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Enabling rapid prediction of quantities to accelerate LCA for decision support in the early building design

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ABSTRACT

Buildings are a significant contributor to climate change. This is why life-cycle assessments (LCA) are becoming increasingly popular for documenting environmental impacts during the detailed design stages of building projects, level of development (LOD) 300–400. In that context, wood is gaining recognition as a material that can reduce the embodied impacts of buildings. However, of particular concern is the incapability of research and practice to generate quantities rapidly in the early design stage. It is an underlying key issue for enabling LCA as decision support in these early building designs. Therefore, this study's aim is two-fold: (i) introducing a simplified design tool for wood dwellings and assessing how the predicted early design climate impacts perform compared to detailed design case studies (ii) evaluating the root causes for predicting trustworthy climate impacts in the early design. The LCAbyg tool assessed the impacts of the life-cycle phases A1-A5, B4, B6, and C3–C4. The climate impacts of the simplified designs (LOD 100–200) were analysed against ten detailed design buildings with the impact disaggregated into life-cycle phases, component types and material categories. The simplified design tool shows it is reliable for comparing the various GHG emissions associated with different designs. Still, the total impact is underestimated by an average of 12% compared with the detailed modelling. It primarily arises from the lack of simplified design metals and that a single product in a component can constitute up to 53% of the climate impact. So, the LCA is sensitive to chosen generic processes, EPDs, and quantities estimations. This study points to the critical elements in material quantification and related climate impact between simplified and detailed building designs. The study also adds to the body of scientific literature on wooden building designs by presenting the quantities and GWP results for ten dwellings constructed between 2010 and 2021. Terraced houses with specific design elements, paper wool, and footing foundation show promising carbon reduction abilities here. In addition, the simplified tool has the potential to get small and medium-sized enterprises in the building industry on board with the sustainability agenda and lead to broader adoption of LCA in their practices.

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1. Introduction

The increased attention on improving the environmental impacts of buildings has steered the focus towards using life-cycle assessment (LCA) in the built environment [1,2] and the adoption of national climate requirements for buildings [3]. These developments have been accompanied by a transition to incorporating embodied impact assessments because of its deficient progress, thus complementing the remarkably improved operational energy efficiency in building design [4,5]. In low- and near zero-energy buildings, research shows that the proportion of life-cycle-embodied energy can range from 26% to 100% [6]. Wood and bio-based materials can play a role in decarbonizing embodied impacts, given that they meet the conditions of sustainably managed production [7,8]. The effective and efficient design of an optimal structural CLT solution compared to a conventional CLT building has saved up to 43% of greenhouse gas (GHG) emissions [9].

1.1. Use of LCA at various levels of design development

Although the early design of a building project entails high design liberation under constrained time and budget resources, many decisions crucially affect the environmental impacts [10]. Therefore, along with the increased application of LCA, more research is directed at digitizing and implementing LCA-based decision support in the early and continuous design of buildings [11]. For instance, Cavalliere et al. [12] introduced a method for conducting LCA by the use of BIM as a project evolves through the levels of development (LOD), and they described it as continuous decision support.

However, manual data inputs and the lack of fully automated processes undermine the complete palette of advantages [13–15], particularly in the very early levels of development (LOD) [16], which usually arises due to the data configurations and terminologies hindering the integrated implementation of BIM and LCA [11]. A popular BIM software program integrated with a regular LCA tool was recently proposed as an automated workflow to assess whether a concrete or a steel structure would be the best building option [17]. In addition, Palumba et al. [18] developed a methodology to correct deviations of impacts occurring at different LODs when impact data progresses from generic unit processes in the early design stage to Environmental Product Declarations (EPDs) at higher LODs. Where most building LCAs are conducted in more detailed stages of the design (LOD 300–400), simplified procedures and tools may enable LCAs already at LOD 100 or 200 [19].

1.2. LCA as decision support in early building design

Quickly generating simplified quantities of buildings in the early design stage still appears as a void in research and practice because of the inadequacies of access to data and information [20]. However, a couple of attempts have been made to introduce parametric models for the renovation of reference buildings [21], as well as the structural and envelope pre-design of industrial buildings [22]. In parallel to this, BIM-informed LCA needs adoption in small and medium-sized architectural and construction enterprises (SMACE) since separately inspecting the implementation of BIM has its barriers. For Canadian SMACEs, BIM entails significant upfront costs and risks [23]. In the Netherlands, the barriers relate to knowledge gaps and the high levels of complexity of BIM practices, where SMACEs are typically already restricted by a lack of financial capacity [24]. This situation leaves opportunities for simplifying LCA decision support during the early design process in SMACEs. However, early design-stage tools must deliver LCA results that are sufficiently close to those of the detailed tools. This ensures that building designers can confidently proceed toward a more detailed design with the solutions tested in the early stages.

1.3. An early-stage quantity-tool for wood-based constructions

To elaborate on the previous paragraphs, research and practice accommodate a need for simplified quantities in the early design to support LCA decision support before BIM enters the process. Furthermore, improving the building design of wood has the potential to decarbonize embodied impacts, for which the early design knowledge should be enhanced. These two needs can be met based on parameterisation built upon predefined components that follow building code requirements. At the same time, making this parameterisation operable for SMACEs will be necessary if LCA as decision support in the building sector is to be widely adopted. To accommodate these needs, a freely available spreadsheet-based tool was developed in 2021 for the early stages of wood-based building design in Denmark (see Supplementary Information (SI) Appendix A). This is called a simplified design tool and requires only a few design inputs to calculate material quantities. The goal of the tool is to speed up LCA by predicting quantities at the early design stage, thus providing decision support more efficiently, already at LOD 100–200. As this has been developed in collaboration with SMACEs, the simplified tool represents this category of company approaches to design.

The developed tool can compute the material quantities of various wood-dwelling designs. The generated design quantities can afterwards be used in an LCA that represents an environmental assessment of the early stage. The quantities of the simplified model can be linked to a user's desired LCA tool. However, the accuracy of the simplified design when conducting LCA on the computed material quantities needs evaluating to understand its applicative reliance and usefulness. Thus, this study evaluates how the simplified design tool performs in the early design stage when assessing the climate impact of the material quantities compared to the results calculated at the detailed design stage. This leads to the following research questions about early-stage versus detailed design:

1. What are the differences and similarities in the material quantities and associated climate change impacts of detailed versus early design stages?
2. Which parameters, component types, and material categories are instrumental in the simplified design prediction, so that trustworthy GWP impacts are obtained compared to when the project reaches the detailed design?

In addition, the study adds to the body of scientific literature about wooden building designs by presenting the quantities and GWP results for ten residential buildings constructed between 2010 and 2021.

2. Methodology

The simplified design tool, representing the early design stage, is evaluated against the detailed design case studies to investigate the accuracy of predicting the detailed design impacts of buildings. Fig. 1 outlines the conceptual approach to arriving at a life-cycle inventory (LCI) for the simplified design tool (simplified LCI) and the detailed design case studies (detailed LCI). In both cases, the inventories are then modelled using the LCAbyg tool [25], a freely available LCA tool developed for the Danish construction industry and described in further detail below.

2.1. LCA

In the case of both the detailed and the simplified design, the climate impacts were evaluated using the LCA methodology following the EN 15978 norm [26]. The goal of the LCA is two-fold: (i) to compare the embodied GHG emissions of ten detailed design wooded buildings; and (ii) to identify the differences in embodied GHG emissions between the detailed and simplified designs. The functional unit (FU) is 1 m^2 of gross living area that complies with the Danish building code regarding the structure, fire safety, energy efficiency of insulation and acoustics (as far as possible) at the time of design for a 50-year reference study period (the building examples date from 2010 to 2021). The EN 15978 norm life-cycle phases considered for the LCA are the production of building products (A1-A3), transport to the construction site (A4), partly A5 limited to the waste at the construction site, replacement of components during the use phase (B4), and end-of-life waste-processing and disposal (C3–C4). The service life of products is acquired from generic Danish data from Aagaard et al. [27]. The LCA tool for modelling the detailed and simplified design of the different cases so as to conduct the impact assessment is LCAbyg [28] version 5 [29]. LCAbyg uses generic unit processes from the Ökobaudat database [30] and environmental product declarations (EPDs) (see SI Appendix B, table B7-B8 for the EPDs used and information on A4-A5). The applicable environmental impact category is the global warming potential (GWP) with a time horizon of 100 years. The declared unit kg CO_2-eq/m^2/year(yr) enables the impact comparison across the different building cases and the detailed and simplified design. The modelling of biogenic carbon in bio-based products adheres to the −1/+1 accounting approach recommended in the EN15804:2019 norm [31].

2.2. The selected case buildings

The sample of buildings comprises two multi-storey buildings (M01-M02) and eight terraced houses (R01-R08) (see SI Appendix B table B1-B6 for metadata on the selected cases). All the projects consist of more than one building block at the site. In the detailed design, the modular prefabricated (prefab) building constructions are classified as volumetric for a block module and panelized for a component module. A block module consists of one whole storey, including exterior walls, interior walls, and floor, all assembled at a factory. Component modules are exterior walls, interior walls and floors separately fabricated at a factory and assembled into a block

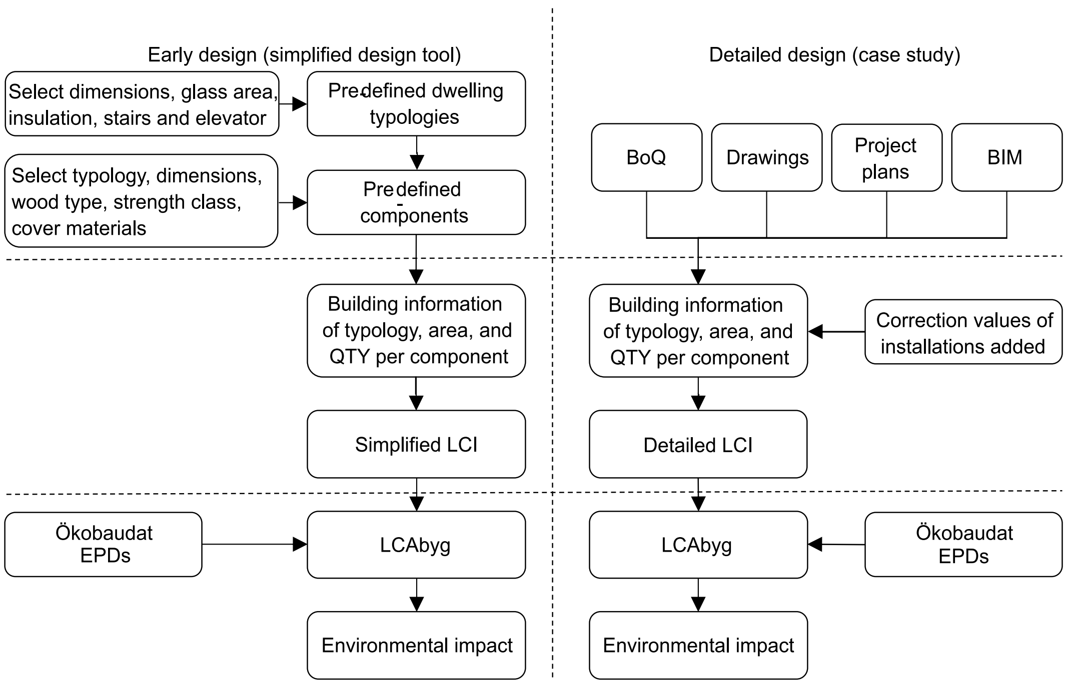

Fig. 1. The workflow of the simplified and detailed design from inputs of information to output as LCI to impact assessment. The inputs and outputs leading to the LCI differ between the two design stages.

on site. Another construction characteristic is cross-laminated timber (CLT). This study excluded common buildings, sheds and other detached constructions associated with the selected sites. The cases were divided into the component groups of foundation, including slab, exterior walls, including doors and windows, interior walls, floors, roof construction and other components, e.g., stairs and elevators. Table 1 gives an overview of the case studies alongside the simplified design.

2.2.1. The simplified design tool model

The simplified design tool can model one building block at a time and contains predefined component typologies which the user can select. The predefined dwelling options comprise single-family houses, two-storey terraced houses, and multi-storey apartment buildings with three to six storeys. One building block in the simplified design tool represents several blocks in the detailed design.

Moreover, the predefined component typologies will sometimes differ from the detailed design, the most representative being selected. The tool cannot model prefab components, so these cases buildings were modelled as timber-frame buildings, mainly affecting the floor component (see Table 2 for specifics on the detailed and simplified component differences).

Terraced houses R01 and R06 were modelled as three-storey dwellings to represent the detailed design most appropriately because the simplified design tool only provides options for terraced houses with two storeys. This approach is considered conservative given the stricter building code for multi-storey residential buildings.

Generally, the tool disregards interior finishings such as paintings, additional products for wet rooms, metal products such as reinforcing steel, assembly fasteners and technical installations in the form of ducts, pipes, boilers, ventilation aggregate and gutters. It includes elevators and stairs if selected.

The simplified design tool computes the components of floors, exterior walls and roof constructions based on structural, insulation (U-value) and fire safety calculations with the minimum necessary capacity to comply with the building code. Interior walls for residential separation rely on a similar computation, though the tool excludes non-loadbearing partition walls. Foundations base their quantities on a factor per area where only the density of insulation type and the number of load-bearing interior walls are changed in size. The simplified design tool can only consider one type of cladding at once. In cases where the detailed design applied two cladding types, the choice of cladding in the simplified design was based on which claddings had the most significant volume. Roof terraces and irregular roof shapes are not available in the tool, affecting the impact comparison of roof components. Fig. 1 displays the workflow of the simplified design tool and the variations to the case studies.

3. Results

The following sections compare theembodied GWP results obtained from the detailed and simplified design building model, i.e., from life-cycle modules A1-A5, B4 and C3–C4. The focus of the results gradually disaggregates the overall impact of the building cases into impact from life-cycle phases, component types and material categories of the selected buildings. Finally, it analyses the detailed and simplified design models' relationships between the mass intensity and the impact difference.

3.1. Overall impact analysis

Fig. 2 shows the GWP from the simplified and detailed design of all ten building cases. The average embodied GWP score for the detailed wooden buildings is equal to 4.5 kg $CO_2e/m^2/yr$, and those from the simplified model to 4 kg $CO_2e/m^2/yr$, with a relative difference of 12%. The impact from the detailed design models varies from 3.3 to 6.3 kg CO_2-eq/m^2/yr. A shift of view to the early design sets the impact ranges to between 2.5 and 5.2 kg $CO_2e/m^2/yr$, hence there is a comparable range between cases in the simplified and the detailed modelling.

Individual cases reveal more significant variations where the impacts of the early design generally exhibit 10–23% lower values. In contrast, in the case of buildings M02, R03, and R06 the impacts of the detailed design are 2–17% lower. To better understand the critical parameters of the variations between the detailed and simplified models, further analyses of the impacts of the different building life-cycle stages follows.

3.2. Impacts distributed among building life-cycle phases

Fig. 3 shows how impact of the production phase (A1-A3) is negative or relatively low. The average of the detailed design models is −0.6 kg $CO_2e/m^2/yr$, whereas it is −1 kg $CO_2e/m^2/yr$ for the simplified designs. Although the impacts between the detailed and simplified models have a 40% difference regarding phases A1-A3, this can be considered less significant in absolute values. The detailed designs extend between −6.3 and 1.5 kg $CO_2e/m^2/yr$, and the simplified designs encompass −8 to 1.3 kg CO_2-eq/m^2/yr. It is worth highlighting that the simplified design reveals a minor impact on the production stage apart from cases R06 and R08.

The life-cycle phases A4, A5 and B4 generally provide limited contributions to the overall impact, as the biggest share of the impact comes at the end-of-life phases (C3–C4). For the detailed design, the end-of-life impacts range between 2.1 and 11.3, close to the range

Table 1
Summary of variations to the detailed and simplified designs. DDS = detailed design stage, SDS = early design stage.

	Dwelling Typology	Structural Typology	Metals	Other
DDS	3 multi-storey, 8 terraced houses	8 volumetric prefab, 1 panelized prefab, 1 CLT.	Including metal assembly fasteners and installations such as screws, pipes, ducts.	Excluding installed powered equipment and solar panels.
SDS	3 multi-storey, 8 terraced houses	9 timber frames, 1 CLT.	Excluding metal fasteners and installations.	Excluding non-loadbearing partition walls.

Table 2
Difference in the design configurations of the detailed and simplified designs for the four relevant components. A "no" before a difference means that it is not present at that design stage, and it is present when "no" is absent. DDS = detailed design stage, SDS = early design stage, blank spaces = no structural or configurational differences.

Case	Exterior wall	Interior wall	Floor	Roof construction
M01 M02	DDS: wood + slate cladding SDS: fibre cement cladding	DDS: paint	DDS: bitumen between storeys	DDS: roof terraces, and no loadbearing materials included
R01	DDS: wood + slate cladding SDS: fibre cement cladding	DDS: paint		DDS: roof terraces
R02		DDS: paint	DDS: no floor component available SDS: only legal for internal storey separation	
R03			DDS: concrete SDS: honeycomb-sand	DDS: irregular shape
R04		DDS: paint	SDS: only permitted for internal storey separation, and no surface cover obeying fire protection regulation	
R05		DDS: paint	DDS: bitumen between storeys SDS: internal separation and no surface cover for fire protection	
R06	DDS: wood + brick tile cladding SDS: brick tile cladding	DDS: paint	DDS: bitumen between storeys	DDS: roof terraces
R07	DDS: wood + slate cladding SDS: wood cladding	DDS: concrete, and paint	DDS: bitumen between storeys	
R08	DDS: steel sheets + wood cladding SDS: steel sheets cladding	DDS: paint	DDS: bitumen between storeys	
General	DDS: treatment or paint of wood cladding and wet room products within the building	DDS: wet room products	DDS: wet room products SDS: prefab components are not available	

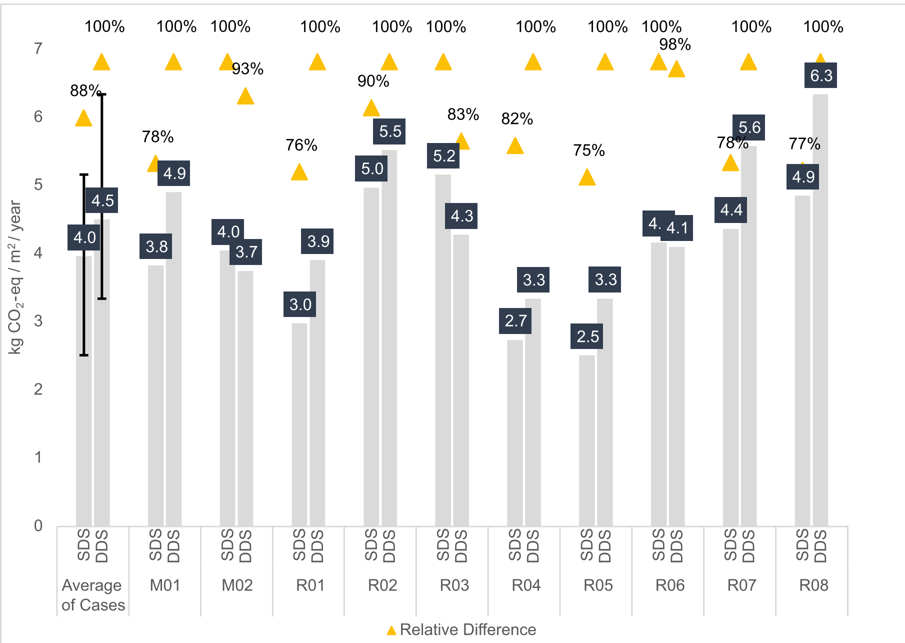

Fig. 2. Total GWP impact in kg CO_2-eq/m^2/yr for the ten sample buildings (including life-cycle modules A1-A5, B4, C3–C4) for the detailed and simplified design and the average across cases, including variance bars showing the buildings with the highest and lowest impacts. The dark blue boxes show the total GWP impact. The design stage with the greatest impact of that specific case has a triangle showing 100%. Triangles below 100% show the proportion that the least impacting design stage constitutes of the highest impacting stage for the building in question (lowest impacting stage/highest impacting stage). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of 2.2–11.9 for the simplified design. The average impacts of both the detailed and simplified design models are approximately 3.9 kg CO_2e/m^2/yr at the end of life, the impact of which can in reality occur long after the selected reference study period of 50 years.

Cases that provide impact reductions (negative emissions) in the production phases emerge with the highest impact at the end-of-life phases for both the detailed and simplified designs. The most considerable discrepancies between the impacts of production and

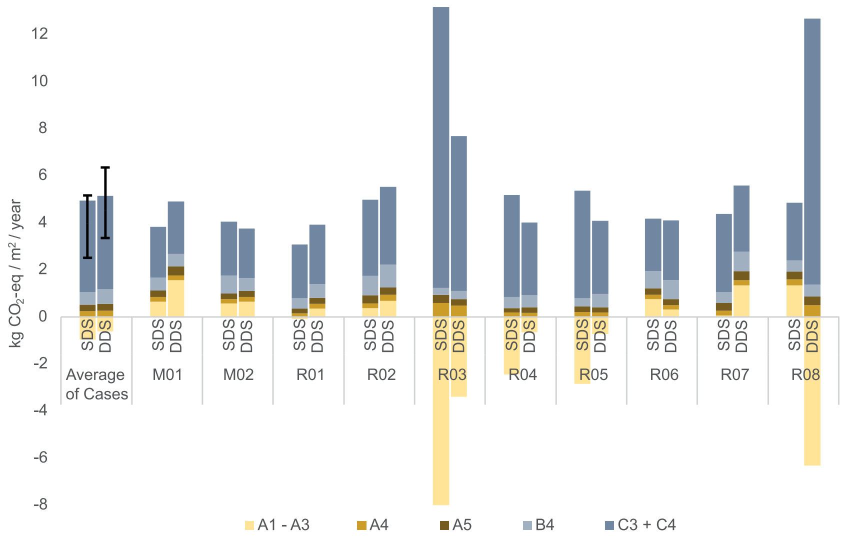

Fig. 3. Total GWP impact (including life-cycle modules A1-A5, B4, C3–C4) distributed on life-cycle phases for each building's detailed and simplified design, and the average across cases, including variance bars showing the highest and lowest impacts.

the end-of-life phases are primarily arising from the approach to calculate the biogenic carbon. The −1/+1 approach supported by EN 15804:2019 norm allocates the uptake of biogenic carbon for bio-based materials at the production phase (−1) and the release of it back to the atmosphere at the end-of-life phase (+1). Nonetheless, the root causes behind the larger release of greenhouse gases in the detailed design rather than the simplified design, viewed broadly, still need localizing by looking at the impact of the components, as shown in Fig. 4.

3.3. *Impacts distributed among component types*

Fig. 4 shows how the foundations, exterior walls and roof constructions contribute most to the total average impact across cases for the detailed design by 1.26 (28%), 1.26 (28%), and 0.70 (15%) kg CO2-eq/m^2/yr. Almost identically, the equivalent figures for the simplified design are 1.17 (29%), 1.15 (29%) and 0.77 (19%). Thus, the proportions of these three components in the total impact are respectively 71% and 77%. The discrepancy in these impact figures appears wider when viewed from the individual cases, where the detailed design demonstrates that the foundations range from 0.6 to 2.3 kg CO2-eq/m^2/yr, or 0.6 to 1.8 for the simplified design. The variations mainly arise from the buildings with footing foundations, which the simplified designs significantly underestimate, while the CLT case, conversely, exaggerates it.

The exterior walls range on average from 1 to 2 kg CO2-eq/m^2/yr in the detailed design and extend slightly lower in the simplified

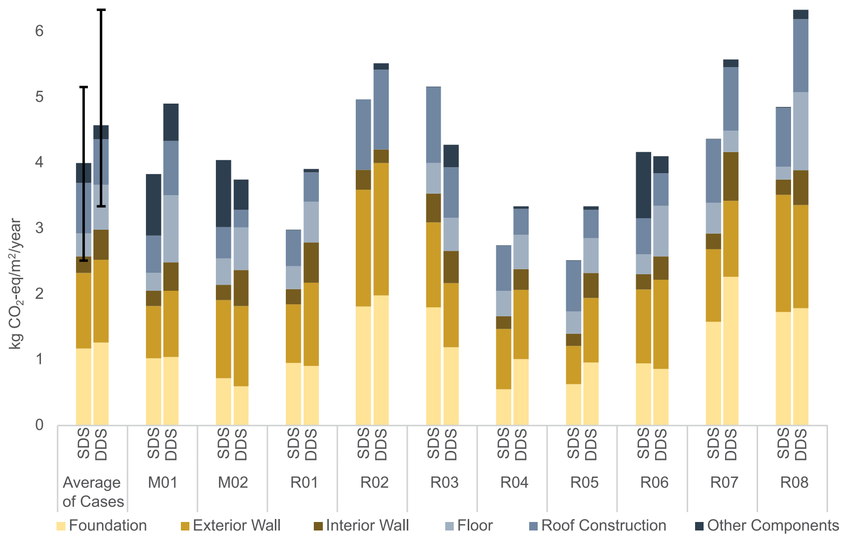

Fig. 4. Total GWP impact (including life-cycle modules A1-A5, B4, C3–C4) distributed among building component types for each building in the case of both the detailed and simplified designs. The average across cases including variance bars shows the cases with the highest and lowest impacts.

design from 0.6 to 1.8. In cases with the most significant discrepancies and with the highest impacts in the detailed design, the differences ascribed to cement-bonded chipboard, paint and assembly fasteners are not included in the simplified design, nor are windows and moisture-barrier impact variations.

The detailed design has an average span for the roof constructions of 0.3–1.2 kg CO2-eq/m^2/yr and for the simplified design of 0.5–1.2. The latter is primarily more impactful regarding roofs, as it includes products related to the ceiling on the top storeys, while the detailed design only sometimes does so, assigning them instead to the floors.

The simplified designs consistently and significantly underrate the impact of the interior walls since they only consider load-bearing, residence-separating walls. The floors also generally have a lower impact in the simplified design. This anomaly stems mainly from five cases in particular, M01-M02, R01, R06 and R08. The omission of wet rooms in the simplified design is one reason for this because tiles, mortar concrete, and other related products are excluded. In parallel, seven of the nine prefabs require bitumen between each storey in the detailed design, constituting 3–10% of the floors' impact.

Generally, a few products have a significant impact share of the floors comprising cement-bonded chipboard of 18–39%, gypsum of 18%, plastic-fibre membrane of 49% and PUR used in flooring underlay of 53%. This suggests the need for a deeper analysis of categories of applied materials in these cases of buildings and of what this means for predicting impacts in the simplified design.

3.4. Impacts distributed among material categories

For the detailed design stage, the three material categories with the largest average impacts are insulations 1.05 (23%), cement-based 0.77 (17%) and bio-based 0.67 (15%) kg CO_2-e/m^2/yr, as shown in Fig. 5. Likewise, the sequence for the simplified design is insulations 0.90 (23%), cement-based 0.78 (19%) and bio-based 0.76 (20%), although the detailed design has a slightly greater impact for insulation and vice versa for the bio-based materials. It is worth noting that the differences in absolute numbers could be considerably greater. Insulation contributes most to the impact on average for the actual cases, but two of the three buildings with the lowest impacts attributed to insulation (R04, R05) use paper wool instead of mineral wool.

The impact of bio-based materials is less for the detailed design, both in absolute numbers and in the share of the total, apart from building R08. The impact intensity (impact per kg of employed material) of bio-based materials is also less in the detailed design for all other cases other than R06 and R08. Hence the trend towards the simplified design tool in generating bio-based materials that have higher impact per FU and a higher impact intensity.

In the context of wooden dwellings, the cases of detailed design still show a notable average impact from metals of 0.51 (11%) kg CO_2-e/m^2/yr. This results from the assembly fasteners, gutters, installations (not electrical or otherwise powered installations) and other products that are necessary for wood buildings. This circumstance is widely omitted from the simplified design, on which metals impact at 0.24 (6%). Only building R08 shows a similar impact from metals in both design stages. When adding the average detailed design impact of metals to the simplified design, the total impact would be 4.27 kg CO2-eq/m^2/yr. That is just 5% lower than the detailed design stage (See SI Fig. B9 and B13 for more information on material categories.).

The biogenic carbon temporarily stored in the bio-based materials in the buildings have negative or low impacts on the production phases (A1-A3) in the detailed design (as shown in Fig. 3). All bio-based materials result in the storage of biogenic carbon. However, in the cases with net emissions, namely A1-A3, the impact of the non-bio-based materials is more significant than the reduction. The stored emissions are, on the contrary, shifted to the end-of-life phases (C3–C4), which is a theoretical burden shift when using the −1/+1 method. This method maintains a carbon-neutral perspective over the life-cycle of the building but attributes the savings in the production phases and the burden at the end-of-life phase.

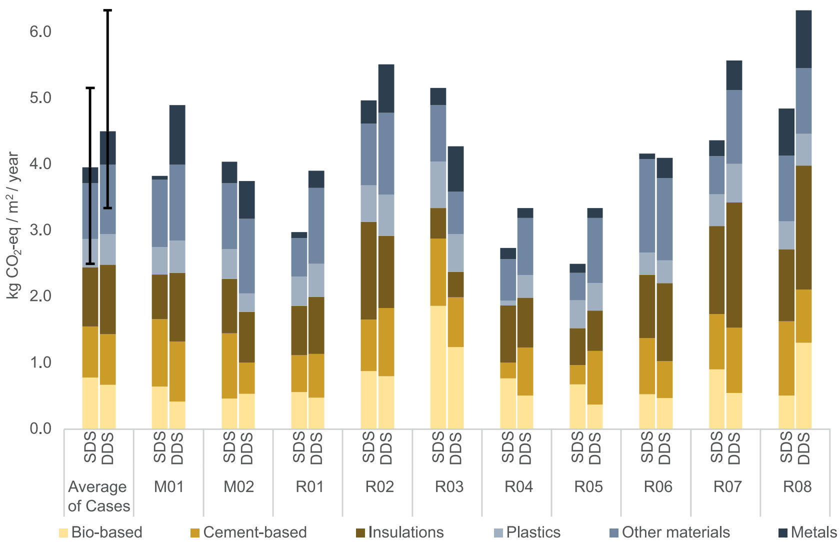

Fig. 5. Total GWP impact (including life-cycle modules A1-A5, B4, C3–C4) distributed among material categories for each building in both the detailed and simplified designs. The average across cases including variance bars shows the cases with the highest and lowest impacts.

3.4.1. Relationship of quantities and impact difference between detailed and simplified design

Fig. 6 presents the differences in quantities (ΔQTY) and impacts (ΔGWP) of subtracting the simplified design by the detailed design for the material categories. This reveals that many cases and their averages (black markers) concentrate around the origin. More substantial differences occur meanwhile among the individual cases and materials. As for the impact of the metals, the quantity is likewise underestimated in the simplified design by 10 kg/m^2 on average.

The figure provides the valuable insight that the materials with the steepest linear regression slope will show the most significant difference in impact by minor alterations to the weight. Nonetheless, the essential materials that require accurate computation of quantities for reliable prediction of impacts are the materials with the coupling of a steep linear slope and considerable ΔGWP scores. See Fig. 7 for a focused presentation of the ΔGWP scores. Therefore, the concerned material categories are insulations, metals, and bio-based materials. Hence, it is important to compute these material categories accurately between a simplified and a detailed quantity take-off. Despite plastics' steep slope and concretes considerable ΔGWP, they are not regarded among the most essential materials since they show less extensive ΔGWP and less steep slope, respectively.

The data markers in the second and fourth quadrants of Fig. 6 imply a disproportionate correlation between the difference in the material quantity and the GWP score. Therefore, materials will have a high impact-to-weight ratio for the detailed design if placed in the fourth quadrant, and similar for the simplified design if placed in the second quadrant. For the former, the anomaly features a cement-based material case, and is slightly the same for two cases of insulation. The detailed design has four cases of bio-based materials (M01, R01, R02, and R06). R01 has circa ten times the quantities of chipboard and laminated veneer lumber in the simplified design and features high emission factors compared to the other wood products. Despite there being more construction wood in the detailed design of case R06, the quantity and emissions factor of the wooden floor cover (twice the quantity) and the laminated veneer lumber in the simplified design result in a higher impact.

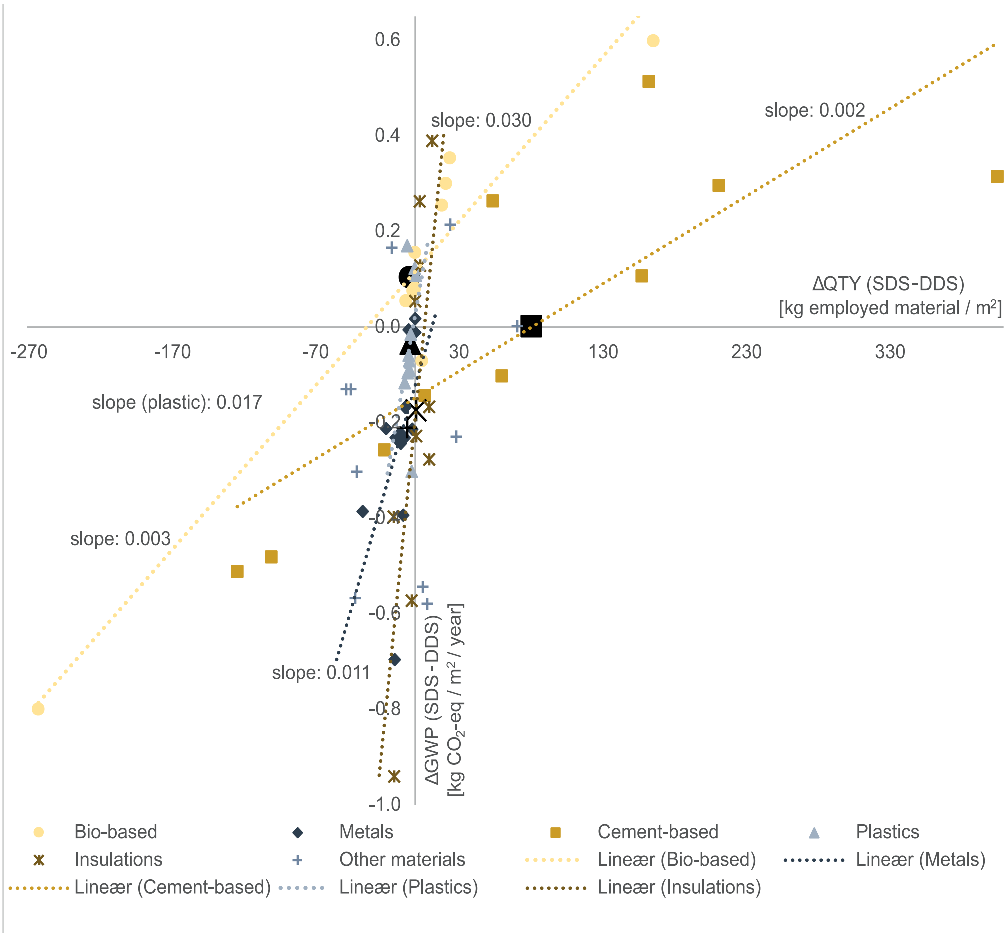

Fig. 6. The figure shows the differences between the material categories when subtracting the detailed design from the simplified design of the quantity (ΔQTY) and impact (ΔGWP) (incl. life-cycle modules A1-A5, B4, C3–C4) of the ten cases. The ΔQTY (kg employed material/m^2) is on the horizontal axis, the ΔGWP score (kg CO_2-eq/m^2/year) is on the vertical axis. The blacked markers show the average of the cases and the materials' linear regression with slope is represented by the dotted lines. DDS = detailed design stage, SDS = early design stage.

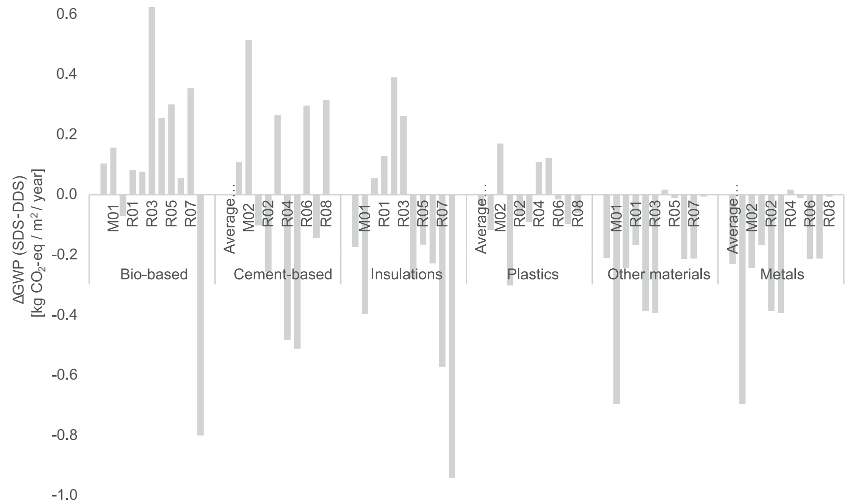

Fig. 7. The differences between the material categories when subtracting the detailed design from the simplified design of the impact (ΔGWP) (incl. life-cycle modules A1-A5, B4, C3–C4) of the ten cases.

4. Discussion

4.1. Characterization of buildings and their impact

The least impactful cases of design are two-storey and one-to two-storey buildings in both design stages, with volumetric modules of a wooden frame and designed with footing foundations. Aside from case R03, nine cases are of modular prefab buildings; eight are volumetric modules, and one is a panelized module. Six of these buildings have greater impacts in the detailed design case. The detailed design of prefab buildings contains additional bitumen in the floors between the storeys for protection. That explains the generally higher impact, as well as some detailed design cases that include upper-storey ceilings and ground-level flooring as a part of the floor components, unlike the simplified tool. The simplified design tool should thus be modified to include suitable modular prefab building components for floors.

4.2. Components: improvements needed for simplified modelling

Table 3 presents the main conclusions and improvement aspects for the different components. For the simplified wooden-frame exterior walls, the limitation is ascribed to the absence of metal assembly fasteners.

The roof construction needs consistency regarding which design stages under- or overestimate the impact. This is primarily because of the incongruity of the components to which the roof ceiling products belong. In addition, consideration of roof terraces, or moving from continuous flat or gabled roof shapes in the detailed design, may result in impact discrepancies, even though this is not apparent in this study.

The inaccuracy of the interior walls confirms that partition walls and wet-room products need representation in a simplified design

Table 3
Main conclusions and improvement aspects of the simplified design for the different component types and their structural typology.

Component type	Typology	Main conclusions and improvement aspects
Foundation	Raft	The one case of CLT structure needs to be more accurate. More cases are needed to evaluate whether it can be validated for the CLT structure.
	Footing	Inaccurate. Needs computation improvement in the simplified design tool.
Exterior wall	Wood frame	Aside from two cases, the simplified design consistently makes a slight underestimation of impact. Two-material cladding cases have a less accurate impact than single-material cladding. A designer should be aware of this when designing with more than one cladding material.
Interior wall	CLT	Quite accurate but needs further assessments of cases for validation.
	Wood frame	Inaccurate i.e., it is important to consider partition walls and wet-room products in the simplified design tool for this typology.
Floor	CLT	Quite accurate but needs further assessments of cases for validation.
	Beam system	Inaccuracies are difficult to validate: first, due to unharmonized data configurations, where some foundation and roof products in the detailed design are registered as floors. Second, prefab components need to be represented in the simplified design leading to the absence of bitumen between storeys, as in the detailed design. Prefab floor components should therefore be added to the simplified design tool.
Roof construction	Rafter construction	The roof shape of the detailed design is not very generic in all cases, which can lead to an inaccurate simplified design. The designer should be aware of this aspect. The ceiling products with the detailed design are often, unlike the simplified design, configured as belonging to the floors. It will keep the overall impact the same but muddle the analysis at the component level.

Table 4
Main conclusions and improvement aspects of the simplified design for the different material categories, excluding the "other materials" category.

Material category	Main conclusions and improvements
Bio-based	The simplified design consistently provides larger relative and absolute impacts and mass per FU. Construction practices could improve bio-based material applications based on the simplified design, as its quantities evolve from building code requirements for structure, fire safety and insulation capacity.
Metals	The simplified design needs an empirically based default factor per gross living area for components for metal assembly fasteners. The simplified design needs an empirically based default factor per building area for installations, e.g., ducts, pipes and water tanks, and for technical installations, e.g., ventilation aggregates and boilers. The impact is responsive to small differences in material quantities.
Cement-based	Slight underestimate in the simplified design, but no further improvement is needed.
Plastics	Small contribution in the detailed and simplified design (6–7%), but no further improvement is needed.
Insulations	The impact is responsive to small differences in material quantities, but no further improvement is needed.

model. The CLT interior wall needs an added default factor for the wooden frame underpinning the insulation because the non-loadbearing partition walls are not of CLT in practice. The simplified footing foundation needs improvement since the impacts emerge significantly lower in the early design. The footing foundations, meanwhile, show the lowest impact of the foundation components for both design stages. One suggestion is to focus on implementing this type of foundation where possible or to construct wooden buildings on sites where this type of foundation is feasible.

The raft foundations are modelled by a default quantity factor per area, still unfolding quite accurately in seven of the nine buildings with wooden frames. Adopting structural calculations for the raft foundation in the simplified tool might be relevant because this component generally has the largest share of the impacts. Another technicality is that the foundations rely on the local site's ground conditions. This aspect can affect the accuracy of the simplified designs of raft foundations.

4.3. Materials: improvements needed for simplified modelling

Table 4 provides an overview of the conclusions and improvements needed concerning the materials embedded in the components. Metals are the main material category requiring modification. Disregarding metals from the average impact of buildings of both detailed and simplified design, the difference in absolute impacts will be 0.2 kg $CO_2e/m^2/yr$ instead of 0.5. Theoretically adding the average impact of metals in the detailed design to the simplified design reveals a difference of only 5%. Integrating a default factor per area for technical installations, such as ventilation aggregates and boilers, and for installations, such as ducts, pipes, water tanks and assembly fasteners, could advance the tool further. Further, generating precise quantities of the metals, insulations and, in part, bio-based materials is more critical than cement-based materials because impact adjustments are relatively responsive to small changes in mass.

4.4. Lessons, inspiration, and recommendations for practice

Overall, the simplified design tool adds a dimension to early-stage environmental assessments by quickly generating quantities of a desired design. Access to the tool's background sheets facilitates the possibility of updating it for any national deviations in building codes and making it applicable in many European countries. The tool also addresses the increased attention being paid to building in wood where the climate-mitigation potential of low-rise residential buildings is most evident, as elaborated in section 1. Hence, it can support designers in making more effective design choices.

Cases R04-R05 mutually exhibit the least impact in this study in both the detailed and simplified design stages. This suggests that two-storey terraced houses of (prefab) wooden frame structure, in conjunction with footing foundations, results in the least impact. This confirms that using footing foundations to obtain the least impactful dwellings means that wooden buildings should be prioritised in areas where soil and ground conditions make this option applicable.

The tool also aimed to thoroughly compute the floor, exterior wall and roof components based on the Danish building code. As a result, some simplified components could be relevant for a deeper assessment to inspire construction practice towards lower component impacts, as discussed below. The outcome of another study confirms that dwellings currently seem to optimize according to labour and other costs rather than materials [32].

The average impact of floors in the case of the simplified design tool is 0.35 kg $CO_2e/m^2/yr$, with the four lowest impacts being from R08 (0.20), M01 (0.28), R06 (0.30) and R05 (0.34). The first and last cases are two-storey terraced houses, while the two in the middle were modelled as three-storey apartment blocks. As a result, the number of storeys does not influence the best-performing simplified floors. Table 5 explains the applicability, properties, and lessons for a further overview. A remark on floor F2 (SI Fig. B4): the structure is scaled up to obey the fire-resistance period and the remaining fire safety regulations, but not the fire safety surface cover requirement. A test to understand if the omitted surface cover reduced the impact interestingly resulted in the component having a low impact.

4.5. Limitations to the study and future research opportunities

The detailed design projects assessed in this study encompass several separate building blocks as a group of buildings, often with a variable number of storeys. In this regard, the simplified design tool's drawback is that it can only model a single building block. Correspondingly, this study does not compare one-to-one building blocks with respect to their dimensions. Instead, the simplified

Table 5
Designated components that show low impact in the simplified design with a description of how it is or can be applied (applicability), its properties and its lessons for practice.

Component	Applicability and properties	Lessons for practice
Floor (F2): beam system with a high-density layer of sand-honeycomb (equivalent to a concrete layer)	Internal horizontal storey separation only. Does not observe fire safety surface regulations.	Valuable to assess practical use potential from a climate mitigation perspective compared to a wooden beam-concrete system.
Floor (F4): beam system	Internal storey separation only. The requirement of the surface cover thickness (gypsum) increases from 2 to 3 storeys.	Increased gypsum thickness should not elicit a higher impact of this component.
Exterior wall (EW1): wooden frame	Two two-storey cases of paper wool insulation and wooden cladding. Two three-storey cases of mineral wool insulation and fibre cement cladding.	Paper wool reduces the impacts of two-storey terraced houses using the −1/+1 method. Wooden frame walls increase efficiency from 2 to 3 storeys.
Roof construction (RC3)	Three three-storey cases of rafter roof with bitumen. One four-storey case of rafter roof with steel sheets.	A low impact intensity also results in low functional unit impact. The roof components need an extended assessment.

design model used a representative building block from each case. Comparison per FU (per area) was still possible. However, this implies some uncertainty regarding the material intensity of the different building cases, which could shift in favour of either design stage, conditional on the project.

The tool's subsequent development is integration with LCAbyg and other LCA tools [28], a feature that can accelerate the LCA outcome to benefit from the added value of the quick quantity generation. The integration could preferably have predefined libraries of the components in the tool by using the generic processes of Ökobaudat or sector EPDs. Ultimately, public availability for industry designers and consultants could progress the LCA of wooden dwellings in practice.

Ultimately, this study assesses climate impacts exclusively by GWP, hence vacating a gap for assessing the tool's accuracy for other impact categories. Analysing a broader range of impact categories would be valuable in comprehensively estimating environmental sustainability.

5. Conclusion

In the effort to improve climate mitigation decision-making in the early stage of building design by LCA, this study has presented a comparison between simplified and detailed design quantities with references to ten actual wooden dwellings. The decision-making in the early building design implies restricted money and time alongside limited experience and knowledge. This a problem the simplified design tool addresses by cutting the time of quantity generation and the subsequent LCA. The conclusions to be drawn from comparing the detailed and simplified design of wood dwellings follow below:

- Dissimilar estimates of bio-based materials between design stages can shift the magnitude and proportion of impact in phases A1-A3 and C3–C4. However, this will not necessarily change the total impact significantly over the entire life-cycle.
- The GWP impact of bio-based materials, metals and insulation materials is responsive to slight quantity differences between the detailed and early design stages. These materials consequently require more accurate quantity predictions in the simplified design than, for instance, cement-based materials in the construction.
- In addition, simplified quantities in the early design stage (LOD 100–200) need added default values per gross living area of metals, such as assembly fasteners, installations, and technical installations, for a more complete impact estimate.
- A single product can have up to 53% of a component's impact. Hence, the accuracy of a simplified design compared to a detailed design may merely rely on the choice of the LCA generic unit process or the EPD representing that product than the prediction of quantities itself.

Based on the ten actual cases of buildings, some additional recommendations for the design of wooden buildings can be made:

- Concrete rafter foundations compose a significant share of a wooden dwelling's GWP impact, whereas a footing foundation, by contrast, results in the lowest total GWP impact in both the simplified and detailed designs. Thus, wooden dwellings could have a priority in areas with soil conditions that can take footing foundations.
- Building terraced houses with horizontal storeys that are not separating different apartments will reduce the impact of the floor components due to fewer requirements for acoustics. In addition, floor components that challenge the building code regarding fire safety surface requirements have a lower impact than those obeying the code. This circumstance provides a basis for further research.
- Using paper wool instead of mineral wool reduces the GWP impact of insulation, which on average is the largest contributory material category for the wooden buildings we studied. Therefore, examining bio-based insulation could be viable, including by studying the potential of insulation made from fast-growing bio-based materials.

The simplified design tool is useful for decision support in the early design phase when dealing with the components of the foundations, exterior walls, and floors. The simplified roof components of rafter constructions might estimate quantities and impact appropriately, but more cases with similar data configurations between the detailed and simplified design are required. Relative comparisons of design proposals are often sincerely used by designers. In contrast, pending further improvements, the total impact of the simplified design should be treated as underestimated compared to a detailed final design by an average of 12%.

Author contributions

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly in order to correct spelling and grammatic. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare no competing interest.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

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