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Influence of BIM's level of detail on the environmental impact of buildings: Danish context

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ABSTRACT

Integrating a BIM-based life-cycle assessment (LCA) in the early design stages of building projects can promote a reduction of environmental impacts. However, the reliability of the analysis depends on the quality of the model. BIM modelling of timber-frame construction is often simplified, potentially hindering the LCA outcome due to quantity inaccuracy and a failure to consider elements regarded as negligible. This study addresses the methodological problem that influences the calculation of the environmental impact by examining the various environmental impacts caused by inventory data obtained from BIM models with a level of detail of (LOD) 350–400 vs LOD200. The environmental impacts obtained from both models of a timber building calculated through an attributional LCA method are compared. Material inventory sourced from the LOD200 model results in a 14.7% lower value of embodied impact. The discrepancies resulted from aluminium, mineral wool and bitumen, which are identified as critical materials requiring quantity adjustment. Relying on simplified BIM models for LCA may lead to the GWP being under-estimated with incorrect identification of hotspots in the early design stages. The results aksi question the cut-off criterion of the current EN15978 norm that serves as a foundation for developing environmental policies within the industry. It recommends exclusion of materials constituting less than 1% of the overall mass from the system boundary. This study underscores the potential significance of materials falling below this threshold, challenging the validity of the criterion, and suggesting that such materials should be carefully evaluated and included in the LCA to ensure a comprehensive assessment of the environmental impacts. The overall objective of the study is to emphasize the importance of employing accurate BIM models in LCAs to make informed decisions that are aligned with the sustainability goals, encouraging practitioners to consider the impact of critical materials, even those with seemingly minimal contributions. With this knowledge, the practitioners are able to take meaningful actions that compensate for the LCA uncertainty, mitigating the environmental burden of the most impactful areas. Most importantly, the findings aim to identify the error in design LCA versus as-built studies, helping to develop design LCA tools that predict the as-built impact more precisely and earlier in the design process. The findings can also improve the expected building model definition in carbon policies.

1. Introduction

The ambitions set out in the Paris Agreement and the UN Sustainable Development Goals unequivocally strive to prevent the irreversible environmental degradation. Despite widespread efforts to reduce the impacts of climate change across various sectors, the construction industry remains a major contributor, accounting for an alarming 42% of total energy consumption and 35% of greenhouse gas emissions [1].

LCA is a widely used methodology for evaluating the environmental impacts of buildings (EN-15978, 2012). It distinguishes between impacts associated with energy consumption throughout its lifetime (e.g. heating, lighting, etc.), and embodied impacts stemming from materials and components (e.g. production, transport, etc.) [2]. While substantial progress has been made in reducing operational energy through guidelines, tools, codes, and low-carbon technologies [3], addressing the embodied impacts lacks global consistency and standardized practices [4]. Several studies indicate that the impacts of the embodied CO_2-e can exceed those from the operational stage [2,5,6].

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Designing projects with low embodied impacts is an iterative process applied through building design stages. This process is guided by hotspot analysis which identifies critical areas for detailed assessment and is used as a precursor for finding optimal solutions [7,8]. Identifying environmental hotspots in the early design stages assists in making informed decision about material substitutions that can contribute to the reduction of embodied impacts [9].

However, integrating the LCA in the early design is hindered by the high level of detailed information required for a reliable analysis [10]. The undefined construction principles may cause large discrepancies in the LCA results. Modifications to materials during the later stages, when LCA is typically performed, are costly and often unattainable [11,12].

There are two main approaches for supporting the building design process in a way, which secures that a given target for embodied environmental impacts can be met in the finished building at hand-over; the first is making default data available and the second one providing a versatile tool which links the LCA to the building design workflow [13]. The first approach includes filling out gaps in the building model by providing generic components and quantities in parts of the inventory, which are difficult to estimate due to lacking specific data [14]. In the programming stage prior to geometric design, default data may even include statistical key figures from similar buildings or a parametric approach, which generates a typical LCA building model based on known key properties [13–15].

The second approach is increasingly related to Building Information Modelling (BIM). BIM-based LCA is a recognized method of providing environmental feedback throughout the project's development, particularly during the initial stages when the potential for impact reduction is at its greatest [16,17]. An increasing number of contractors use BIM as the primary source of material quantities for life cycle inventory (LCI) [12,18,19]. However, it is expected that varying pieces of information, can impact on the LCA results. While numerous studies assess buildings' impact through BIM models only a few of them address the variation of impacts through the project design stages. This study aims to evaluate whether the LCA performed in the early design stages provides sufficient insight into the building's environmental profile and the extent of the variation from as-built studies due to the differences in the BIM models that serve as the main information source.

Existing research investigated the impacts of models with an undefined level of detail (LOD) [16,20], indicating the granularity of information at a particular point in the project design stage (LOD100-conceptual, LOD200-approximate geometry, LOD300-precise geometry, LOD350-precise geometry with connections; LOD400-fabrication ready geometry, LOD500-as built [21]). Soust-Verdaguer et al. concluded that LOD300 provides the most appropriate material-related information while also allowing time-efficient modelling [22]. A similar conclusion was obtained by Lee et al. [23] who defined LOD300 as sufficiently accurate for the LCA of most building materials. and the trade-offs between data accuracy and modelling efforts are not taken into account. Given that a building is more than the sum of its main components [24], other elements should be incorporated into the analysis to provide a full representation of the environmental impact. Rezaei et al. [25] compared the environmental impacts of a reinforced concrete building based on the BIM-model with different LODs. Impacts calculated using a LOD100 model show 20% lower impacts than those assessed with a LOD 300 model. Nevertheless, the studies do not analyze the variation of results in the case of buildings with biobased materials which are defined as low-carbon solutions.

Wood has increasingly been utilized in large-scale constructions and the potential environmental benefits of substituting common materials with wood-based products are recognized [24–30]. Duan et al. [28] reported that mass timber building emits 22%–50% less carbon than their concrete counterparts. In terms of multi-story buildings, there is a greenhouse gas reduction potential of between 9% and 48% when constructing with timber as opposed to mineral materials (brick, porous or reinforced concrete) [29,30].

Naturally, the LOD increases along with the development of the project. However, BIM modelling of timber-frame structures often remains at the lower LODs, due to the intricacy of connections that are resolved by the contractor in-house. Thus, the complexity of the wooden frame structures requires simplifications to be applied in BIM modelling. For example, the timber stud frame may overlook the complex construction connections and may be considered as a homogenous insulation layer, regardless of the volume of timber. This situation can also be reversed by treating the timber frame as a homogenous timber construction and neglecting the volume of insulation in between. The quantity adjustment in Wiberg et al.'s study [31] resulted in an 84% reduction in the timber volume, indicating a six-fold overestimate of the timber volume if no corrective measures are applied. Components that are crucial for structural integrity and airtightness, such as fasteners and membranes are typically neglected in the LCA, despite being used in large quantities.

Observations reveal that none of the reviewed studies have fully incorporated all the essential components for the construction of wooden buildings into their assessments of the environmental performance. This omission is likely to be rooted in the limitations of BIM modelling practices, which fail to provide these data. Typically, BIM models are developed for strictly architectural or MEP engineering purposes and overlook the information needed for LCA. It is assumed that the person responsible for LCA must have a good understanding of the project at hand to be able to execute the analysis accurately. LCA is information heavy and requires detailed input for robust results. Without adequate familiarity with the project, there is a risk of omitting components that have not been directly specified in the model or miscounting the project inventory, leading to skewed results. Therefore, a comprehensive investigation of the potential variations arising from different LODs is crucial to identify significant consequences and foster a consensus on mitigating them. It is anticipated that these additional impacts may result in unfavorable repercussions on the final results and impose extra work and associated costs related to BIM modelling. Thus, the magnitude of the impact is investigated in this study.

Furthermore, the ever-evolving environmental regulations have prompted numerous countries to introduce new legislation pertaining to LCA requirements. These regulations now mandate specific targeted values that constructions must adhere to. However, the embodied energy has only recently come in focus. Therefore, this study has the potential to influence the carbon policies on the extent of the required building model definition by providing result variations between design LCA and as-built LCA. The results may challenge the current approach taken towards reduction of the uncertainty of LCA results performed in early design stages, such as addition of 20% on top of the carbon equivalent emissions. The following research questions are developed:

1. How significant is the difference in global warming potential (GWP) when the LCA is performed for a timber building model detailed to LOD200 and LOD350-400?
2. What components are most influential for the LCA results when comparing the two levels of inventory completeness?
3. What is the influence of often omitted components in the inventory of timber building LCA?

2. Methodology

A project's life cycle-inventory (LCI) can be obtained through the extraction of information from the BIM model, though, the data-gathering process may vary depending on the project stage. This study aims to find potential deviations in LCA results when LCI is obtained from BIM models of different qualities that are developed for the analysis. The models are created using a common BIM software Autodesk Revit which contains a geometrical representation of the building materials and associated project-specific information. The modelling practice consists firstly of 3D element creation and is followed by a definition of the parameters, their extent depending on the desired LOD. The LOD200 (simplified) model follows the industry modelling standards in the early design stages and contains uniform layers, approximate size, and the location of most objects, while some elements serve as generic placeholders for space reservation. LOD200 is common in the early design stages due to the short time that it takes to get it developed. On the other hand, the LOD350-400 (detailed) model is a 3D representation of the construction details and corresponds to precise geometry and accuracy for element production and assembly. Such detailed modelling is typically reserved for later stages of the project, when no further changes to the building construction are expected, as it requires a heavy workload. Both models are developed solely for the purpose of this study, basing the information on the received technical documentation from the early design stage (used for LOD200) and construction stage (used for LOD350-400). In practice, LOD specifications do not apply to models but rather to objects in the models. However, to simplify this study, it is assumed that all components are developed to the same LOD. A detailed explanation of the LOD differences is provided in Appendix A. Fig. 1 outlines the conceptual approaches in generating LCI and assessing the environmental impacts of building projects. In the simplified method, the data are gathered from multiple parties involved in the project development (architects, engineers, and contractors), increasing the risk of material quantity inaccuracies due to schedule variabilities or unit inconsistency. This approach requires the material quantity to be averaged per area per building component and can be extracted at any stage of the project. Conversely, when accurately modelled, the detailed BIM model is a single-source option for LCI. Utilizing the assembly function, a single schedule automatically combines the volume of the materials used per component (e.g. walls or floors), rather than generating multiple ones. Due to the complexity of the modelling, the accurate volume of materials can only be extracted in the further stages of the modelling process. The LCI is based solely on the 3D elements of the BIM model, except for fasteners and specific sealants whose information is stored in the model in the form of parameters that automatically calculate the approximate amounts based on the modelled object and manually defined rules. In both cases, the operational energy is obtained through energy performance estimation (here BE18 – the national reporting method), as required for the LCA input.

2.1. Data collection

The difference between the workflow selected for this report and the process currently followed in the industry is illustrated in Fig. 1.

In this study, the developed BIM models serve as a base for specifying a building's properties, size and quantification of the materials. The model geometry and contained information varies based on the desired LOD (Appendix B), but the LCI is obtained through information extraction from the model. The simplified LCA uses the default calculation method defined in LCAbyg that calculates the environmental impact based on the area or length of a given component. For this purpose, component schedules (walls, roofs, ceilings, floors) are exported with area and the component build-up.For the detailed model, assembly schedules are created for each component individually. For the desired precision, the compound material volume is reported for each component category (e.g. insulation volume in all external walls). For the detailed analysis, the hierarchy in the LCAbyg is modified to calculate the impact based on volume (Appendix B, C).

To avoid 3D modelling of fasteners (screws, nails, brackets), as the amount of fasteners would make the model unwieldy, a calculated parameter approach was incorporated. An automatic calculation of their amount was enabled based on the length of the timber element and the desired spacing. A manual entry accounts for other fasteners (e.g. brackets) that occur periodically. The amount of fasteners is converted into weight using standard weights defined per fastener size.

The input values related to the OE are based on the energy framework conducted in BE18 (Appendix E). The same values for OE are used in both models for comparability of the LCA results, even though the energy efficiency would be expected to change as the project develops.

The findings are interpreted in relation to the building, component, and material levels (see detailed analysis in Appendix D). Conclusions are drawn about whether the simplified model is sufficiently accurate to represent a reliable environmental profile calculated from the LOD350-400 model.

2.2. LCA

The applied LCA method follows the EN15978 [32] norm that

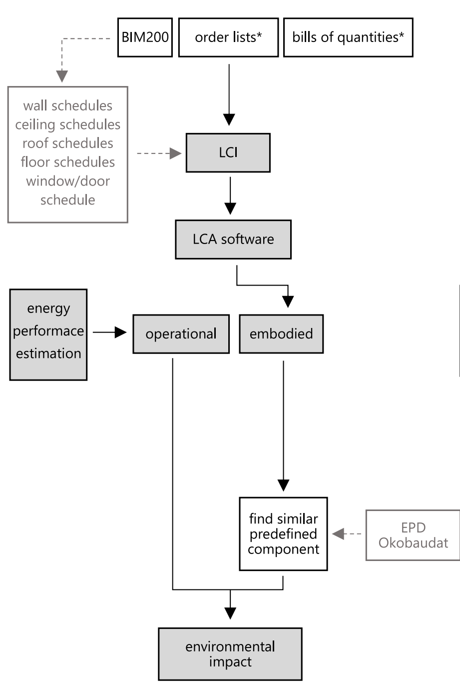

Fig. 1. Process flowchart followed in the industry/simplified case (left) and the detailed case (right).
* sources excluded from this study

recommends the use of established and widely recognized methods for LCI and LCIA, such as those provided in the ISO 14040 [33] and ISO 14044 [34] standards. According to EN15978, several assumptions are typically made in handeling data limitations. Since LCA studies often rely on data from various sources, assumptions are made regarding data quality, completeness, and representativeness. For instance, when specific data for a particular material or process is unavailable, data from similar materials may be used as a substitute. Further assumptions are made concerning the selection of system boundaries, expected service life, applicability of data from different regions or countries or end-of-life scenarios (recycling rates, disposal methods, energy recovery options) [35]. The assumptions must be transparently reported to improve the reliability of the study's findings. An important aspect is that the EN15978 does not specify a particular method of calculation for LCA but rather provides the general framework for conducting it and the general principles that should be followed. This approach allows for flexibility and adaptation to different building types, regional contexts, and available data. A quasi-similar method has been developed which, following specific guidance, integrates an automated BIM-based approach into the assessment of the environmental impacts of modular high-rise buildings [36].

More specific requirements are laid down in the current Danish building regulations [37]. The functional unit is set as a one-square meter gross floor area (GFA) per year for a reference service life of 50 years as recommended by the Danish Agency for Housing and Planning [38]. The system boundary of the study is limited to the life cycle of the product stage (A1-A3), replacement (B4), operational energy use (B6), waste processing (C3), and disposal (C4). Module D (benefits and loads beyond the system boundary) is additionally covered for some materials whose data provided the information. Related to the process flowchart followed for the assessment of the embodied impacts, the lifecycle inventory (LCI) of the foreground system is based solely on the BIM model. The LCI of foreground systems coupled with SBI2013:30 [39] determining the material's standard service life is used to calculate the impacts of the replacement (B4) life-cycle stage.

The HVAC systems and fixed furniture are considered to fall outside the scope of the modelling and LCA analysis in this paper. Any cut-outs made to the building materials due to duct/pipe penetrations are also beyond its scope. Materials, whose weight falls below 10 kg on the building level (e.g. tape), are excluded from the modelling and computations due to their insignificant impact on the results. Prefabricated interior concrete elements (e.g internal staircase walls, staircases) are excluded, as they could be replaced by timber alternatives. Due to this paper's focus on timber structures, the only concrete elements considered in the analysis are those that are integral to the building's construction, for which bio-based alternatives are neither easily accessible nor widely used (e.g. concrete foundations or terrain decks).

The operational energy required for heating, cooling, ventilation, hot water, lighting, and appliances is calculated in conformity with Danish national requirements using BE18 software, which applies a monthly regime model [40].

The source of the environmental impact data alters between the generic ÖKOBAUDAT library, the Danish EPD library and manual entries based on the manufacturer's values. The ÖKOBAUDAT library and the Danish EPD can be advantageous in providing standardized and region-specific data. To reflect the practice of LCA, the simplified case analysis with LOD200 LCI prioritized the use of software-integrated library. Detailed analysis of data obtained from LOD350-400 LCI also prioritized the use of the available library but supplemented the analysis with EPDs, if specific products and their producers were defined within the scope of LOD. As the databases are integrated into LCAbyg software, it replicates the process of LCA in the design stage, where the focus is put on time efficiency, and thus data availability. This replicates the approach an LCI analyst would use if presented with data from the respective LODs, using generic data with approximate environmental impacts for low-detail analysis, versus a precise product-related EPDs in a detailed assessment.

However, the availability of certain materials in the database may be limited, especially if they are not widely used in LCA, for example certain specialized sealants or certain types of membranes. In such case, supplementation of the data with information for missing life cycle stages or impact categories from other sources was required. Thus, the library data used in this study is aggregated from various sources and might represent average values for specific materials. The difference between the emission data from the various sources that are part of the design LCA is not a part of this study. Furthermore, due to the local nature of the databases, their use for projects outside their respective regions (Germany, Denmark) may introduce uncertainties related to regional differences in material sourcing.

The study focuses only on the assessment of the Global Warming Potential (GWP) indicator through the IPCC impact assessment method [41]. According to EN15804:2019 [42] and subsequently EN 16449 [43] the $-1/+1$ method is used for the calculation of the biogenic carbon, which considers both the uptake during growth and the release at the end of life [44,45]. The findings are interpreted at the building, component, and material levels. As the GWP obtained from the detailed case study is considered more accurate, it is used as a baseline.

2.3. Case study

This study investigates a four-story residential building with 2572 m^2 of heated floor area (Fig. 2). By investigating a Danish timber building, the study can showcase a sustainable construction trend that is aliged with the country's increasing environmental goals. As the long-standing tradition of utilizing timber in construction provides a wealth of experience and expertise in timber construction techniques, a modern modular timber construction of the case building is a representation of the progress the industry has made for the construction sector in both Denmark and more widely [36]. The construction consists of prefabricated timber frame elements, where the framework is insulated, sealed, and fitted with pretested plumbing and electrical lines off-site, requiring only final connections. The interior is executed to a delivery standard, including surface finishing (plastering, painting) and the installation of fixed furniture before being assembled on a concrete strip foundation and a concrete ground-floor deck with expanded polystyrene insulation. Combined with the module's floor consisting of a timber frame with mineral wool insulation, the U-value falls between 0,06 and 0,07 W/m^2K for a ceramic tile finish and linoleum respectively. With six types of external walls made of timber frame with mineral wool insulation, PE foil and gypsum boards, the U-values range between 0,09 and 0,17 W/m^2K depending on the thickness of the insulating material and the external finish (wooden planks, fiber cement slates). Due to the timber frame construction of the roof using mineral wool insulation in the ceiling rafters, additional polystyrene on top and a bitumen felt finish, the U-value is calculated at 0,1 W/m^2K. The roof terrace, with a similar construction, measures 0,09 W/m^2K and hosts wooden planks supported on steel profiles. The U-value of windows, glass doors and skylights is calculated at 0,86 W/m^2K. Thermal bridges between the elements are minimized with the help of stone-wool insulation strips, and the continuity of the vapor-resistant layer is ensured through the sealing of overlapping membranes on site.

For heating, a district connection is used, whereas electricity production is supported by 77 m^2 of photovoltaic panels. The demand for operational heat and electricity is 21,3 kWh/m^2/year and 28,1 kWh/m^2/year respectively.

Investigating a case study in a region with widespread BIM adoption is likely to provide access to comprehensive BIM data. The availability of detailed BIM models can facilitate the integration of LCA processes and encourage research to progress in that direction. However, the level of detail is dependent on the undertaken architectural practice that varies depending on the assignment type and project scale. Furthermore, using a case study limited to one country may potentially lead to regional

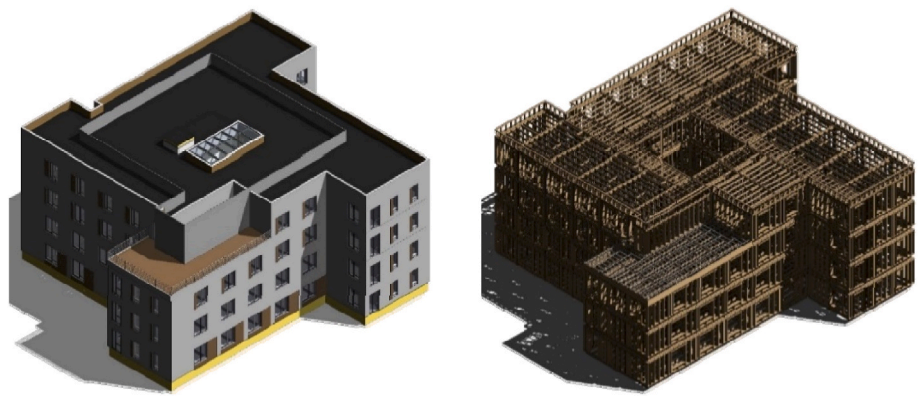

Fig. 2. Overview of the simplified model (top) and examples of the objects modelled in the detailed model (bottom).

biases mainly due to different forestry practices, transportation distances for timber, energy mixes, and waste management systems, all affecting LCA results [46]. The applied case study method is nonetheless considered representative for demonstrating the issues arising from BIM-based LCA in the design process rather than calculating deviations across projects.

Basic model is developed from scratch and based on floor and ceiling plans, sections, and elevations, as well as several overviews and detailed drawings without exact geometry or material specifications (Appendix D). This documentation is provided by the design team, though, the design stage remains unknown. Nonetheless, the developed model is a basis for its further detailing according to specifications provided by both the manufacturing and engineering companies. The documentation consists of mostly construction drawings developed for the on-site building assembly.

3. Results

3.1. Impact of the LCI quality on the GWP

The results presented in Fig. 3 show the global warming potential (GWP) indicator assessed through a detailed model (LOD350/400), considered as a baseline, and simplified (LOD200) BIM models. The detailed model's GWP of 7,6 $kgCO_2e/m^2/year$ is 8% higher than the simplified model. The difference is solely caused by the stages related to the embodied impacts since the operational stage B6 remains unchanged at 3,38 $kgCO_2$-$e/m^2/year$. The embodied impacts in the detailed model are 55% of the total GWP and fall to 52% in the simplified model, mainly as a consequence of excluding the building components from the system boundary. The production phases (A1-A3) reach 0,308 $kgCO_2$-$e/m^2/$year from the simplified model, significantly lower than the 0,633 $kgCO_2$-$e/m^2/year$ baseline calculated in the detailed model. This difference correlates with the material quantity used for the LCI. The omission of materials or their inadequate weight in the simplified model leads to the impacts being under-estimated by decreasing the share of the A1-A3 phases on the total GWP from 8% to 4%. In addition, the material quantity discrepancies in the simplified BIM model has additional repercussions for replacement (B4). The share of B4 to the total GWP changes from 7% (0,502 $kgCO_2$-$e/m^2/year$) to 6% (0,406 $kgCO_2$-$e/m^2/year$), requiring less material replacement throughout the calculation reference period of 50 years. Of the embodied impact, the waste processing phases, and end-of-life phases (C3–C4) have the most significant CO_2e emissions due to the timber origin of the building elements and the −1/+1 method used to calculate the biogenic carbon. As expected, due to the smaller material quantities being used for the simplified analysis, the CO_2e is reduced. However, the share of the phase in total GWP increases from 40% (3,05 $kgCO_2$-$e/m^2/year$) to 42% (2,95 $kgCO_2$-$e/m^2/year$), as the total GWP is lower in the simplified stage. The

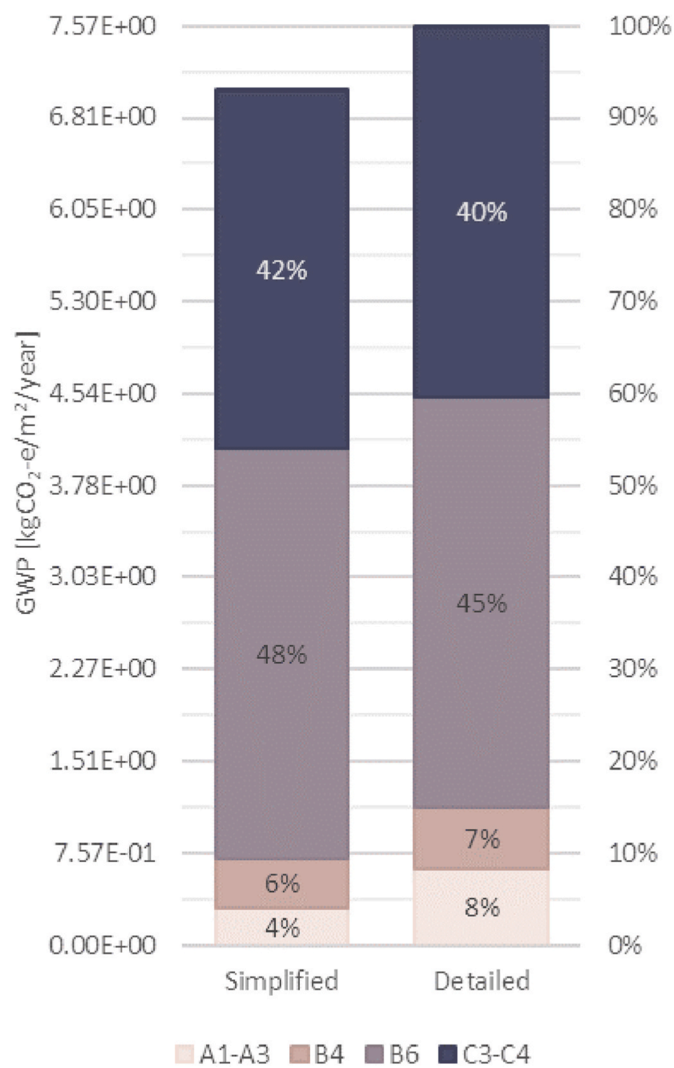

Fig. 3. The GWP share of the life cycle stages.

ranking of the life cycle phases based on their contribution to the GWP score changes. In the detailed analysis, the replacement phase (B4) is ranked last, with a 7% contribution, followed by the production phases (A1-A3) at 8%. The simplified analysis changes the ranking, where A1-A3 has the least significant influence on the GWP with 4%, followed by B4 at 6%.

However, to further analyze the differences between the results obtained, Fig. 4 summarizes the impacts disaggregated into building components. The embodied impacts assessed with the detailed and simplified models have a relative difference of 14,7%. When executing calculations with the simplified model, most building elements face a decrease of GWP values. The external façade (22%) and internal timber frame walls (21%) have the largest share of CO_2-e emissions at 0,924 and 0,875 kgCO_2-e/m^2/year. Compared to the detailed assessment, the impact of the façade reaches a lower value (0,825 kgCO_2-e/m^2/year) when the LOD200 model is applied. The internal walls also rank lower in the GWP score, equal to 0,693 kgCO_2-e/m^2/year. The relative contribution of the façade and internal walls changes to 23% and 19% respectively. A slight accuracy difference in the CO_2-e for the terrain deck component (0,632 kgCO_2-e/m^2/year) appears when simplifications are applied (0,586 kgCO_2-e/m^2/year). This changes the component influence on the results from 15% to 16% while preserving the component rank as the third largest contributor to the GWP. Similarly, the influence of floor partitions on results changes from 11% to 12%, with an absolute GWP value of 0,431 kgCO_2-e/m^2/year in simplified and 0,475 kgCO_2-e/m^2/year in detailed assessments. The ranking of the components remains uniform in both case studies, the only difference occurring in the ceiling and roof components. Initially, the ceiling's contribution to the overall assessment was 10%, and the roof 9%. However, the applied simplifications switch the ranking by assuming the roof makes a 10% contribution and the ceiling 8%. The CO_2-e of the roof component decreased from 0,405 kg kgCO_2-e/m^2/year to 0,316 kgCO_2-e/m^2/year. On the other hand, the GWP of ceilings from 0,34 in the detailed assessment changed to 0,381 kgCO_2-e/m^2/year in the simplified version. This is the only component in this study where the impact has increased when implementing a LOD200 model. The LCI for windows and doors changes marginally between the two scenarios. Frequently omitted, the fasteners are excluded from the simplified analysis, resulting in an impact of 0,234 kgCO_2-e/m^2/year, slightly lower than the 0,248 kgCO_2-e/m^2/year from the detailed case study. This insignificant change sustains the 6% contribution of the windows/doors' components to the GWP of the building. The foundation is measured as making a 5% contribution to the overall GWP with an absolute value of 0,226 kgCO_2-e/m^2/year. Using the LOD200 model achieves a 4% share with 0,142 kgCO_2-e/m^2/year. Lastly, the accuracy of the simplified modelling of the roof terrace changes the CO_2-e from 0,058 to 0,045 kgCO_2-e/m^2/year, preserving the 1% component contribution to the GWP results at the building level. The observed differences in the components is accredited to the materials whose modelling is omitted entirely due to the extensive time required for their development (fasteners, steel or aluminium profiles, timber frame) or their inaccurate modelling due to the use of simplified modelling techniques (homogenous insulation layer, no membrane overlaps). The almost-unchanged ranking may suggest that no significant variation between the LCAs occurs.

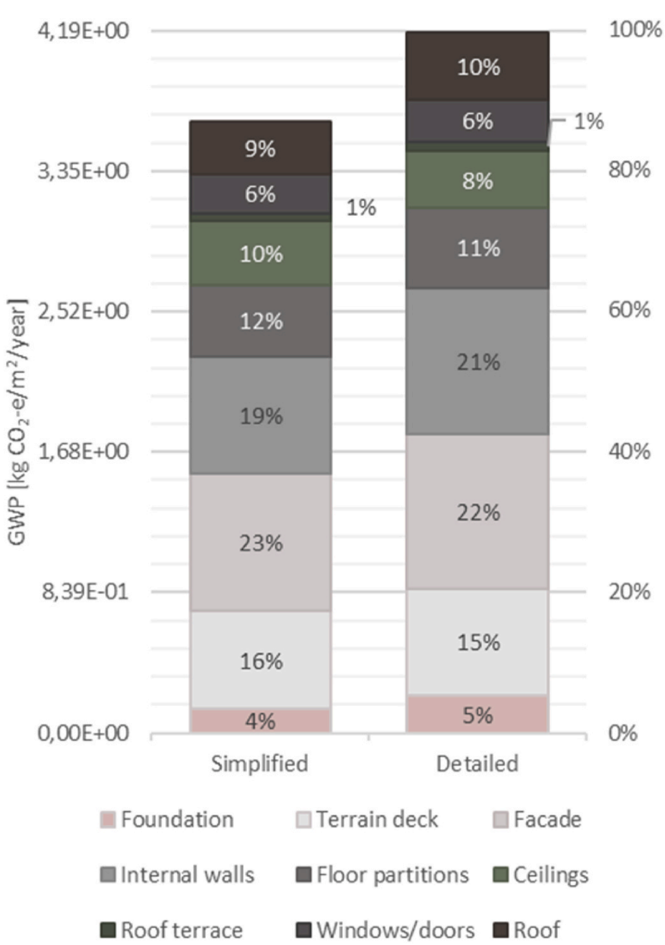

Fig. 4. The GWP share of the components in the embodied stages.

However, a detailed contribution analysis is addressed further at a material level. Fig. 5 shows the relation of the weight, volume, and embodied impacts of the materials employed in the building project for both detailed and simplified calculations. Although the insulation category has a GWP score equal to 0,78 kgCO_2-e/m^2/year and contribution of 24%, it is composed of mineral wool and EPS with similar GWP values (0,42 and 0,36 kgCO_2-e/m^2/year respectively) . Consequently, aluminium, as a single material, has the highest value (0,47 kgCO_2-e/m^2/year) and influence (14,9%) on the building's impact. An equal contribution to the GWP score comes from bio-based materials composed of OSB (9,9%), plywood (0,5%), and timber (3,8%). Cement-based materials have a lower impact (0,4 kgCO_2-e/m^2/year) and influence (12%) on results. As presented in the figure, gypsum, aggregates, and other materials employed in the building case study make less than a 10% contribution to the GWP score. Based on the results obtained, the material with the most significant influence on impacts but with low mass and volume is aluminium. Mineral wool presenting 61% of the materials' volume, has a lower contribution to environmental impacts. The same results are obtained for concrete representing 35% of the overall building mass. These analyses allow us to conclude that there is a lack of correlation between the volume, weight, and impacts of the materials employed in buildings. Moreover, these results challenge the commonly applied cut-off criteria whereby materials with a contribution of less than 1% of mass or volume contribution are neglected in the LCA. Results obtained with the simplified BIM model identify insulation (1,35 kgCO_2-e/m^2/year) with the most significant contribution (41%) to the GWP score. Mineral wool shares 30% and EPS 11% of the impacts. Ranked as follow according to their contribution to the GWP score, bio-based, cement-based, and aluminium materials have impacts respectively equal to 0,41, 0,37, and 0,28 kgCO_2-e/m^2/year. The discrepancies between the results obtained through the simplified and detailed model are significant for a detailed analysis of a building decomposed in accordance with its material composition. Aluminium with the most significant absolute and relative impacts is ranked fourth in the simplified model. On the other hand, the double influence of insulation materials has softened and consequently hidden the contribution of other materials to the building's GWP score. Based on the findings, the results obtained through a simplified BIM model can hinder the identification of most contributing materials, as misidentification of the hotspots may mislead the process to be focused on nonprioritized hotspots with a low contribution to the GWP score.

3.2. Material analysis

3.2.1. Aluminium

Flashings (around the roof perimeter, openings, cladding junctions, and plinth) along with the aluminium rails and brackets, are found to be

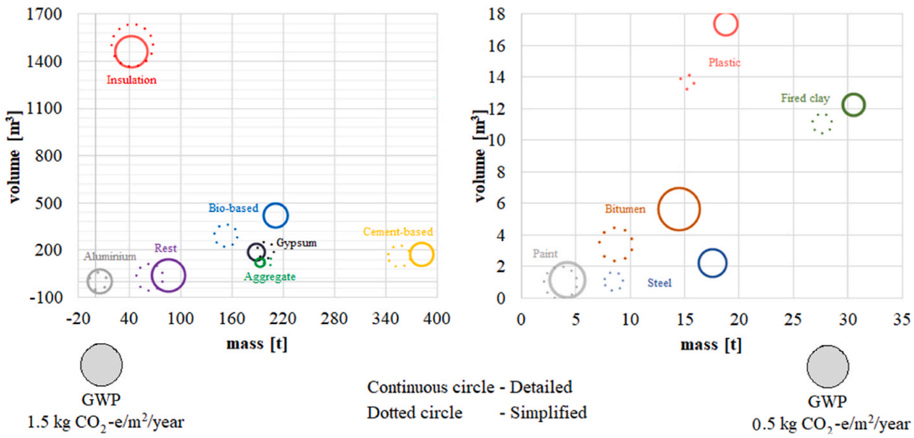

Fig. 5. Relation between the material's weight, volume and the GWP (solid line represents the detailed case, and the dashed line represents the simplified case). The graph on the right is a breakdown of 'other' materials marked on the left graph.

the largest contributors to the façade's GWP with a share of 51%, despite its small volume of 2,05 m^3. This emphasizes the necessity of including thin metal sheet products in the BIM modelling due to large CO_2-e emissions.

3.2.2. Insulation

Approximately 0,16 m^3 of the insulation is replaced with studs in 1 m^2 of an average internal wall uninterrupted by openings. This can peak at up to 0,804 m^3/m^2 in areas with complex connections. It may be claimed that the extra modelling effort required for the adequate representation of structural studs and beams is not valuable as the GWP share of construction timber studs is only 2% in the simplified and 3% in the detailed versions. However, without advanced modelling of timber, there is no feasible solution to account for cut-outs and thus reduce the environmental burden of the mineral wool on such a large scale.

Although mineral wool should be given a high priority in modelling, that does not apply in all cases. The extra modelling efforts associated with the insulation strips around the opening or the angle edges at the roof are not proved to have a noticeable effect. This is linked to the material's low density.

On the other hand, even a small quantity of high-density PIR or stone insulations may have a large environmental burden. This occurrence is observed at the terrain deck component, where 5 m^3 of PIR insulation exceeds the impact of 75 m^3 of mineral wool by 130%, which further supports the hypothesis that a high volume does not result in the largest GWP.

When a lower impact is desired, the identification of the hotspot materials is often prioritized. Mineral wool with a 30% share of the total GWP would be identified as such. To reduce emissions, the insulation thickness might be reduced, thus lowering the building's energy performance. Multiple variant studies may be developed to assess the material alternatives or quantities to find the most advantageous solution. Based on the detailed assessment, aluminium is the highest contributor. Therefore, hotspot detection in the simplified scenario is faulty due to the quantity of the insulating material being over-estimated. If this quantity is corrected by taking cut-outs for studs into account, there is no need for further reduction of the environmental burden by reducing the thickness. This study concludes that there is a link between correct hotspot identification and the quality of the BIM model.

3.2.3. Bitumen felt

The GWP of the bitumen is sensitive to any changes in quantity due to its fossil origin and short reference service life. Considering the default 1 × 5 m roll and the requirements of a min. 120 mm longitudinal overlap and 150 mm overlap in the cross joint, the coverage area corresponds to 4,27 m^2 instead of 5 m^2 as typically assumed. Hence, a quantity correction for the overlaps is highly recommended.

3.2.4. Cement-based materials

The GWP increase of the cement-based materials is primarily caused by implementing reinforcement in the concrete elements as well as modelling the often-omitted extra footing that must be cast around the building's perimeter to provide moat/level access. It is highly recommended that the concrete elements should be thoroughly analyzed, as it is not a structural material where any reductions can be applied to reduce the environmental burden. However, this is hindered by the lack of information about reinforcement quantities in the early design.

Furthermore, when modelling materials with a high GWP, the precision increases in importance, as even small changes may have large implications on the results. This is demonstrated in screed layers, where a one third reduction of the GWP was achieved by modelling the floor slope.

3.2.5. Steel

The steel profiles are typically excluded from the modelling process due to their complex geometry. Unlike timber, the steel profiles are thin and soft insulating material can easily be fitted in between them. Hence, they do not contribute to reducing of the insulating material. However, their amount tends to be underestimated in the simplified case due to the manual estimate of the profiles' length. In the detailed case, where the material's volume is used for the estimate, the impact doubles. However, the impact of steel on the total GWP of the building is insignificant, reaching up to 3% in the detailed assessment.

3.2.6. Bio-based materials

The share of the studs along with uniform layers of plywood and OSB have the GWP share of 12% in the simplified and 11% in the detailed versions. Therefore, it can be concluded that a simplified estimate of the timber is acceptable, but only in terms of the GWP of the material in question. It is unacceptable for further estimates of soft insulation and fasteners that are dependent on the precise quantities of timber frames. The findings demonstrate that every component in the detailed stage faces an increase of timber studs of between 42 and 631% due to the higher timber volume at corners and junctions.

3.2.7. Gypsum

The largest difference in the modelling of gypsum occurs in the material wrapping at element connections and edges. Because of the vast use of this material, the applied simplifications are inconsequential to the results, with only a 2% decrease in the GWP when applied.

Both the joint compound and the plaster used for the completion of the gypsum surfaces are used in large quantities (2543 kg and 1609 kg respectively), with insignificant impact on the LCA results. Therefore, their inclusion is not required.

3.2.8. Floor finishes

The results indicate that the corrected quantity from the detailed model does not significantly affect the results. However, accounting for the adhesive that linoleum requires, the GWP is inflated by 183% (detailed case) compared to the impact of linoleum alone (simplified case).

Ceramic tiles together with the waterproofing and adhesive layers, contribute 2% to the overall GWP of the building. Detailed modelling accounts for the slope in the floor construction, which, when modelled, requires a larger quantity of tiles to be used on the surfaces. In the simplified case, due to a smaller overall area used for the tile, a 28% reduction in the GWP is reached.

3.2.9. Fasteners

Often considered negligible due to their small size, the fastening elements add up to several tons. The share of the fasteners corresponds to 6% of the total embodied GWP. For illustrative purposes, this impact corresponds to the CO_2-e from over 17 000 m^2 of gypsum. It is challenging to quantify which fastener types can be excluded as even extreme quantities of the small ones may alter the results. Based on this study, screws with a length of below 40 mm can be disregarded in the LCI. In this case, the larger quantity does not imply a substantial increase in weight and consequent impact, as it goes hand in hand with the fastener's dimensions.

3.2.10. Membranes

The area obtained from the simplified BIM model is sufficient for an accurate representation of the membrane's impact in the LCA. In the case study, the overlaps from the detailed model account for an extra 1970 m^2 but due to the inconsequential impact on the building's GWP, this quantity correction is not required.

3.2.11. Sealing materials

Sealants are an ideal example of a material small amounts of which can be neglected though they have substantial influence on the GWP in large quantities. While the weatherproofing silicone around the openings has only a 2% share of the component's GWP, the acrylic sealant in the internal walls accounts for 13% of it. Seen from a broader perspective, sealants make up the same share of GWP as e.g. steel that forms internal walls, and bathroom and terrace floor frames. This finding indicates the need for industry-wide discussion about their inclusion in the LCA.

3.3. Material ranking

As indicated in Fig. 6, for a material to be considered significant for the LCA, its share of the building's GWP must exceed 5% [41].

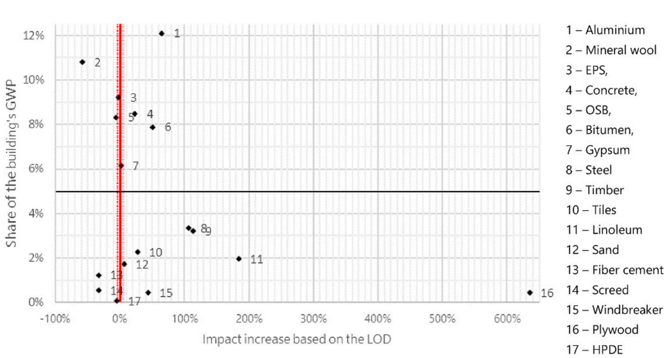

Fig. 6. Y-axis: Material impact increase in detailed modelling. X-axis: Material share in the GWP of the building.

Simultaneously, more than a 10% variation in the GWP between the simplified and detailed models must be detected to require improvements to modelling improvement. These criteria are established due to the large costs associated with developing the detailed model, which in this study is estimated to require seven times more modelling time. In a professional setting, the associated costs and the increase in GWP would outweigh the benefits of detailed modelling.

The results show that the simplified modelling of aluminium (1), insulation (2), and bitumen (6) requires critical adjustment to improve the reliability of the LCA results. Both aluminium (1) and insulation (2) rank as the top two materials with the highest share of GWP on the building level, with 12% and 11% respectively.

Bitumen felt, due to its fossil origin is also a great contributor, with approximately an 8% GWP share. The impact between the simplified and detailed models for these materials is severely overestimated (insulation) or underestimated (aluminium, bitumen). Therefore, the modelling accuracy or quantity adjustment of LCI should be prioritized.

On the other hand, although the GWP share of EPS (3) or OSB (5) considerably exceeds the 5% setpoint, its estimate in the simplified model is sufficiently accurate for LCA purposes. Unlike aluminium (1), insulation (2) or bitumen (6), their modelling at LOD200 gives results within an acceptable margin, requiring no further modelling improvement or quantity adjustment.

Lastly, the graph points out that materials such as plywood (16), linoleum (11), timber (9), and steel profiles (8) require refinement to reduce the gap between the quantities in the simplified and detailed cases. However, their share of GWP has no impact on the building results. Hence, advanced modelling is not prioritized, though it is recommended if an accurate LCA is desired. Table 1 provides an overview of the demand for more accurate material quantification when using BIM inventories for LCA.

4. Discussion

This study investigates the discrepancies between the LCA results of a timber building calculated based on the LOD200 (simplified) and LOD350-400 (detailed) BIM models. A previous study [47] has shown 144% higher values in the energy consumption calculations when the LOD200 model was used. They found LOD350 to be the most accurate model for the calculation of energy consumption with only a 2,7% difference from the measured data. In this case study, a variation of 8% was identified between the results for the GWP indicator. If the BIM model's influence on energy consumption during the operational phase was

Table 1
Overview of the demand for more accurate material quantification when using BIM inventories for LCA.

Highly prioritized improvement in modelling/quantity correction	Timber studs/joists Soft insulation Aluminium (flashings, cladding underlays) Bitumen felt Fasteners (framing screws, wind rods, brackets) Façade cladding Concrete elements
No modelling improvement required	Uniform timber layers (plywood, OSB) Steel profiles Interior gypsum Homogeneous layers of rigid insulation Floor finishes (tiles, linoleum) Membranes
Materials that can remain excluded from both the BIM model and LCA	Small quantities of low-density insulation Joint compounds and plaster Sealing materials

taken into account, the GWP variation would be expected to be even higher. However, the development of zero to low-energy consumption building projects has the ability to eliminate the discrepancies coming from the impacts of the operational phase. Consequently, the difference in LCA results would come solely from the embodied impacts, which were found to be equal to 14,7%. Previous studies have found 20% uncertainty influencing input data on the reliability of buildings' LCA results or even higher when the methodological aspects have been investigated [35,48].

On that basis, DGNB certification [49] or scientific studies [48] have recommended a correction factor of 20% when calculating the impacts in the early design stage using a simplified model. Although the increase of 20% in impacts calculated through a simplified model enhances the accuracy of the final results, it might cause a deterioration to the contribution analysis, which guides the process of minimizing the impacts of a building. For instance, the mineral wool was identified with a contribution of 30% based on the simplified BIM model. As the impacts of these materials are significantly overestimated, a further increase of 20% would not bring any benefits to the robustness of the contribution analysis. This study finds that awareness of the building's inventory is detrimental. To minimize the gap in results, an uncertainty factor can be applied, but it should be adjusted depending on the building's type and construction. Furthermore, the factor's implementation should be viewed on the material level, taking into consideration the increase or decrease in the GWP found in the study.

To strengthen the results of the contribution analysis, the components can be classified into different groups in relation to the BIM model and the contribution of materials or components to the total impacts. The first group consists of materials that are not modelled in the simplified BIM model but that have a significant influence on the GWP indicator (e.g. aluminium flashings). The impacts for this group may be considered through default values. The second group are the materials modelled in the detailed BIM model that make a significant contribution to the GWP indicator (e.g. plywood connections). The third group are the materials modelled in the simplified BIM model that make a significant contribution to the GWP indicator (e.g. insulation). The inaccuracies for materials of the second and third groups can be improved through correction factors. These suggestions, which are expected to improve the accuracy of the results, would not increase the workload of the building actors during the early design stage. This study provided a list of materials and components requiring additional attention during the assessment of the impacts of the building project through the LOD200 BIM model. However, the provided list and recommendations are based on a single case study, and to strengthen the findings additional building projects must be analyzed.

Additionally, this study omits the impacts of the transport of materials to a construction site (A4), construction (A5), demolition (C1), and transport of materials to a waste processing site (C2). Although these life cycle stages can have a significant contribution, the uncertainties of the impacts they may convey if assessed simplified or detailed are significant. The discrepancies between the results assessed through different BIM models were primarily caused by materials with low weight or volume (e.g. aluminium). The impacts of transport, construction and demolition are strongly related to the mass of materials [50]. Therefore, if the omitted stages were to be implemented in the LCA, the potential variation in the results obtained due to LOD 200 and LOD 350–400 LCIs would be insignificant.

Aluminium, having both low weight and volume (less than 1%), is found to be the largest contributor to GWP. This material could be neglected due to its mass if the cut-off rule recommended by the EN-15978 norm were followed. This study recommends a revision of the cut-off rule since excluding such materials from the system boundary may convey large uncertainties. Instead, the recommendations should be provided in relation to the classification of materials into three groups, as indicated above. Furthermore, Cavalliere et al. [51] recommended the development of building components following different LODs. The results of this study show that the biggest discrepancies are caused by the materials and components that connect the building elements. The findings of this study coupled with the recommendations of Cavalliere et al. could be sufficient to strengthen the calculation of the building's environmental impacts through a simplified BIM model at the early design stage of the project. In that sense, the development of building components following different LODs should take into consideration the specific details and differences of the components that are present in different building areas. For instance, the composition of walls close to windows is different from the composition of external walls where this relates to the column, beam, or slab. Moreover, the development of the macro components should consider how the building elements are connected with each other (column with beam, presence of thermal bridges, façade with intermediate floors etc).

5. Conclusion

This study has demonstrated that the total GWP from the simplified model is 8% lower when compared to the baseline LCI from the detailed model. Although the total difference is not detrimental to the LCA results, it may have significant implications in the early decision-making process. The embodied phases, which are affected by the accuracy of the material quantities (A1-A3, B4, C3–C4), account for a larger share of the building's GWP (55%) compared to the operational energy (45%), and thus its correct estimation should be prioritized.

The impact of the modelling in less detail (LOD 200) is prominent in the embodied emissions, where the GWP is 14,7% lower than when the LOD350/400 model serves as the data source. The accuracy of the simplified modelling for LCI ranges from 26% to 95% (depending on the building component), highlighting the scope for changes that affect the model. All building components (except for the ceiling) show a decrease in impact in the simplified case due to incomplete quantity calculation or material omission. When evaluating the LCA on the component level, a distorted image of the component emissions may appear. However, the ranking of both the life cycle stages and the component's contribution to the GWP of the building does not change significantly.

If the sustainability goals or regulatory requirements are strict and require specific reductions in GWP, an 8% deviation might prevent the project from achieving those targets. This could have implications for obtaining certifications, meeting the legal requirements, or fulfilling corporate sustainability commitments. Furthermore, organizations striving for a competitive advantage based on sustainability performance might be affected by an 8% deviation. If competitors use more accurate LCAs and make better-informed decisions, this could impact their market positioning. Ultimately, the decision on whether a deviation is found to be detrimental depends on the specific project's goals and the context in which the LCA results will be used.

The key findings are identified at a material level. Materials that are the heaviest (concrete) or the largest in volume (mineral wool) do not result in the most significant CO_2-e emissions. Materials such as aluminium, mineral wool/timber and bitumen felt are recognized as critical and as needing quantity improvements to enhance LCA accuracy. The EN 15978 standard excludes materials with a share of less than 1% of the overall mass from the LCI. However, this study identifies aluminium, with a weight share of less than 1%, as the highest GWP contributor suggesting a revision of the cut-off rule in the standard. Furthermore, the ranking of the critical material on the contribution they have on the total environmental burden shifts during the project stages. This indicated that hotspots detected in the simplified model may misguide the decision-makers in the early design stages, when the potential for undertaking the largest carbon-saving measures is the highest. Inaccurate identification of the highest carbon emitter (hotspot) may lead to the unconscious omission of actions that would have the highest impact on carbon reductions. Thus, the paper emphasizes that simplified models may lead to the GWP being under-estimated when no inventory correction is applied. The application of strategies addressing the material quantity deviation is dependent on the specific construction method and the type of building being investigated. It is believed that the integration of correction factors could be a way of minimizing the issue, but the applicability of the method is a matter beyond the scope of this research. Detailed analysis reveals that often-omitted components ensuring airtightness and structural integrity contribute 16% to the embodied GWP, and thus should be considered in the LCA process. However, sealing materials, joint compounds, and plasters, can be excluded from the LCA, as their impact on the building's GWP is negligible.

Overall, the identified differences in the GWP based on the two BIM models are sufficient to raise concerns about the availability of data for environmentally conscious design. The detail heavy LCA requires a large workload to ensure the reliability of the results, which stands in contrast to the early design work that relies on approximations of the material quantities. The difference of 14,7% GWP found between the analyzed models does not negate the necessity for a carbon profile calculation to guide the early design process, but rather points out the gap that the industry faces. At the moment, the mere integration of LCA in architectural processes is a step in the right direction from an environmental standpoint, but there is work to be done to raise the quality of data in LCA integration. In terms of future research, researchers could focus on refining methodologies for bridging the gap between simplified and detailed LCAs. This might involve developing conversion factors, adjustment methods, or estimation techniques to account for the missing data. The deviations across different project types and materials should also be explored. A more holistic assessment through integration of the discrepancies between the LCA results from simplified and detailed energy consumption calculation may be a potential future perspective worth investigating.

CRediT authorship contribution statement

Natalia Nawrocka: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michaela Machova:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rasmus Lund Jensen:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Conceptualization. **Kai Kanafani:** Writing – review & editing, Visualization, Validation, Methodology, Conceptualization. **Harpa Birgisdottir:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Investigation, Funding acquisition. **Endrit Hoxha:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

We acknowledge that the submission declaration of "Building and Environment" journal has been complied with. We also confirm that all necessary permissions have been obtained. The authors declare that there is no conflict of interest regarding the publication of this article.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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