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Lessons from architectural practice

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Low carbon design strategies for new residential buildings - lessons from architectural practice

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Low carbon design strategies for new residential buildings - lessons from Danish architectural practice

This study presents the environmental life cycle assessment of four low carbon design strategies applied in Danish, architectural practice. The subject of analysis is a set of five buildings erected within the same constrictions in terms of floor area, operational energy performance and construction costs. The four tested design strategies were: the use of recycled materials, design for extended durability of components, adaptable design, and design for reduction of operational energy demand. The results of the five buildings are compared with a reference building (i.e. a typical, Danish single-family dwelling). Results show that the recycling/upcycling strategy is the most effective in reducing the embodied carbon. The use of structural wood in the same design furthermore points to the use of wood as a viable strategy for improving the carbon footprint of buildings. In combination, these two strategies result in an approximate 40 % saving of life cycle embodied carbon compared to the reference building. The design strategy of using durable materials yields up to 30 % lower embodied carbon compared to the reference building, whereas a design for adaptability results in 17 % lower embodied carbon. However, these results are sensitive to the scenarios made for the service lives of materials and the implemented disassembly solutions. In a life cycle carbon perspective, the emissions from energy use prove to be of importance, although depending on the modelling approaches of the energy mix. With the shrinking, global carbon budgets in mind, there is justified reason to holistically optimize the design of new buildings by integrating various design aspects addressing the whole life cycle of the building.

Keywords: embodied carbon; life cycle assessment; building design; mitigation strategies, carbon budgets

Introduction

Low carbon building design denotes the concept of minimising greenhouse gas emissions from the life cycle of the building, and is a concept receiving increased attention in recent years from building research, practice and policies (Pomponi, De Wolf, & Moncaster, 2018). For decades, reductions of operational carbon have been in focus, for instance via the European Energy Performance in Buildings Directive (EPBD), resulting in all European Union countries addressing the issue at an ambitious level.

Research has previously pointed to the shifting energy balances of the life cycle stages in new constructions with low operational energy demands (see e.g. Feist, 1996; Sartori & Hestnes, 2007). Recently, the near-zero energy building (NZEB) concepts for new buildings and retrofits have also brought the challenge about embodied environmental impacts in focus. This is due to the accumulated impacts from limited (or zero) energy use being superseded by the embodied impacts associated with production, replacements and end-of-life (EoL) treatment of materials (Blengini & Di Carlo, 2010;

Georges, Haase, Houlihan Wiberg, Kristjansdottir, & Risholt, 2015; Lützkendorf, Foliente, Balouktsi, & Houlihan Wiberg, 2014; Rasmussen & Birgisdóttir, 2016b).

Countries, organisations as well as policy-makers have taken up the theme of embodied impacts in strategies and specific initiatives (Lützkendorf, 2017). In parallel, European as well as international standards offer a common, specified framework for life cycle assessments of buildings (CEN, 2012b; ISO/TC 59/SC 17, 2017). The multitude of initiatives indicate that there is a growing awareness of the need to address the embodied impacts associated with the built environment.

In Denmark, an increasing number of building designers attempt to incorporate LCA perspectives in their integrated design (Landgren, Jakobsen, Wohlenberg, & Jensen, 2018). However, since no regulation on the topic is in place, the incentive to integrate LCA mainly relates to the building certification schemes requiring it, such as the DGNB scheme (Danish Green Building Council, 2016). In a series of interviews with Danish practitioners, Sørensen et al. (2020) showed how design practitioners address the environmental perspective of design solutions based on experience from earlier projects where LCA have been in focus. Only few companies have the sufficient in-house LCA expertise to apply LCA consistently on their building projects (Sørensen et al., 2020), and the application of existing low carbon strategies, from outside the company, is thus potentially useful.

Existing research include several individual case studies in which design options are tested, although, in general, only one design parameter is evaluated at a time, e.g. using bio-based materials (Salazar & Meil, 2009; Sodagar, Rai, Jones, Wihan, & Fieldson, 2011), design for disassembly (Tingley & Davison, 2012; Eberhardt, Birgisdóttir, & Birkved, 2018) or design for low operational energy use (Kristjansdottir, Heeren, Andresen, & Brattebø, 2017). However, these single-case examples apply different methodological approaches in the LCA. This means that it is challenging, if not impossible, to use individual case studies, to determine which strategies are most efficient in achieving low carbon building designs (Malmqvist et al., 2018).

There are also examples of design strategies evaluated on the basis of larger samples of existing buildings. For instance, De Wolf (2017) evaluated different design strategies for low carbon structural design of existing buildings. A large-scale Norwegian research project evaluated the different pathways to achieving 'zero emission buildings' of different levels of ambitions (Wiik, Fufa, Kristjansdottir, & Andresen, 2018). The larger sample sizes of these studies ensure a harmonised methodological approach although the assessed buildings vary notably as functional entities, e.g. in terms of type, size and location.

In summary, there is a knowledge gap regarding similar types of cases from architectural practice presenting various low-carbon design strategies assessed by use of comparable methodological approaches.

In 2013, the five MiniCO_2 houses were planned and erected as a demonstration project in Nyborg, Denmark. The project aimed at demonstrating how CO_2 reductions in the built environment can be carried out via focus on different life cycle stages of the building. Realdania By & Byg, a subsidiary of the Realdania philanthropic organisation, funded the design development and set a common framework for the buildings concerning size (135-150 m^2 floor area – housing for a family of four, construction costs, and operational energy performance of the buildings corresponding to the 'low-energy' building code 2015 (The Danish Transport and Construction Agency, 2015).

Due to the similar outset of the five MiniCO_2 houses concerning, location, size and costs, they represent an opportunity to evaluate real examples of applied low carbon design strategies within the Danish context of building and assessment practice.

The following research question serves as the backbone of the analyses:

- How do the design strategies of the five MiniCO_2 houses, targeting four different life cycle stages, perform in life cycle and embodied carbon emissions against a reference building design?

The assessments of the buildings are carried out applying a consistent methodological framework used in the Danish assessment context, and thus provide examples of how well each design strategy performs in comparison to a traditional new-built dwelling. The focus of the five MiniCO_2 houses and the Reference House are displayed in Table 1. Table 1 also displays the low carbon design initiatives employed by the design teams of the different buildings.

Materials and methods

LCA is used as the core method to evaluate the carbon profiles, i.e. the life cycle greenhouse gas (GHG) emissions of the MiniCO_2 houses. The goal of the LCA study is to use a commonly applied Danish LCA method to compare the MiniCO_2 houses and their individual CO_2 minimizing focus against a typical, Danish detached dwelling, the Reference House. The functional equivalent is expressed by 1 m^2 gross floor area (GFA) per year of building service life, which is set as 120 years for all buildings. This functional equivalent is chosen because it is the functional equivalent prescribed by the common, national approach described in the following.

The LCAs of the buildings are carried out with the methodological approach developed as part of the national adaptation of the DGNB certification scheme for sustainable buildings. This common method, based on the EN 15978 standard, was collaboratively developed by the Danish Green Building Council, the building authorities, industry stakeholders and research bodies (Birgisdóttir & Rasmussen, 2019; Danish Green Building Council, 2016; Rasmussen & Birgisdóttir, 2016a). The common LCA method specify core methodological choices such as the functional equivalent, or the service life of materials on a general level. However, the general method was adapted for this research in some areas to assess the attributes of the different MiniCO_2 houses' designs. The common LCA method and the adaptations used in this study are illustrated in Figure 1 and described in detail in the following sections. Figure 1 further specify the sensitivity checks used to evaluate the assumptions for the MiniCO_2 Houses.

Table 1. Table 1. Details of the six assessed buildings.

Table 1. Details of the six assessed buildings

Case building	Upcycle House	Maintenance Free House (MFH)		Adaptable House	Quota House	Reference House
		Traditional	Innovative			
Size, GFA (m^2)	134	136	139	146	141	150
Core CO_2 minimizing focus	Reduction of embodied emissions from materials from construction	Prolongation of service life of materials and building, thereby reducing embodied emissions from replacing materials in the building's use stage. Employing a traditional architectural expression	Prolongation of service life of materials and building, thereby reducing embodied emissions from replacing materials in the building's use stage. Employing an innovative architectural expression	Reduction of embodied emissions from materials used for refurbishing/expanding building.	Reduction of operational emissions from energy consumption in the building's use stage	None intended
CO_2 minimizing design initiatives	Sourcing second-hand/reused materials, e.g. EPS from packaging waste, steel container from shipping industry, windows discarded by manufacturer Sourcing building materials with large fractions of recycled input , e.g. aluminium plate, gypsum boards, wood-plastic composite	Attention towards designing building envelope in homogenous, durable material (brick) to avoid construction layers with low service life. Designing with large overhangs that protect vulnerable elements (windows and doors) against wear and tear	Cladding of the structural frame in tempered, naturally ventilated glass. Designing with large overhang that protects vulnerable elements (windows and doors) against wear and tear	Interior design made with movable inner walls. Building envelope designed for disassembly, i.e. flexible for expansion with direct reuse of elements	Building design 'nudging' to low-energy behaviour, e.g. cooling chamber for food storage, roofed terrace for drying clothes Integrated 'smart' technology, e.g. self-regulating thermostats on radiators Built-in devices that creates awareness about consumption, e.g. showerhead that turns on a red light after 5 minutes of showering.	None intended
Structural principles	Structural frame by use of two 40 feet high cube containers. Wood-based floor and roof constructions. Steel-screw foundation	Load-bearing brickwork in exterior and core inner walls. Concrete slab and wood-based roof construction. Concrete strip foundation	Pre-assembled wood-framed modules coated with tempered glass. Inner concrete core around bathroom. Concrete well foundations	Load-bearing external walls of aerated concrete blocks in two storeys. Built-up roof. Concrete strip foundation	Load-bearing external walls of aerated concrete blocks in one storey. Built-up roof. Concrete strip foundation	Load-bearing external walls of concrete-mineral wool – brickwork. Concrete slab and wood-based roof construction. Concrete strip foundation

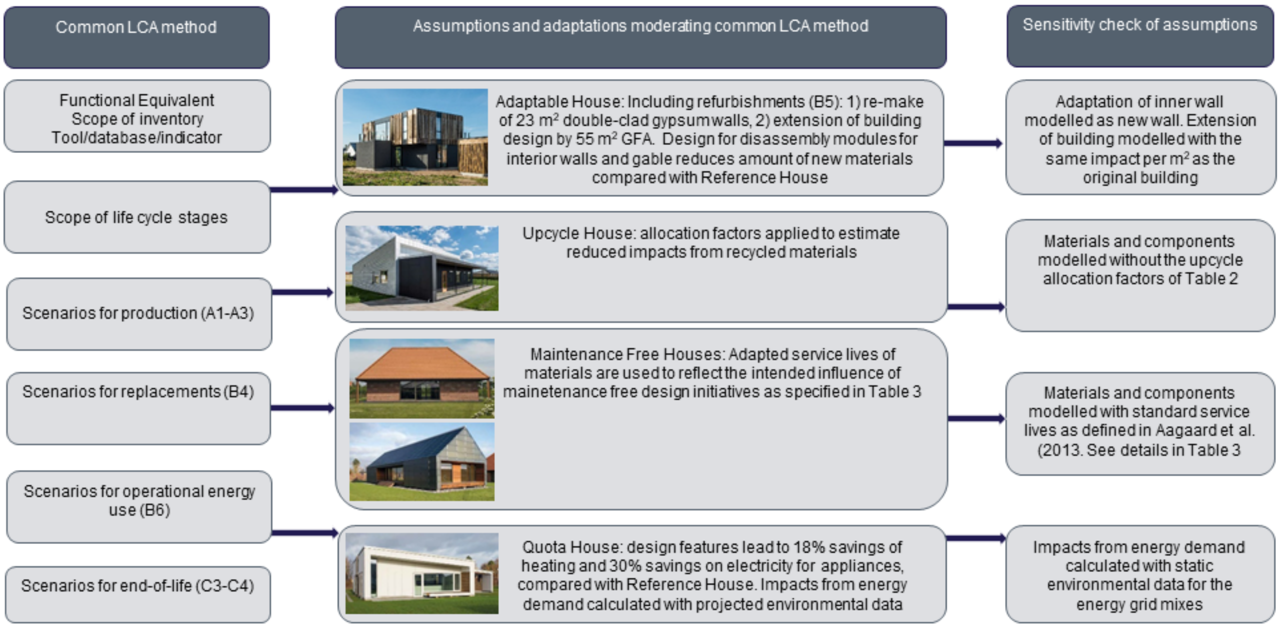

Figure 1. The methodological set-up of current study: The common LCA method, the adaptations/assumptions and the sensitivity check of these assumptions.

Common LCA method

Scope of inventory

All building materials and main technical equipment for the buildings are modelled as declared by the design teams. Inventories were manually checked for consistency and eventually validated by the design teams. The inventory scope reflects the assessment practice of Danish building LCAs as expressed in the Danish adaptation of the certification scheme DGNB (Danish Green Building Council, 2016). The scope covers foundations, frame, external walls, doors and windows, internal walls, staircases, roof, floor, ceiling, and central, technical aggregates. The inventory does not include connective items (e.g. screws and nails) nor technical distribution systems due to the cut-off rules of EN 15978 and the Danish adaptation of the DGNB LCA method (CEN, 2012b; Rasmussen et al., 2019). Detailed inventories can be found in supplementary material.

Tool, database and indicator

The LCAbyg tool (Birgisdóttir & Rasmussen, 2019) was used for modelling of the buildings. The tool integrates the Ökobau 2016 database which is a database that provides environmental impact potentials from pre-defined flows of specific building products and materials (Gantner, Lenz, Horn, von Both, & Ebertshäuser, 2018). The allocation of product and emission flows between systems follows the 100:0 method as implemented in Ökobau 2016 in accordance with the EN 15804 standard (CEN, 2012a)

The impact category used for expressing the carbon profiles of the buildings is the Global Warming Potential (GWP_{100}), expressed in kg CO_2 equivalents (CO_2eq) as found in the Ökobau 2016 database. The category refers to the characterisation method of CML-IA version 4.1, Oct 2012 (University of Leiden, 2012).

Scope of life cycle stages

Embodied impacts are assessed for all buildings, i.e. life cycle stages (modules according to the EN 15978 standard); Production (A1-A3), Replacements (B4), Waste treatment (C3) and Disposal (C4). These key life cycle stages for the embodied impacts constitute the scope frequently applied in assessment practice (see e.g. Moncaster, Rasmussen, Malmqvist, Houlihan Wiberg, & Birgisdottir, 2019) and is used in the common, national method.

Scenarios for production (A1-A3)

Data used for the production stage of building materials includes exchanges with the environment from extraction of materials, transport and manufacturing as specified in EN 15804 (CEN, 2012a).

Scenarios for replacements (B4)

Building products are assumed replaced at the end of their service life. The replacement step involves production of a new building product and EoL treatment of the displaced material. Default service lives of building products and materials under Danish conditions are taken from Aagaard et al (2013).

Scenarios for operational energy use (B6)

The common LCA method includes the calculation of impacts from operational energy use in the building. For the current study, operational impacts are only calculated for the Quota House, being the building with this particular design focus, and the Reference House for comparison. The carbon emissions from the provided energy are based on the Danish electricity mix and the national average of district heating respectively. These mixes are modelled to reflect the future development of the grids towards the adopted, political agreements for low-carbon energy supply by 2050. Figure 2 displays the projected carbon intensity of the two energy carriers as they have been modelled for the Danish authorities (COWI consulting, 2016).

Scenarios for end-of-life (C3-C4)

Data and scenarios used to calculate impacts from waste handling (C3) and disposal (C4) correspond to standard Danish practice at the material level (Birgisdóttir & Rasmussen, 2019).

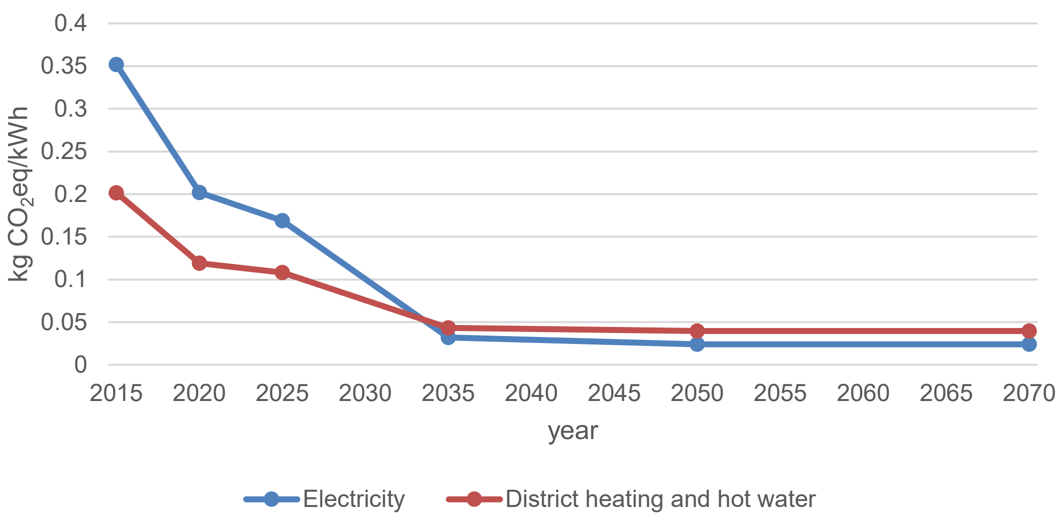

Figure 2. Modelled projection of the carbon intensity of the national Danish energy grids (based on COWI Consulting, 2016).

Adaptations of common LCA method

In this section, the assumptions and adaptations of the common LCA method are presented in detail for the individual building designs of this study. The assumptions are based on the design teams' own expectations in terms of durability of components, in terms of adaptability of construction solutions, and in terms of the energy demand in the building. For the Upcycle House, the factors used for impact calculations are derived by the authors.

Adapted scope of life cycle stages: Refurbishments

Besides the life cycle stages included as part of the common LCA method, the Adaptable House and the Reference House furthermore include evaluation of a refurbishment (B5) scenario. In both cases, the refurbishment scenario involves 1) an interior re-make of room partitions of a total of 23 m^2 double-clad gypsum walls, 2) an extension of the existing building design by 55 m^2 GFA.. The Adaptable House is constructed in a modular concept with elements designed for disassembly. This leads to the assumptions that a lower amount of materials are needed for the refurbishment actions in the Adaptable House than in the Reference House. Details on the specific material amounts can be found in the supplementary material. It is assumed that the buildings, after refurbishments, provide the same function as earlier, i.e. housing of a family of four.

Adapted scenarios for production: Upcycle allocation factors

For the Upcycle House, production data are modified to reflect the reused/recycled content of materials.

This modification is applied due to data gaps in the life cycle impact assessment data used for the upcycled materials, i.e. the aggregated impacts from processes taking place between the end-of-waste state of the previous system and up to the re-manufacturing of the product in the building system under study (Rasmussen, Birkved, & Birgisdóttir, 2019). Two distinct approaches are made for these calculations depending on the recycling type being characterized as direct or indirect. Indirect recycling is here defined as a material being made from processed waste, thereby changing the original, physical properties of the recycled product. For the indirect recycling, environmental impacts are calculated based on the recycled content of the materials used, assuming that the recycled materials come practically burden free, save for some preparatory processes (e.g. shredding of the expanded polystyrene (EPS), see Table 2). Direct recycling is here defined as a material or component being sourced and used in its current form without a change in its physical properties, i.e. reuse. For the direct recycling of products or materials, no harmonised approach exists on how to adapt and allocate the environmental impacts (Eberhardt et al., 2018) In this study, economic allocation (based on the market prices of new and upcycled materials) is applied to distribute the impacts between virgin and recycled product. This approach is based on the work of Sander (2012). In this way, impacts of directly recycled materials are calculated from data on virgin material multiplied with an upcycle-factor that expresses the relationship between prices of the upcycled product and the total price of the material in a 2-loop system, i.e. where the virgin material is processed and sold in the first loop, then sold as upcycled material and later as waste material in a second loop. The upcycle factor is calculated as:

$$Fu = \frac{Pu}{Pu+Pi+Pw} \quad (1)$$

Where Fu is the upcycle factor, Pu is the price of the upcycled product, Pi is the initial price of the virgin product and Pw is the price of the waste after use (Sander, 2012).

Table 2 specifies the upcycle-factors used for the calculation of specific materials from direct and indirect recycling. Material recycling are, in some cases, e.g. aluminium or OSB boards, common industrial practice. Generic data of Ökobau can be expected to already incorporate the recycling benefits of those cases although documentation about this is limited. Hence, to avoid doublecounting of recycling benefits in current study, the upcycling factor is only applied to materials where direct/indirect reuse or recycling is judged *not* to represent common industrial practice.

Table 2. The calculation factors used to modify LCA data from virgin materials.

	Product/material		Upcycle factor of material production
Direct recycling (Sander, 2012)	Shipping container	Price of waste represents price of metal scrap waste	0.12
	Construction wood	Construction wood is primarily sourced from demolished buildings. The price of the reused wood is considered the same as the price of wood for incineration	0.14
	Windows	Upcycled windows are provided from flawed glass production that is being sold from the manufacturer to the design/construction team	0.12
Indirect recycling	Wood-plastic composite	This product is made of recycled paper 60 % and recycled polypropylene 38 %. Assuming recycled wood/plastic is burden-free. The factor is based on Sommerhuber et al. (2017) specifying the GWP contributions from virgin products to the wood-plastic-composite: HDPE (44%), wood particles (13%), leaving 43 % as process related impacts	0.43
	Gypsum boards	The selected gypsum board manufacturer operates production with 25 % of recycled input which is then considered burden-free	0.75
	Expanded polystyrene	Upcycled styrofoam is produced from discarded shock absorber product packaging. This production process requires only sorting and shredding of the Styrofoam. Impact is calculated based on impacts from energy mix use for shredding (specifications from shredder with the specifications of 8 kW, 350 kg EPS/h)	0.0078 kg CO_2eq/kg EPS

Adapted scenarios for replacements: Longevity of materials

For the Maintenance Free Houses, a set of adapted service lives are used to reflect the intended influence of maintenance free design initiatives as specified in Table 3.

Table 3. Number of replacements in the modelled Maintenance Free Houses (MFH) and the Reference House. Numbers in parentheses specify the number of replacements in the Maintenance Free Houses if following the service life table by Aagaard et al. (2013) used in the common LCA method.

	MFH Traditional	MFH Innovative	Reference House
Deck, insulation	0 (1)	0 (1)	1
Wall, insulation	0 (0*)	0 (1)	1

Wall, covering	0 (0)	0 (1)	0
Roof insulation	0 (2)	0 (2)	2
Roof covering	0 (1)	0 (1)	1
Window frames	1 (1)	1 (1)	1
Window glazing	2 (4)	2 (4)	4

* Not relevant, since the wall is constructed with a monolithic, insulating building system of fired clay blocks

Adapted scenarios for operational energy: Quota House

Impacts from operational energy use are calculated for the Quota House and the Reference House. In both cases, the energy demands for building operation are calculated by the engineering consultants of the Quota House (MOE engineers, 2016). The operational energy demand is calculated as the total demand for heating, hot water and ventilation in accordance with the mandatory thermal energy calculations of new residential buildings in Denmark (The Danish Transport and Construction Agency, 2015). The energy demand for the Reference House is modelled as 44.5 kWh/m^2/y of heating and hot water provision, and 2.6 kWh/m^2/y of electricity for building ventilation. In the Quota House, expectations based on the building design and technology, amount to a saving in heating of almost 18 % compared to the Reference House, resulting in an expected demand of 36.9 kWh/m^2/y of heating and hot water and 2.7 kWh/m^2/y of electricity for building ventilation. The thermal energy for all the MiniCO_2 Houses is provided by district heating supply.

Energy demand for the users' appliances is included in calculations of the Quota House and Reference House due to the building design of the Quota House aiming to also reduce this part of the energy use. Estimations of energy use for appliances are based on average data for Danish households within the categories of entertainment, cooking, lighting, refrigerators, tumble drying, clothes washing, dishwashing and other (MOE engineers, 2016). For the Reference House, the electricity demand amounts to 3762 kWh/year. In the Quota House, an expected saving of approximately 30 % results in an expected electricity demand of 2595 kWh/year.

Sensitivity check of assumptions

The sensitivity of a model describes the extent to which the variation of an input parameter or a choice leads to variation of the results (Rosenbaum, Georgiadis, & Fantke, 2018). LCA results are potentially sensitive to a range of uncertainty types, e.g. concerning data variability as well as parameter-, model-, and scenario uncertainties (Huijbregts, 1998). On a general level, there are two types of methods applied for sensitivity analyses in LCA: the local sensitivity analysis that determines the effect of a change in one of the input parameters at a time, and the global sensitivity analysis that determines the effects of parameters when these may vary over a significant range of uncertainty (Groen, Bokkers, Heijungs, & De Boer, 2017; Wei et al., 2015).

This study of the MiniCO_2 Houses is confined within the common Danish LCA method as earlier described. Hence, it is not of immediate relevance to test parameter variations of, for instance, materials' service lives, because these are set as default boundary conditions of the current practice. However, this study challenges the common method in terms of the model adaptations and assumptions. Thus, to test the sensitivity of the conclusions drawn from these assumptions, a discrete check of the scenarios for each building was performed. This means that each of the MiniCO_2 Houses is modelled for a sensitivity check with the default, standard assumptions and calculation rules that form the base of the common LCA method (and of the Reference House model). The only exception from this is the sensitivity check of the Quota House that concerns the carbon intensity of the provided energy. Table 4 specifies how the building models are adapted for the sensitivity check.

Table 4. Modelling details of the sensitivity checks.

Upcycle House	Materials and components modelled without the upcycle factors defined in Table 2
MFH Traditional	Materials and components modelled with standard service lives as defined in Aagaard et al. (2013). See details in Table 3
MFH Innovative	
Adaptable House	Adaptation of inner wall modelled as new wall. Extension of building modelled with the same impact per m^2 as the original building
Quota House	Impacts from energy demand calculated with static environmental data for the energy grid mixes

Results and discussion

The GWP in kg CO_2eq/m^2/year obtained for each of the five MiniCO_2 Houses and the Reference House are shown in Figure 3. The figure presents the contribution of the life cycle stages covered for each building and further highlights the life cycle stages that were targeted by the individual design strategies. For comparison, the aggregated embodied carbon in Figure 3 denotes the scope of the life cycle stages calculated for all the buildings, i.e. the production (A1-A3), the replacements (B4) and the waste treatment and disposal (C3-C4).

The results presented for the Adaptable House furthermore include GWP for refurbishment and the Quota House results include GWP related to energy use. The Reference House, being the building to which the other result sets are individually compared, include GWP from all life cycle stages covered by the study's LCA.

Figure 3 presents how the production stage impact of the Upcycle House is lower than the production stage of the Reference House to the extent of actually presenting a net CO_2eq saving. The use of recycled materials contribute, as anticipated, to the low impact results of the building. However, the negative GWP is only possible due to the background database accounting for the storage of biogenic carbon in wood-based products. The stored carbon is emitted in the waste treatment stage, i.e. the eventual incineration, which explains why this life cycle stage of the Upcycle House is notably higher than that of the Reference House.

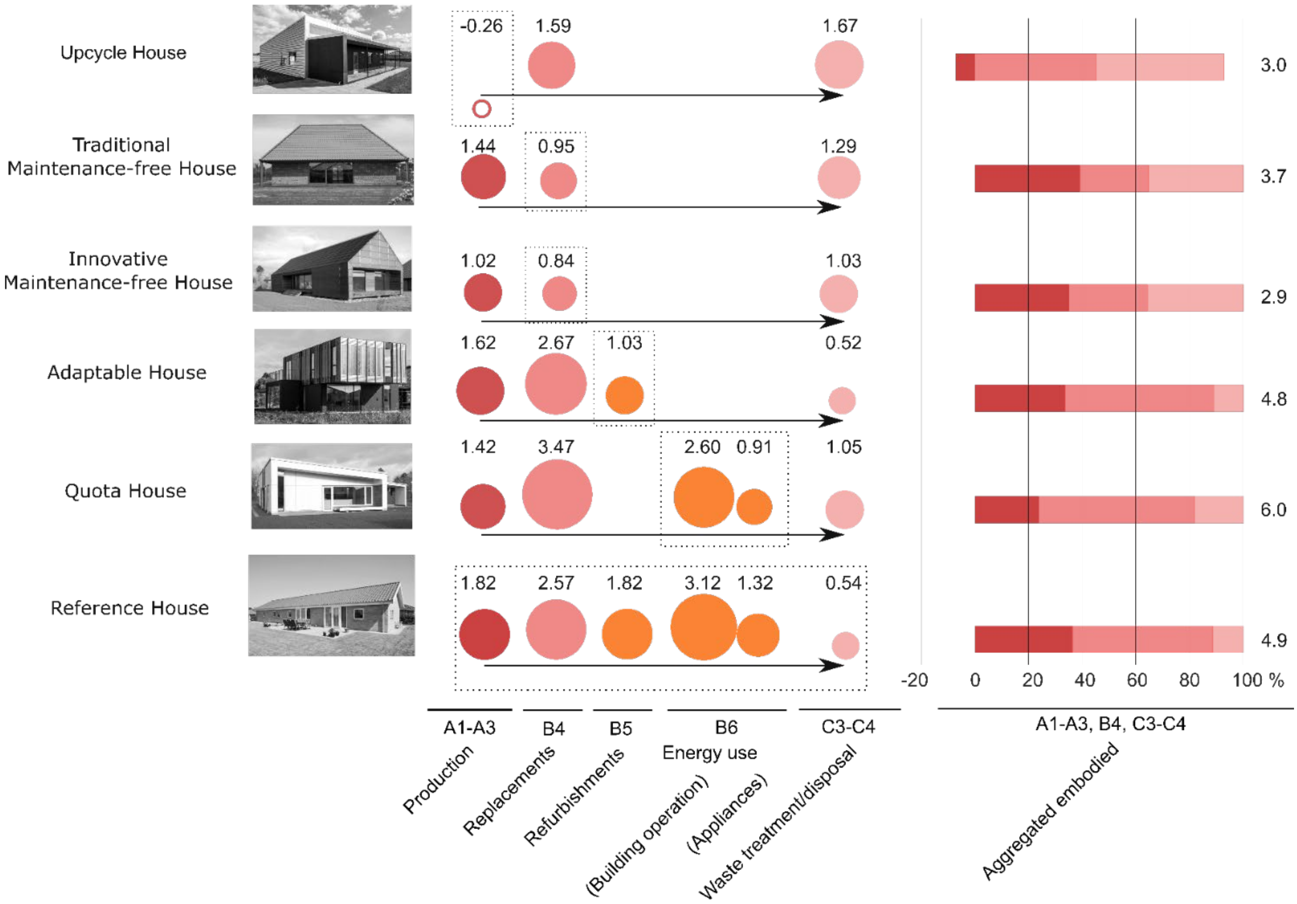

Figure 3. The GWP contributions in kg CO2eq/m2/year and percentages from the life cycle stages of the five MiniCO2 Houses and the Reference House. The life cycle stage(s) in focus within each project is marked by the dotted lines.

In the MFH Traditional and the MFH Innovative, the impacts induced by the recurring replacements of materials throughout the life cycle of the building are 66-70% lower than the baseline scenario for replacements (B4) represented by the Reference House. The assumptions about durability of materials in the MFH's are key parameters for the profiles of these buildings. Thus, only half the number of window replacements are assumed necessary for the MFH's, due to their roof designs integrating large overhangs to protect windows from wear and tear. Furthermore, the building envelopes, including the insulating layer, are assumed to endure for the same number of years as the building itself. This is not the case for the Reference House where the insulation is assumed to be replaced after a service life of 80 years in accordance with the Danish guidelines for replacements of building materials (Aagaard et al., 2013).

In the Adaptable House, the design for adaptability and disassembly ensures a potential GWP saving from the refurbishment stage (B5) that is 47% lower than that of the Reference House. The lower impacts from the Adaptable House reflect that the Adaptable House does not need additional materials for the rearrangement of inner walls, and only a limited amount of materials for the building extension is needed since the existing elements can be reused directly.

The Quota House is designed to nudge its residents towards a limited use of energy in relation to building operation (mainly heating and hot water) as well as for appliances (entertainment, cooking, washing etc.). Figure 3 reveals how the 2.6 and 0.91 kg CO_2eq/m^2/year associated with energy use for building operations and appliances total an emission of 3.5 kg CO_2eq/m^2/year, which is 21% less than the total of the Reference House. On the other hand, the aggregated embodied carbon from the Quota House is 22% higher than that of the Reference House.

In-depth results and sensitivity checks

In the sensitivity checks of the MiniCO$_2$ Houses, each building is subject to a critical evaluation of its specific design strategy and the assumptions made for its assessment.

Upcycle House

The design strategy applied for the Upcycle House targets the production stage of the building. Thus, a low-carbon profile is ensured by using recycled and upcycled materials that are partly burden-free (see Table 2 for the impact share in relation to virgin materials). Figure 4 presents how the composition of materials applied for construction of the Upcycle House and the Reference House are notably different.

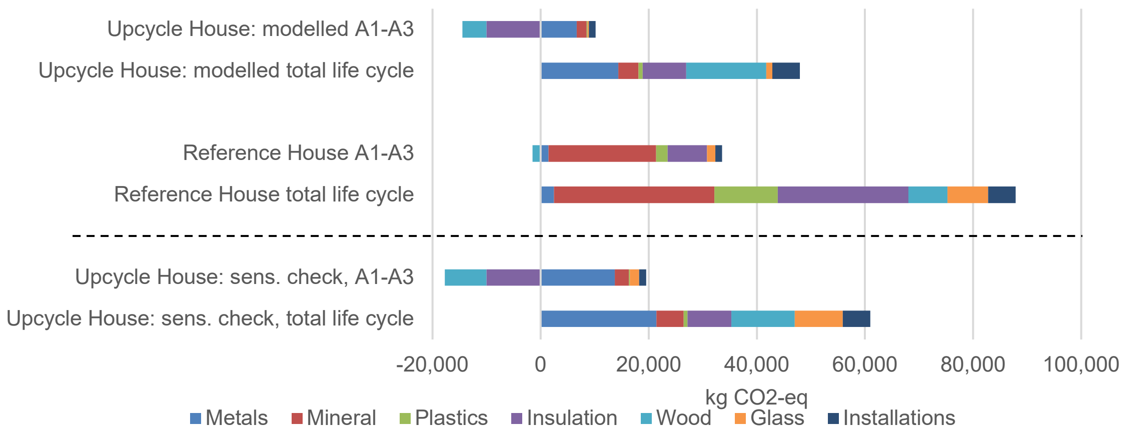

Figure 4. Details of Upcycle House with and without Upcycle-factors (refer Table 3).

This material difference relates to the structural materials of the Reference House being of mineral origin (concrete and bricks) whereas the structural parts of the Upcycle House consists of recycled metal and wood. In the sensitivity check of the Upcycle House presented in Figure 4, the materials are modelled without the impact reduction associated with the upcycling factors of Table 2. This means that all elements are modelled as produced from virgin materials. The associated impacts of the building are still notably lower than the Reference House although the contributions from the virgin glazing and steel components affect the GWP advantage of the production stage of the

Upcycle House. Consequently, the aggregated embodied carbon of the sensitivity check model of the Upcycle House corresponds to 69% of the Reference House's life cycle embodied carbon. Hence, even with virgin materials there is a carbon saving from the specific design compared to the Reference House.

The stored carbon plays an unmistakable role in the results of the Upcycle House. In the life cycle perspective of the Upcycle House, carbon neutrality is assumed, which means that the stored carbon in the production stage is balanced by corresponding emissions from the waste treatment, i.e. incineration (see Figure 2). In reality, the building design thus reflects the low-carbon benefits of recycling as well as the benefits of using wood based materials - under the specified assumption of carbon neutrality. In the research community, there are diverging approaches to the way stored carbon is included or excluded from carbon footprints of products (Brandão et al., 2013; Tellnes et al., 2017). Further, the simplified carbon neutrality assumption can be criticised for not properly taking into account the temporal significance of carbon fluxes from biomass growth, harvesting and degradation, which is related to the rotation time of the biomass growth (Cherubini, Peters, Berntsen, Strømman, & Hertwich, 2011). Additionally, the GWP impact category in LCA is an emission-based metric that does not include biogeophysical factors (e.g. the albedo-effect) contributing to global warming (Bright, Cherubini, & Strømman, 2012).

Maintenance Free Houses

For both Maintenance Free Houses (MFH), the focus of the design strategy is on durability of the building components. Figure 5 reveals how, when applying the assumptions (see Table 3), the design strategy successfully achieves a reduction in life cycle embodied carbon of 26-30% compared to the Reference House. Figure 5 further pictures a sensitivity check for the MFHs without the assumptions about durability and longevity, i.e. applying standard, reference service lives of materials as modelled in the Reference House. In the sensitivity check, only the Traditional MFH performs better than the Reference House in a life cycle perspective. In this scenario, the Innovative MFH more than triples the impacts associated with replacement of materials. This remarkable change is caused by the more frequent replacement of materials of the building skin as well as replacements of the relatively larger window areas.

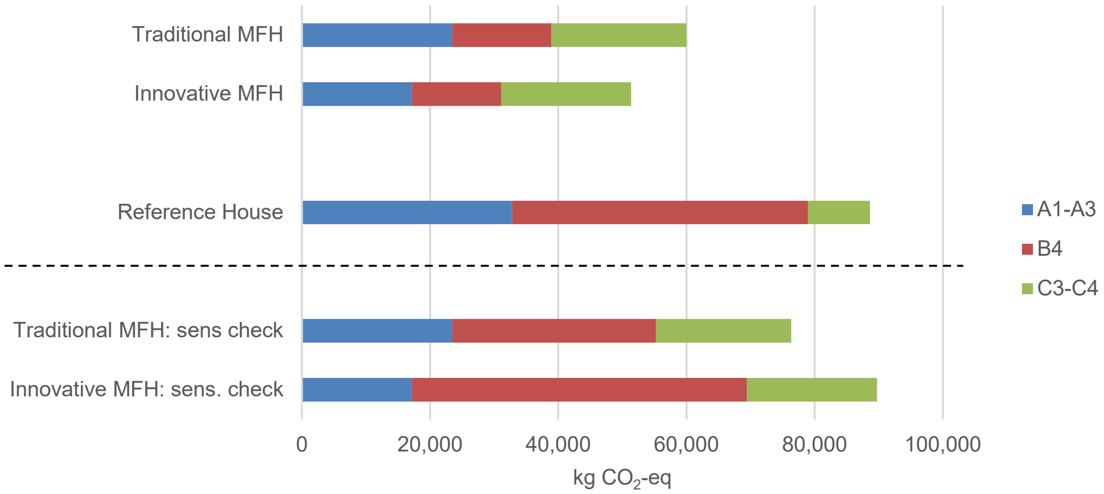

Figure 5. Details of the Traditional and Innovative MFHs and the Reference House.

Adaptable House

The design strategy applied for the Adaptable House focuses on the refurbishments occurring throughout the building's use stage. Figure 6 presents the impacts from the two defined refurbishment actions, i.e. rearranging internal walls and expansion of the existing building. The impacts associated with rearranging internal walls are burden-free in the Adaptable House. However, the action of rearranging internal walls constitutes only 2 % of the life cycle embodied carbon of the Reference House. The expansion adds a considerable share of 37 % to the life cycle embodied carbon of the Reference House. Due to the design for disassembly initiatives of the Adaptable House, the expansion corresponds to only 56 % of that of the Reference House, giving the Adaptable House an overall impact advantage of 20 tons CO_2eq, i.e. 17 % better than the Reference House if assessed in terms of life cycle embodied carbon from life cycle stages production (A1-A3), replacements (B4), refurbishment (B5) and waste treatment and disposal (C3-C4). In the sensitivity check, the advantage of the Adaptable House diminishes to perform only 4 % better than the life cycle embodied carbon of the Reference House.

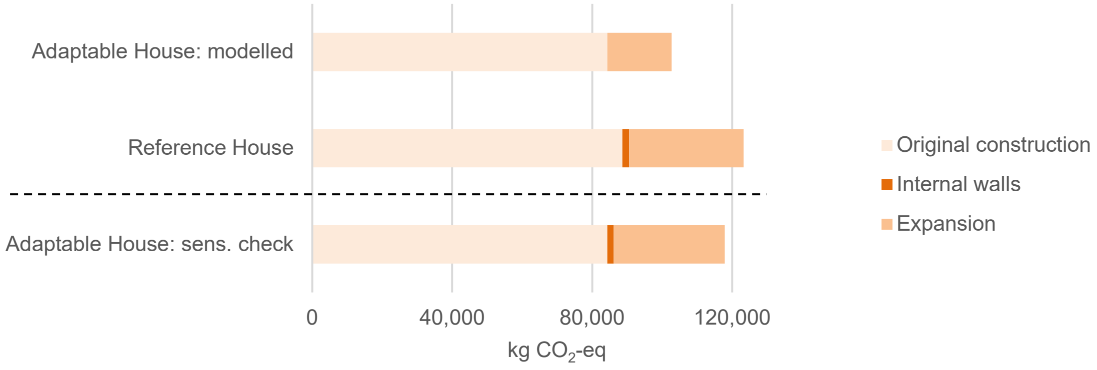

Figure 6. Details of the refurbishment actions modelled for the Adaptable House and the Reference House.

Quota House

Figure 7 displays details of the embodied and operational impacts of the Quota House and the Reference House calculated with the projected energy mixes of the common LCA method. In spite of the expected energy savings from the Quota House, the overall performance equals that of the Reference House, because the embodied impacts induced by the Quota House design are higher. The sensitivity check, also displayed in Figure 7, tests the buildings when modelled with a static energy modelling approach. A static energy modelling approach is prevalent international practice in building LCA although an ongoing decarbonisation of the energy systems is acknowledged (Röck et al., 2020). As seen from Figure 7, the life cycle carbon by modelling with the static approach is around two-to-three times the amount as calculated with the projected grid mixes. Further, in this case the Quota House outperforms the Reference House by inducing 17% less life cycle carbon. Thus, depending on the approach (i.e. static/projected) applied for the energy grid modelling, there may be notable impacts associated with operational energy demands for building operation and operating appliances. The uncertainties related to the future grid composition, thus highlight the difficulties associated with relying on lower operational energy demand as a viable low-carbon design strategy for buildings in itself. However, this is without considerations about new buildings using notable more energy for heating than modelled – the so-called performance gap (see e.g. Gram-Hanssen et al., 2018), which should be further investigated in terms of LCA.

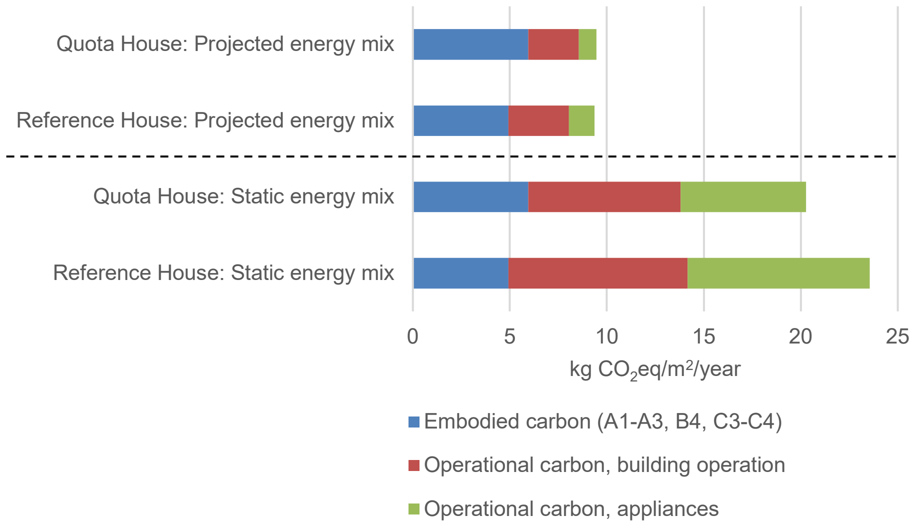

Figure 7. Details of the Quota House and the Reference House.

Critique of the functional equivalent

The MiniCO_2 Houses are all assessed with a long reference study period of 120 years. This long reference study period is prescribed by the common LCA method and reflects a balancing of functional, aesthetical, economic and technical service lives as described for Danish building types in Aagaard et al (2013). Even though a long service life may more genuinely represent the actual time that a residential building will serve its function, the long service life entails a higher level of uncertainty regarding the modelled scenarios of replacements and EoL.

Figure 8 explores the accumulated emissions from all buildings presented in this paper. For all buildings except the Upcycle House, considerable emissions – between 17 and 33 tons CO_2eq - occur in the year of construction. For each replacement taking place during the course of the life cycle of the buildings, additional impacts are induced by production of new materials. These replacement impacts are seen as the 'jumps' (mainly from year 20 to 100) made by the line graphs. These smaller pulses of additional emissions are especially notable halfway through the service life of the building. At the EoL treatment of the building materials after 120 years, another major pulse of emissions takes place. However, as noted earlier, the uncertainties related to these future emissions are profound and related to the processes defined for the waste treatment. Conversely, the impacts from construction of the building are far less uncertain because these emissions are taking place now. Hence, even though the life cycle perspective of the building is important to keep in mind, a parallel focus on the current carbon emissions from construction is imperative to avoid exceedance of the global carbon budget towards laid out by the International Panel on Climate Change in the Paris agreement (Rovers, Lützkendorf, & Habert, 2017). The significance of the construction phase is previously addressed in the literature (e.g. in Säynäjoki, Heinonen,

& Junnila, 2012) and has additional relevance in light of the recent development of life cycle benchmarks being pursued in national and international contexts (Lützkendorf, 2017; Rasmussen et al., 2019). With this temporal focus in mind, the design approach of Upcycle House, i.e. using recycled materials with low impacts and/or bio-based materials with carbon storage, stands out as the preferable design option to pursue current low-carbon buildings. Future development of the common LCA method and its functional unit should incorporate this temporal perspective of the carbon emissions.

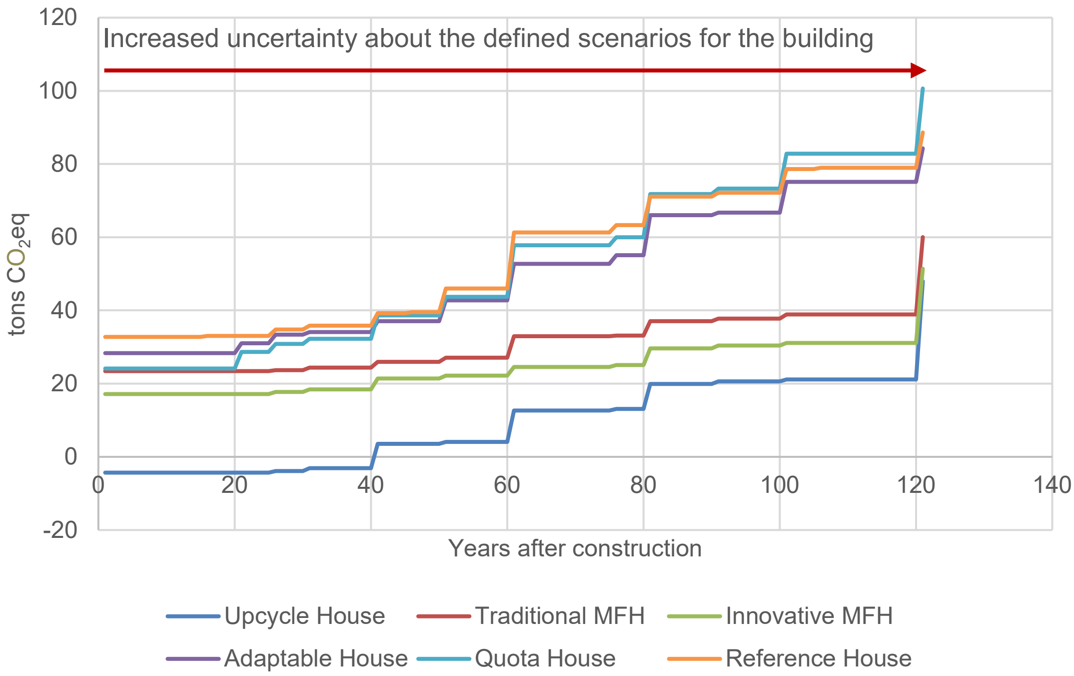

Figure 8. Accumulated carbon emissions from the production, replacement and end-of-life stages of the MiniCO2 Houses and the Reference House.

Conclusion

This study assesses the carbon footprint of five residential stand-alone dwellings, the $MiniCO_2$ Houses, designed with four different low carbon strategies and compare these with the carbon footprint of a reference building. The study shows that the recycling/upcycling strategy applied in the Upcycle House is the most efficient in reducing the embodied carbon of a single-family building. The use of structural wood in the same design furthermore points to the use of wood as a viable strategy for improving the carbon footprint of buildings – under the methodological assumption that the wood is considered carbon neutral. In combination, these two strategies result in an approximate 40 % saving of life cycle embodied carbon compared to a reference, typical building. At the same time, both the recycling- and the wood-based material strategies address the temporal challenge of lowering GHG emissions immediately, and not only focusing on reductions in the long life cycle perspective of a building. Future research should elaborate on other types of allocation for the recycling and on the carbon fluxes related to the use of wood in the construction industry.

The design strategy of using durable materials reduces the embodied impacts up to 30 % compared to the reference, whereas a design for adaptability results in 17 % lower embodied carbon than the reference. However, these strategies are sensitive to the assumptions made for the defined service lives of materials and the disassembly solutions applied.

In a life cycle carbon perspective, the impacts from energy use in the building prove to be of importance although there are notable differences between the modelling approaches of the future energy mix. The viability of a design strategy targeting the users' energy demand thus proves dependent on the context of evaluation. Future research should look into the energy performance gap in new buildings to investigate its relevance to LCA results.

However, all of the assessed strategies; recycling, durability, adaptability and reduced energy demand, show potentials for notably reducing the climate burden of residential buildings. With the shrinking, global carbon budgets in mind, there is thus all the reason to, not just applying the most efficient of the assessed strategies, but to holistically optimize the design of new buildings by integrating various design aspects addressing the whole life cycle of the building. The cases of the current study provide real life examples of affordable design strategies and thus serve as inspiration for architectural practice focusing on low carbon emissions in the building life cycle.

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