INFLUENCE OF BIM'S LEVEL OF DETAIL ON THE GLOBAL WARMING POTENTIAL OF A TIMBER BUILDING

MSc. BUILDING ENERGY DESIGN

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SYNOPSIS

The absence of guidelines on BIM modelling for LCI is a potential cause for deviations in the LCA, particularly when measuring the GWP of timber building components which are either typically omitted, such as fasteners, sealants, membranes, or modelled without accurate representation of the real quantity. This study attempts to identify the deviation that occurs based on the inventory data obtained from simplified (LOD200) and detailed (LOD400) BIM models. The developed BIM Revit models serve as a base for the quantification of the materials, including the elements that are currently neglected in all the researched studies. Conclusions are drawn about whether the simplified model is sufficiently accurate to represent a reliable environmental profile. The study case results are compared against a company-developed BIM model confirming the variation in LODs between the disciplines. Due to the industry's reservation towards advanced BIM modelling, this study suggests feasible methodologies to eliminate the deviations.

By signing this document, each member of the group confirms participation on equal terms in the process of writing the project. Thus, each member of the group is responsible for all contents of the project.

Alphabetized list of abbreviations:

BIM: Building Information Modeling

BR: Danish Building Regulations

DGNB: Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)

EE: Embodied Energy

EPD: Environmental Product Declaration

EPDM: Ethylene Propylene Diene Monomer

EPS: Expanded Polystyrene

GHG: Greenhouse Gas

GWP: Global Warming Potential

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LOD: Level of Detail

OE: Operational Energy

OSB: Oriented Strand Board

PE: Polyethylene

PIR: Polyisocyanurate

PP: Polypropylene

PU: Polyurethane

Abstract

The operational energy in construction projects has already reached its lowest, so the production and use of building materials have a significant share in CO_2-e emissions. Wooden buildings are commonly used to reach a reduction of embodied emissions. The impact analyses are generally conducted based on the LCI obtained from the BIM models. The absence of guidelines on BIM modelling for LCI is a possible cause for deviations in the LCA, particularly when assessing the environmental burden of timber building, as certain components are modelled without accurate representation of the real quantity or completely omitted. This study investigates the differences in the GWP of a modular timber building comparing the inventory originated from simplified (LOD200) and detailed (LOD400) BIM models. The impact evaluation is executed through the LCA method. The GWP increase of 14,7% is observed when the LOD400 model serves as the LCI source.

With cut-off criteria at the GWP contribution above 5% and more than 10% variation in the GWP of the material based on the two models, the adequate quantity estimation of the following materials is found to be critical: insulation, bitumen felt, and aluminium flashings. Elements typically omitted in modelling (fasteners, sealants, membranes, etc), and thus LCA is found to contribute by 15% to the total GWP, with the highest share of 6% belonging to fasteners. Currently overestimated GWP of the insulating material by over 50% tends to be wrongfully identified as the hotspot, calling for its reduction. The outcome of this study provides correction methods for the analysis based on LCI obtained from BIM models. Due to the industry's reservation towards advanced BIM modelling for LCI purposes, this study suggests alterations which can be applied in the current enforcement of 2023 Danish LCA legislation or can direct the industry's development in the long run.

Key words: Life Cycle Assessment (LCA), Life Cycle Inventory (LCI), Global Warming Potential (GWP), Building Information Modelling (BIM), Level of Detail (LOD)

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1 Introduction

The importance of the building sector delivering the ambitions set in the Paris Agreement and the UN Sustainable Development Goals is high. The Danish Climate Act sets a near-term target of reducing Denmark's total greenhouse gas emissions by 70% by 2030 compared to the 1990 level while attaining climate neutrality by 2050 [1]. Considering the whole lifecycle of buildings, the sector accounts for an estimated 42% of total energy use, 35% of greenhouse gas emissions, 50% of extracted materials and 30% of water use [2]. The pending legislation which comes to force in 2023, requires all new buildings below 1000 m^2 to undergo a lifecycle analysis (LCA) without any targeted value, while constructions above 1000 m^2 must meet a maximum of 12 kg CO_2-e/m^2 of heated floor area/year. Regardless of building size, this demand will gradually tighten with the reference value dropping to 9 kg CO_2-e/m^2/year in 2027 followed by 7,5 kg CO_2-e/m^2/year in 2029 [3]. The current Danish BR (Building Regulations) impose limits for operational energy (OE), while the embodied energy (EE) of the building materials is a disregarded area. A study of 60 Danish case buildings indicates the embodied CO_2-e of building materials being 2 – 4 times higher than the impact related to the operational stage [4]. The emphasis should thus be put on overall building emissions, including the investigation of EE, instead of relying solely on improvements in energy efficiency.

With the recent emergence of engineered wood products such as cross-laminated or glued-laminated timber, wood has increasingly been utilized in large-scale constructions. Available literature recognizes the potential environmental benefits of substituting common building materials with wood-based products [5]. However, the issue lies in neglecting other components essential for timber construction in these studies [6], [7], [8], [9], [10], [11], [12], [13]. For instance, the integrity of any timber building depends on the fasteners that transfer and anchor the acting loads. In almost all cases, these fasteners, membranes or sealants that initially appear negligible are neglected, yet used in large quantities. Therefore, the purpose of this study is to reduce the aforementioned information gap by examining the additional impact of these fasteners, screws, and brackets, along with the materials such as membranes and sealants guaranteeing the airtightness of timber frames.

It is suggested that this issue originates in the common BIM modelling practices that omit these components due to the non-standardized Level of Detail (LOD) and associated additional labour [14]. Consequently, their impact is not accounted for by engineers in the environmental assessments. It is predicted that these added impacts have negative repercussions on the final results. Thus, this study attempts to identify the potential deviation that may occur based on the inventory data precision obtained from BIM models. Naturally, advanced BIM modelling results in extra work and associated costs in the short term. Therefore, the ratio between the time spent on the simplified BIM model compared to the time dedicated to the thorough modelling for the purpose of life cycle inventory (LCI)

1 Introduction

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1.1 Research questions

How significant is the difference in global warming potential (GWP) when the LCA is performed for a model detailed to LOD20 and LOD350-400?

The modelling of which elements is considered essential to provide adequate LCA results and which elements prove to make no significant impact on the GWP of the building?

How vastly is the environmental impact of a timber building affected by components commonly omitted in the LCA analysis?

Can the process of detailed modelling be simplified while maintaining a high detail of information for LCI?

1.2 Project outline

Chapter 1: Introduction – background for the study is defined by highlighting the importance of embodied energy investigation along with the research's goals and limitations.

Chapter 2: Methodology – presentation of the investigated study case along with the obtained documentation and literature review of the relevant topics, i.e., operational vs embodied energy, timber construction and BIM-to-LCA integration.

Chapter 3: Influence of the LOD on the GWP – display of the results on the building and the material level. Followed is the interpretation of the cause for the GWP variation between the LCA based on the LCI from the simplified and detailed models. The chapter is summarized by the categorization of the materials with significant impact on the LCA, which should be adjusted based on the proposed methodology, elements, whose modelling does not require improvement, and materials that can remain omitted due to their minimal impact on the results. For validation of the study, the GWP is compared to the information that was used for DGNB certification obtained from the design team.

Chapter 4: Discussion – identification of the key findings and limitations encountered in this study. Formulation of other observations emerging from them which can serve as a basis for further research of the topic.

Chapter 5: Conclusion – the results of the study are summarized and the key elements requiring modelling improvement are pointed out.

2 Methodology

This study aims to find potential deviations in LCA results that may occur based on the BIM model's quality. In addition, the objective includes identifying the critical materials and providing a feasible approach for their integration into the LCA. The project's focus is the embodied CO_2-e in both the key materials of timber building and the frequently neglected ones, such as fasteners or sealants. The calculated energy translates into the impact category of GWP measured in kg CO_2-e/m^2/year due to its relevance to the 2023 legislation. The other environmental indicators are excluded from this study. The reference study period is set to 50 years as recommended by the Danish Agency for Housing and Planning [15]. The general LCA is performed with a "cradle-to-grave" methodology, as stated in EN-15978 [16], accounting for life stages (modules) starting with the cradle (resource extraction) to the grave (disposal). This analysis focuses on the CO_2-e emitted from the materials. The embodied energy in the A1-A3 module goes hand in hand with the B4, C3 and C4, i.e. a variation in one phase causes a change in all of them. For certain materials, module D is additionally covered (benefits and loads beyond the system boundary). Since the embodied CO_2-e forms the study's core, the B6 stage (operational energy use) is set in the background. The A4-A5 modules (transport and construction) are disregarded as the actual values are unknown and the recommended standardized values do not contribute to the detailed assessment, nor does it include repair and maintenance of the materials, which can potentially increase GWP.

The assessment is conducted with the following cut-off criteria in mind:

- impact of any HVAC systems and fixed furniture is disregarded as well as any cut-outs made to the material layer due to the duct/pipe penetrations
- any prefabricated concrete element inside of the building (i.e. internal staircase walls, staircase) is excluded, however, investigated is the concrete used for the envelope due to its structural need (i.e. foundation)
- materials weighing more than 10 kg are included in the modelling and computations
- only components that are modelled in the 3D model are included in the inventory, except for fasteners and specific sealants whose information is stored in the model without its 3D representation
- for the simplification of this study, it is assumed that all components in the 3D model are developed to the same LOD while in reality, each object can be categorized differently

The difference between the workflow selected for this report and the process currently followed in the industry is illustrated in Fig. 1, 2. The developed BIM Revit models serve as a base for specifying building properties, size and quantification of the materials. The model geometry and contained information vary based on the desired LOD (Appendix B). Assembly schedules are created for each component from the foundation to the roof, containing information on the material composition, areas, volumes and the number of fasteners. Material take-offs are filtered and treated based on the required LCA inputs. The hierarchy in the LCAbyg software is modified based on the complexity of the analysis. Detailed process descriptions of the data extraction and treatment can be found in Appendix B and C. Additionally, the input values related to the OE are based on the energy framework conducted for this study in BE18 (Appendix E).

The study analyzes the GWP score based on IPCC 2013 impact assessment method [17]. It is conducted in LCAbyg, the software authorized by the Danish sector, where the relevant information about the components is manually entered to calculate the environmental profile and resource consumption. The biogenic carbon is assessed through the -1/+1 approach according to EN15804 [16]. The quantity input values for calculations vary based on the two degrees of detail described in Appendix D. The summary of components and their associated properties in the assembly schedules serve as a guide for finding the most accurate match in the software's database. The source of the environmental indicator values alters between the generic ÖKOBAUDAT library, Danish EPDs or manually created components. Elements for which no suitable material can be found in the database (e.g. specific adhesive types) are excluded from the assessment. The material's impact is calculated based on the relevant characteristic defined in the library or by the manufacturer (e.g. density). The material's service life is determined based on the SBI2013:30 charts [18]. The input values along with the results and their comparison can be found in Appendix D.

The findings are interpreted to different extents, i.e. on the building, component and material levels. The results of case studies are compared to the LCA results developed on the information extracted from the company-developed BIM model. Consequently, conclusions are drawn about whether the simplified model is accurate enough to represent a reliable environmental profile. The interpretation of the results for each component can be found in Appendix D. The alterations and solutions proposed in Chapter 3 of this study are suggested to resolve the observed issues, however, the validity of their application is not tested.

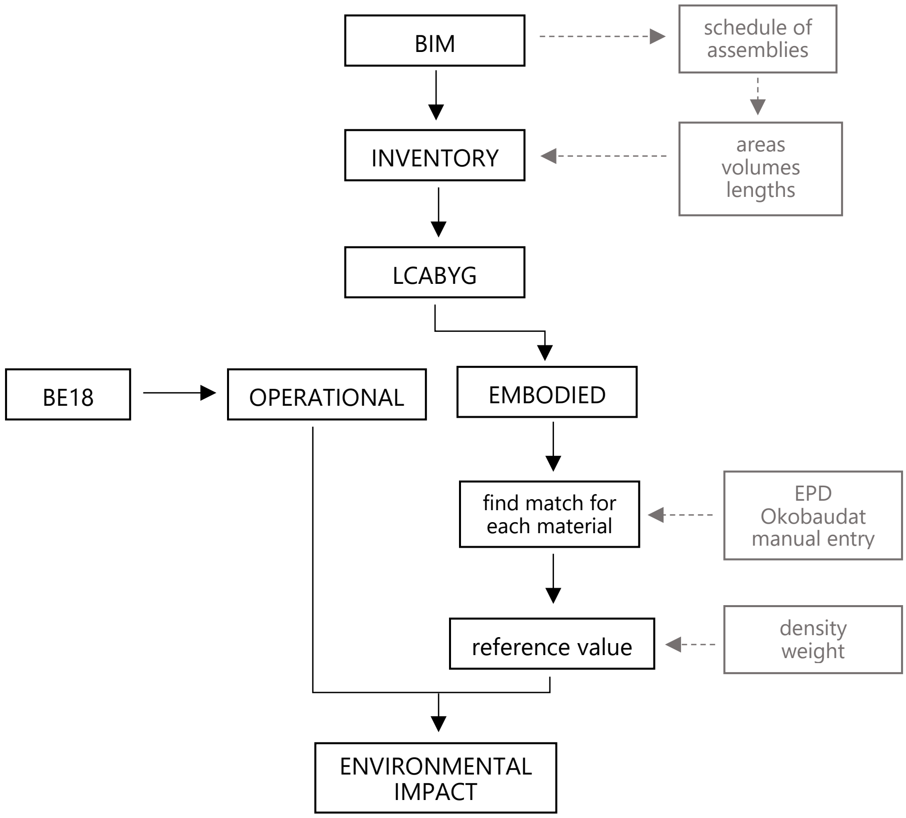


Fig. 1: Process flowchart followed in this study.

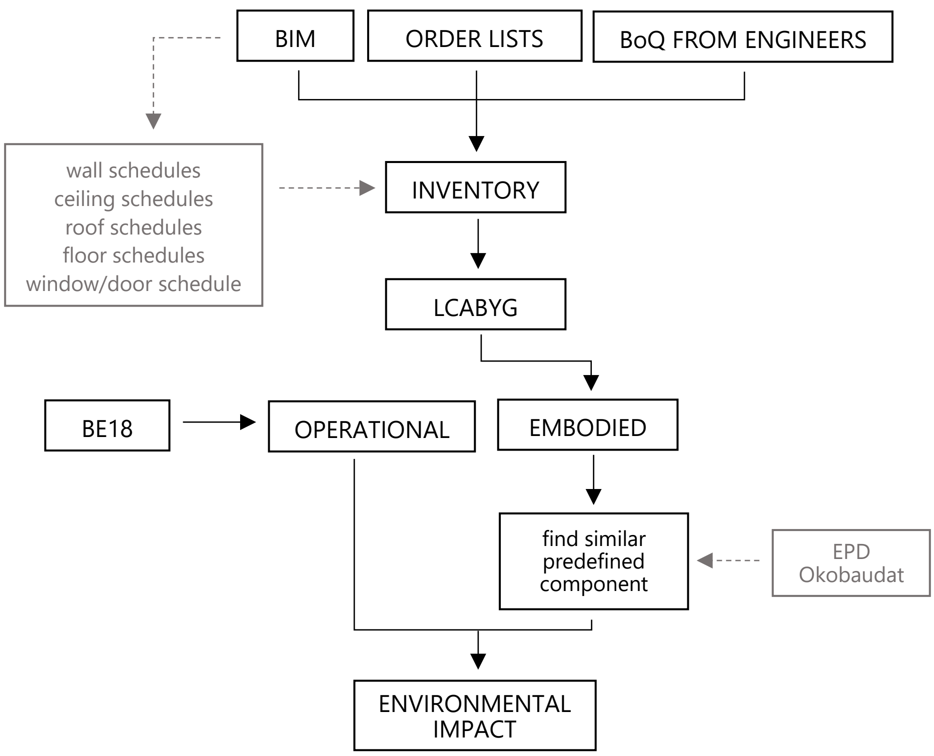


Fig. 2: Process flowchart commonly followed in industry practice.

2.1 State of the art

2.1.1 Operational vs. embodied energy

The reduction of operational greenhouse gas (GHG) emissions has been the major focus of European efforts to reduce the environmental impact of the building sector. As the study [19] points out, measures for OE efficiency have been implemented successfully. The area of research and practice concerning OE has been well-established in recent decades, proven by the vast availability of tools, technologies, guidelines and codes required for assessment and optimization. In contrast, EE remains a largely unexplored area, where the necessary tools or methods are neither globally consistent nor fully established.

As a result of OE reductions, the proportion of EE in the building's life cycle has increased, since executing the above-mentioned strategies requires an increase in material use, which corresponds to higher EE [20]. As highlighted in the study [21], the relative contribution of embodied carbon to the life cycle emissions varies depending on the typology, function, location or material construction among others. The study [20] analyzing conventional and low-energy buildings shows that EE's share accounts for 2 – 38% in conventional buildings and 9 – 46% in low-energy ones.

A study [22] describes the environmental impact of EE of key materials as a neglected factor in the carbon footprint evaluation. It also emphasizes the importance of concentrating efforts towards making wise decisions on a material level during its selection, especially in low-carbon buildings.

2.1.2 Impact of timber construction

Studies on the environmental impact of timber construction consistently highlight that wood-based practices result in less environmental burden in terms of lower CO_2 emissions from the manufacturing standpoint as well as lower energy use in the construction stage. More specifically, a study [23] reported that the mass timber building emits 22 – 50% less carbon than concrete counterparts while the emissions increase with the building's height. In terms of multi-story buildings, there is a GHG reduction potential between 9 – 48% when constructing with timber as opposed to mineral materials (brick, porous/reinforced concrete) [7].

The limitations related to the different system boundaries, functional units and exclusion of some impact categories are defined in the study [24] as the reason for the large deviations between the results and challenges in comparing and validating them. The issue of using multiple databases in LCA has been discussed in the study [22], followed by a study [25] drawing attention to the lack of EPDs in the Danish market.

The recent efforts in a detailed investigation of the EE concern only installations and HVAC systems [26] that account for 6 – 8% of the 12 kg CO_2-eq/m^2/year 2023 benchmark.

Moreover, concerning the 2023 legislation, standard values for the installation inputs were developed by MOE [26], Sweco and Teknologisk Institut [27]. However, only one of the reviewed studies has defined the impact of steel fasteners and vapour barriers. According to Statens Byggeforskningsinstitut [28], the contribution of the fasteners to the total GWP is 0,3 – 0,4% while the vapour barrier's portion is 0,3 – 0,7%. However, this is estimated for concrete-based construction. For this reason, the study will investigate the EE and GHG emissions of all necessary components of timber construction.

2.1.3 BIM/LCA integration

Multiple studies such as [29], [30], [31] recognize the rising demand for software-neutral integration between BIM and LCA to enhance information flow and interoperability. However, these experimental plug-ins [32], [33], [34] do not resolve the main LCA drawback, i.e. quality and availability of the data (Appendix A). This is further supported by the study [35], which defines LCA process issues related to the detail of BIM modelling [30]. The literature review rises questions about the quality of modelling and develops a theory that more detailed BIM models providing more data result in higher embodied energy.

2.2 Study case

2.2.1 Building information

For the investigation of the environmental impact in this study, a residential building complex designed for student housing is used (Figure 3). Delivered in the summer of 2021, it offers 478 residential units, consisting of two-room and one-room apartments, as well as rooms with en-suite bathrooms. Developed as eight separate buildings with a total area of 17 500 m^2, the complex also hosts other shared communal spaces, e.g., common kitchens, laundry rooms or atriums spread across the buildings.

Figure 3: The building complex used for this case study [36].

A single building unit with the greatest material quantity used for its construction is determined and used for the analysis (Figure 4). Compared with the other units, this one is characterized by the largest floor area as well as the most apartments with en-suites, both of which contribute to the large material usage per area.

Figure 4: Location and layout (1st floor) of the investigated building.

2.2.2 Construction

The core of this project is its modular timber structure (Figure 5). Adding to the benefits of building with timber, such as lower CO_2 emissions, this construction method contributes towards more sustainable construction practices. A streamlined prefabrication process in a closed indoor environment, where approximately 80% of the building construction takes place, lowers resource consumption, both in terms of energy and materials. Individual elements that create the framework are assembled to form an enclosed module, which is insulated, sealed, and fitted with mechanical, electrical and plumbing installations. The interior is executed to a delivery standard, including surface finishing (plastering, painting) and installation of fixed furniture. As the groundwork and casting of the foundations or the terrain deck can take place during module production, the delivery is scheduled for instant assembly. The building blocks are craned in place and fixed individually. The elimination of thermal bridges between the elements is obtained with stone wool insulation strips, and the continuity of the vapour-resistant layer is ensured through the sealing of overlapping membranes. Such an approach has the potential of efficiently reducing construction time by up to 50% while maintaining high-quality results. [37]

Figure 5: Modular timber construction process [38].

2.2.3 Certification

Although not mandatory, highly recognizable in sustainable practice is the DGNB certification. This holistic point-based evaluation weighs various qualities against each other, providing an overall score for the building's performance throughout its lifetime. The case building is awarded DGNB Gold certification, meaning the score lies between 65-80% of the total achievable points in the evaluation. Based on the production date of the technical documentation, the evaluation likely employed the DGNB 2016 version. However, due to the unavailability of the certification documentation, it is not possible to determine the contribution the LCA results had on the overall score.

2.2.4 Documentation

The documentation analysed for this study consists of architectural drawings, containing floor and ceiling plans, sections, and elevations, as well as several overview and detail drawings presenting proposals for solutions of complex building parts (e.g. staircase connections, window installation). Those drawings do not specify the exact geometry or material specification of the building elements, and only provide an approximation regarding the components' shape and dimensions (Figure 6). This documentation is used as groundwork for the analysis of the simplified case. To meet LOD 200, further information regarding the component's construction is obtained from drawings provided by the manufacturing company.

The detailed specifications of physically feasible solutions are extracted from construction details provided by both the manufacturing and engineering companies. The drawings contain detailed information regarding the used materials and their dimensions, including fasteners.

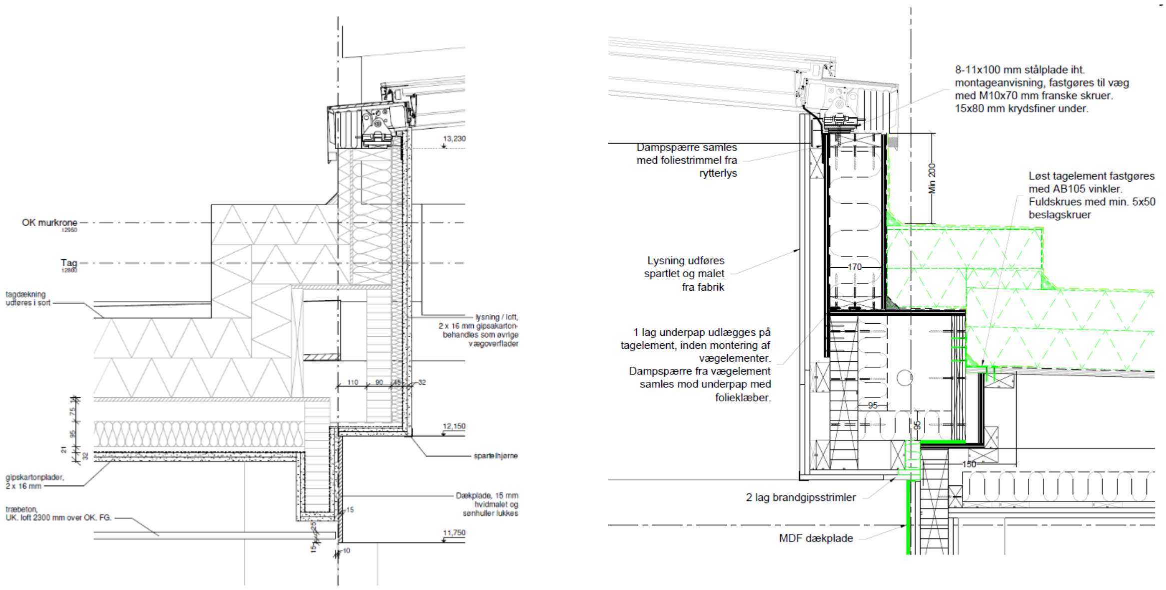


Figure 6: Comparison of drawings used for the development of the simplified (left) vs detailed (right) model (detailed drawing contains additional information about the use of screws, insulation edges, bitumen overlaps, timber sizes, slope, description of membrane placement, etc.).

2.3 Life cycle assessment

LCA is a standardized method of evaluating environmental impacts in relation to the 9 impact categories [39]. Its long-term outlook ensures that impacts from the building's full life cycle are accounted for. The LCA assumes reference service life for the building as a whole as well as individual components, however, it does not reflect the real-life span. This service life is first included in the calculation of the accumulated OE. Secondly, it determines how many material replacements contribute to the environmental impact.

The life cycle is divided into 5 phases and 7 underlying modules, as defined in EN 15978 [16]. Despite its phased structure, the life cycle can accommodate both linear processes from production to waste as well as circular flows, where materials are part of a new cycle. The sum of all modules constitutes the building's environmental profile.

The production stage (A1-A3) entails the extraction of raw materials, their transportation to the production site, manufacturing of final products, assembling as well as packaging and distribution of finished products.

The construction stage (A4-A5) represents the transport from the production line to the installation in the building as well as the transport of the cranes, soil, construction waste and the construction itself.

The use and maintenance or building operational stage (B1-B7) includes activities related to the performance of products during their reference service life. It accounts for overall energy use, waste generation, water use, and potential replacement or repair of components.

The end-of-life phase (C1-C4) concerns consumed energy and waste which is produced due to the building demolition, which is followed by the disposal of materials to landfills, incineration or reprocessing. Energy in the form of fossil fuels consumed by machinery must be included along with average transportation data to a recycling facility or landfill.

Benefits and loads beyond the system boundary (D) do not form an actual part of the LCA but reflect the potential gains or drawbacks from the reuse, recovery or recycling of materials.

The results of LCA can be interpreted using a selected set of measurable indicators. The commonly used ones are GWP, Ozone Depletion Potential, Acidification Potential, Eutrophication Potential, Formation Potential of Tropospheric Ozone Photochemical Oxidants, Abiotic Depletion Potential for Non-fossil/Fossil Resources, Total Use of Primary Energy and Use of Renewable Secondary Fuels.

3 Influence of the LOD on the GWP

As mentioned in Chap. 2 the LCA analyses are performed based on the two degrees of detail. The bill of quantities is generated from two models corresponding to LOD 200 and LOD350-400 (Fig. 7; Appendix B). A detailed interpretation of the results both on component and material levels that serve as a base for this chapter can be found in Appendix D.

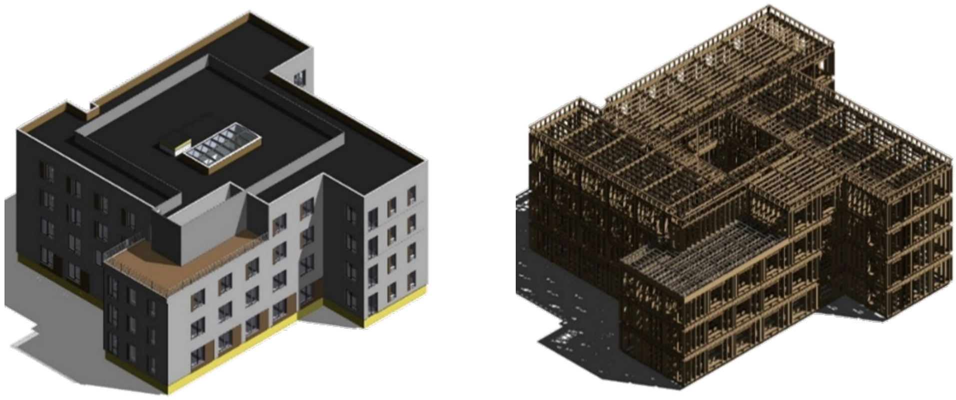


Figure 7: Overview of the simplified model (left) and examples of the objects modelled in the detailed model (right).

The purpose of this chapter is to define the total influence on a building level and categorize the materials essential for the construction of a modular timber building into 3 categories:

a) **Materials with a significant environmental burden** whose inclusion in the 3D models is deemed necessary for the correct bill of quantities. For materials that are currently omitted in the traditional modelling practices but should be accounted for, either a feasible modelling approach is proposed or a methodology for quantity adjustment is developed.

b) **Materials whose modelling is sufficiently accurate** and does not require adjustment. Those materials can continue to be obtained through commonly applied modelling approaches.

c) **Materials with negligible environmental burden** whose modelling can continue to be neglected by the industry for the purpose of life cycle inventory (LCI). According to EN 15804, the total sum of the impacts of materials excluded from the analysis should not exceed 5% of the energy use per module [40], which further increases the relevance of this study.

It deserves to be highlighted that every material in large quantities may result in a high environmental impact. Similarly, small quantities of materials with adverse GWP may be neglected. However, this summary represents reasonable quantities for timber construction rather than extreme scenarios. For analysis of other materials refer to Appendix D, as this chapter describes only a selection of materials that significantly contribute to the LCA accuracy.

To increase the robustness of the calculations and modelling in this study, the LCA results based on the company's model are compared to the results from the models developed for this analysis. Consequently, the extent of the BIM model usage for LCA can be determined, as well as the modelling practices of the industry.

3.1 Results: building level

As the simplified case represents the industry's standard for BIM-obtained LCI, the result is considered the baseline for any further analysis developed in this study. As shown in Fig. 8, the GWP calculated with the data generated from the LOD350/400 model is 14,7% higher than in the simplified stage, where the LOD200 model serves as the data source. The completeness of the modelling points out that the elements of a timber structure whose modelling is commonly overlooked, contribute to a higher environmental impact. It is indicated that the results of the detailed analysis contribute to a higher GWP of the building, with a slight increase in the majority of the components. The timber frame walls (internal and external), two key components ensuring structural integrity, have the largest share of the CO_2-e emissions.

The manufacturing/production A1-A3 has the highest increase of 105% (Fig. 9). Since replacement and waste processing are correlated to the material increase, a 24% and 4% rise is observed respectively.

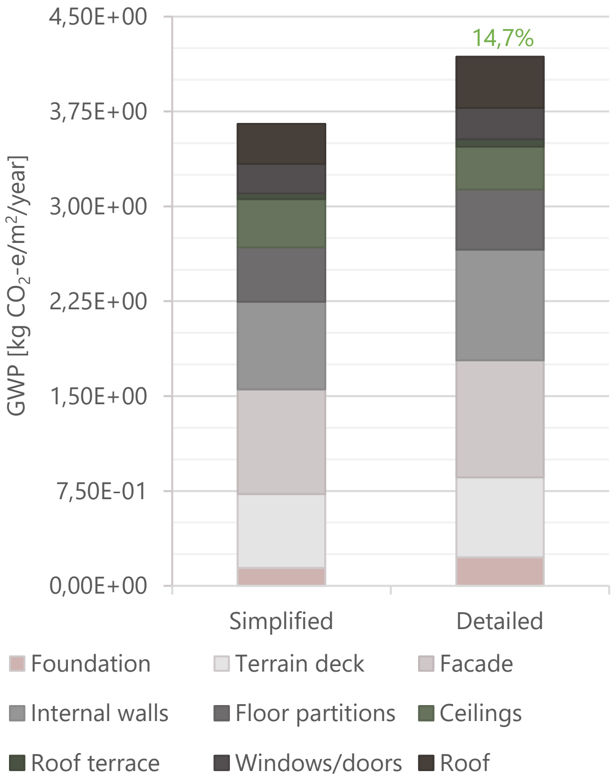


Fig. 8: The influence of the increased LOD on the GWP of the building.

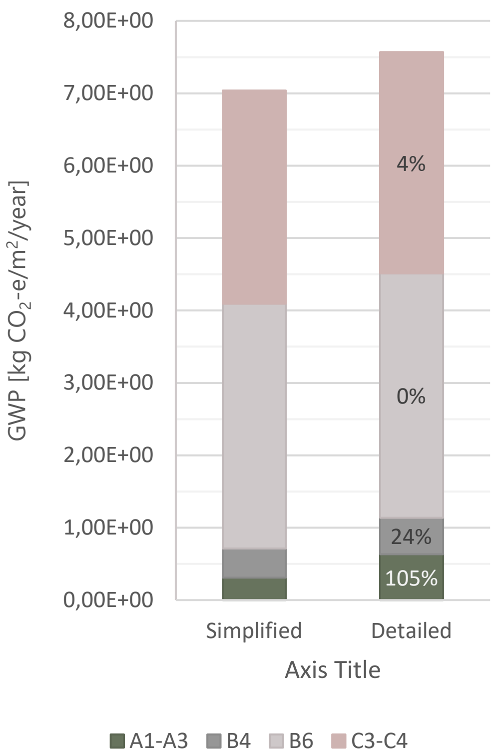


Fig. 9: The share of the lifecycle stages.

Further examination is based on the individual component's CO_2-e emissions portrayed in Fig. 10. All building elements accounted for in the simplified case, face an increase in GWP between 6% (windows/doors) and 59% (foundation) when the detailed evaluation is implemented. The difference occurs from the implementation of new material previously unaccounted for or the correction of the material's quantity due to an improved modelling technique. The highest increase of 284% is observed in the columns component as a result of inconsistent drawing information used for the development of the simplified and detailed models. The only component with a GWP reduction of 11% is the ceiling due to reduced insulation quantity resulting from the timber frame cut-outs.

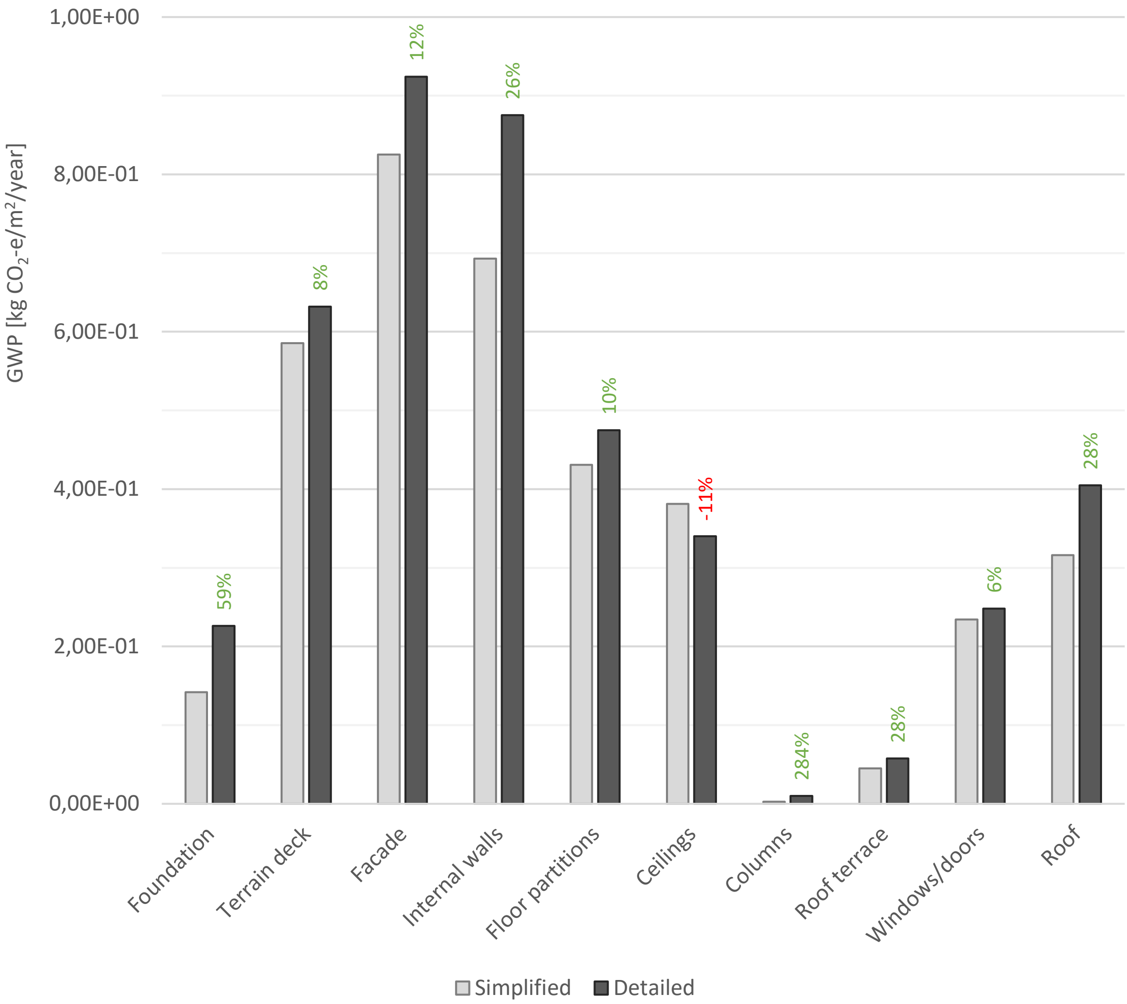


Fig. 10: The influence of the increased LOD on the GWP of the individual components.

The following subchapters in combination with Appendix D break down the components into individual materials, investigating their impact on the component and the building levels. In addition, Appendix F delves into the challenges and limitations encountered in this study, describing the implications it has on the LCA results.

3.2 Results: material level

3.2.1 GWP

The evaluation of the materials' significance is based on two factors:

- the material's share of the building's GWP,
- the material's variation in the CO_2-e obtained from the simplified and detailed LCAs.

Fig. 11 illustrates the material's contribution to GWP. Mineral wool and aluminium are the two largest contributors. Furthermore, materials like concrete, EPS or OSB are indicated, as they have the next largest share of the GWP. This study focuses on the potential improvement of the modelling practices that affect the LCA, thus any elements whose contribution to the total GWP of the building exceeds 5% is prioritized. However, although the share of the materials may be above the setpoint, making it substantial for the analysis, it does not imply that their estimation in the simplified LCA is not sufficiently accurate.

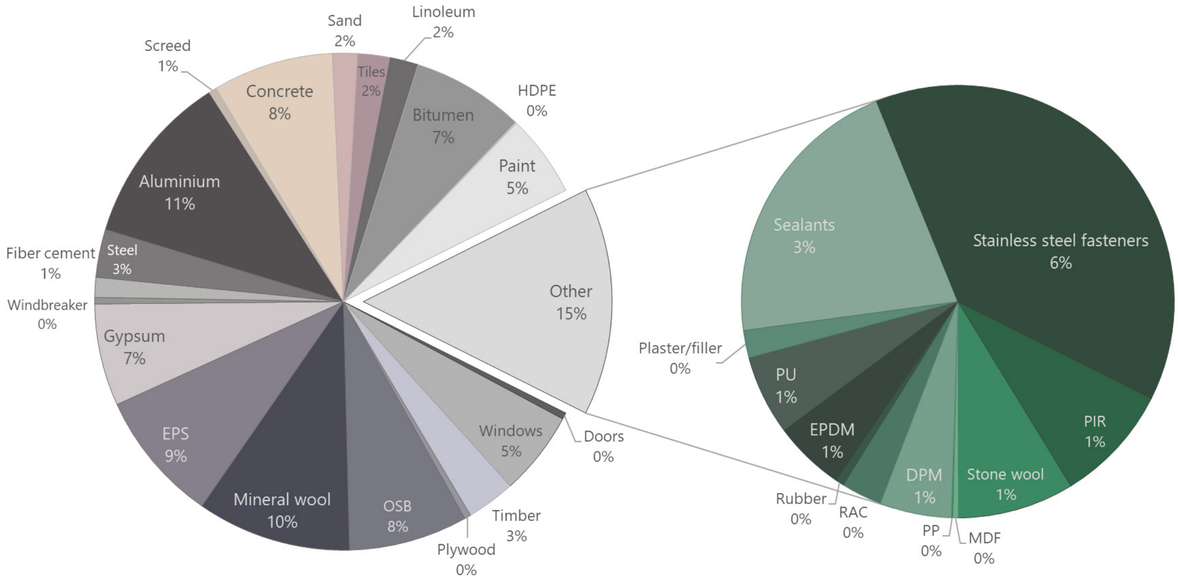


Fig. 11: The share distribution of GWP of all materials in the detailed assessment (left) including the share of materials excluded from the simplified assessment (right).

Fig. 12 assists to reveal the uncertainty of modelling and gives a sense of how precise the generated quantity from LOD200 is. The result's increase or decrease is indicated with an arrow next to the material's name. If the results obtained from the simplified analysis fall close to the results obtained from the detailed case (+/- 10%), the difference is recognized as not significant, and thus the number is marked in green. On the other hand, when the results fall significantly below or above it (e.g. mineral wool, timber, steel), the quantity estimation is not accurate and requires further investigation (number marked in red).

This approach applies only to the materials whose modelling was integrated into both detail stages (Chapters 3.3.1 – 3.3.4). Additional elements that were not considered in the simplified LCA are evaluated solely on their contribution towards the building's GWP and are described further in this chapter (Chapters 3.3.5 – 3.3.8).

For example, when results from simplified and detailed cases for EPS or OSB are compared, no significant variation is observed (94-98% accuracy), thus their modelling for LCI can remain unchanged. On the other hand, steel or plywood points to the need for quantity correction (207-735% CO_2-e increase in the detailed LCA). However, due to their total GWP share being below 5%, their advanced BIM modelling is not prioritized, categorizing them as materials with a negligible impact. If a material has simultaneously large result variation and a high GWP share, such as mineral wool, it is an indication of the need for modelling improvement. The cause for the material's result deviation based on the model's LOD is further elaborated in Chapters 3.3.1 – 3.3.4.

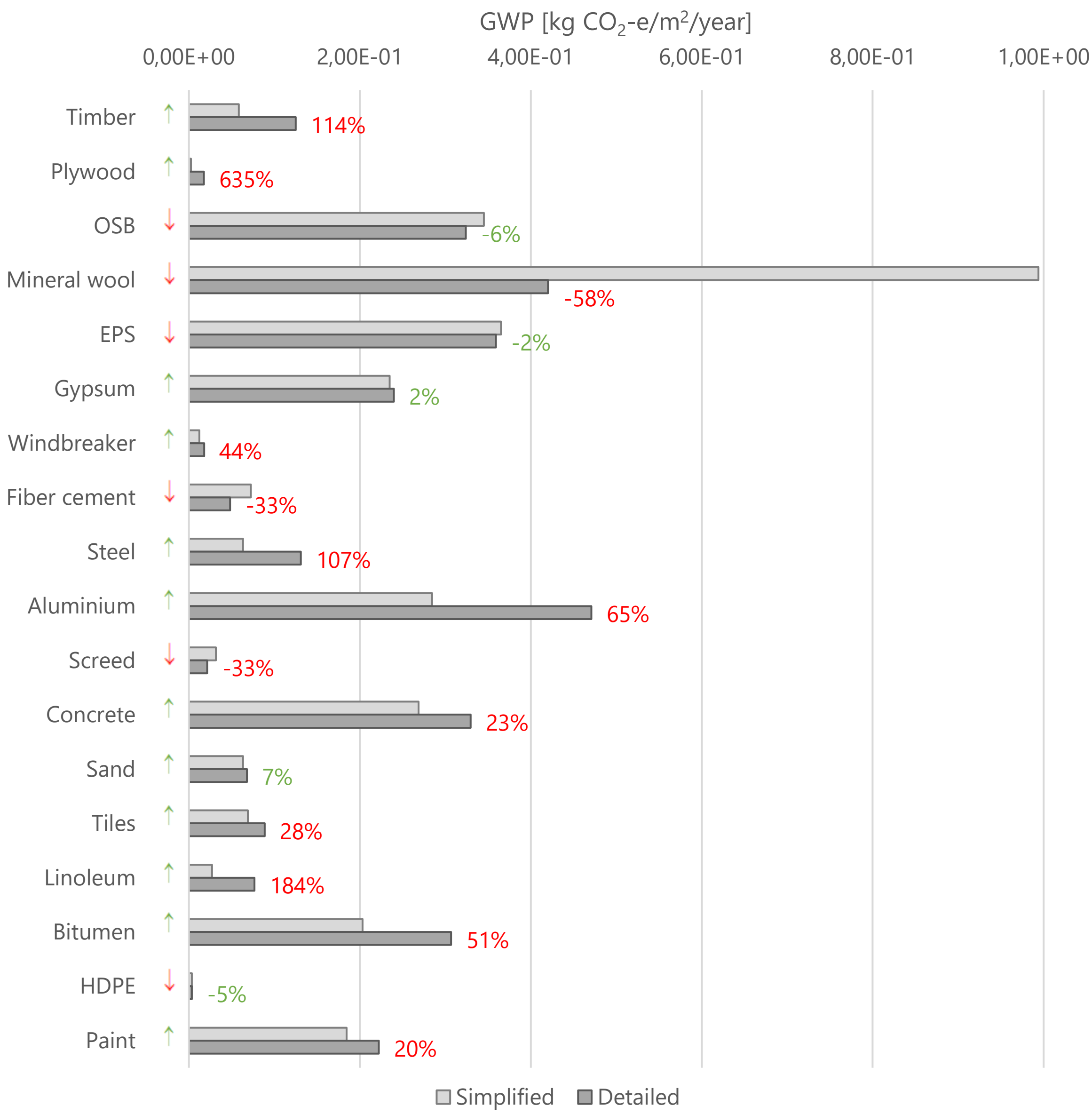


Fig. 12: The change in the GWP of the materials modelled in both stages at different LOD levels.

3.2.2 Weight/volume

Table 1 identifies the 3 materials with the largest share in GWP, weight and volume. It could be assumed, that the heaviest or largest elements in the construction have the lead in the CO_2-e emissions. The 4-storey construction is made predominately with timber, but the concrete elements are used to form the terrain deck and the foundation. Considering the ratio of the timber and concrete used in the building (2:1, Fig. 14), the concrete's 30% share of the weight of the building is surprising (Fig. 13). With a 17% share for sand and 16% for gypsum, it is observed that the materials predominant in the construction (e.g. timber) are not the heaviest. A similar observation is drawn from Fig. 14, where the share distribution of materials' volume is presented. Extensive use of EPS (15% of the total volume) or timber (12% of the volume) does not correlate to the high GWP. Both the large volume and the high CO_2-e emissions are however noticed in the mineral wool. However, the example of insulation alone is not enough to confirm the correlation between the high GWP and the material's weight/volume, as more elements prove against it.

Table 1: Ranking based on the GWP, weight and volume of the materials.

GWP	Weight	Volume
Aluminium	Concrete	Mineral wool
Mineral wool	Sand	EPS
Concrete/OSB	Gypsum	Timber

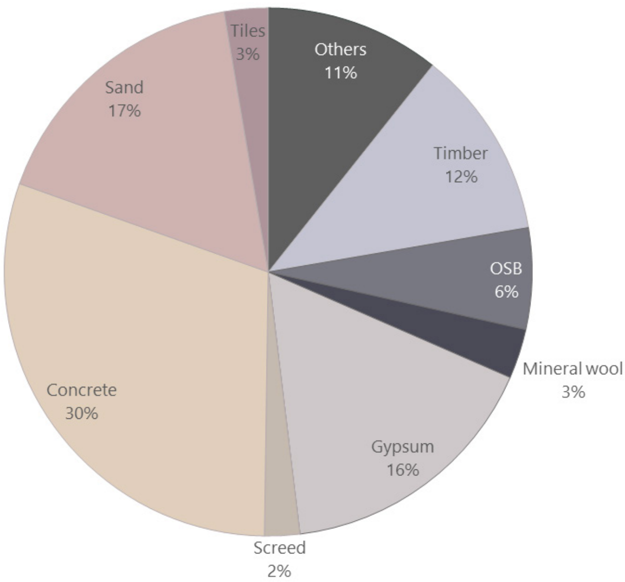


Fig. 13: The share distribution of the weight of all materials in the detailed assessment. 'Others' include materials with the share of less than 5%.

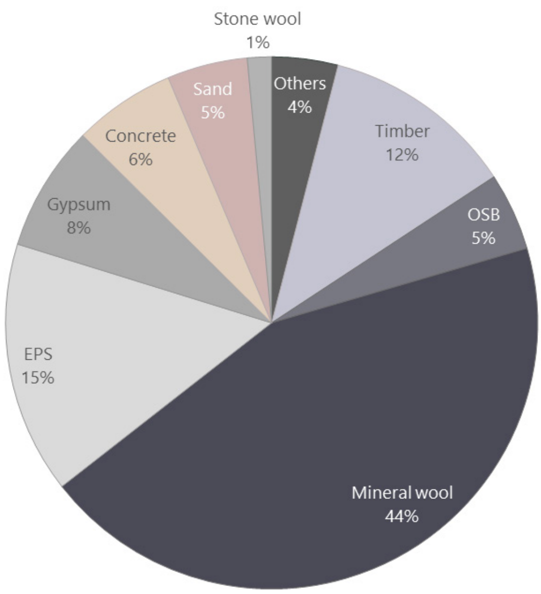


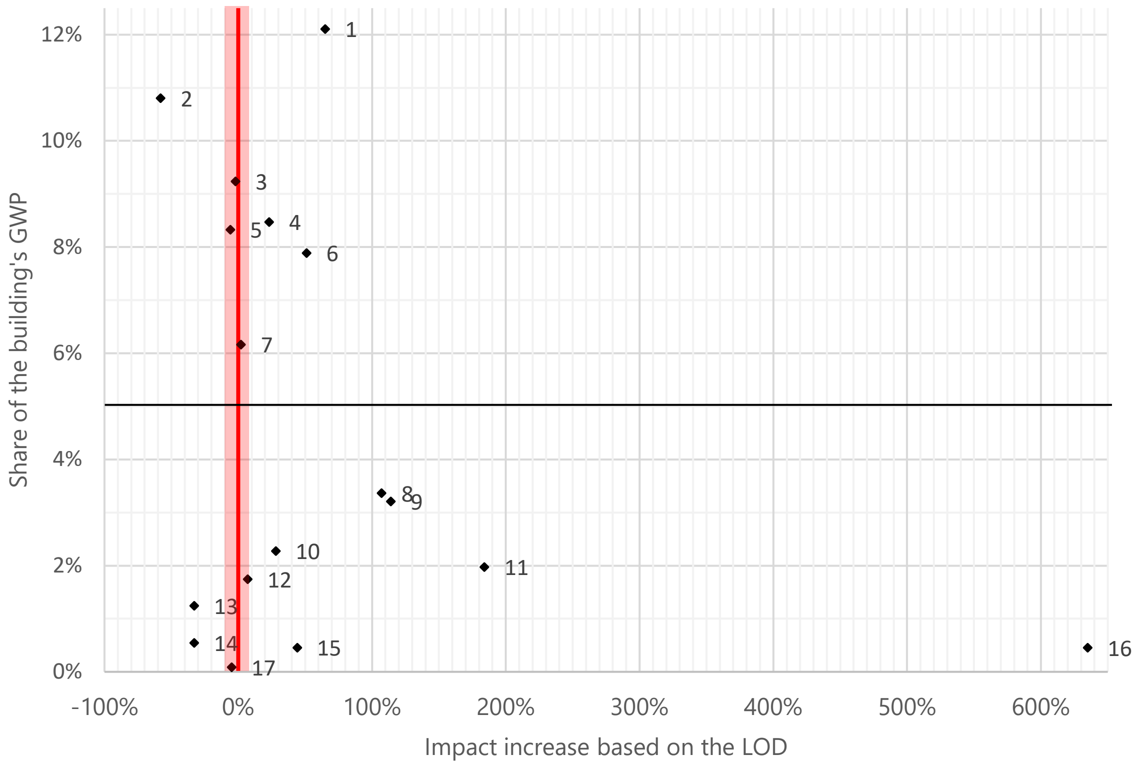
Fig. 14: The share distribution of the volume of all materials in the detailed assessment. 'Others' include materials with the share of less than 1%.

3.2.3 Result classification

Through the analysis conducted in Chapter 3 and Appendix D combined with the presented methodology, the materials are categorized into the following:

- materials whose modelling requires advanced BIM modelling or another approach towards the quantity adjustment,
- materials where no quantity adjustment is required and the simplified BIM model can be used successfully,
- materials that can remain excluded from the LCA, and thus the BIM model as it poses no significant impact on the LCA results.

Fig. 15 presents the classification results. At a 5% share of the total GWP a cut-off line is determined, indicating that the materials below it do not contribute significantly to the overall results, thus their improvement is not prioritized. The same GWP results obtained from models in LOD200/350-400 are marked with a red line, requiring no improvement in material modelling. Due to the large costs associated with the development of the detailed model and thus the accuracy of the LCA, a 10% margin is added to the category, as the results that fall within it are accurate enough for their correct interpretation.



1 - Aluminium, 2 - Mineral wool, 3 – EPS, 4 – Concrete, 5 – OSB, 6 – Bitumen, 7 – Gypsum, 8 – Steel, 9– Timber, 10 – Tiles, 11 – Linoleum, 12 – Sand, 13 - Fiber cement cladding, 14 – Screed, 15 – Windbreaker, 16 – Plywood, 17 - HPDE

Fig. 15: Materials' impact increases based on the LOD vs its share in the GWP of the building.

The findings are summarized in Table 2.

Table 2: Summary of the materials and their needs for improvement in relation to BIM/LCA.

Highly prioritized improvement in modelling/quantity correction	Timber studs/joists (in relation to the insulation)
	Soft insulation
	Aluminium (flashings, cladding underlays)
	Bitumen felt
	Fasteners (framing screws, wind rods, brackets)
	Façade cladding
	Cast-in-situ and prefabricated 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, usually the ones minimizing the thermal bridges
	Joint compounds and plaster
	Sealing materials (silicone, acrylic, EPDM, PU, rubber)

3.3 Modelling deviations

3.3.1 Timber

Timber products act as temporary carbon storage and as a greener substitute for more fossil-fuel-intensive materials, therefore a high contribution to the total GWP is not anticipated. At the end of life (module C3-C4), carbon may leave the system through decay or combustion.

Looking at the GWP share of construction timber (Fig. 10) used for structural studs and beams (2% in simplified, only 3% in detailed), it may be claimed that the extra modelling effort is not worth it. On the other hand, it is deemed beneficial for insulation (Chap. 3.3.2), one of the highest GWP contributors. 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 big scale. More specifically, approximately 0,16 m^3 is cut out by studs out of the insulation layer in 1 m^2 of an average internal wall uninterrupted by openings. Considering for instance 1000 m^2 wall area, it results in a 160 m^3 decrease in insulation quantity. In terms of the external wall, 0,2706 m^3 is removed by studs in a 1 m^2 wall without openings, which rarely occurs. This can peak at 0,804 m^3/m^2 in areas with complex connections (Fig. 16).

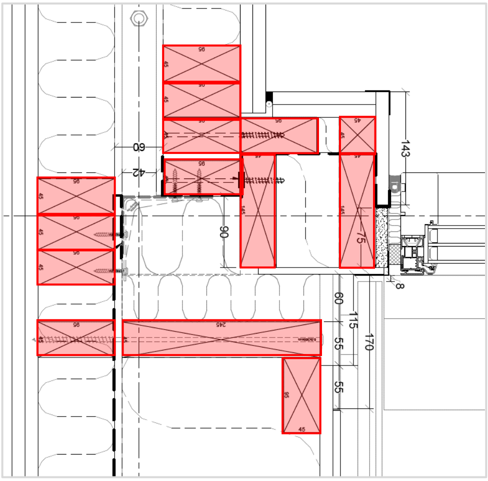


Fig. 16: Increased volume of timber cutting the insulation at the complex connection.

As observed (Table 3), the timber studs are substantially underestimated in the external and internal walls. As presented in Appendix D, the following factors may be the cause:

a) using standardized spacings in the simplified LCA that does not portray reality accurately enough

b) generalizing the dimensions or lack of information about them (e.g. 4 main stud dimensions for the façade are used for the simplified LCA, while in reality, 20 types exist)

c) predefined LCAbyg components make it challenging to account for horizontal studs, which are an integral part of a timber frame

d) predefined LCAbyg components require averaged volume of timber per m^2, while every m^2 is different

e) the more complex the architectural design, the higher volume of timber at corners/connections to achieve structural integrity of the construction

A couple of omitted studs are not considered an issue, but it must be noted that it grows proportionally, especially if the amount compounds across multiple storeys.

Table 3: GWP of timber frame in simplified and detailed cases.

Component	**GWP: simplified** [kg CO_2-eq. m^2/year]	**GWP: detailed** [kg CO_2-eq. m^2/year]	**% increase**
Terrain deck	5,59E-03	7,92E-03	42%
Facade	4,63E-03	3,39E-02	631%
Internal walls	1,26E-02	2,54E-02	101%
Floor partitions	1,51E-02	2,27E-02	51%
Ceilings	1,78E-02	3,26E-02	83%

If the perspective is shifted from the studs that impact the insulation layer to the uniform layers of plywood and OSB, the share of the GWP is higher (12% in simplified, 11% in detailed). Therefore, it can be concluded that the simplified estimation of a timber frame is acceptable but only in terms of the GWP of the material in question. It is unacceptable for further estimation of mineral wool and fasteners that go hand in hand with understanding precise quantities of timber frames.

3.3.2 Insulation

For most of the components in the simplified LCA, the insulation layer has the highest GWP contribution (Appendix D). In practice, performing LCA serves as a base for hotspot analysis, an effective method of identifying the areas to be prioritized for action when lower environmental impact is desired. As indicated in Fig. 12, mineral wool with a 30% share of the total GWP would be identified as the hotspot area in the simplified scenario. Afterwards, it would be investigated if the thickness can be reduced to lower the impact, which might consequently diminish the energy performance. Multiple variant studies may be developed in order to experiment with material alternatives or quantities to find the most advantageous solution. However, based on the detailed assessment, aluminium is the highest contributor to the GWP (12% of the total) instead. Therefore, it can be concluded that the hotspot detection in the first case is faulty due to the overestimated quantity of insulation. If this quantity is corrected by taking cut-outs for studs into account (Chap. 3.3.1), there is no need for further reduction of the environmental burden by reducing the thickness, preserving the energy efficiency of the building.

Table 4: Insulation's share of the total GWP in simplified and detailed cases.

Component	Share of the total GWP: simplified	Share of the total GWP: detailed
Terrain deck	47%	35%
Facade	43%	20%
Internal walls	34%	13%
Floor partitions	29%	9%
Ceilings	56%	35%
Roof terrace	21%	17%
Roof	43%	37%

To correct the quantities, the following methodology is suggested:

1. It must be ensured that the LCAbyg input for the insulation is volume-based rather than the commonly used area-based value.
2. The volume of both vertical and horizontal studs is calculated per generic 2 m x floor height x wall thickness (e.g. 2x2,5x0,25 m) of a façade without any interruptions using general spacing (e.g. c/c 600 mm).
3. The volume of both vertical and horizontal timber studs is calculated for 1 facade corner based on the detail drawing, followed by multiplying it by the number of corners.
4. The volume of both vertical and horizontal studs is calculated for 1 connection of the internal wall to the façade multiplied by the total amount of junctions.
5. The volume of both vertical and horizontal studs around 1 opening is calculated and multiplied by the number of openings in the façade.
6. Steps 2-5 are repeated for the internal walls.
7. The sum of the calculated timber volume is subtracted from the total volume of the insulation layer.

Although it is demonstrated that mineral wool should be given a high priority in modelling, it doesn't apply in all cases. For instance, the extra modelling efforts associated with the insulation strips around the opening (Fig. 17) or the angle edges (Fig. 18) at the roof, are not proven to have a noticeable effect. This is mainly linked to the material's low density (46 kg/m^3 for external use, 26 kg/m^3 for internal use). On the contrary, it must be noted that even a small quantity of PIR or stone insulation characterized by large densities may have a large environmental burden. This is proven on the component level, for instance in the terrain deck, where 5 m^3 of PIR insulation exceeds the impact of 75 m^3 of mineral wool by 130%.

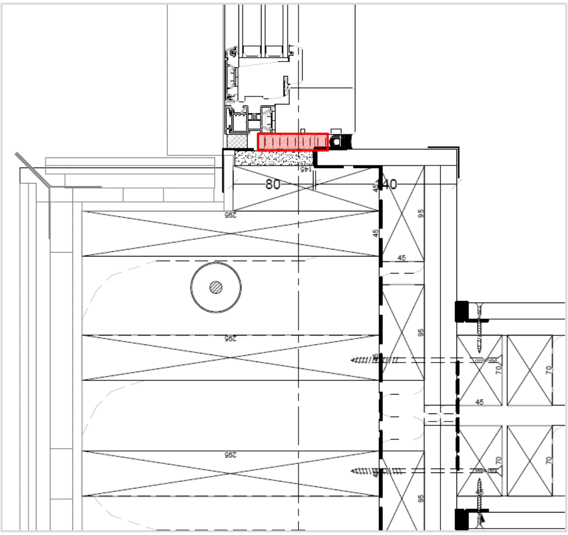


Fig. 17: The mineral wool strips around the openings.

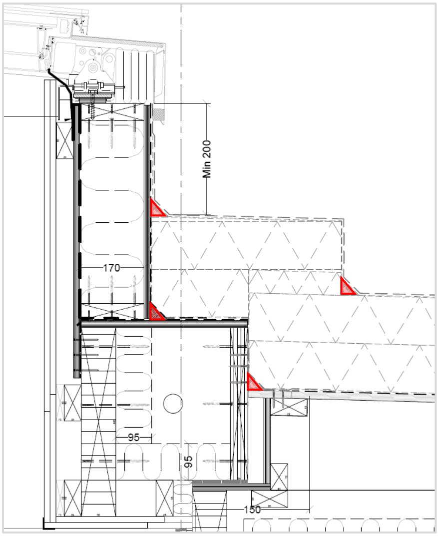


Fig. 18: Insulation edges around the roof perimeter.

3.3.3 Aluminium

The majority of flashings nowadays are produced of light-gauge aluminium. The thickness of the continuous metal that prevents water from passing through the joints to the interior may appear negligible. The environmentally weak spot of aluminium is the considerable energy use and the impact associated with the manufacturing of new, so-called primary aluminium. As presented in Appendix D the exposed flashings are mechanically fastened around the roof perimeter, around the window/door boundaries and at the junctions between wooden and fibre cement cladding while base flashing is found at the bottom of walls. Sill flashing or drip caps are concealed and put under windows or doors thresholds. The thickness can range from 0,9 to 3 mm which in the case study results in 0,521 m^3. This makes flashings the third biggest contributor to the façade's GWP with a share of 15%. The first contributor with 32% is also an aluminium product, i.e. aluminium rails and brackets for the fibre cement cladding of 1,53 m^3. This emphasizes the necessity of including thin metal sheet products in the BIM modelling.

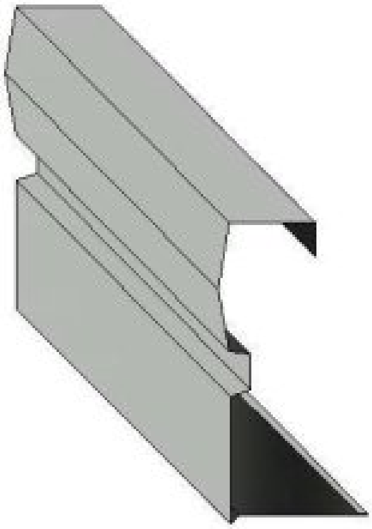


Fig. 19: Example of the aluminium flashing profile.

1. Due to the non-uniform shapes and numerous bends (Fig. 19), the easiest solution lies in creating 1 parametric flashing family. This can be eventually reused in any project and modified to fit, for example, the width of the window. This is perceived as the easiest method for extracting the volume of utilized aluminium. The 3D component can also be provided by the manufacturer. The use of a such detailed elements in the early design phases would provide a sufficiently accurate volume for further LCA, encouraging correct hotspot identification for impact minimization.
2. If modelling is not desired, the following approximate estimation can be applied. The length of all the openings is derived from the model. An aluminium profile with a reference value of 0,24 kg/m replicates the flashing. This is a default value for 0,6 mm thickness and should be ideally interpolated if thicker sheets are used in the project. The same principle can be applied along the roof and plinth perimeter.

In terms of the aluminium profiles for the cladding underlay, their GWP increases in the detailed LCA by 17% due to the precise number of brackets and accurate shape of the profile. Therefore, the simplified assumption of the rectangular profiles at the default spacing is sufficient and the issue lies in the exclusion of flashings.

3.3.4 Bitumen felt

As proven in the analysis of the foundation, roof terrace and roof components, the GWP of the bitumen is sensitive to any quantity change due to its fossil origin and short reference service life. In certain areas, it is challenging to account for small pieces that cannot be assigned as a layer to any component in the model (Fig. 20). In the foundation component, it results in a 270% increase in the bitumen GWP, however, these cases can be solved only by model-in-place elements or inaccurate manual calculation. On the roof level, the quantity can be corrected without the extra modelling effort. Considering the default 1x5 m roll and the requirements of min. 120 mm longitudinal overlap and 150 mm overlap in cross joint, the coverage area, in reality, corresponds to 4,27 m^2 instead of 5 m^2. Therefore, the following correction for the overlaps can be applied:

1. The number of rolls is calculated per roof area: roof area/5 m^2 (e.g. 100 m^2/5 m^2 = 20 rolls)
2. The area required for overlaps is calculated per roof area: 0,73 m^2 x number of rolls (e.g. 0,73 m^2 x 20 = 14,6 m^2)
3. The overlap area per each bitumen layer is added to the basic area generated in quantity schedules (e.g. 100 m^2 + 2x14,6 m^2 = 129,2 m^2 in double-layered bitumen)

In the study case, this simple correction increases the area of the bitumen felt from the simplified model by 225 m^2 for the roof and 34 m^2 for the roof terrace. Additionally, if a flat roof is in question, an extra area of the layer's extension to the parapet is needed (Fig. 21). Despite its easy modelling by the model-in-place sweep, the m^2 can be manually calculated by multiplying the roof perimeter by the total length of the extended part on the section.

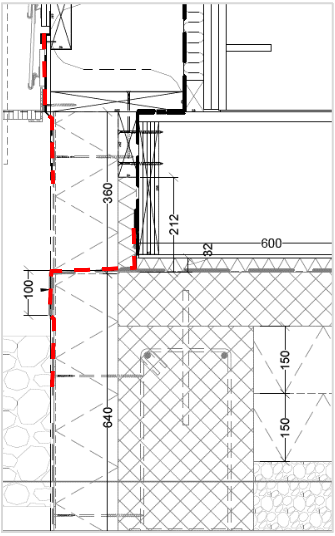


Fig. 20: Example of the bitumen felt difficult to account for in the

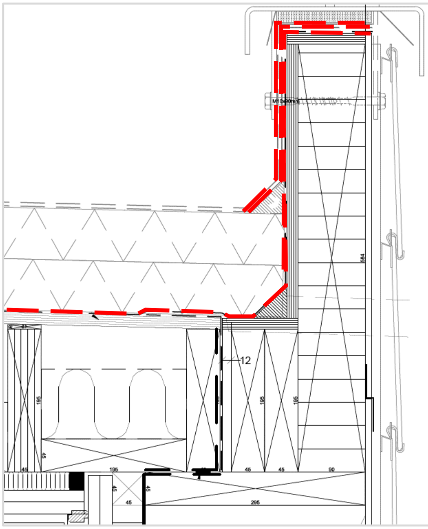


Fig. 21: Extended layers of bitumen felt to account for.

3.3.5 Membranes

The thin 0,0002 m PE foil used as a vapour barrier in the envelope covers the largest envelope area of 3 386 m^2. As it guarantees the airtightness of the construction, its installation requires numerous overlaps, e.g. around the openings, corners (Fig. 22) or between the sheets. It is assumed that this layer is commonly excluded in the LCA, which is further supported by the company's results (Chap. 3.4). Even if it would be accounted for, the area of the wall (1279 m^2) would be used which doesn't represent the real amount of 3 386 m^2 that the overlaps cause. It is concluded that the BIM model does not need to account for the overlaps and the simplified wall area is sufficient to include in the LCA due to its inconsequential GWP on a building level.

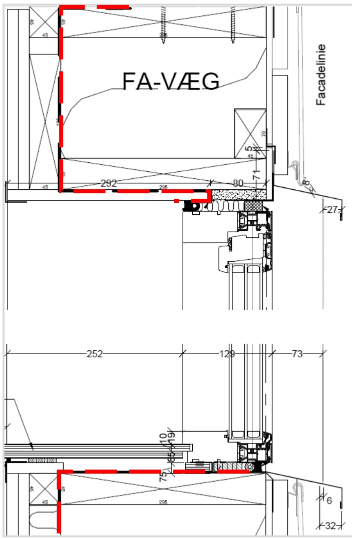


Fig. 22: Extended layers of the DPM accounted for in the detailed model.

The same applies to the radon-resistant PE-based membrane at the terrain deck. Despite its slightly higher GWP due to 0,0008 m thickness, a layer of aluminium foil and a reinforced geomembrane, the influence on the building's GWP is minimal.

3.3.6 Gypsum completion

All interior angles and joints between the boards must be filled in with a thin layer of joint compound. As a final step before applying paint, a skim coat of plaster is applied on the entire surface. Although both of these materials are used in large quantities, 2 543 kg for the joint compound and 1609 kg for the final plaster, their combined impact is insignificant, therefore their inclusion in the LCA can remain omitted.

3.3.7 Fasteners

Constructing a timber frame building takes more than just nails. The mechanical strength, stiffness and ductility of the joint affect the way the structure reacts to static and dynamic loads. Dowel-type fasteners such as screws and bolts distribute the load through the depth of the wood whereas shear connectors such as plates distribute the load across the contact surface. Angle brackets installed using screws and bolts are used for connecting perpendicular joists and beams. This study considers screws instead of nails for their demountability and better pull-out resistance (Fig. 23). Additionally, lifting forces resulting from wind loads acting on a structure must be transferred into the ground through wind rods. All of these elements add up and contribute to several tons of the building's weight. Only one available study performed by Statens Byggeforskningsinstitut has defined the contribution of the fasteners to the total GWP, i.e. 0,3-0,4%, however, the example's structure is concrete-based. This research also claims that it is difficult to argue that fasteners do not have a great influence without any experience. Therefore, this study investigates the unexplored area and the total GWP share of the fasteners corresponds to 6% (Fig. 11). To emphasize this significance, it equals the environmental impact of over 17 000 m^2 of used gypsum.

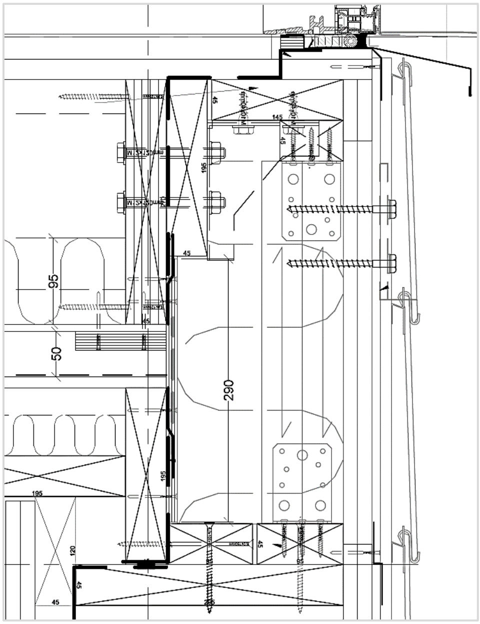


Fig. 23: Example of the number of fasteners in the façade.

The previously mentioned pattern applies – a small quantity of fasteners is inconsequential; however, it is difficult to quantify the threshold. Based on this case study, the following fasteners are the major contributors and their inclusion in the LCA would account for 60% of the total weight of the fasteners, adding extra value to the total GWP.

a) Screws used for the assembly of the wooden frame elements:

This represents an issue as the wooden elements are prefabricated in a factory and the LCA analyst or the constructing architect creating the drawings has minimum knowledge of the assembly procedure

b) Wind rods that span from the roof to the foundation in the façade and internal walls as well as columns
c) Screws used for the installation of cladding underlay
d) Continuous steel profiles installed e.g. around the plinth's perimeter to carry the load of the steel mesh or around the roof terrace to transfer the loads from the steel beams
e) Angle brackets

It is challenging to quantify which fastener types can be excluded as even the smallest ones in extreme quantities may alter the results. Nevertheless, based on the experience acquired from this study, the screws with a length below 40 mm can be disregarded. This includes, for instance, screws for the installation of flashings, cladding, or edges of the bitumen felt. For illustrative purposes, the 23 100 pieces of 4x30 mm screws used for the windbreaker correspond to only 58 kg, whereas 25 300 pieces of 6x90 mm used for timber frame weigh 7 times more, 424 kg. Thus, the larger quantity does not necessarily imply a substantial weight and consequent impact, as it goes hand in hand with the fastener's dimensions.

Applied methodology

The methodology used for the calculation of fasteners is described in detail in Appendix B and follows the steps:

1. Timber elements are modelled in 3D and categorized in the schedule based on the components they form.
2. Two types of parameters are added to the schedules: calculated parameter, and text parameter.
3. The required inputs are defined by the user (e.g. type of screws/brackets, default spacing, number of screws/brackets).
4. Each fastener type is defined, and its number is summed up in an excel spreadsheet based on the component type (separate table for walls, ceilings, floors, etc.)
5. The quantity of fasteners is converted to mass (required for LCAByg) using relevant DIN or ISO standards.

However, this approach is only feasible if the timber frame is 3D-modelled which is not a common practice. Moreover, a knowledge of the general spacing and approximate required screw length is essential. Therefore, this approach can only be undertaken at later stages of a project when sufficient technical documentation is developed.

Simplified methodology

Due to the large complexity of this process, a simplified methodology is proposed, utilizing a yes/no parameter that defines the connection type. It is expected that the accuracy of the calculation is reduced compared to the integration of the calculated parameter, yet such an approach can be proven to be more time efficient.

1. Identification and calculation of the fasteners used for the connection of vertical timber studs to the horizontal frame elements. Assuming that each vertical piece of timber is attached to a horizontal one with x number of screws at either end (e.g. 2 screws*2 = 4). The length of each wall is divided by the general spacing (e.g. 600 mm c/c) and multiplied by the number of screws (e.g. (10 000/600*4 = 67).
2. Identification of the common connection points, e.g. internal wall to façade, door opening.
3. Identification and manual calculation of fasteners used in each connection type.
4. Integration of an instance-based parameter with a yes/no tick box, where element connections are predefined and chosen based on the application (Fig. 24).
5. Calculation of the total quantity of each fastener type (utilizing the schedules filtered by the connection type).
6. Conversion of the quantity to mass.

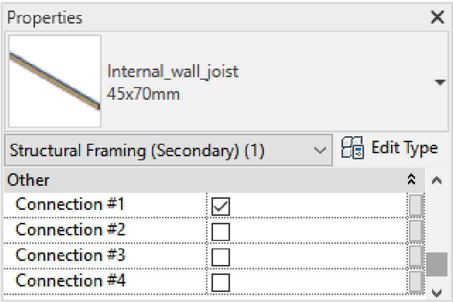


Fig. 24: An example of an Instance-based yes/no parameter defining the connection type.

Although the GWP rises with the addition of the fasteners, the end goal for this study is not the complete calculation of their weight in each building model. but rather an industry's awareness that these elements should not be ignored during the LCA. It is believed that with a detailed evaluation of additional projects, an average weight of fasteners can be found based on the building's construction method and typology. With sufficient data points, expansion of the LCAByg library is proposed and could cover:

- fasteners used for the assembly of a timber frame – based on the component's length
- fasteners used for element connections – based on an average weight obtained in the studies

It must be noted, however, that this study focuses on modular timber construction where the process is streamlined and takes place in a controlled environment. Therefore, the LCAByg expansion would need to specify the construction method as fasteners used for on-site construction may vary in dimensions and quantity.

3.3.8 Sealing materials

Sealants are an ideal example of a material that can be neglected in a small amount while having a substantial GWP influence 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. No improved modelling practices are required as a wide range of calculators for sealants are developed on the market. For their use, only the length, width and depth of the joint are required. Alternatively, the volume of the sealants is calculated manually based on the dimensions of the wall and the joint's size, which is then multiplied by the density applicable for the used sealant (1600 kg/m^3 for an acrylic sealant). However, this process is lengthy and requires diligence, as each material connection needs to be accounted for. In the case of modular construction, the calculation is simplified due to the repetition of modules, but each variation in the design requires an individual approach.

Apart from the silicone and acrylic sealants, polyurethane (PU), ethylene propylene diene monomer (EPDM) and rubber are also categorized as sealing products. However, quantities of PU tape and rubber in the window/door joints are negligible. The single peak can be observed in the PU elastomer used in the floor partition (Appendix D, Chap. 3.7) in a form of sound protection strips. These have a significant impact on a component level, however, on the building's level, it's the opposite. The same pattern can be observed in EPDM supports for the elements at the terrain deck or floor partition.

Looking at a broader perspective, sealants make up 3% of the building's GWP, the same proportion as e.g. steel that forms internal walls, bathroom and terrace floor frames, which opens up the discussion about their inclusion during the modelling process.

Apart from the increase in the building's GWP that emerges from the increased BIM LOD (see Chap. 3.1), another observation is illustrated in Fig. 25. If the omitted materials (fasteners, sealants, membranes,…) would be included in the simplified LCA, they would account for 14,7% of the total GWP.

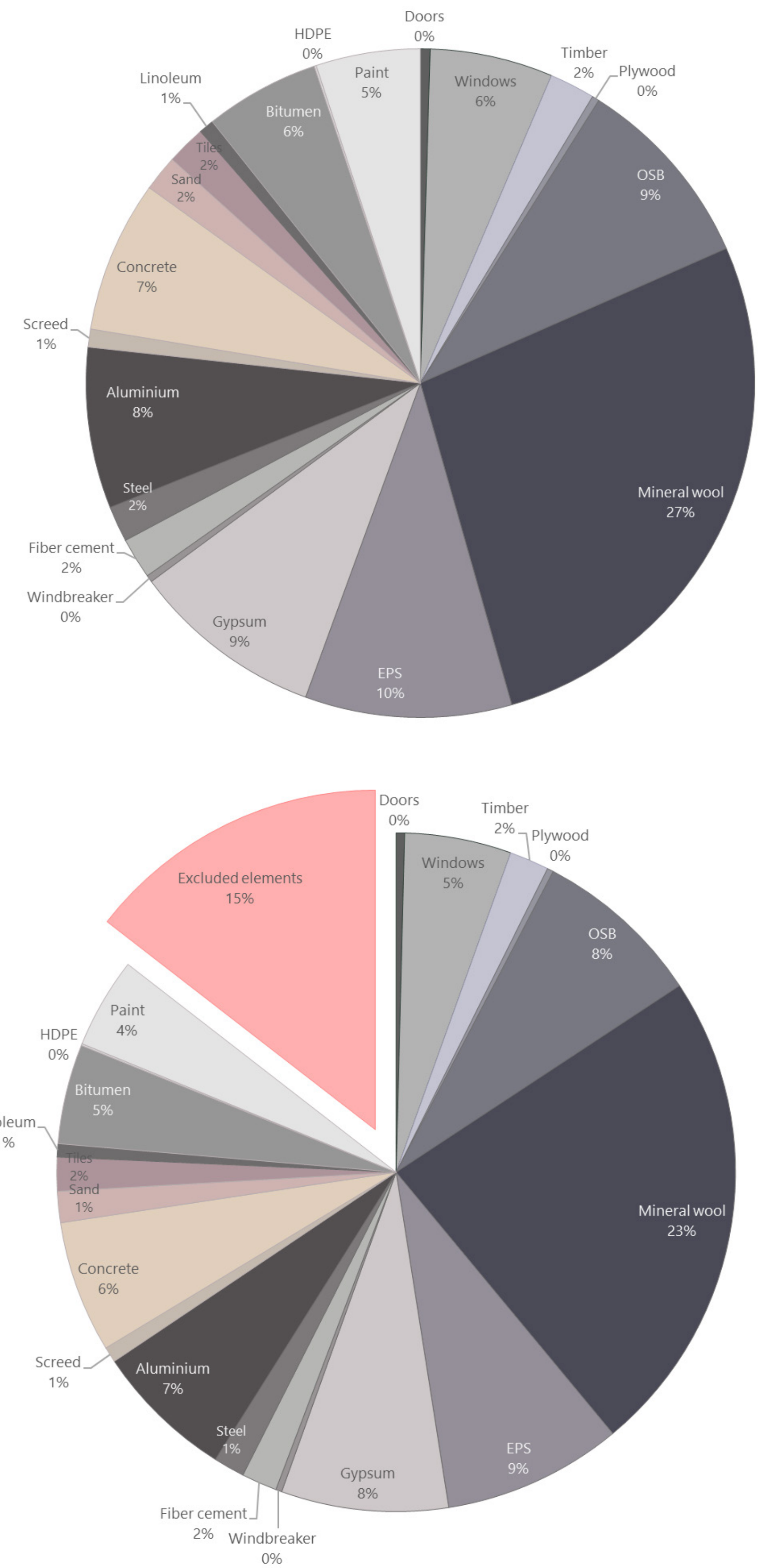


Fig. 25: The impact of excluded elements if added to the GWP results of the simplified model.

3.4 Validity of the research

3.4.1 Company's BIM model

This research has been supplemented with the third BIM model that was developed by the total contractor. It cannot be defined with certainty which LOD the model corresponds to, as certain components are more detailed than others. Although the windows and doors can be considered as LOD300, the majority of the model contains only approximate geometry and numerous placeholders, thus corresponding to LOD200. For instance, even though the floor partitions are modelled as separate elements with different names, suggesting a difference in the construction (material type, thickness, etc), no deviations in the materials are observed. It is expected that the BIM model was developed for strictly architectural purposes, or as a base for the development of the production documentation done entirely in-house. In cases when the contractor has full control of the construction method, as in the prefabricated timber modules, no detailed project development is required from the architectural office. This highlights the fact, that the person responsible for LCA must have a good understanding of the project to be able to execute the analysis correctly. Without the project familiarity, there is a risk of double counting the inventory or overlooking some components. However, there are 3 plausible causes for the choices made in the development of the company's BIM model:

1. The BIM was not developed for the purpose of LCI but for architectural and engineering purposes.
2. It is unknown which project stage the BIM model belongs to.
3. The components were omitted intentionally as another contractor may be responsible for their modelling.

However, the model can be modified to fit the LCA needs with minimum effort. The main guidelines to achieve this are described in Appendix B.

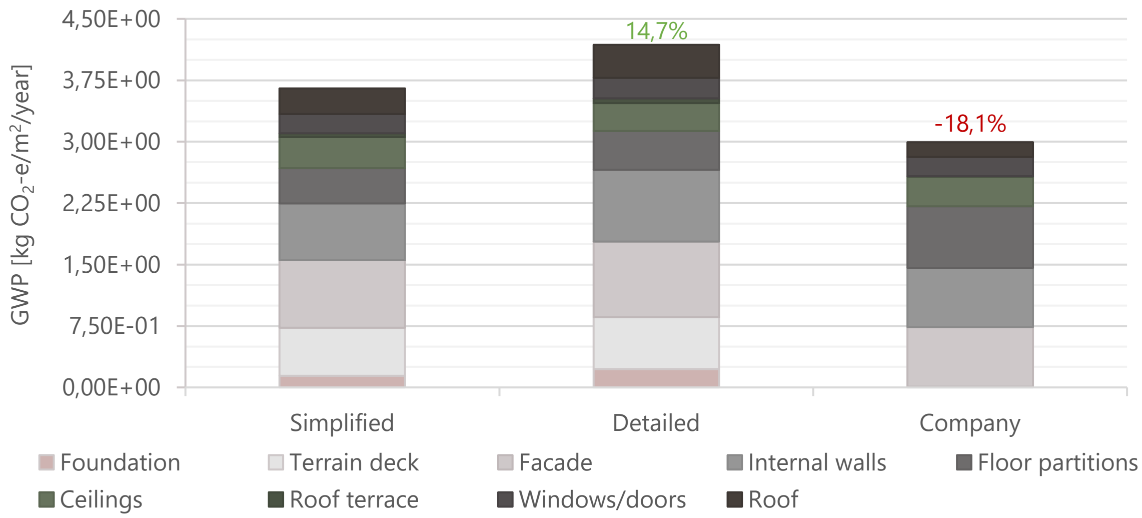


Fig. 26: Comparison of total GWP among LCAs based on the simplified, detailed and company model.

3.4.2 LCA based on the company's BIM model

The significance of the variation in the LCA results due to the model's LOD is further supported by the LCA that is carried out based on the generated quantities from the company's model. As indicated in Fig. 26 the GWP based on the company model is 18,1% smaller than a simplified case, and 29% less than detailed. From Fig. 27 the minimal difference between the simplified and the company's model is observed in the windows/doors, internal walls or ceiling components, while a significant difference between -100% to +74% occurs in other components. The absence of the internal foundation and terrain deck is considered a major source of the deviation along with the inconsistent scheduling used for LCI. Furthermore, certain components are not differentiated when their structure varies depending on their location, e.g. the floor component used for the terrain deck is duplicated in the floor partitions, disregarding the thickness of the used insulating material. The prepared schedules do not provide a distinction of such components, thus resulting in an overestimation of the GWP of the partition component in comparison to the detailed LCA, and omission of the terrain deck.

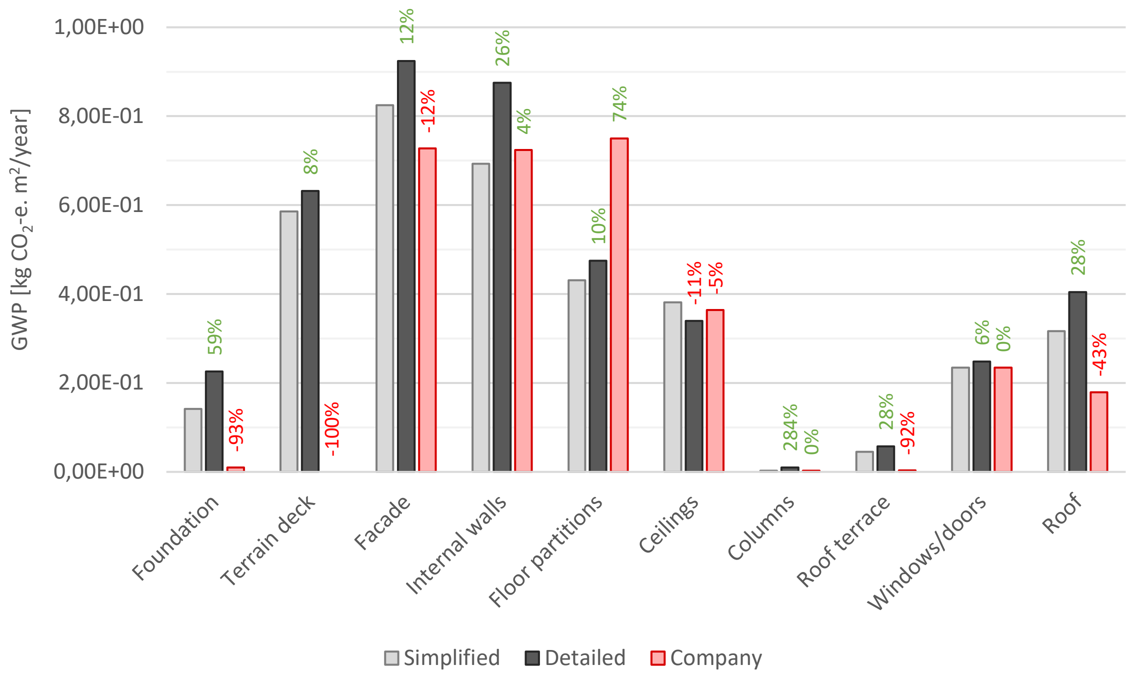


Fig. 27: Comparison of the components' GWP based on the LCIs obtained from the simplified, detailed and company models

Even though a difference in the GWP is observed, the results give a reasonable representation of the environmental impact the building has. However, the analysis performed in this way does not support the conscious choice of the materials. Fig. 28 illustrates the CO_2-e distribution between all the materials in a ceiling component, whose GWP is placed the closest to the study cases, with only a 5% reduction from the simplified case. It is observed that:

- based on the company's BIM model, the evaluation of the steel amount is not possible, as the location or size of the steel profiles is not indicated
- the quantity of OSB or plywood is larger than in the simplified case by 23-34% and remains overestimated when compared with the detailed case by 21-56%
- the quantity of wooden joists is underestimated when compared to the simplified case by 12% and remains underestimated by more than half when compared with the detailed case
- the quantity of the mineral wool varies from the simplified analysis by only 6%, however, it remains significantly overestimated when compared with the detailed case, tripling the GWP of the material

Supporting the thesis stated in Chapter 3, the analysis observes that the correct hotspot identification is dependent on the quality of the BIM model. Insufficient detailing of the timber structure and the dependent insulating layer may point to the significant GWP of the insulating layer, while the focus should be shifted to the gypsum, whose CO_2-e emissions are higher.

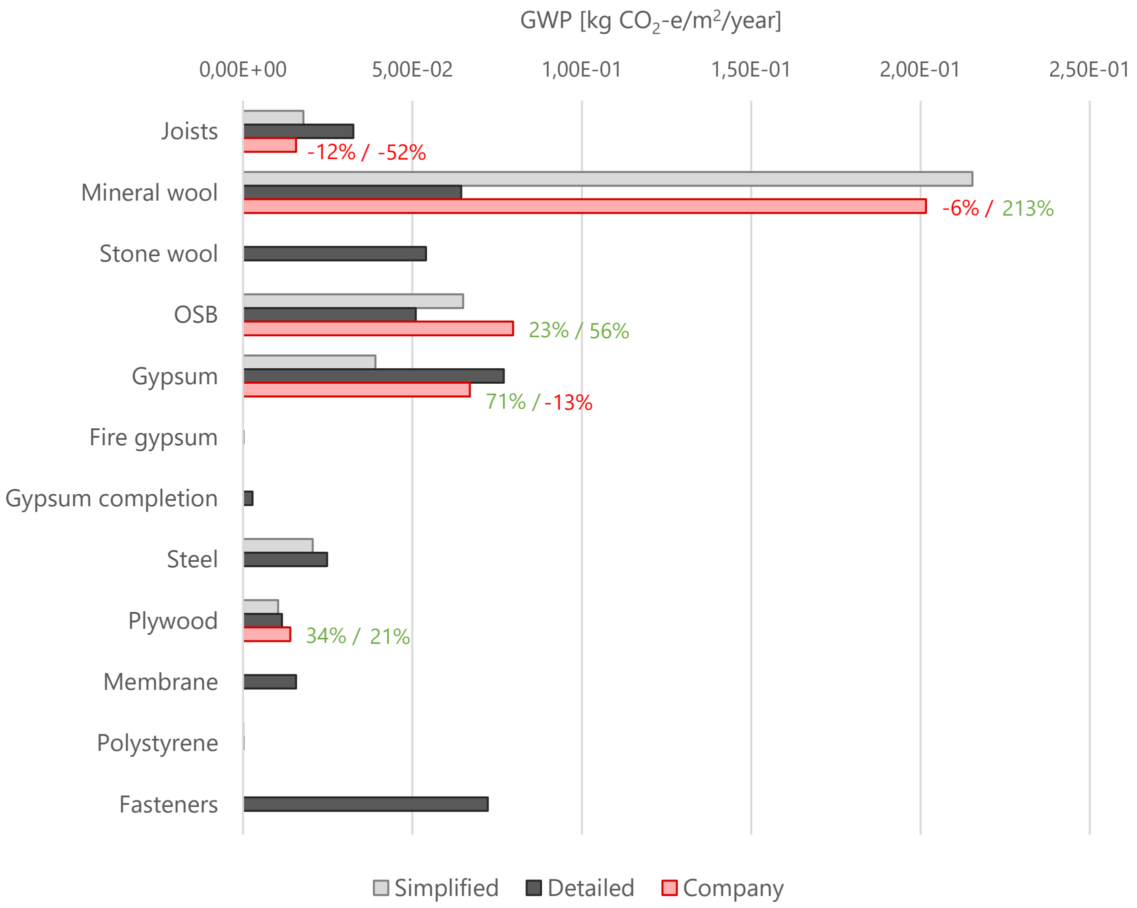


Fig. 28: Variation of the ceiling's GWP among LCAs based on the simplified, detailed and company model – the value is indicated as simplified % / detailed %.

3.4.3 Company's LCA

It is believed that the company uses a different information source for LCA rather than basing the LCI on the received BIM model. The results of the LCA developed for this construction project are examined and compared to the GWP obtained from the 3 BIM models (simplified, detailed and the company's). The difference between the results is illustrated in Fig. 29. The results however cannot be validated nor further investigated in this study, as the company's LCA accounts for the entire building complex (8 building units), while this study focuses on one building only. There are observed fluctuations in the buildings' components (e.g. dissimilar window sizes) and the construction (e.g. cantilevered floors, lack of roof terraces, external staircases) which compromise the comparability of the results.

Nonetheless, this performed comparison strengthens the study's validity, and it supports the hypothesis that the LOD of the BIM model has a direct influence on the generated quantities and thus the building's GWP.

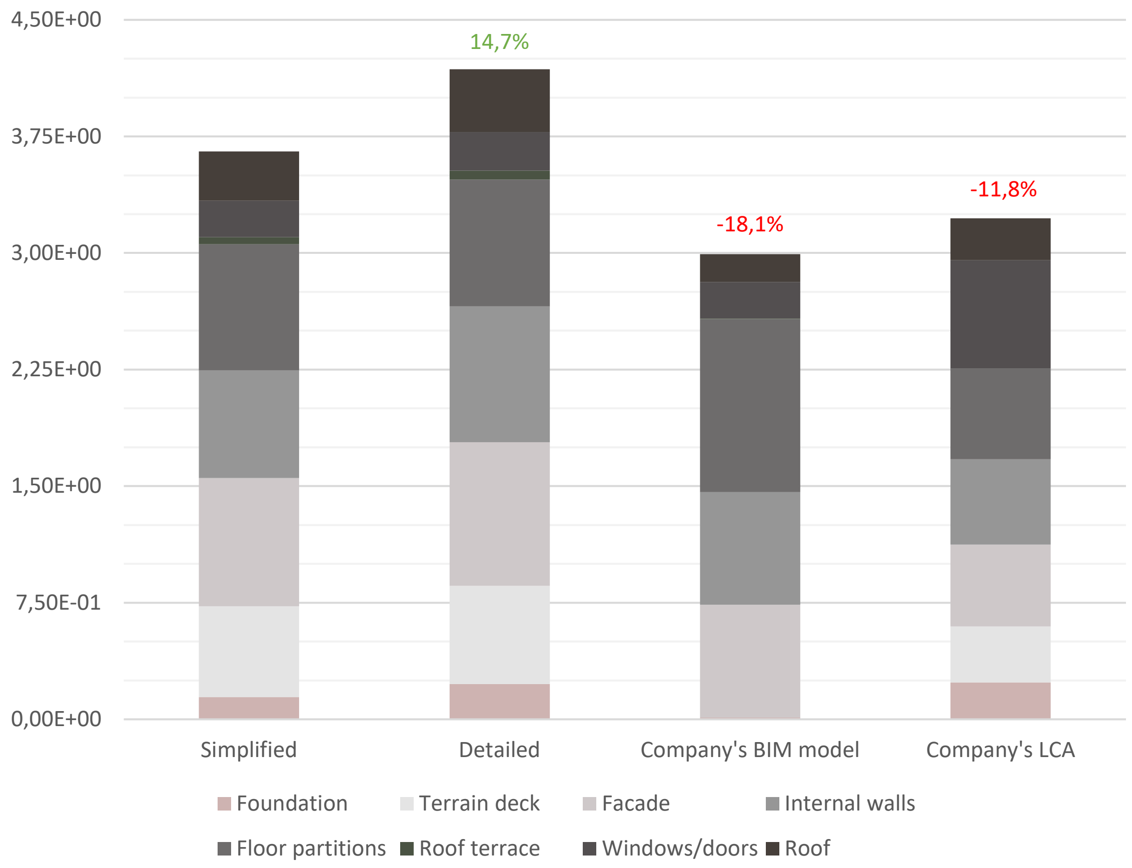


Fig. 29: Comparison of the total GWP among LCAs based on the 3 BIM models (simplified, detailed and company's) and the LCA performed by the company.

4 Discussion

4.1 Key findings

The conducted research confirms the initial theory that the LOD of BIM's model directly affects the LCI and thus causes the deviation of the total environmental impact. The GWP calculated based on the data obtained from a LOD200 model increases by 14,7% when using the inventory generated from the LOD350-400 model.

Uncorrected quantities result in incorrect identification of the hotspot area which is frequently modified to reduce its impact (e.g. reduction of the insulation thickness). The importance of correct modelling is therefore highlighted, as the reduction of insulating materials has other implications, including reduced energy efficiency and thus higher operating costs. Although timber is regarded as a low GWP substitute, its proper quantity estimation influences the insulation layer, the highest GWP contributor. It has been proven that every component that contains insulated timber frames results in overestimated insulation layer in the simplified stage. Another major cause of the deviation between the simplified and detailed LCA is the aluminium and bitumen felt, whose modelling improvements are highly prioritized. Therefore, this study finds that LCA based on the detailed LCI is crucial for environmentally conscious project development.

4.2 Limitations

In this study, the acquisition of the relevant EPDs creates a barrier to the detailed LCA. Where possible, the materials are obtained from the general library Ökobaudat and their density is adjusted based on the specific application. However, the environmental impact from this approach may not be equivalent to the specific product's EPD, resulting in inaccuracy.
Moreover, consideration of elements typically omitted in simplified LCA is hindered by the lack of environmental research done on such materials (e.g. tape used for connection of DPMs).

4.3 Further observations

The suggested modelling improvement requires a considerable amount of modelling time, and thus associated labour costs, especially in terms of the frame structures and its fasteners. As indicated in Appendix F, Chap. 7, the advanced model for the LCI purpose requires almost 7 times more time than the simplified one. Such detailing is not beneficial for any of the parties involved in the project's development, hence it's difficult to define who would be in charge. Following this path, modelling for the sole purpose of a more precise LCA may be deemed inefficient time-wise, especially when, as demonstrated in this study, the LCA increases by 14,7% when using the detailed material inventory. Due to these worse results and the extra costs associated with the development, the process would find little to no interested investors.

An approach implemented in the 2020 international version of the DGNB distinguishes between LCI obtained from a simplified and a detailed model. The factor of 1,2 is applied on top of the LCA results that follow a 'simplified calculation method', accounting only for listed structural and technical components. In doing so, a margin of 20% is provided, accounting for the impact of the unmodelled elements and any changes that occur in the modelled ones.

There are two possible ways to account for the factor. Firstly, the 20% margin is added to each material, increasing their GWP individually. In certain cases (e.g. insulation), the increase further contributes to the overestimation of the GWP which already exists without it. In other materials (e.g. OSB, gypsum) the changes in the model throughout the project development do not widely contribute to their GWP, thus making their simplified modelling sufficiently accurate for the analysis. Therefore, the addition of the 20% uncertainty on top of the materials' GWP is proven to be an unreliable solution.

The second approach towards the 1,2 factor is its calculation based on the total GWP of the embodied energy. In doing so, the 20% uncertainty is applied and accounts for unmodelled elements (e.g. fasteners). This study shows that elements omitted in the simplified modelling add up to 16% of the total GWP and in such a case, the factor is sufficient to account for it as well as the quantity changes in other materials. With such an approach, the deviation between the simplified and detailed GWP is 5% (Fig. 30). The downside of such an approach is that it neglects the GWP of individual materials and prevents accurate identification of the hotspots, not assisting in the conscious reduction of the building's environmental impact.

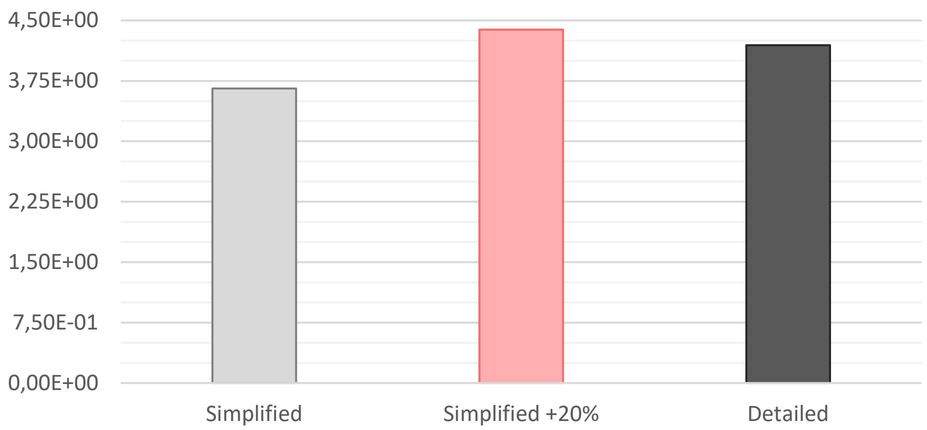


Fig. 30: Comparison of the total results with a margin.

Although the variation between the GWP due to the use of different LODs is sufficiently reduced, the application of the factor to the simplified results does not help to achieve the study's objective of improving the analysis of the embodied CO_2-e.

Moreover, this study's focus is on new construction projects which from 2023 must fulfil the BR requirements of GWP lower than 12 kg CO_2-e/m^2/year, with a further reduction of the limit in the future, and not on buildings awarded with sustainability certification where the factor applies.

Currently, there are no regulations in place defining the LOD of the model for the material quantity extraction nor an uncertainty margin stated in the Danish BR for the commonly simplified LCI. Hence it might be argued that there is no value in the improvement of modelling practices, as the results would not be favourable for anyone involved. Combined with the increased workload in the design stages for the model development, no improvement in the industry would take place, unfairly favouring a simplified LCA.

This research implies that the impact of fasteners and other frequently omitted elements accounts for 15% of the building's embodied environmental burden, although their individual impact shares (except for fasteners) range up to 3%, making it negligible in the analysis. It could, however, be argued that this impact of the small elements should be accounted for by the use of a factor added on top of the detailed results. In the case of the simplified LCI, the factor should be proportionally larger, covering not only the differences between the model's LOD but also the elements whose modelling this study finds as not obligatory.

4.4 Future research

This research has raised many questions in need of further investigation. Although the obtained results are promising, a single case study is not sufficient to generalize the data required for improvement of the LCA and should thus be validated by a larger sample size. Therefore, it is suggested to repeat the study for more typologies to develop more objective conversion factors. Similarly, it is encouraged to perform the study for other construction types (e.g. concrete, brick, steel) to investigate the actual difference in GWP when fasteners, reinforcement and other omitted materials are included.

Since the discovered limitations described in Appendix F are highly linked to the Danish market and LCAByg software, the comparison of other LCA software available on the market is highly encouraged in order to get insights into whether any available alternatives are more compatible with BIM.

While this study focuses on the improvement of the BIM modelling practices for LCI, the findings might suggest several courses of action in the current development of LCA plug-ins. An opportunity is observed for the problem to be overcome by the utilization of a 'transition' software, that could translate the simplified architectural model into a set of data required for a more accurate LCA. Even though a scheduling function can be used for such, Autodesk Revit and other programs commonly used for the development of a 3D model used for collision control and information sharing between the involved parties are not intended for LCI. On the other hand, LCAByg heavily depends on human input, although few plug-ins for automatic data extraction are developed. However, the plug-ins extract the information directly from the model, reducing the workload but adding no further value to the LCA results. If a new software that could benefit the LCA was developed (e.g. by automatically translating that a certain construction type contains a timber frame, which volume needs to be subtracted from the insulating layer), the time committed to the development of the models could be reduced, making it a feasible and easily applicable solution.

Another important matter to resolve for future studies is whether the LCA process should be performed by a third party or an architect/engineer who is partially responsible for the model and familiar with the project.

Due to the limited availability of materials' EPDs, further work can explore materials that do not have environmental impact data available and nudge the companies to provide more information in order to add them to the libraries. Having the possibility to include them in the LCA might encourage professionals to not omit them in the process, but instead, evaluate the environmental implications they have when used in large quantities.

Furthermore, the research was limited to specific LCA phases. As the industry's knowledge of A4-A5, B3 and B5 increases, it is suggested to repeat the study with all phases incorporated. The same applies to the other 8 environmental categories, as only the GWP was analyzed due to its relevance to the 2023 legislation.

5 Conclusion

The results of this study indicate the GWP calculated based on the LCI generated from the LOD200 model increases by 14,7% when the LOD350/400 model serves as the data source. The research's outcomes point to materials that require more accurate quantity estimation for the LCI. This selection is based on the 2 criteria, i.e. material's contribution to the total building's GWP exceeds 5% while the GWP increase due to the higher LOD surpasses 10%.

The analysis is performed on two levels, starting from the environmental evaluation of the materials followed by extending the view to the GWP of the building. Due to the undertaken approach, the analysis at the component level is limited and does not contribute to the final assessment of the results. Attention is given to the accuracy of the modelling at the material level, as their interpretation is the first step towards an environmentally conscious construction.

On the material level, the GWP increase is detected in every material except for the insulation, whose impact is overestimated by more than 50% in all components where a homogenous layer is considered. The result variation is believed to be caused by the omission of the timber frame modelling which decreases the volume of soft insulation. Even though the total GWP share of timber is at 3%, its modelling is required to rectify the environmental burden of the insulating material. Such severe inaccuracy may lead to incorrect identification of the material as a hotspot, resulting in actions taken to reduce the GWP generated by it (typically by reduction of the insulation's thickness) resulting in the diminished energy efficiency of the building. Assumptions regarding the materials whose modelling is currently disregarded by the industry are supported by the BIM model developed by the total contractor, which is analyzed for validation of this study's results.

When LCA accuracy improvement is desired, an emphasis should also be put on the incorporation of aluminium flashings and bitumen felt components in the analysis due to their high GWP at even small quantities and a shorter reference service life.

It is proven that fasteners, along with other often omitted components that ensure airtightness add up to 16% of the total GWP of the building. However, only stainless-steel fasteners are observed to have an embodied environmental burden of 6%, whereas other elements (including sealants, small pieces of insulation or EPDM) contribute by less than 3% individually. Therefore, this study finds their impact negligible, however, their contribution is recognized, opening up the discussion for a possible solution.

From all the fasteners included in the study, the ones longer than 40 mm are found to have significance when their weight is considered. Typically, those are the screws essential for the structural integrity of the timber frame, as well as wind rods, cladding fasteners and continuous steel profiles used to transfer the loads from supporting structures.

Subsequently, a simplified methodology for quantity correction is proposed for all the above-mentioned issues.

On the building level, the embodied environmental burden corresponds to 8%, whereas the operational stage of the building has the highest share of 45%. It must be noted that the embodied energy in the A1-A3 module goes hand in hand with the B4, C3 and C4, which sum up to 55% of the GWP share. Therefore, the correct material estimation directly affects the replacement or waste processing. Moreover, as existent research suggests, the impact of the use stages is vastly researched and already at its minimum. This makes the embodied CO_2-e an area of potential reduction.

This study shows that the time, and thus the resources required to obtain a detailed LCI are almost 7 times larger when compared to the simplified one. Although only a 14,7% difference in the GWP is observed, the detailed LCI ensures an accurate representation of the individual material's environmental burden. The industry's resistance towards the detailed LCA process is anticipated due to the excessive efforts that it requires. Thus this study proposes alternative approaches to the modelling of elements in which improvement is considered essential:

- if not 3D modelled, the average volume of timber frame must be calculated per m^2 and subtracted from the volume of soft insulation,
- the reference value of 0,24 kg/m is used for aluminium flashing, requiring the analyst to define only the length of the spaces where the material is expected,
- the overlap area of the bitumen felt is added to the basic area generated from the model,
- stainless steel fasteners shorter than 40 mm are not included in the analysis due to their low total weight.

The solution that accounts for detailed LCI and is compatible with LCAByg is volume-based material quantification. Following the methodology presented in this study, each material volume is calculated, either through advanced BIM modelling or the alternative manual approach, with a focus on materials whose environmental impact is significant for LCA. The unit for the materials must be defined before the modelling commences, guiding the BIM process, and typically it is set as volume for maximum precision. In LCAByg, the hierarchy is altered from 'element-component-material' to 'element-material'. Avoiding the use of predefined components, a new library is created based on the material specifications from the Ökobaudat database.

The commonly used BIM software is not developed for the purpose of LCI. However, several adjustments to the architectural model can be applied to make such a process simple while retaining the high level of detail required for accurate LCA.

6 Appendices

Appendix A: Industry's practice of LCA/BIM integration

Appendix B: BIM modelling for life cycle inventory

Appendix C: LCA process

Appendix D: Analyses of LCA results

Appendix E: Operational energy input for LCA

Appendix F: Limitations

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