	C3	11	67	65
Disposal	C4	52	186	246
Outcome per spatial FU ($kgCO_2eq/m^2$)	675	512	361	
Total Outcome ($kgCO_2eq$)	69,725	52,883	37,291	
Reduction Percentage	0%	24%	29%	

impact of renovation measures were excluded. Articles that investigated temporary timber housing with lifespans below 25 years were excluded. Lastly, to increase comparability, articles that did not convey the material impact expressed in kilograms of carbon dioxide equivalent per square meter of floor area were excluded.[13] The resulting studies vary between literature reviews, case studies, benchmark studies, and global trend studies with a particular focus on timber construction and residential buildings or dwellings.

Fig. 10 consists of a visual representation of where this study's outcomes stand in comparison to previous studies. Under timber reduction percentages, ranging from 10 to 56%, they fall in the lower range of the band with the EC savings from the use of timber limited to an average of 23%. Under EC outcomes, ranging from 17.6 to 1050 $kgCO2eq/m^2$, they fall in the upper range of the band with a minimum of 512 $kgCO2eq/m^2$ and a maximum of 722 $kgCO2eq/m^2$. When looking into reasons underlining variations in outcomes, apart from major variations in study characteristics such as geographic context and building design as is the case with study 16 located in Uruguay where a full wooden design is assessed including foundations, cladding and flooring [25], several differences in study scope come to light.

3.5.1. *Differences in temporal system boundaries*

Accounting for different life cycle modules explains some of the large differences in outcomes [18], as is the case with studies 5 [63], 8 [65], 11–13 [13,27,57], 17–19 [16,18,69], 21–29 [13,18,20,26,27,32,56–58,63,65,71,73–75]. For instance, study 18 excluded maintenance and replacement modules B2 and B4 in their investigation of an increased use of biobased materials [69]. In this paper, these modules alone constituted up to 37% of the timber dwellings' EC footprint. Studies 11 and 12 on modular and prefabricated timber housing only include modules A1 to A5 limiting the scope to the construction site stage [27,57]. Applying such system boundaries to this paper's outcomes would lead to a much higher average reduction of 51% from the use of timber and much lower total EC values with an average 61 $kgCO_2eq/m^2$ from cradle to gate, 93 $kgCO_2eq/m^2$ from cradle to site, and 299 $kgCO_2eq/m^2$ from cradle to end of use. Adopting a different ESL can also cause differences in outcomes considering a shorter ESL of up to 50 years is not indicative enough as it does not factor in the full EC related to the maintenance and replacement of building components, as is the case with studies 1 [34,62], 9 [19], 13 [13], 14 [67], 22 [58], 23 [26], 26 [32], 27 [74] and 29 [56]. Likewise, a ESL of a 90–100 years factors in advantages that go beyond the service life of a building and attenuates the initial, replacement and end-of-life carbon spikes that occur in the first 60 years, as is the case with studies 3 [24], 4 [31], 6 [64], 12 [27], and 18 [69].

3.5.2. *Differences in biogenic carbon accounting*

Differences in outcomes are further accentuated by adopting a different biogenic accounting approach. For instance, studies 10 and 11 adopt the static 0/0 model for biogenic carbon [57,66]; whereas this study adopts the static −1/+1 model, hence the lower reported impact throughout modules A1 to A5. In contrast, studies 3 and 18 adopt the dynamic model which better represents the actual benefits of using timber versus concrete, hence their higher reduction percentages reported [24,69]. The importance of decision making around the end-of-life of timber appears with study 26 where long-term carbon storage in landfilling resulted in a 40–60% difference in GHG emissions outcomes [32] as opposed to not accounting for carbon storage. This is in agreement with other studies that identified landfilling as the least carbon intensive end-of-life scenario compared to incineration or recycling [19,24,32]. Considering this study assumes 85–100% incineration of its wood, this is another explanation to the difference in outcomes. In confirmation, study 9 demonstrates through an uncertainty analysis the extent to which EC savings are dependent on the assumptions made and the input data used which in turn explains the low reduction percentage reported [19].

3.5.3. *Differences in physical system boundaries*

Variations in the building elements included in previous studies also explain differences in outcomes. For instance, study 7 restricted its boundaries to the building envelope [55], study 21 excluded internal partitions and doors due to variations based on residents' spatial needs [71], and study 23 categorized the following elements; flooring, external cladding, roofing, shading, windows, and doors, as finishing and omitted them [26], while study 26 did not consider components like insulation, proofing membranes or coatings [32]. Studies prioritizing comparative outcomes excluded building elements arguing that they would not influence differential percentages. These range from design details such as wall coating, glass, or roof asphalt to core elements such as foundations, basement and ground floor [26,32,69,71]. While this approach sheds light on the intended purpose of the study, it does not give an outcome representative of the total emissions of a dwelling as a whole. Less detailed inventories lead to lower EC emissions and do not represent a comprehensive picture of a dwelling's emissions [16]. Despite also having a comparative purpose, EC models in this paper were based on actual dwelling designs and user choices around spatial distribution and varying finishing materials were included in the analysis. Building elements were composed to the slightest detail based on architectural drawings, bill of quantities and input from professionals, hence the outcomes that were higher than 25 reference studies in terms of total EC expressed in $kgCO_{2eq}/m^2$.

Overall, it is recognized that the results looked at for comparison are not harmonized in terms of study characteristics and scopes which entails systematic uncertainties. Nevertheless, these general trends provide a precedent against which findings of this paper can be compared.

4. Discussion

4.1. *Academic, industry and policy implications of study outcomes*

The goal of this research was to investigate the impact of the simultaneous implementation of downsizing and the use of timber as EC reduction strategies by conducting a detailed assessment that aligns closely with real-life scenarios. In pursuit of this goal, the study not only achieved an in-depth analysis of the designated strategies but also brought to the forefront implications extending beyond its immediate scope. From the academic perspective, in the attempt of situating its outcomes in existing literature, this paper faces the lack of comparability of LCA studies, reiterating it as a significant barrier as was flagged by previous research [10,19,29,30]. By tracing discrepancies in study characteristics and scoping, this study highlights the importance of prioritizing transparency in LCA studies emphasizing the need in the

Table 4
An overview of literature specific to EC studies and timber construction.

Study	Reference	Description	Location	Building Type	Floor Area[14] (m^2)	ESL (years)	Outcome ($kgCO_2eq/m^2$)	TR[15] (%)	Life Cycle Modules[16]	Biogenic Carbon[17]	Database[18]
1	[62]	Literature review	V[19]	Building	V	50	179 to1050	–	V	V	Mixed[20]
2	[30]	Case study	Norway	Building	102 (HFA)	60	968[a]	–	A1-4, B4	No	Self-acquired
3	[24]	Case Study	France	Dwelling	122 (NFA)	100	574 to 820	33%	A1-5, B4, C1-4	Yes	Ecoinvent 3.01
4	[31]	Case study	Sweden	Dwelling	180 (GFA)	100	600	–	A1-5, B1-5, C1-4	No	OneClickLCA
5	[63]	Benchmark study	V	V	V	≥30	<500	–	V	V	Mixed
6	[64]	Case study	New Zealand	Dwelling	198	90	446	–	A1-4, B2, B4, C1-4	No	Ecoinvent 3.0
7	[55]	Case study	New Zealand	Dwelling	230 (GFA)		124 to 445	–	A1-D	No	BRANZ
8	[65]	Benchmark study	V	Building	V	60	444	–	V	No	OneClickLCA
9	[19]	Case study	Australia	Building	43,229 (GFA)	50	417	10%	A1-5, B1, B4, C1, C3, C4	Yes	Mixed
10	[66]	Case study	New Zealand	Dwelling	107 (GFA)	90	414	–	A1-5, B4, C1-4	Yes	Okobandat
11	[57]	Case study	U.K.	Dwelling	45 (GFA)	–	405	34%	A1-5	No	Mixed
12	[27]	Case Study	V	Dwelling	56 (GFA)	100	380	34%	A1-4	No	ICE v. 2.0
13	[13]	Global trend study	V	V	V	50	377	–	A1-A5	No	Mixed
14	[67]	Case study	Poland	Building	153 (GFA)	25	311 to 362	15–20%	A1-5, B1-5	No	OneClickLCA
15	[68]	Literature review	V	V	V	–	−445.6 to 333.5	32%	V	Yes	Mixed
16	[25]	Case study	Uruguay	Dwelling	63 (GFA)	60	328.5[a]	50%	A1-5, B2–B4, B6, C1, C2, C4	No	Mixed
17	[18]	Case study	U.S.	Building	356 (HFA)	60	297	–	A1-5, B4, C2-4	No	Mixed
18	[69]	Case study	Sweden	Building block	–	100	281	42%	A1-5, B6, C1-4	Yes	Ecoinvent 2.2
19	[16]	Case study	Norway	Dwelling	102-202 (HFA)	60	263	–	A1-4, B4[b]	No	Ecoinvent 3.0
20	[59,70]	Case study	Sweden	Building	180 (GFA)	50–100	174 to 245	–	A1-4, B1-5, C1-4	Yes	OneClickLCA
21	[71]	Case study	Italy	Building	820 (GFA)	–	224	25%	A1-3	No	Ecoinvent 3.0
22	[58,72]	Case study	Denmark	V	238-805 (GFA)	50	200	–	A1-5, B4, C3-4	Yes	Okobandat
23	[26]	Case study	Germany/ Austria	Dwelling	176	50	<200[a]	35–56%	A1-3, B2, B4, C3–C4	Yes	Oekobau.dat 2015
24	[20]	Literature review	V	V	V	V	174.03	43%	V	V	Mixed
25	[73]	Case study	Slovakia	Dwelling	80	60	148	–	A1-5, B1-2, B5, C4	Yes	CoM
26	[32]	Case study	Australia	Dwelling	221–296	50	100 to 145[a]	50%	A1-4, B2-3, C4[b]	No	Mixed
27	[74]	Case study	Chile	Building	1405	50	105	37%	A1-5	No	Mixed
28	[75]	Case study	China	Dwelling	143.56	–	41.54 to 44.19	–	A1-5, C1-4	No	EPDs
29	[56]	Case study	Poland	Dwelling	139.8 (GFA)	50	17.56	–	A1-3	No	Okobandat

[a] These values were extracted from graphs.
[b] Specific life cycle modules were not listed in the study and the corresponding data entry was formulated based on the understanding of the text.

global scientific community for clear, harmonized guidelines on how to perform their assessment, document their process and report their outcomes [13,14,31]. From the industry perspective, by focusing on material impact alone and through its hierarchical analysis, this paper demonstrates how design decisions shift when the focus is to lower EE versus when it is limited to lowering OE. Notably, the consideration of various insulation types with equivalent thermal performance but differing EC impacts serves as a concrete example [31]. Another example is user choices encompassing finishing, flooring, and roofing [32,55]. These choices are typically excluded from design considerations due to their dependency on individual preferences. However, the focus on material impact reduction emphasizes their significance, making the role of designers pivotal in advising users towards more informed decisions. From the policy perspective, this paper demonstrates how adopting different temporal and physical system boundaries can lead to truncation errors and the underestimation of a dwelling's carbon footprint. Such discrepancies may pose potential long-term issues, giving rise to an EE performance gap resembling the challenges encountered in managing an OE performance gap [10]. Building on this premise, it becomes important for regulations concerning EE to transition from recommendations to mandatory requirements. This would create a ripple effect, prompting the construction and product industry to get familiar with different LCA tools, develop their environmental product declarations, which would in turn enhance the accuracy of carbon footprint calculations [14]. Drawing a parallel to the history of NZEBs, which were introduced years ago, attaining a zero OE balance took longer than anticipated. Similarly, incorporating EE into regulations is likely to face a learning curve. Given this, it becomes all the more crucial to initiate this transition sooner rather than later, aligning policies with sustainability aspirations for a more effective and timely

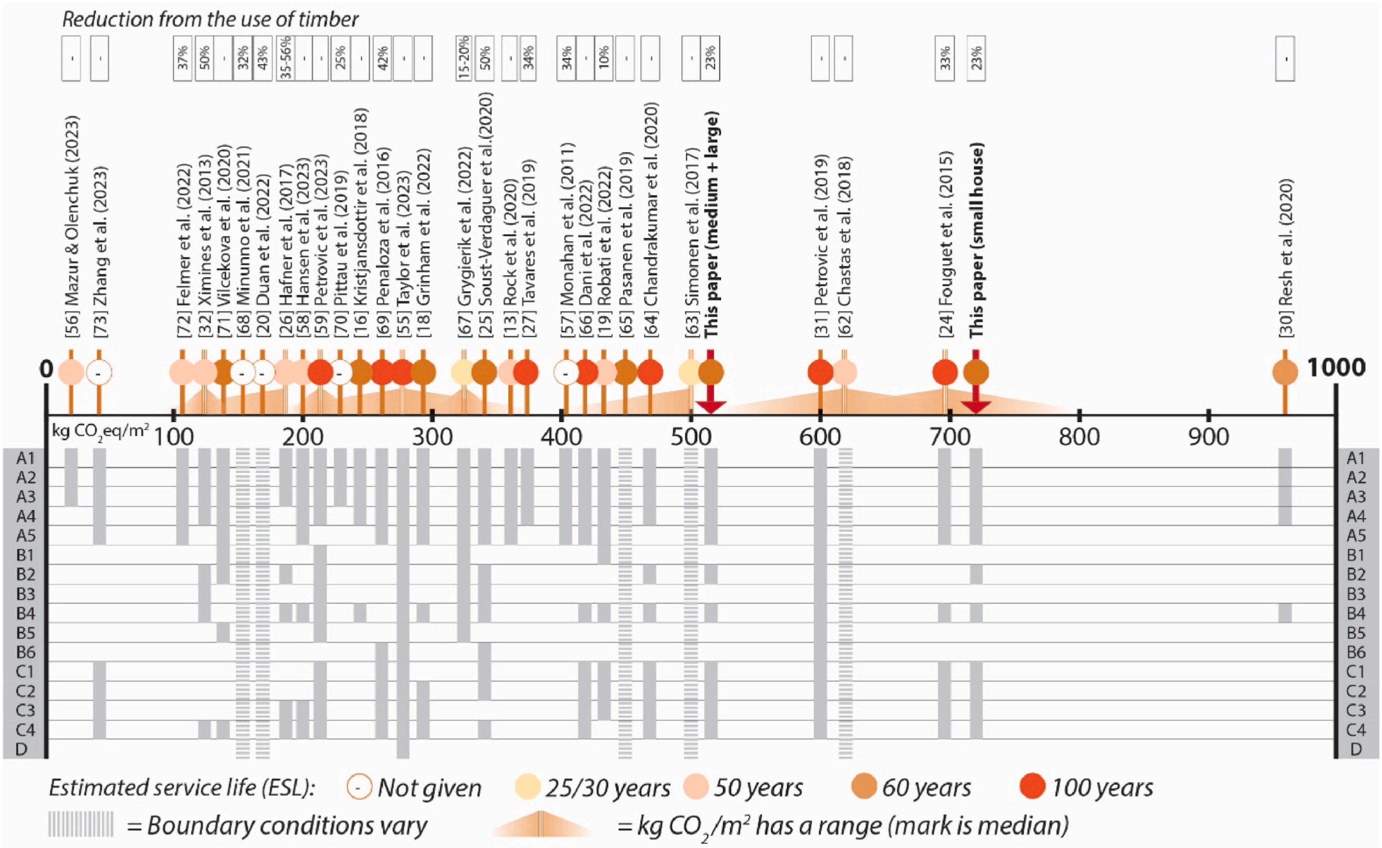


Fig. 10. A visual representation of situating this study's outcomes in previous literature.

impact.

4.2. *Challenges of implementing downsizing and timber construction*

This paper effectively demonstrates how downsizing and the use of timber reduces the carbon footprint of dwellings. However, the practical implementation of smaller, timber dwellings already confronts numerous challenges, let alone the implementation of the optimized design. A prior study investigating institutional barriers to the uptake of smaller, low-carbon, and (near) zero-energy dwellings identified several hindrances within local policies [76]. For instance, land allocation policies that favour large plots for single detached dwellings may impede the development of compact construction. Social housing policies that aim for universal architectural designs to facilitate the allocation process can obstruct housing designs aiming for compact space efficiency. Another study investigating the development of timber construction in European countries identified the lack of knowledge and skills and concerns regarding fire safety and structural stability as major barriers [77]. Affordability concerns, user preferences favouring larger conventional dwellings [78], and extended testing periods for timber constructions further increase the complexities [76]. From a broader perspective, concerns around the insufficient supply of timber and deforestation arise. While it is argued that the benefits of timber construction could counter deforestation concerns through afforestation, it is recognized that the anticipated surge in demand requires immediate proactive measures [79]. This emphasizes the complexity in implementing sustainability mitigations and highlights the need for a broader outlook to achieve more effective outcomes. Thus, this paper acknowledges the intricate nature and challenges associated with the uptake of smaller timber dwellings and highlights the need for them to be addressed for overall better chances at achieving the 2050 decarbonization goals.

4.3. *Limitations and future research*

4.3.1. *Geographical representativeness*

This study is subject to a low geographical representativeness as most EC data is specific to Europe including some that are made more specific to the Belgian context [52]. This is recognized to potentially have induced systematic uncertainty in this study's calculations. In subsequent research, a comparative assessment can be conducted to contrast national databases across Europe and highlight the potential differences in the energy mix, in the transportation of materials, and other underlying factors influencing construction practices, material sources and energy production methods. Likewise, this study adopts the tool's maintenance and replacement scenarios and biogenic carbon accounting approach. Considering the assumptions and underlying uncertainties involved in both, future research can complement their assessments with a sensitivity analysis exploring the impact of changing these assumptions which will emphasize their significant role.

4.3.2. *Temporal and physical system boundaries*

Another study limitation lies in the temporal and physical system boundaries. In an effort to conduct an in-depth EC assessment, life cycle modules related OE consumption were assessed separately.[21] For a complete overview of the full life cycle performance of smaller timber dwellings, future research should account for OE use while maintaining a high level of detail in its EC assessment. Additionally, furniture and sanitary elements were excluded due to data scarcity as including these building elements is not common practice in LCA studies. Likewise, building services were also excluded since calculating their EC has still not been standardized and modelling uncertainties remain. In terms of

[21] Refer to Appendix B: Operational energy use.

the relation between house size and EC, these exclusions render this study's outcomes conservative. Taking into account these additional elements would have further accentuated the relationship between house size and EC seeing as larger dwellings usually require more amenities and bigger building services systems [40,54]. As such, future research should also aim to gauge the additional EC emissions from sanitary elements, furniture and building services for a more comprehensive total EC footprint further accentuating the benefits of downsizing.

4.3.3. Environmental impact category

This study restricts its analysis to the GWP impact indicator as it is crucial for climate change policies [25]. However, it is essential to acknowledge that LCAs encompass a spectrum of impact categories. In the specific context of this study, considering various end-of-life scenarios unique to timber, such as incineration or landfilling, could introduce additional impact indicators of significance. For instance, the evaluation of toxic substance emissions or the potential contamination of groundwater resources becomes pertinent in a broader environmental context [32]. While this study does not delve into these aspects, it recognizes the importance of expanding LCA boundaries to encompass other impact indicators. Future research endeavours could explore the broader environmental implications associated with timber use, providing a more comprehensive and holistic understanding of the contribution of GHG emissions to climate change and other environmental concerns. Even more so when considering that the inclusion of additional impact indicators is said to favour timber dwellings over concrete dwellings [80].

5. Conclusions

This paper addresses three main research gaps. The first gap pertains to the need for research that examines the simultaneous implementation of downsizing and the use of timber as EC reduction strategies. The second gap revolves around the lack of comparability in existing LCA studies on the use of timber. The third gap concerns the need to contribute to the limited body of knowledge on downsizing as an EC reduction strategy. Specifically, this gap addresses the contradictory findings on the relationship between house size and EC and investigates the impact of downsizing at the lower end of the range for outcomes that are more representative of the European context. To address these gaps, this study conducts partial LCAs of three actual new-build timber dwellings (small, medium and large) and their concrete counterparts.

In terms of the direct implications of study outcomes, this paper demonstrates that having a smaller dwelling leads to a disproportional decrease in EC depending on the architectural design choices made considering the relationship between house size and EC was revealed to be sublinear with a correlation ratio below 1:1. Outcomes highlight that downsizing or the use of timber alone is not enough and the simultaneous implementation of both strategies is necessary to increase the chances of achieving a linear or super-linear decrease of EC emissions considering the simultaneous implementation of both reduction strategies led to the most significant carbon savings of 53%. More importantly, results suggest there being an optimal threshold beyond which further reductions in dwelling size may not result in significant justifiable reductions in EC emissions. This serves as a foundation for future research to build on and focus on finding that optimal balance between dwelling size and EC emissions reductions. Such investigations would play a vital role in safeguarding the comfort and well-being of residents from being compromised.

In terms of implications beyond the direct study context, from the academic standpoint, this research points out the lack of comparability of LCA studies emphasizing the global need for harmonized implementation and documentation guidelines in the scientific community. From the industry standpoint, by focusing solely on material impact, this study highlights how design decisions shift when the reduction of EC becomes the goal, stressing on the pivotal role of designers in helping users make more informed choices. From a policy standpoint, this study confirms truncation errors with its higher EC outcomes and sheds light on the risk of giving rise to an EE performance gap thus underlining the need for a timely transition towards mandatory EE regulations.

Besides addressing the identified gaps, this study makes two main contributions. The first contribution is practical. By proposing a hierarchical data analysis approach that covers building, element and component, this study allows a gradual gain of insight in understanding design choices that increases in depth with every level of information. This division allows a closer alignment between the requirements for conducting a LCA and the needs of housing designers and practitioners, overall providing a more representative depiction of the housing design process and making LCAs more accessible within the realm of housing design. This study also demonstrates how this gradual gain of insight can be turned into actionable applications for designers and practitioners. It showcases the implementation of insights gained from its hierarchical analysis through modelling an optimized design that confirms further improvement with 29% of additional EC savings. The second contribution is empirical. By conducting detailed partial LCAs of actual dwelling designs, this study serves as a valuable reference on the material impact of smaller, new-build, timber dwellings in the European context achieving outcomes that better reflect real-life scenarios. More importantly, through its meticulous documentation of its research process, study scope and assumptions, and its use of a freely accessible online platform, this study facilitates its replication. Accordingly, researchers and practitioners alike can use this study to build their own models and implement the suggested hierarchical analysis to inform and enhance their design at an early stage, thus improving the EC footprint of dwellings and preventing unnecessary emissions simultaneously.

Despite all outcomes confirming the advantages of smaller timber housing, this study recognizes the practical challenges of their implementation. Many barriers exist, whether in public perceptions, construction practices, or policies. The alignment of such designs with current housing demand, economic feasibility and compatibility with urban planning and housing policies remains to be seen. Considering the aspect of permanence of EC, it becomes worthwhile for future research to investigate current housing preferences, assess affordability and cost-effectiveness, and identify institutional barriers. Such investigations would help in promoting the establishment of practices that align more closely with the environmental imperative of striving for sufficiency. It is also essential to note that this study has certain limitations, including a low geographic representativeness, limited system boundaries, and a focus restricted to the GWP environmental impact indicator. Future research can address these limitations by conducting more extensive geographic analysis, expanding system boundaries and exploring additional climate change indicators for a more comprehensive understanding of the climate impact of smaller, new-build timber dwellings.

CRediT authorship contribution statement

Cynthia Souaid: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Pieter Nick ten Caat:** Writing – original draft, Visualization, Investigation. **Arjen Meijer:** Writing – review & editing, Supervision. **Henk Visscher:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

The study inventory can be found in the supplementary material.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2024.111285.

Appendix B. Step-by-step Guide

- Step 1: Data collection

This step revolves around gathering the necessary data and information needed about the composition of the dwelling/building to be modelled on TOTEM. In the case of this study, data sources varied between bill of quantities (BOQ), architectural drawings, and architectural details provided by housing practitioners.

- Step 2: Data extraction as per the TOTEM taxonomy

Unlike conventional life cycle assessment tools that require quantities in bulks of materials, the TOTEM tool requires data at the building, building element and building component levels. This hierarchical approach is referred to herein as the TOTEM taxonomy. Accordingly, when extracting data from sources such as BOQs, architectural drawings, and details, the following must be retrieved:

At the building level: *How big is the building/dwelling?*

- Gross floor area in square meters,
- Net floor area in square meters,
- Number of floors

➢ In this study, this information was extracted from architectural drawings.

At the building element level: *What are the main elements that make up the building/dwelling?*

- Building element type: examples are pitched/flat/terraced roof, external/internal wall, ground/story floor, main/inside doors, excavation, among others.
- Building element quantity: in square meters for roofs, walls, floors and windows, in linear meters for beams, in units for doors.
- Building element's overall thickness expressed in meters.
- Building element's thermal performance described by the U-value in W/m^2K.
- Building element's lifetime in number of years.

➢ In this study, this information was extracted from both BOQs and architectural drawings.

At the building component level: *What are the main components making up the different building elements of the building/dwelling?*

- Building component type: examples are softwood battens, plywood boards, glass wool blanket insulation, plaster coating, galvanized steel sheets roofing, among others.
- Building component's thickness expressed in millimetres.
- Building component's service life expressed in number of years.

➢ In this study, this information was extracted from both BOQs and architectural details.

- Step 3: Data input as per the TOTEM library[22]

Considering the TOTEM library includes predefined buildings, elements, and components, the user is given a choice between modelling their building/dwelling by employing predefined elements/components or by composing their own. In composing building elements, a match must be made between the details provided by BOQs, architectural drawings, and architectural details and the materials and components provided by the TOTEM library. In this study, all building elements were composed.

- Step 4: Data Output

The environmental impact of the building/dwelling can be extracted from the TOTEM tool at the building, the building element, and the building component levels. The user can filter their data output depending on their specific research goals and scope. In this study, the focus was the embodied carbon of new-build dwellings, otherwise known as the material impact, with a particular focus on the global warming potential.

At the building level: The material impact of the building/dwelling is provided by TOTEM per life cycle stage expressed in $kgCO_{2eq}/m^2$. The addition of all impacts and multiplication per the GFA provides the total material impact of the dwellings in $kgCO_{2eq}$ as per the specific research scope and boundaries.

At the building element level: The material impact of the building elements is provided by TOTEM in percentage shares of the total material impact

[22] Refer to Study Inventory in the supplementary materials for the detailed and complete data input inventory.

of the building/dwelling. The multiplication of this percentage share by the total material impact computed at the building level provides the material impact of building elements in $kgCO_{2eq}$.

At the building component level: The material impact of the building components is provided by TOTEM in percentage shares of the material impact of the building elements in the building/dwelling. The multiplication of this percentage share by the material impact computed at the building element level provides the material impact of building components in $kgCO_{2eq}$.

- Step 5: Data processing and visualization[23]

Data processing and visualization varies depending on the study aim and objectives. In this study, data processing and visualization at the building level was used to situate study outcomes in existing literature. Whereas, data processing and visualization at the building element and building component levels were used to identify carbon intensive elements and components and inform primary and secondary design choices respectively.

- Step 6: Optimized design

Having identified EC intensive design choices, the final step consisted of remodelling the dwelling design according to the knowledge gained in Step 5. This iterative approach, which revisits and refines the initial design based on newly acquired insights effectively closes the design loop.

Appendix B. Operational energy use

In the context of residential buildings, operational CO_2 emissions arise from the combustion of carbon-based fuels (like oil, natural gas, wood) that occur through processes like heating the house with a boiler, warming tap water with a heater, or cooking on a gas stove. These CO_2 emissions are considered to be direct. However, operational CO_2 emissions can also be indirectly generated when using electricity that is produced from fossil fuels. As a result, to accurately assess the CO_2 emissions associated with OE consumption, it becomes essential to account for both gas and electricity usage. In doing so, a comprehensive view can be obtained of the operational environmental impact stemming from the energy needs of residential dwellings.

Various models exist for assessing the OE performance of houses, differing in their level of detail and complexity. These models range from generic ones, which rely on a handful of key parameters like floor area, insulation thickness, types of installations, and location. These are often employed in relation to the EPBD [81]. More intricate models such as Transient System Simulation Program (TRNSYS) demand much more detailed information, including specifics like air leakage areas, and are typically implemented by experts due to their complexity [82].

While these theoretical energy models can provide a preliminary estimate of a house's OE consumption, they often diverge from actual energy usage due to variations in real-world parameters and the dynamic behaviour of residents. This concept is well known in existing literature and is referred to as the energy performance gap [83]. As a result, to accurately gauge the true energy performance of a dwelling, it becomes essential to employ a monitoring approach for OE consumption. This approach ensures that real-life data is collected, offering insights that generic and even detailed models might overlook, which is why it is the approach that was adopted in the H4.0E project.

Within the H4.0E project, the monitoring equipment consisted of electricity meters, indoor climate sensors, and a central hub. The electricity meters were installed in the fuse box of the houses continuously measuring the electricity consumptions at a 5 minute interval. Indoor climate sensors were used to measure indoor temperature, relative humidity and air quality through the level of CO_2 concentration at a 30 minute interval. The central hub collects and stores both electricity and indoor climate data that is sent in regular intervals to the server where it can be accessed for analysis. The monitoring period varied between the dwellings as can be seen in Table B1 Below.

Table B.1
Operational energy monitoring periods.

Dwelling	NL1	NL2	NL3	NL4
Start	06–02-2022	05-03-2022	20-02-2022	05-03-2022
End	23-02-2023	23-02-2023	23-02-2023	23-02-2023

All dwellings had the same heating system installed which consisted of a heat pump and all dwellings had PV panels installed for the generation of renewable energy. Additionally, all installations in the dwellings run on electricity and there are no connections to natural gas. Table B2 presents the total OE consumption resulting from the monitoring of four dwellings. The table lists the dwellings' total uptake and feedback from and to the grid which leads to the net consumption over the monitoring period. These outcomes are then extrapolated to obtain the net energy consumption of the dwellings throughout the year. The yearly energy consumption (presented in kWh) is then multiplied by the CO_2 emissions factor for electricity to obtain the yearly total operational CO_2 emissions in kilograms of CO_2 equivalent. The CO_2 emissions factor for electricity in the Netherlands is 0.456 [84]. Table B2 also provides the energy generated from the PV panels for reference.

Table B.2
Total operational energy consumption.

Dwelling	NL1	NL2	NL3	NL4
Main meter uptake from the grid (in kWh)	3019.3	7517.5	3855.1	6035.3
Main meter feedback to the grid (in kWh)	4252.6	3026.7	5149.9	4631.9
Net consumption (in kWh)	−1233.3	4490.8	−1294.8	1403.4
Net yearly energy consumption (in kWh)	−1226.2	5159.8	−1245.9	1688.8
Total operational CO_2 emissions ($KgCO_{2eq}$/year)	**−559**	**2352**	**−568**	**770**
*PV Panel production (in kWh)	5245.7	5046.9	6779.5	5707.1

[23] Refer to Study Output in the supplementary materials for the data processing and visualization document behind the output presented in this study.

The results exhibit significant variations among the four monitored dwellings, with NL1 and NL3 standing out as energy-positive examples. However, due to privacy constraints, the monitoring data had to be disassociated from the specific monitored dwellings, limiting the ability to directly correlate OE consumption with factors such as dwelling size, NFA, and household size. An in-depth analysis of these correlations could have provided valuable insights into the observed discrepancies. It is important to note that the monitoring encompassed both installation-related energy consumption (heating, cooling, ventilation, hot water) and user-related energy consumption (appliances), and considering the influence of dwelling and household size could have further clarified the variations in the results.

Combining the operational carbon emissions outcomes with the embodied emissions outcomes results in a full energy consumption ranging between 142 and 3062 $KgCO_{2eq}$/year for the Small House, 313 and 3233 $KgCO_{2eq}$/year for the Medium House and 605 and 3525 $KgCO_{2eq}$/year for the Large House. Overall, the total energy consumption results do not reach a net-zero yearly balance despite both the OE-plus and low EC.

These findings are a direct manifestation of the fact that achieving a net-zero balance in terms of carbon emissions of a dwelling is a great challenge. The interplay of various elements, including user behaviour, energy systems, and construction materials, ultimately determines a dwelling's overall carbon footprint. Notably, the results demonstrate that efforts to minimize both operational and EC do not guarantee successful outcomes. Nevertheless, it is crucial to highlight that these findings do not contradict the central argument put forth in this paper, which advocates for a heightened focus on reducing EE. In fact, these results further support this position, particularly when considering the energy-positive dwellings. The outcomes suggest that even greater reductions in EE could have led to the attainment of a net-zero yearly balance. In essence, reducing EE remains a critical priority, as it significantly enhances the prospects of achieving favourable life cycle energy consumption outcomes, especially when considering the element of permanence that is peculiar to EE versus the future decarbonization of the electricity grid which will further decrease the impact of OE.

Indoor environmental conditions

Table B3 presents the average monthly indoor temperature and relative humidity (RH) per dwelling. Indoor temperature thresholds for overheating vary based on regional climate conditions, building design, and individual comfort preferences. In the Netherlands, in dwellings designed to be NZEB, overheating occurs when the indoor temperature is above 27 °C exceeding the 450 WHOs (Weighted Overheating Hours) threshold [85]. The optimal level of the RH falls within the range of 45–60% [86]. As can be seen, the dwellings did not overheat throughout the monitoring period considering the maximum average indoor temperature did not reach 27 °C that summer. The recorded maximum was 26.2 °C in NL1 and NL4 during the months of July and August 2022. Nevertheless, this does not exclude the possibility of overheating in the future. For that, there are certain post-construction strategies that can be implemented to mitigate this issue. The most common ones are shading to block direct sunlight and cross-ventilation.

Table B.3
Indoor environmental conditions in the dwellings throughout the monitoring period.

		NL1		NL2		NL3		NL4	
Monitoring period		06-02-2022 23-02-2023		22-07-2022 23-02–2023		20-02-2022 23-02-2023		05-03-2022 23-02-2023	
Year	Month	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
2022	February	21.3	46.5	–	–	20.8	43.2	–	–
	March	22.9	40.3	–	–	21.7	38.4	19.4	47.5
	April	23.1	42.0	–	–	21.7	40.6	19.7	48.4
	May	24.7	45.7	–	–	21.8	46.7	22.5	50.5
	June	25.8	48.6	–	–	22.5	50.8	25.2	50.2
	July	25.7	50.4	23.8	52.6	22.5	52.6	26.2	49.9
	August	26.2	53.0	25.3	52.9	23.2	54.6	26.0	52.3
	September	24.0	51.0	22.7	51.6	21.3	52.3	21.5	54.1
	October	23.0	54.0	21.2	54.7	20.7	53.9	21.2	56.0
	November	21.0	52.3	20.5	50.1	20.0	50.8	18.8	53.6
	December	19.2	48.3	19.3	44.5	19.6	44.0	16.4	50.6
2023	January	19.7	49.3	20.6	44.7	19.5	45.7	17.8	50.9
	February	20.1	50.5	20.8	44.4	20.0	45.1	17.8	50.1

Appendix C. Miscellaneous

Figure C1. displays the assumptions around the end-of-life scenarios of the main building components used in this assessment.

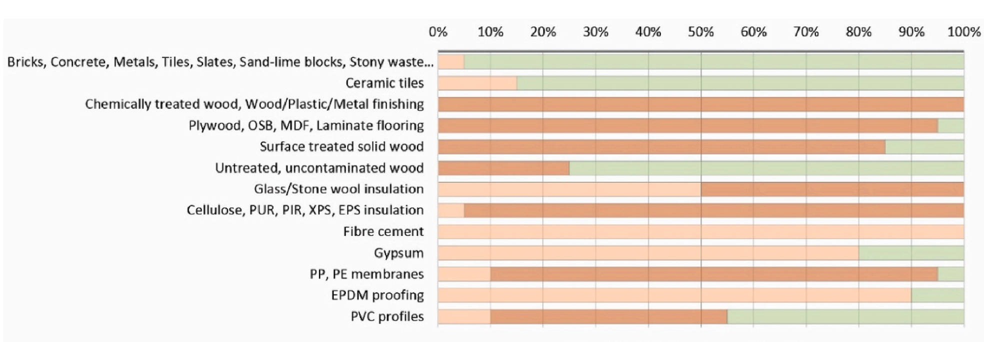

Fig. C.1. End-of-life scenarios (adapted from Ref. [52]).

Figure C2 displays the material impact of different insulation types versus their thermal performance. Generally, soft insulations have a lower material impact than rigid insulations. Yet, within the different types of soft insulations, cellulose insulation has the lowest material impact while maintaining a similar thermal performance as its counterparts.

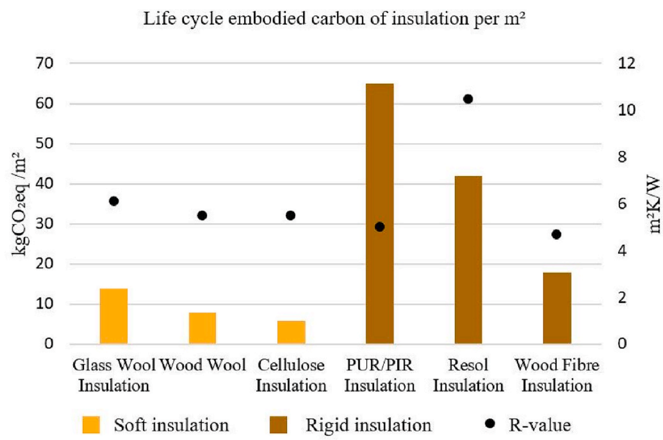

Fig. C.2. Material impact versus thermal performance of different insulation types for the same thickness of 220 mm.

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