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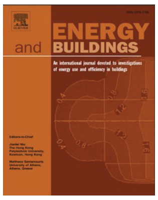

A comparative cradle-to-grave life cycle approach for addressing construction design choices: An applicative case study for a residential tower in Aalborg, Denmark

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ABSTRACT

Energy demand reduction targets and sustainable design paradigms are fueling the search for more and more effective design solutions in the building sector, and new technologies and construction systems are being presented. However, each design solution has its own consequences for the environmental impact of the building. The use of Building Information Modelling (BIM) and Life Cycle Assessment (LCA) can be profitably adopted for supporting the decision-making process. This paper reports a comparative methodology developed to analyse the impacts of alternative structural solutions for timber-based high-rise structures. Embodied, operational, and end-of-life environmental impacts based on two structural frame types, a reinforced concrete (RC) structure and cross-laminated timber (CLT) are explored. Two main inputs are used for performing a comprehensive cradle-to-grave LCA for the whole building: the bill of quantities from a Revit BIM model and the energy demand from DesignStudio. Then, an LCA is performed using the One Click LCA tool for a service life of 50 years and 12 impact categories. The environmental impacts of building materials are based on Environmental Product Declarations (EPDs) directly embedded in the tool. The method is then applied to a case study in Aalborg, Denmark. Results indicate that the total emissions for the considered case study are 9.6 kg- CO_2 eq./m^2/y for the CLT structure against 10.8 kg- CO_2 eq./m^2/y for the RC structure. The production stage of building materials, including building systems and installations, accounts for around 55% of the total emissions, while energy use (B6 phase) during the in-use stage of the building recorded a lower environmental impact (45%). The outcomes confirm the opportunity to base the discussion on alternative design options on more objective and data-based elements to support the different positions which already involve a wide range of architectural, functional and financial criteria. This is of great relevance in achieving balanced and informed decisions which do not simply follow green-labelled ideas but are grounded on evidence-based considerations.

1. Introduction

The ever-increasing proportion of the population living in cities is a challenging factor in the debate about urban forms and building typologies. Density levels and the liveability of the present and future built environment are hot issues [1,2]. Particularly in new developments, the option to work with taller buildings to reduce land use while ensuring adequate outdoor spaces for collective and socialization purposes is largely considered as a viable option for balancing density and green or open spaces. However, the typology of tall buildings, typically between

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15 and 20 levels (45–60 m height), requires careful consideration of some critical issues dealing with the assumed greater amount of energy for operating or the greater amount of material and resources used for building large volumes in comparison with smaller volumes [3,4]. However, this depends largely on construction choices and energy-related issues. As highlighted by the latest report of the Intergovernmental Panel on Climate Change (IPCC) (AR6), the urgent requirement to cope with the 2030 and 2050 carbon emission reduction targets places the building sector, and larger structures in particular, at the core of the discussion about the related impacts [5–7]. There is a call for defining more conscious and reliable approaches to make design-decisions more responsive and more effective for tackling climate change [8].

Huge efforts were made in the past decades to develop and implement policies and regulations aimed at strongly decreasing the energy demand during the operational stage and at improving the building envelope and systems performances [9,10], while only in more recent times have the weight of embodied emissions at production and construction stages has gained the attention of the scientific community only in more recent times [11–13]. By decarbonizing the electricity grid, improving Heating, Ventilation and Air Conditioning (HVAC) systems, and implementing passive energy efficiency measures, operational Greenhouse Gas (GHG) emissions have been decreasing while embodied emissions assume an increasingly important role [14]. To ease the decision-making process, it could be very helpful to quantify the environmental impacts of a building during its lifetime at the early design stage [15]. In this regard, the introduction and adoption of Life Cycle Assessment (LCA) in design processes [16] is assisting decision-making towards more climate- and environment-friendly consumption and production [6,8,17], thus helping to support the achievement of the UN Sustainable Development Goals, SDG11 (Sustainable Cities and Communities) and SDG13 (Climate Action) in particular [18].

A comparative LCA approach has been adopted in many studies to evaluate the different impacts of alternative structural solutions in several building typologies [19–21], and particularly in tall structures [5,22,23] due to the large energy demand and consumption of materials [24]. It clearly emerges that structural and construction choices play a critical role in determining embodied environmental flows [25]. This is of great relevance in the case of high-density residential towers, which are often greeted as an effective solution for controlling city growth and urbanization [26,27].

For these tall structures, the choice of appropriate structural materials and systems plays an important role [28] both with reference to their overall performances and also their potential environmental impacts. Wooden-based systems, such as glulam and Cross-Laminated Timber (CLT), have been increasingly valued as alternatives to concrete and steel, as highlighted by Shishegaran et al. and Hart et al. [4,12]. The progressively increasing use of these alternatives is due to the advances in the design, manufacturing and construction processes, and is also due to the recognition of the related ecological advantages, assuming wood as a renewable resource [29]. According to the current available literature [22,30,31], taller buildings are considered to have greater operational and embodied carbon per m^2 of floor area than conventional buildings. However, this position is still under discussion and some studies (e.g. [26]) have aimed to demonstrate the opposite. This uncertainty underlines the need for further investigations that consider the different construction options and possibly take into account the context and related economic streams. The study presented here is therefore a contribution to the discussion on how alternative structural configurations may impact feeding the contemporary architectural debate.

During the last four years the world's five tallest timber high rises were completed, including the 87-metre Ascent in the USA. In addition, new ones such as the Atlassian by SHoP Architects and BVN, and Rocket & Tigerli by Schmidt Hammer Lassen - both expected to break the height record - are under construction and are contributing to a global race to build taller timber. However, the benefit of adopting mass-timber in tall buildings is a controversial topic which is fuelling an international debate. Arup fellow Andrew Lawrence recently stated [32] that "For most buildings, tall timber does not make sense, timber's natural home is low-rise construction. […] The reality that timber is best suited technically to smaller buildings, and that this is where it can have the most impact on reducing embodied carbon, has been lost." He points out the limitations of this system due to both the size of the pieces over certain spans and the need for steel or concrete elements for stabilization purposes. However, despite the drawbacks, several experts agree that the race to mass-timber in high-rise will continue due to the green label and due to some suitable features which improve the living quality for users. In addition, there is strong competition to break the record. Pioneering timber architect Hermann Kaufmann confirms the trend but, at the same time, underlines the force of mass-timber as a driver of innovation.

More accurate studies and indicators should therefore be introduced into the debate to support the different positions. Alternative structural systems suitable for tall buildings should be environmentally assessed in terms of climate change impacts and mitigation potential, rather being evaluated with reference to their supposed architectural qualities. To this end, LCA has been widely used since 1990 as a tool for evaluating the environmental impact of building materials over their different life cycle phases [33] from the production of materials/components to the construction, use, and end-of-life stages, as specified in ISO 14040 [47]. Various software with different levels of complexity have been developed for performing LCA, such as SimaPro [34], One Click LCA [35] and openLCA [36]. Most of these software are far to being regularly integrated into the conventional design process, due to the huge amount of data required and the highly demanding time investment. However, they can be profitably adopted in specific studies to address or investigate design trends based on a more scientific and theoretical approach. To facilitate the collection of information/data needed for performing an LCA, some studies have relied on digital building models [37], which were originally developed to provide a comprehensive and systematic overview of components and systems for rapid, efficient and accurate construction planning [38–40].

Building information modelling (BIM) LCA integration is a valid approach to performing an environmental assessment during the design stage [41]. The BIM file embeds all the essential information about the life cycle inventory of a building, such as bill of quantities (BoQ) and material specifications, which can be extracted and imported into an LCA software [42]. The method is useful in comparing different building designs and component options in terms of their environmental impact. An integrated LCA and BIM design approach has already been explored in some studies (e.g., [6,12,39–41,43,44]) in an attempt to take impacts of a building under control. In most of the cases [12,39–41,43], this was limited to specific construction solutions focusing on how data could be gathered via BIM to feed the LCA engine. A small number of studies [6,12] have explored the adoption of a comparative approach to address the different impacts of alternative solutions. In the current body of literature, the use of integrated BIM and LCA evaluation in mass-timber high rises is still limited. This field of research still leaves room for exploration, particularly with reference to the impacts that it may have.

1.1. Scope of the study and limitations

The main purpose of the study reported in this paper is to adopt a BIM-LCA integrated method to explore and analyse the impacts of a mass-timber solution compared to a conventional solution in tall residential buildings. Although BIM-LCA integration is not a novelty, the comparative approach to buildings of this type involves innovative experimentation. An attempt is made to provide objective data and evidence to feed the discussion on whether the choice of a timber-based solution truly leads to impact reduction of the type that is usually achieved in low-rise buildings. This would demonstrate that the methodology is a suitable option in a such competitive and structurally challenging field.

The study focuses on residential towers (not mixed-use buildings), in order to avoid excessively heterogeneous functions that would limit the capacity to correctly predict the energy demand within the operational stage. The aim is to base the simulation on a wide range of reliable data to set and double-check the operating conditions and energy profiles. The considered reference height ranges between 15 and 20 levels (45–60 m), in order to address the widest application possible in the timber-based market and to avoid focusing on supertall examples, which are still exceptions and are based on pioneering approaches. The study accepts the several constraints and typology-driven limitations which affect high-rise structures, assuming a conventional solution based on a reinforced concrete frame for comparative purposes. This is much more widespread use in the real market compared to steel-framed ones due to the lower cost and also for fire safety reasons.

The cost of the two alternative solutions was not included in the investigation, on the assumption that the choice is not strictly dependent on financial constraints but rather on the commitment of investors to a design paradigm reflecting their attitude towards different visions about sustainable constructions.

The study compares the life cycle environmental impacts of a cross-laminated timber (CLT) structure and a reinforced concrete (RC) structure of functionally equivalent residential towers – embodied, operational, and end-of-life impacts are considered in the assessment. The building materials and their quantities are gathered from BIM models, are measured, and are then entered into the LCA software. This provides a quantitative assessment of how each material contributes to different impact categories. Considering the efforts required, which can be justified in such developments but affect the ordinary process in design practice, a major goal and an expected outcome of this study is to provide a clear framework of reliable and accurate information on impact assessment to officials, policymakers, designers, and all the other stakeholders in the construction sector. This assessment will allow to let them take informed evidence-based decisions about the materials and construction choices, and also about the related overall energy performances.

2. Materials and methods

The proposed comparative approach requires the two alternative solutions of structural frames (assuming the building's envelope and its energy performance to be the same in both scenarios), to be properly defined in terms of geometrical configuration and construction systems. In order to focus on the different impacts generated by the two CLT and RC structures – which are assumed as the main variables of the process – it is necessary to ensure that the other elements and key choices are as constant as possible. Since the purpose is to investigate the overall sustainability level, the building is assumed to achieve the best energy performance possible, and therefore both the super-insulated building envelope and the HVAC systems are shared by the two buildings. The shape of the tower, the typical floor plan, the exposure and all the possible decisions influencing the thermal behaviour and the energy performance of the building are fixed in advance to meet the functional brief and the targeted energy performance as well as the related thermal transmittance values (U).

Coherently with the pre-defined shape, the two alternative structures are defined taking into account the different configurations required to meet the optimal structural response. However, in order to keep the functional capacity between the two alternatives stable, the net usable floor area on each level is not compromised or altered.

2.1. Workflow of the study

Fig. 1 provides a workflow diagram of the three main phases of the methodology and the three interconnected outputs.

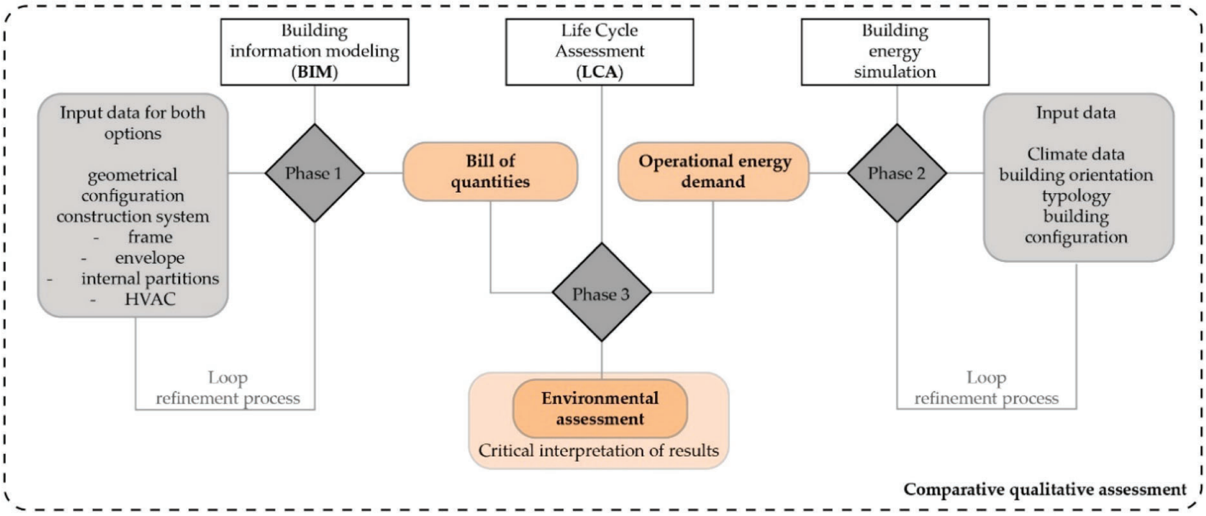


Fig. 1. Workflow diagram of the methodology.

2.1.1. *Phase 1 - Building Information Modelling (BIM)*

Each of the alternatives is modelled via BIM software according to categories and a classification system which are organized according to the way in which the elements have to be extracted, grouped or listed for calculation purposes (Fig. 2). In order to facilitate the comparison of any variation, it is very convenient to adopt at least Level of Developments (LOD) 300 [45], which is close to the project documentation required for a building permit. The model should contain as many material details as possible in order to facilitate a systematic mapping process and to reduce the number of approximations due to estimation. In the proposed study Revit software by Autodesk is used due to its high compatibility and diffusion.

The overall organization of the model follows a strict separation between the constant elements and the variable elements, in order to identify as easily and as quickly as possible the variations in the structural elements that then enter the LCA investigation. Fig. 3 shows an example of the main levels in which a BIM file is organised. The main output from this phase is the Bill of Quantities (BoQ) for each version of the project.

2.1.2. *Phase 2 – Building energy simulation*

Operating an energy simulation on such a detailed BIM model can be challenging due to the hundreds of thermal zones that are involved. Solving such a complex system therefore requires extensive computational resources, a powerful RAM, and a considerable amount of time. For the scope of this work, it was not necessary to optimize the results for each zone; a simplified energy model based on the building geometry was developed to assess the overall energy consumption. Furthermore, the transition of the BIM model to specialized simulation software resulted in errors and missing information. In fact, a simplified model corresponding to main thermal zones can be obtained with more conventional 3D software such as Rhinoceros [47] while the energy simulation can be carried out using commercial specialised software, in this case, ClimateStudio [48] (the simulation engines are OpenStudio [49] and EnergyPlus [50]). This combination enables the energy simulations to be set up quickly using the built-in libraries for occupancy and activity schedules in addition to the energy loads and HVAC controls based on the purposes of individual zones. Templates from the library can be modified to provide a more accurate description of the modelled building. Following the simulation, the detailed hourly energy demand for each type of use (e.g., heating, cooling, lighting, etc.) is provided.

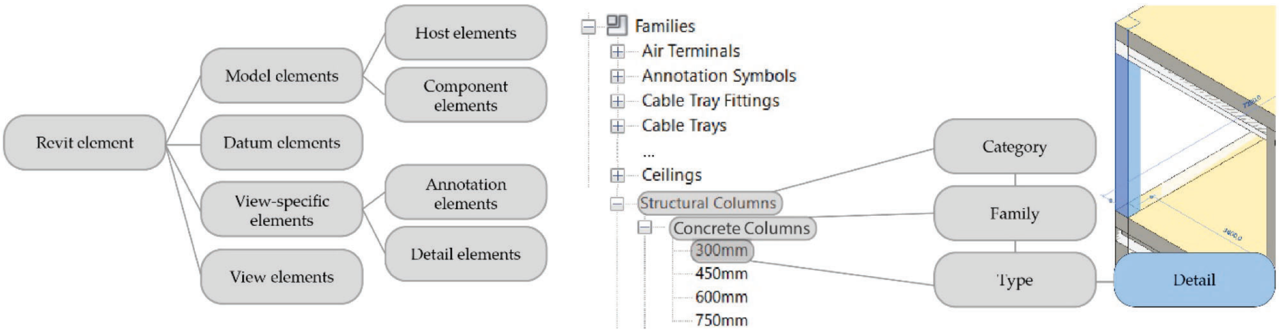
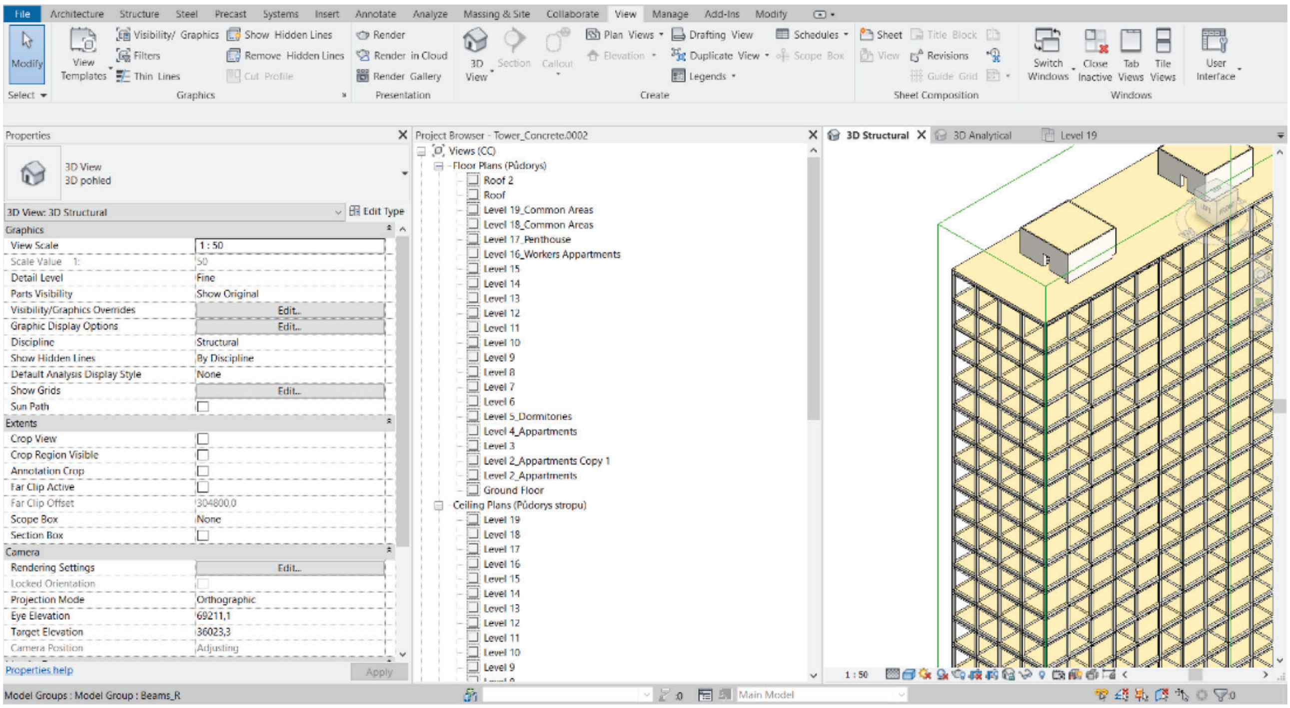


Fig. 2. Revit and family terminology. Visualization readapted from Li et al., 2018 [46].



Graphics	
View Scale	1 : 50
Scale Value 1:	50
Detail Level	Fine
Parts Visibility	Show Original
Visibility/Graphics Overrides	Edit...
Graphic Display Options	Edit...
Discipline	Structural
Show Hidden Lines	By Discipline
Default Analysis Display Style	None
Show Grids	Edit...
Sun Path	☐
Extents	
Crop View	☐
Crop Region Visible	☐
Annotation Crop	☐
Far Clip Active	☐
Far Clip Offset	304800,0
Scope Box	None
Section Box	☐
Camera	
Rendering Settings	Edit...
Locked Orientation	☐
Projection Mode	Orthographic
Eye Elevation	69211,1
Target Elevation	36023,3
Camera Position	Adjusting

Model Groups : Model Group : Beams_R

Fig. 3. Example of a Revit working area and the main levels of a BIM model.

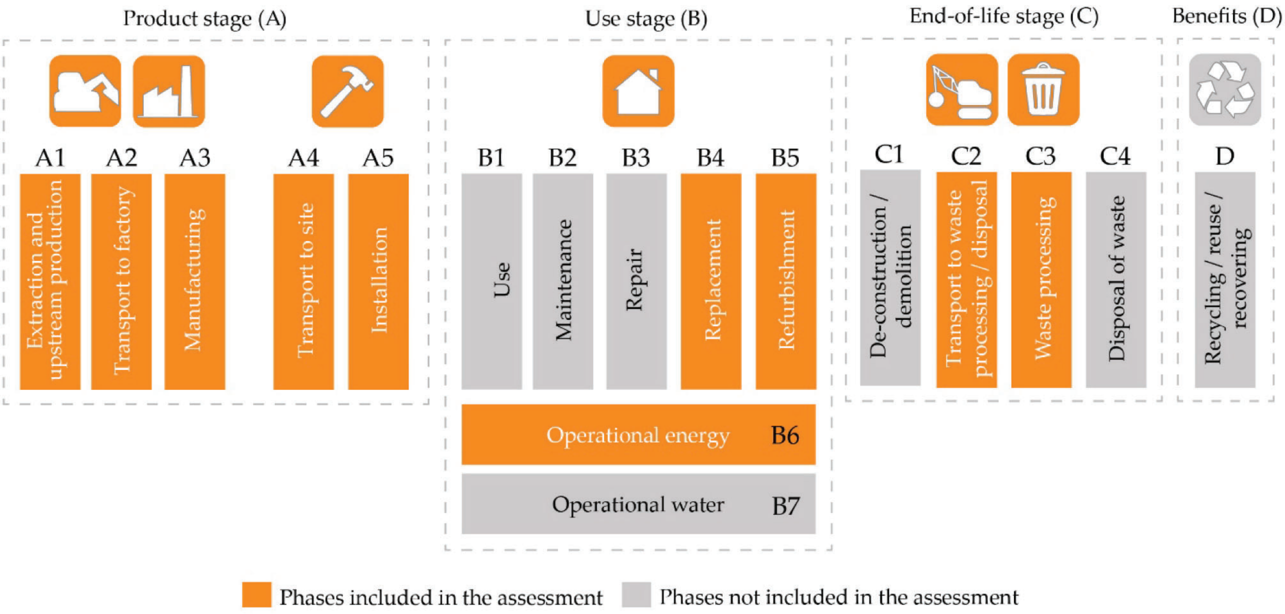


Fig. 4. Life cycle stages classification, as defined in EN 15978 [52]. Orange rectangles highlight the life cycle phases considered in this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.1.3. Phase 3 - Life Cycle Assessment (LCA)

LCA is performed considering the “cradle-to-grave” approach according to the stages highlighted in Fig. 4, namely, product stage (A), use stage (B), and end of life (C). Sub-stages (A1-A3) are characterized by embodied emissions and energy due to the extraction and manufacturing of raw materials. This stage is referred to as the “cradle-to-gate” phase and many studies (e.g., [6,8]) include this phase since it enables the embodied impacts that result from the material production process to be determined. Since the operational impacts are decreasing with the advent of energy-efficient buildings, it is vital to focus more and more on this phase and to minimize its impact. Sub-stage (A4) refers to impacts related to the transportation of building materials from the manufacturing site to the construction site. Sub-stage (A5) adds in the emissions and the energy used for installation. (B4 and B5) refer to the replacement and refurbishment of building components. (B6) mostly refers to operational energy, which is the primary part of the total energy used in buildings for cooling, heating, ventilation, lighting, and for heating water. (B6) therefore requires the operational energy to be simulated in Ph2. Substages (C2) and (C3), i.e. the impacts due to waste transportation to the landfill and processing for reuse, recycling, and/or recycling are considered, while (C1) and (C4) for disassembling/demolishing and disposal have been excluded, because they are difficult to predict. Stage (D) takes into consideration the positive impacts on the environment of certain materials when reused/recycled.

Constant elements such as the building envelope cladding, insulation and complementary layers are processed separately from the structural elements to identify clearly the impacts due to the variable elements. The process is implemented using One Click LCA [35], a software tool used in more than 140 countries. Its database accounts for Environmental Products Declarations (EPDs) in accordance with the EN 15804 + A2:2019 [51] standard. Interoperability with BIM software is ensured via a plugin directly available on Autodesk Revit.

The outputs of the first two phases serve as inputs for the analysis of the environmental impacts in the third phase. Then, the results can be analysed and interpreted according to the scope and objectives of the study. A demo case in Denmark (Section 2.2) is used as a concrete example of an application to better describe the steps and provide an opportunity to discuss the outcomes with reference to objective data and output. This should assist the decision-making process from the early stage in the real market.

2.2. Applicative case study in Aalborg, Denmark

The proposed methodology was applied for demonstration purposes to a case study in Aalborg, Denmark (57.0488° N, 9.9217° E). The climate is classified by the Köppen-Geiger as marine climate. This is a humid temperature climate sub-type, in which the coldest month averages above −3 °C, all months have average temperatures below 22 °C, and at least four months averages above 10 °C [53]. The residential tower is part of a new development of four high-rise volumes and a connecting wing devoted to commercial activities to be located, according to the city Urban Plan (lokalplan 1-4-106), in the Østre Havn area (Fig. 5) (135,000 m^3). Originally devoted to industrial production and exchange due to its location along the Limfjorde fjord, the site was abandoned in the 1970 s. The site is now included in a regeneration initiative aimed at boosting the service-based economy, and at hosting spaces for leisure, socialization and sports facilities. The new volumes directly facing the fjord are located on the peer (highlighted in orange in the box) which defines an artificial basin. The tower, as well as the three other ones that are projected in the development plan for the site, is located on a free piece of land serving as a pier facing the fjord on the north side and a water basin connected to the fjord where ships originally served the production site. Therefore, there is no neighbouring

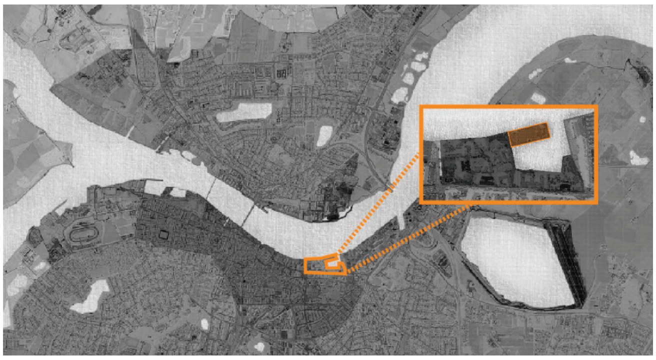


Fig. 5. Area of interest in the urban regeneration project for the city of Aalborg (DK). The orange-perimeter and the coloured area is the area where residential towers will be built. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

building or existing vegetation that generates direct shading. Additionally, the location of the four volumes was specifically defined to avoid unsuitable natural shading or visual interferences. Fig. 6 shows a 3D model of the building of interest and the rest of the proposed building complex within the 3D model of the city of Aalborg. The included Sun path suggests that the current building stock does not significantly shade the building. The only considerable shading effect is provided by the rest of the intended building complex. The shades provided in the figure were calculated for September 23rd, 13:00. The thermal model of the building therefore used the rest of the building complex for the shading calculations.

The building chosen for simulations is the tallest of the four towers with its 19 stories. It is oriented north–south (with north facing the fjord and south facing the basin) where the main elevations are located (one exploiting the natural solar gain, the other offering a stunning view over the fjord).

According to the proposed methodology, the geometrical configuration is defined following a rectangular plan of approximately 44 × 15.3 m which hosts two symmetrically located cores for the staircases, the elevators and the technical spaces. The overall plan is organised according to squared modules on which the different dwelling typologies can be sized. Typically, eight residential units per floor can be obtained with the living spaces oriented on the north and south faces (Fig. 7).

The building envelope is a multilayered highly insulated façade, based on dry construction systems, and cladded with Glass-fiber Reinforced Concrete (GRC) panels, which serve both as an architectural skin and as shielding elements facilitating natural ventilation for summer heat extraction. The HVAC systems are designed to work synergically with the envelope to meet high-performance standards and are distributed through the ceiling technical spaces. Both the windows on the main façades and the windows protected by the GRC skin are high-performance double pane glazed surfaces. All these elements are assumed to be constant in the two structural alternatives entering the simulation process. They also both choose to maintain reinforced concrete cores to ensure appropriate stability for the tower, and both choose to build the double-height hall level as a glazed lobby with Y-shaped reinforced concrete columns directly supporting the first-floor concrete slab. This decision was taken to meet the requirements for resistance to flooding envisaged by the local resilience plan for tackling the effects of

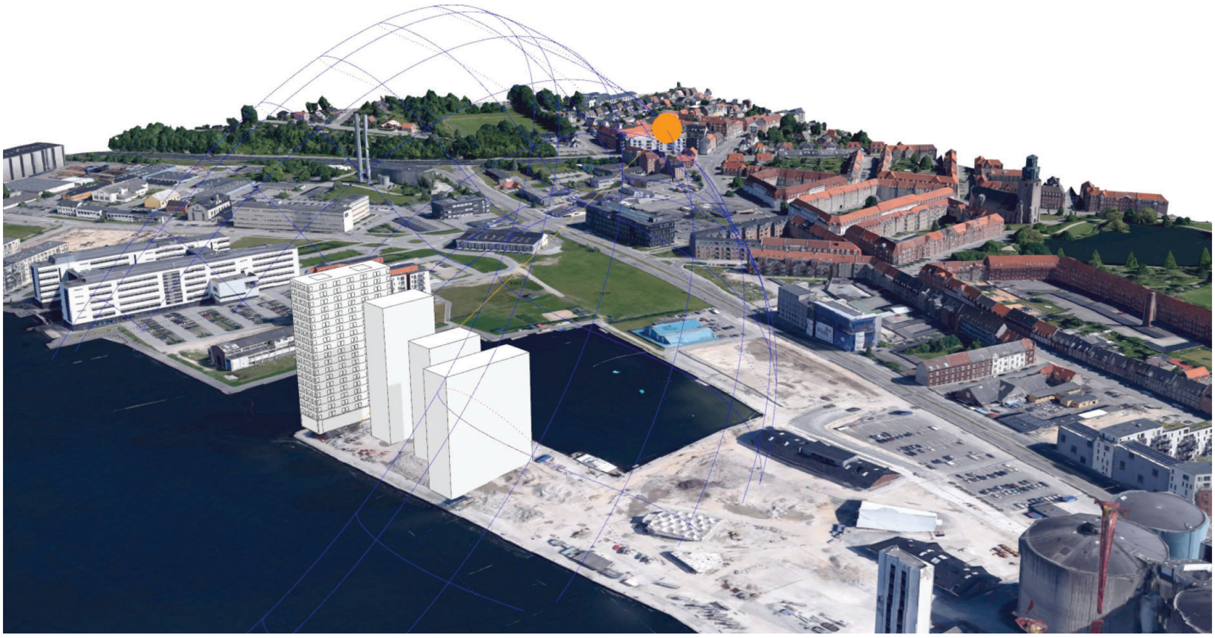


Fig. 6. 3D model of the proposed buildings with their surroundings (view from the North-East).

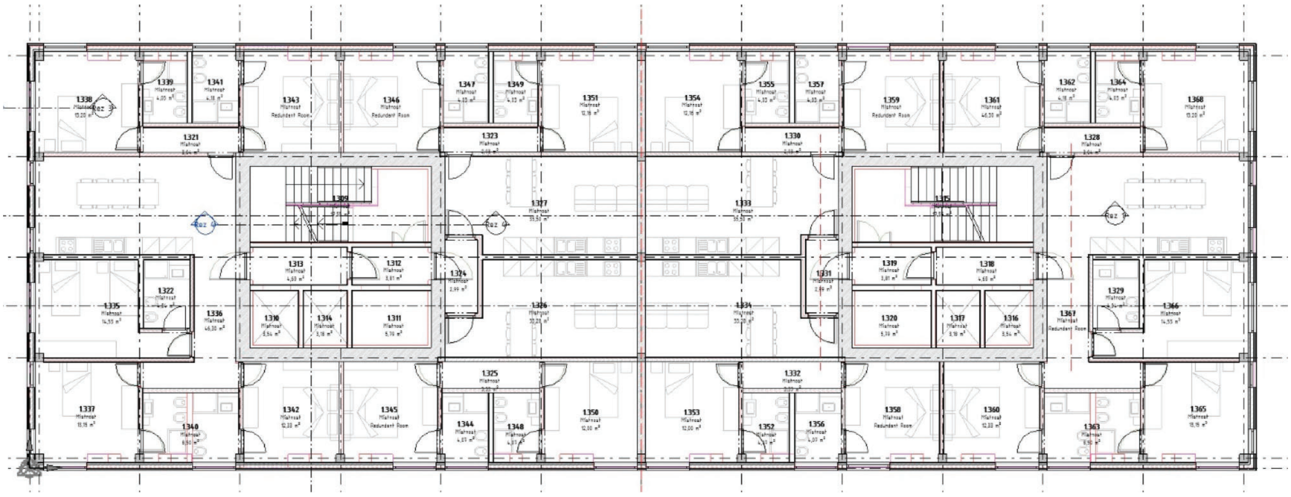


Fig. 7. Shared plan of a typical floor.

climate change. These requirements have been considered carefully due to the proximity of the fjord.

Above the first floor, two alternative structures were defined: Option A (RC), a reinforced concrete frame and Option B (CLT), a cross-laminated timber-based frame, which can be considered well-developed technologies in Denmark (Fig. 8). Option A is a very conventional solution based on concrete regular pillars along the plan connected to the cores by concrete edge beams and slabs. Option B is a vertical structure that combines glulam pillars connected on the east and west elevations by cross reinforcements with transversal Vierendeel transversal beams supporting that CLT flooring directly connected to the cores. This provides a very efficient and stable configuration limiting the glulam element acceptable size sections.

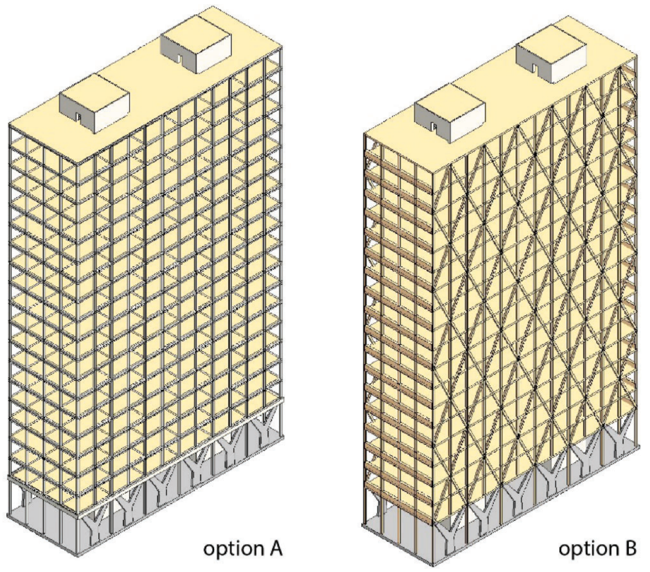


Fig. 8. 3D diagrams of the two alternative solutions, Option A (RC) and Option B (CLT).

All input data were converted into BIM models to feed both the operational energy simulation and the LCA assessment. Based on the limited knowledge and feedback about the service life of mass-timber-based solutions (especially in high-rise structures) the expected life cycle of the building for calculation purposes was fixed at 50 years, which is also the reference study time indicated in Level(s) indicator 1.2: Life cycle Global Warming Potential [54]. Option A could easily be extended in its service life by replacing the façade and interiors. For Option B, the CLT panels could be used elsewhere, since both framing systems are protected from the outdoor environment.

2.2.1. *Phase 1 - BIM design*

A separate layer is created in the BIM model for constant elements that are shared by Option A (RC) and Option B (CLT). By show/hide levels, the model allows for exporting separate Options A and B, dividing the file into two twin files in order to correctly extract the BoQ and construct a separate dataset for both options (Fig. 9).

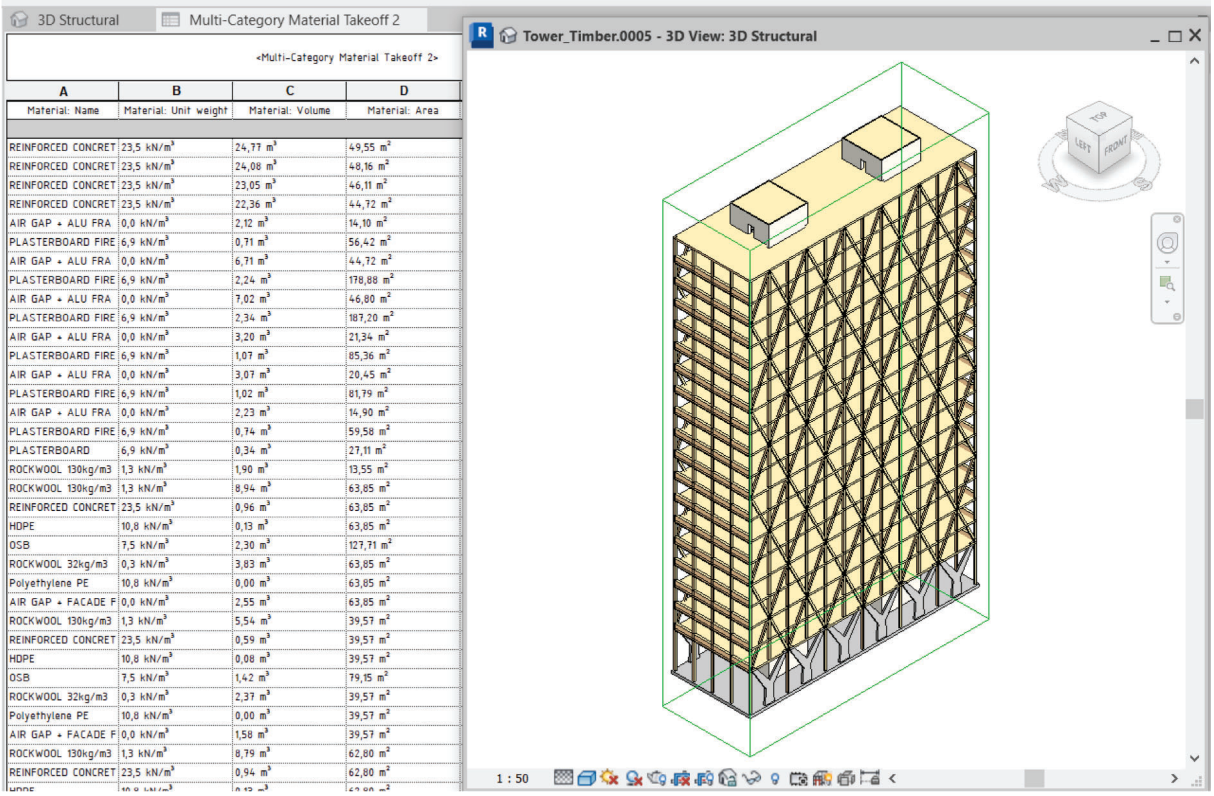
Table 1 outlines the dimensions of the two structures. This information provides an easy understanding of how the two options are designed. The dimensions were selected according to common practice that had already been tested and proven to be sufficient for the given application and after consultation with a structural engineer. This eliminated the need to perform any structural calculations.

Fig. 10 shows the cross-section of the building, highlighting the elements that differ between the two options and also provides a detailed

Table 1

Dimension of the structures for the two options.

	Vertical structure	Floor slab	Roof
Option A - RC	400x300 mm RC	250 mm RC	250 mm RC
Option B - CLT	300x300 mm CLT	240 mm CLT	240 mm CLT



<Multi-Category Material Takeoff 2>

A	B	C	D
Material: Name	Material: Unit weight	Material: Volume	Material: Area
REINFORCED CONCRET	23,5 kN/m^3	24,77 m^3	49,55 m^2
REINFORCED CONCRET	23,5 kN/m^3	24,08 m^3	48,16 m^2
REINFORCED CONCRET	23,5 kN/m^3	23,05 m^3	46,11 m^2
REINFORCED CONCRET	23,5 kN/m^3	22,36 m^3	44,72 m^2
AIR GAP + ALU FRA	0,0 kN/m^3	2,12 m^3	14,10 m^2
PLASTERBOARD FIRE	6,9 kN/m^3	0,71 m^3	56,42 m^2
AIR GAP + ALU FRA	0,0 kN/m^3	6,71 m^3	44,72 m^2
PLASTERBOARD FIRE	6,9 kN/m^3	2,24 m^3	178,88 m^2
AIR GAP + ALU FRA	0,0 kN/m^3	7,02 m^3	46,80 m^2
PLASTERBOARD FIRE	6,9 kN/m^3	2,34 m^3	187,20 m^2
AIR GAP + ALU FRA	0,0 kN/m^3	3,20 m^3	21,34 m^2
PLASTERBOARD FIRE	6,9 kN/m^3	1,07 m^3	85,36 m^2
AIR GAP + ALU FRA	0,0 kN/m^3	3,07 m^3	20,45 m^2
PLASTERBOARD FIRE	6,9 kN/m^3	1,02 m^3	81,79 m^2
AIR GAP + ALU FRA	0,0 kN/m^3	2,23 m^3	14,90 m^2
PLASTERBOARD FIRE	6,9 kN/m^3	0,74 m^3	59,58 m^2
PLASTERBOARD	6,9 kN/m^3	0,34 m^3	27,11 m^2
ROCKWOOL 130kg/m3	1,3 kN/m^3	1,90 m^3	13,55 m^2
ROCKWOOL 130kg/m3	1,3 kN/m^3	8,94 m^3	63,85 m^2
REINFORCED CONCRET	23,5 kN/m^3	0,96 m^3	63,85 m^2
HDPE	10,8 kN/m^3	0,13 m^3	63,85 m^2
OSB	7,5 kN/m^3	2,30 m^3	127,71 m^2
ROCKWOOL 32kg/m3	0,3 kN/m^3	3,83 m^3	63,85 m^2
Polyethylene PE	10,8 kN/m^3	0,00 m^3	63,85 m^2
AIR GAP + FACADE F	0,0 kN/m^3	2,55 m^3	63,85 m^2
ROCKWOOL 130kg/m3	1,3 kN/m^3	5,54 m^3	39,57 m^2
REINFORCED CONCRET	23,5 kN/m^3	0,59 m^3	39,57 m^2
HDPE	10,8 kN/m^3	0,08 m^3	39,57 m^2
OSB	7,5 kN/m^3	1,42 m^3	79,15 m^2
ROCKWOOL 32kg/m3	0,3 kN/m^3	2,37 m^3	39,57 m^2
Polyethylene PE	10,8 kN/m^3	0,00 m^3	39,57 m^2
AIR GAP + FACADE F	0,0 kN/m^3	1,58 m^3	39,57 m^2
ROCKWOOL 130kg/m3	1,3 kN/m^3	8,79 m^3	62,80 m^2
REINFORCED CONCRET	23,5 kN/m^3	0,94 m^3	62,80 m^2

Fig. 9. Example for Bill of Quantity of Option B (CLT).

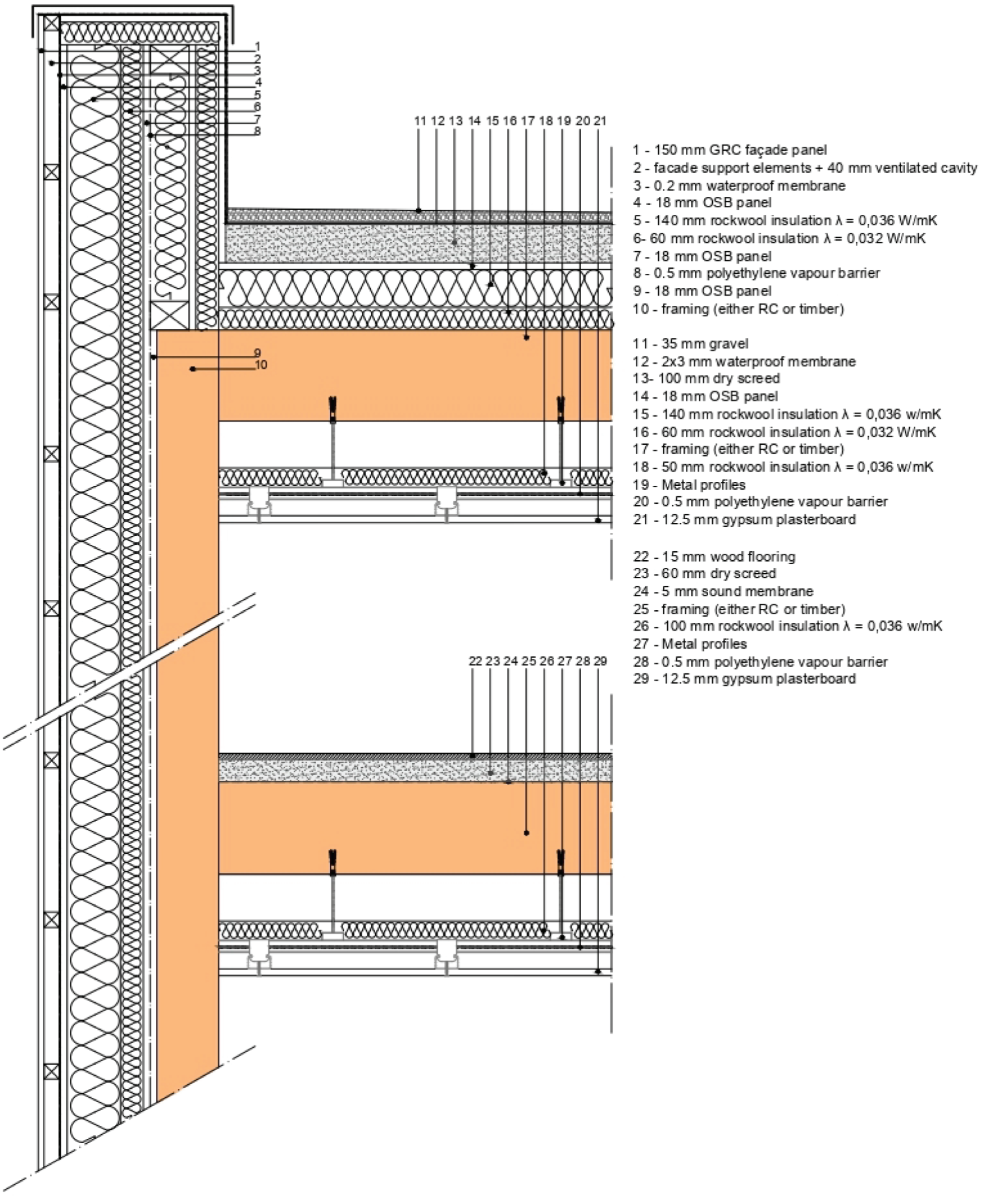


Fig. 10. Cross section of the building – the orange-coloured elements are those that differ between Option A (RC) and Option B (CLT). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

description of each layer, including the common layers.

As shown in the cross-section, both structures include common elements. For example, the façade of the load-bearing exterior wall is fabricated in GRC panels measuring 150 mm each and is ventilated. By installing two layers of thermal insulation that differ in transmittance the thermal loss through the façade is reduced. Thermal loss would otherwise occur due to the temperature difference between the inside and outside of the wall. The insulation also acts as a barrier to air movement, further reducing the amount of heat that is lost.

It should be noted that the steel joints of the timber structure were not defined for the purpose of this study, and the precise related impact has therefore not been included. However, considering the limited amount of material compared to the quantities in the whole construction, this can be neglected at this stage. It can also be observed that the weight of the reinforcement steel bars in the nodes of Option A should be more precisely defined in the structural calculations. In both cases, a certain level of approximation has to be accepted, but it is assumed not to significantly compromise the overall balance.

Once the model was set up with the quantity and a description of the materials, the plugin of One Click LCA, directly available in Revit, was used to automatically export the BoQ and assign the most appropriate EPD to each material. It may be necessary to repeat this process several times to select the most appropriate EPD.

2.2.2. Phase 2 - Operational energy simulation of the case study

ClimateStudio software was used to calculate the energy consumption during the use phase (LCA B6) [48]. The simplified calculation took into account three zones at each level of the building - two concrete cores and a large, occupied area (see Fig. 7 and Fig. 11). To describe the internal loads and schedules, predefined zone templates representing the purpose of the zone were used. The upper floors (1 to 19) were modelled using the template for a whole multi-unit residential building (NECB 2020 [55]) (Fig. 12), while the ground floor was modelled using a modified breakroom template (ASHRAE 90.1 2019 [56]). During this step, various assumptions and parameters were entered, such as building type, location, thermal properties, project phase, building envelope, analysis mode, conceptual construction, occupancy, HVAC system, and outdoor climate conditions. Thermal mass was added to account for the

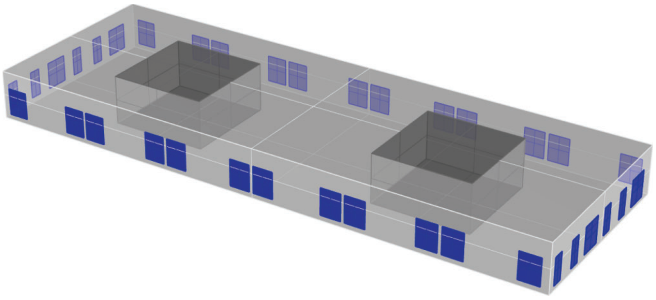


Fig. 11. A typical residential floor in the energy model consisting of tree thermal zones – two cores (dark grey) and one large occupied area (light grey).

partitions on the upper floors (1.2 m^2 of a lightweight timber-based partition for every 1 m^2 of floor space). Building design drawings from Revit were used to model the sizes and positions of the windows.

The façade panel and ventilated cavity of the external wall have been neglected in the calculation - it is a standard procedure for ventilated cavities because the air in the cavity is considered external. A triple-glazed insulating glass unit (IGU) was used to model the transparent parts. The U-value for the triple-glazed IGU was 1.05 W/m^{2}K, the solar heat gain coefficient was 0.605, and the visible transmittance (T_{vis}) was 0.713. Typical meteorological year (TMY) climate data were used in the simulation based on statistical data from years 2004 to 2018 from the ClimateStudio library [57], and were compared with the statistical data of the Aalborg environmental agency.

Assuming that the profile of the users, the systems, and the envelope characteristics remain constant between the two building options, it is considered that the energy consumption is substantially the same, apart from minimal differences resulting from a few parts of the structure interacting with the envelope. These differences are, therefore, negligible. The energy consumption in these systems is mainly determined by the characteristics of the envelope, such as its thermal resistance and airtightness, which remain constant for a given structure. Any minor changes in the structure would not affect the energy consumption significantly. For the external wall, for example, the difference is the use of timber or concrete pillars in the interior that do not influence the heat conduction through the façade. Only the thermal capacity of the interior is affected, but the total mass difference is small when only linear columns are used. As a result of the different horizontal structures in the considered variants, there is a slight increase in the heat conducted through the roof. However, due to the building's height, the roof area is relatively small compared with the rest of the envelope. A horizontal structure has a greater thermal capacity than a vertical structure, however, it is not exposed to the interior due to the floor and roof layers on top and the acoustic insulation beneath it. The predicted operational energy has been compared with similar completed buildings and particularly with the Treet tower in Bergen [58,59] which has a comparable timber-based structure for 14 floors and is located in Norway, where the climatic conditions are quite similar to those in Denmark.

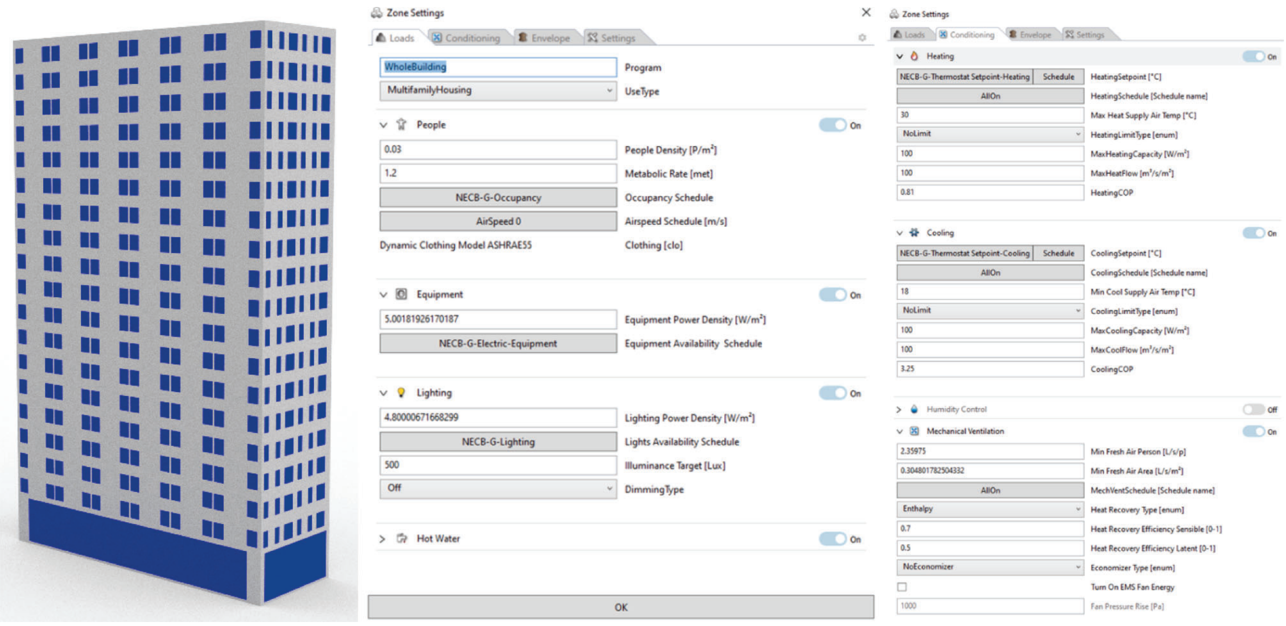
2.2.3. Phase 3 - LCA of the case study

In the first phase of the LCA, the goals and the scope of the study must be defined, along with the boundary of the system, variants and set of data, functional unit, type and impact of analysis, assumptions, and limitations. Specifically, in this study, the system boundary focuses on several phases during the life cycle of the case study, including mining raw materials (cradle), manufacturing, replacement, operations, and disposal (grave) - a cradle-to-grave approach. The functional unit is represented by the whole building as a single unit for a period of 50 years (service life). However, the scope of this work is to consider the early design stages of constructing a tall residential building in Denmark and prove that a CLT structure is the more environmental-friendly variant than an RC structure.

The outputs from Ph.1 and Ph.2 were used for performing the LCA. The information on the BoQ was extracted from the BIM model and was automatically inserted in One Click LCA. For an estimate of the energy

Table 2
Emission factors for electricity consumption from 2020 (tCO$_2$/MWh) [60].

Country	GHG emission factor	Difference
Denmark (reference)	0.058	–
Austria	0.130	+55%
Czech Republic	0.594	+924%
Germany	0.375	+546%
Poland	0.722	+1144%
Sweden	0.013	−78%



WholeBuilding	Program
MultifamilyHousing	UseType
0.03	People Density [P/m²]
1.2	Metabolic Rate [met]
NECB-G-Occupancy	Occupancy Schedule
AirSpeed 0	Airspeed Schedule [m/s]
Dynamic Clothing Model ASHRAE55	Clothing [clo]
5.00181926170187	Equipment Power Density [W/m²]
NECB-G-Electric-Equipment	Equipment Availability Schedule
4.80000671668299	Lighting Power Density [W/m²]
NECB-G-Lighting	Lights Availability Schedule
500	Illuminance Target [Lux]
Off	DimmingType

NECB-G-Thermostat Setpoint-Heating · Schedule	HeatingSetpoint [°C]
AllOn	HeatingSchedule [Schedule name]
30	Max Heat Supply Air Temp [°C]
NoLimit	HeatingLimitType [enum]
100	MaxHeatingCapacity [W/m²]
100	MaxHeatFlow [m³/s/m²]
0.81	HeatingCOP
NECB-G-Thermostat Setpoint-Cooling · Schedule	CoolingSetpoint [°C]
AllOn	CoolingSchedule [Schedule name]
18	Min Cool Supply Air Temp [°C]
NoLimit	CoolingLimitType [enum]
100	MaxCoolingCapacity [W/m²]
100	MaxCoolFlow [m³/s/m²]
3.25	CoolingCOP
2.35975	Min Fresh Air Person [L/s/p]
0.304801782504332	Min Fresh Air Area [L/s/m²]
AllOn	MechVentSchedule [Schedule name]
Enthalpy	Heat Recovery Type [enum]
0.7	Heat Recovery Efficiency Sensible [0-1]
0.5	Heat Recovery Efficiency Latent [0-1]
NoEconomizer	Economizer Type [enum]
☐	Turn On EMS Fan Energy
1000	Fan Pressure Rise [Pa]

Fig. 12. The whole building simulation model (left) and the zone simulation settings used in the occupied areas of the upper floors (centre and right).

Table 3
Impact categories and their units of measurement [63].

Environmental impact categories	Acronym	Unit measure
Abiotic depletion potential fossil fuels	ADPF	[MJ]
Abiotic depletion potential elements	ADPE	[kg - Sb eq.]
Acidification potential	AP	[kg - SO_2 eq.]
Biogenic carbon storage	BIO	[kg - CO_2 eq. bio]
Eutrophication	EP	[kg – PO_4 eq.]
Global warming potential	GWP	[kg - CO_2 eq.]
Ozone depletion potential	ODP	[kg - CFC_{11} eq.]
Photochemical ozone creation potential	POCP	[kg - Ethenee eq.]
Freshwater use	FW	[m^3]
Use of primary energy ex. raw materials	PET	[MJ]
Use of renewable primary energy	PERT	[MJ]
Use of non-renewable primary energy	PERNT	[MJ]

performance, a simulation run in DesignStudio gave the results divided by the heating, cooling and lighting demand to be inserted in the LCA tool to determine the emissions during the operational phase (B6) of the building. In particular, the heating system was powered by the biomassed-fuelled district heating system, which produces hot water for heating (the generation of hot water was also not included in the energy and environmental assessment). Additionally, the cooling and lighting demand of the residential tower has been calculated considering the Danish electricity mix as a source. With the use of a different electricity mix, the amount of emissions generated could have been varied, even if the operational energy needed for the building was the same. The GHG emission factors for electricity consumption in fact indicate how much CO_2 and other GHG are emitted for each unit of electricity produced (tCO_2/MWh) [60]. In Table 2, for example, the emissions factors for five European countries are presented to illustrate how they differ from the Danish value. The climatic conditions in the countries selected for comparison are similar to those in Denmark.

To make it easier to understand the environmental assessment results, the findings are translated into impact categories using impact assessment methods [61]. In this study, the methodology presented in the Level(s) framework [62] was used in compliance with EN 15978 [52] and EN 15804:2012 + A1 [63]. In particular, Table 3 presents the impact categories used in the study, which are among the most thoroughly investigated impact categories in the construction industry [63].

As part of this last phase, various results were compared by utilizing tools such as MS Excel to create graphs that make the reader's understanding of the results as easy as possible.

It must be noted that EPDs may vary depending on the dataset of each software, and they influence almost all LCA modules, from A1 to A5, B4-B5, and from C2 to D; thus, if the process is replicated with a different product than One Click LCA, some differences may occur. However, the methodology is reliable and represents a consolidated approach. It can therefore be replicated using other EPDs or different life-cycle inventory databases. Datasets were selected by considering Denmark and its neighbouring countries as primary sources. For modules A4 and C2, the calculation was made directly on One Click LCA, considering the transport and the distance between the manufacturing site and the construction site based on typical regional values for the product type. Transport is also re-considered in module B4-B5 (replacement).

3. Results and discussion

3.1. Cradle-to-grave approach – Overall LCA results

Fig. 13 compares the two options taking into account the entire building during its whole life cycle, from A1 to C3. The comparison is made based on one value, either RC or the CLT option, as 100%, and is then compared either to CLT or to RC to show how much smaller this second value is. For instance, when considering Bio-CO_2 storage, which is normally expressed in kg – CO_2 eq., Option A (RC) provides for a 69% lower value than Option B (CLT), which is considered as 100%, because CLT is derived from a biological source. Option B, however, performs much better than Option A when considering impact categories such as GWP or ODP, in which Option A accounts for 100%, as it reports respectively 12% and 17% less emissions.

Fig. 14 compares the two options with respect to every environmental impact category and LC phase. It is worth noting that the GWP impact of Option A is totally present (100%) in the production phase (A1-A3), whereas the FW impact is split evenly amongst all the categories, though the majority is used in A1-A3. By contrast, the greatest amount of ADPE is present in stage C2 (66%) of the process. A similar situation is valid for Option B.

Finally, Table 4 presents the LCA results of the two options at all life cycle stages, taking into account, in particular, GWP and PET, two of the parameters that are most often considered when conducting an LCA for a building [63]. The CO_2 eq. emissions from the project calculated for the GWP indicator divided by the assessment period (50 years) and the gross internal floor area (approximately 12600 m^2) is 10.8 kg CO_2 eq./m^2/y for Option A and 9.6 kg CO_2 eq./m^2/y for Option B. However, the core source of carbon emissions for Option A is cement production itself that is much higher for Option B. In terms of PET, the greatest consumption is

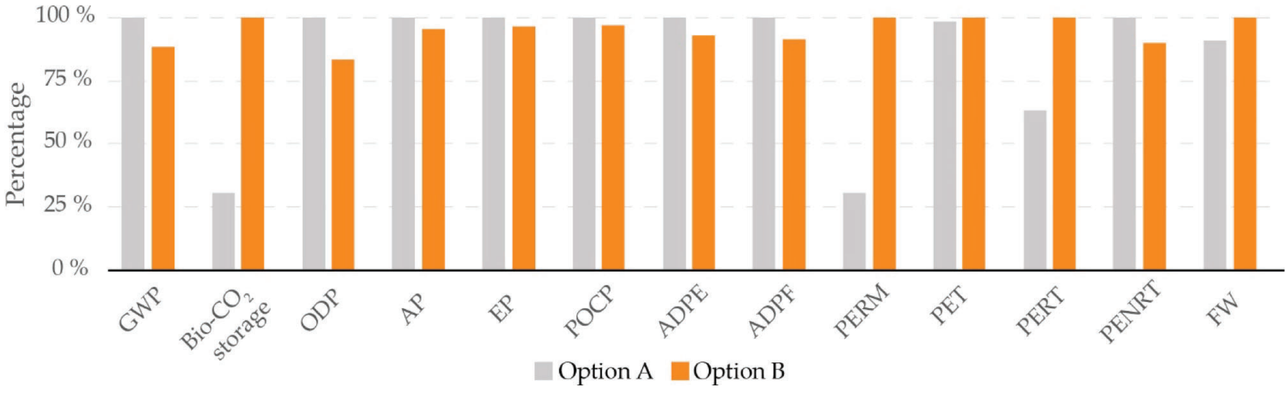


Fig. 13. Comparative analysis of the two options based on all environmental impact categories during the life cycle phases assigned in the system boundary.

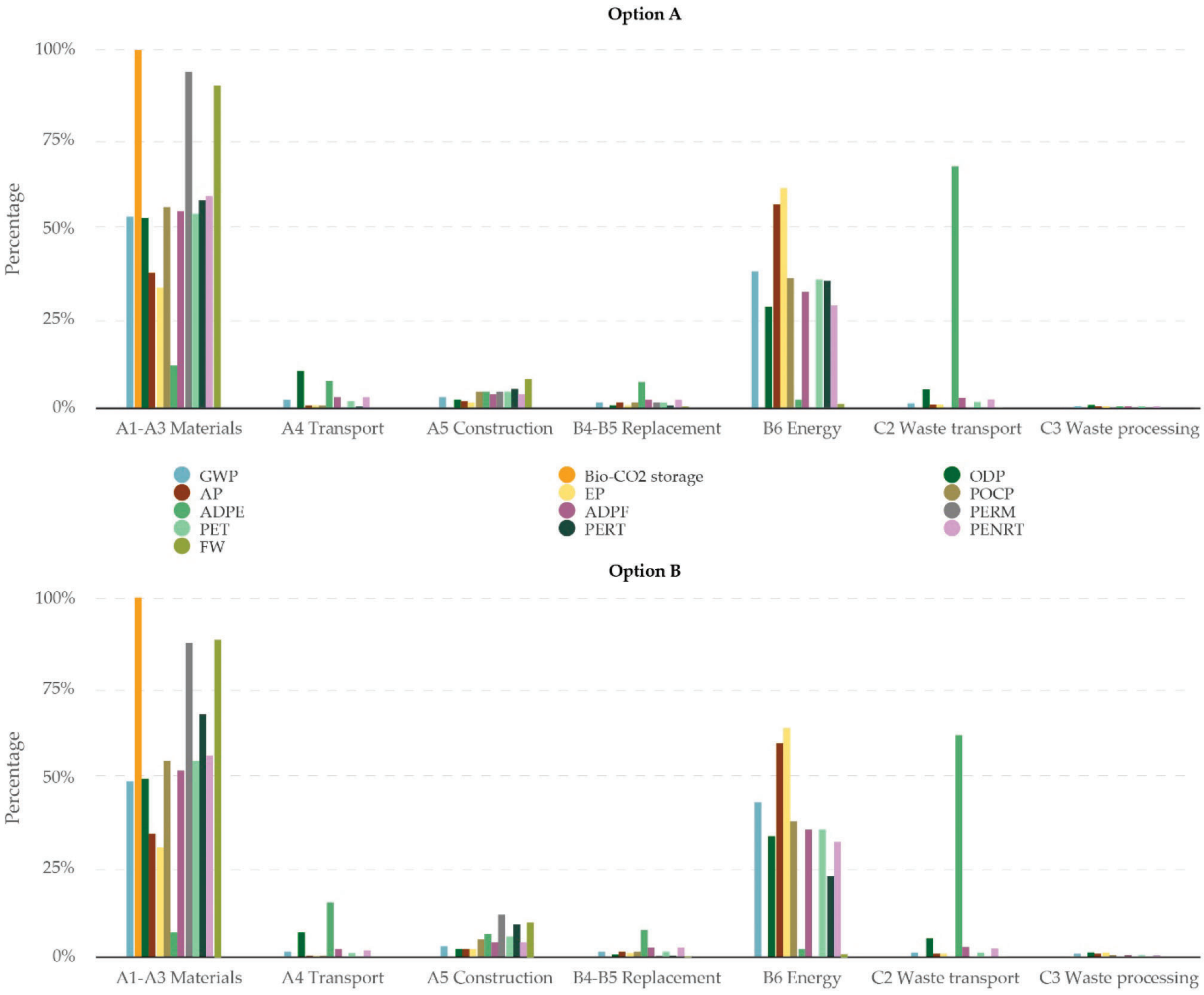


Fig. 14. Comparative analysis of two variants considering the entire building life cycle and all environmental impact categories.

Table 4
LCA results for Option A and B in terms of global warming potential (GWP) and use of primary energy resources (excluding raw materials) (PET) from different life cycle stages.

Life cycle stages	**Module**	**Option A**				**Option B**			
		GWP		**PET**		**GWP**		**PET**	
		kg CO_2 eq./m^2/y	Total (%)	MJ/ m^2/y	Total (%)	kg CO_2 eq./m^2/y	Total (%)	MJ/ m^2/y	Total (%)
Production stage	A1-A3 Production	5.8	53.6	116.5	54.2	4.7	48.8	119	54.6
	A4 Transportation	0.3	2.5	4.2	2.0	0.1	1.5	2.5	1.2
	A5 Construction	0.3	3	9.6	4.4	0.3	3.2	12.2	5.6
Use stage	B4-B5 Replacement	0.2	1.5	3.6	1.7	0.2	1.7	3.6	1.7
	B6 Operational energy	4.1	38.1	77.3	36	4.1	43.1	77.3	35.4
End-of-life	C2-C3 Waste disposal and processing	0.0	1.3	3.6	1.7	0.2	1.7	3.4	1.6
Total		**10.8**	**100**	**214.9**	**100**	**9.6**	**100**	**218.1**	**100**

shown in both production phases (A1-A3) – around 54% of the total, followed by operational energy (B6) – 35/36%.

3.2. *Embodied impacts (production phases)*

The embodied impacts highlight how the two options produce more or less evident effects during the 'cradle-to-gate' stage (LCA A1-A3). Fig. 15 shows, in terms of GWP - expressed in kg CO_2 eq/m^2/y, that the CLT structure (Option B) has a significantly lower impact than the concrete one (Option A), and is approximately 20% less impactful. The only difference between the two options was the structure, and given that many materials remained unchanged between them, it was

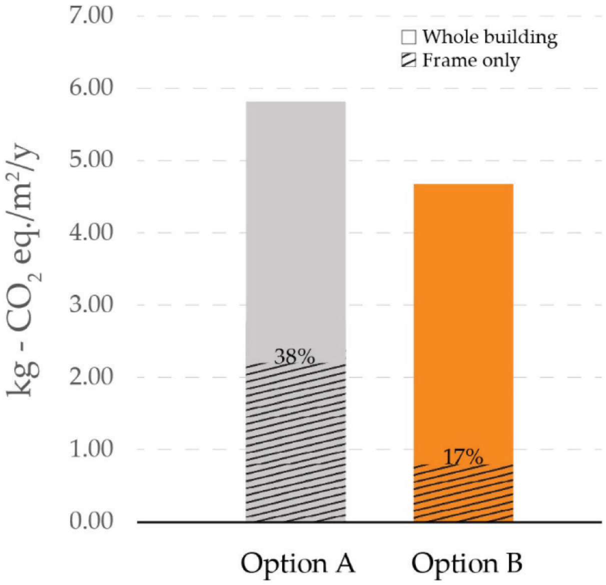


Fig. 15. Embodied impacts in terms of CO_2 emissions, considering respectively the whole building and frame only.

necessary to determine how the structure affected the embodied impacts. Accordingly, as shown in Fig. 15, the embodied impacts of the frame (which takes into account beams, columns, and slabs) vary greatly between A and B. There is a difference of about 55%.

The total use of primary energy (expressed in MJ), divided by renewable and non-renewable sources, is another important factor to consider. As shown in Fig. 16, Option A consumes 45% less renewable energy than Option B while using 15% more non-renewable energy. Again, if only the structural frame is considered in the evaluation, Option A consumes 60% more non-renewable energy than Option B due to concrete and steel reinforcement bars production.

3.3. Operational impacts (use phase)

Simulations on building energy software were conducted in order to calculate the operational energy and consequently the resulting operational emissions. It was assumed that the energy consumption is similar between the two building options, because the users' profile, the systems, and the envelope characteristics remain constant and because the building structure has no direct impact on the energy consumption. As part of the simulations, heating, cooling and lighting demands were taken into account.

The Energy Use Intensity (EUI), expressed in kWh/m^2/y, referring to the energy required to operate and sustain the building once it is occupied, is shown in Fig. 17, divided by the heating, cooling, and lighting demand. Finally, the total annual heating energy intensity of the building is 17.7 kWh/m^2/y, i.e. 7.4 kWh/m^2/y for lighting and 18.8 kWh/m^2/y for cooling. The model only considered mechanical ventilation with heat recovery (sensible heat recovery efficiency of 70% and latent heat recovery efficiency of 50%). Further cooling energy savings could be achieved by natural ventilation in suitable weather conditions. The operational energy has been compared with similar completed buildings and particularly with the Treet tower in Bergen (NO), which has a comparable timber-based structure in similar climatic conditions.

Having calculated the operational energy demand for heating, cooling, and lighting, the final result, expressed in kWh/y, was entered into the LCA tool. Specifically, the heating demand was incorporated into the district heating system, which is becoming increasingly widespread in Denmark and is fuelled by biomass. As for the remainder (lighting and cooling demand), it was calculated based on the Danish electricity mix. Considering that the energy demand is the same for both options, the weight of operational impacts versus their embodied impacts became worthy of investigation. This was done to evaluate whether they had a greater effect on the environment than the impacts of the raw materials and energy used in their production taking into account the GWP impact. In Fig. 18, Option A accounts for 58.5% (5.8 kg – CO_2 eq./m^2/y) of the embodied impacts and 41.5% (4.1 kg – CO_2 eq./m^2/y) of the operational energy, of which around 15% is from district heating (for both options). Option B accounts for 53.1% (4.7 kg – CO_2

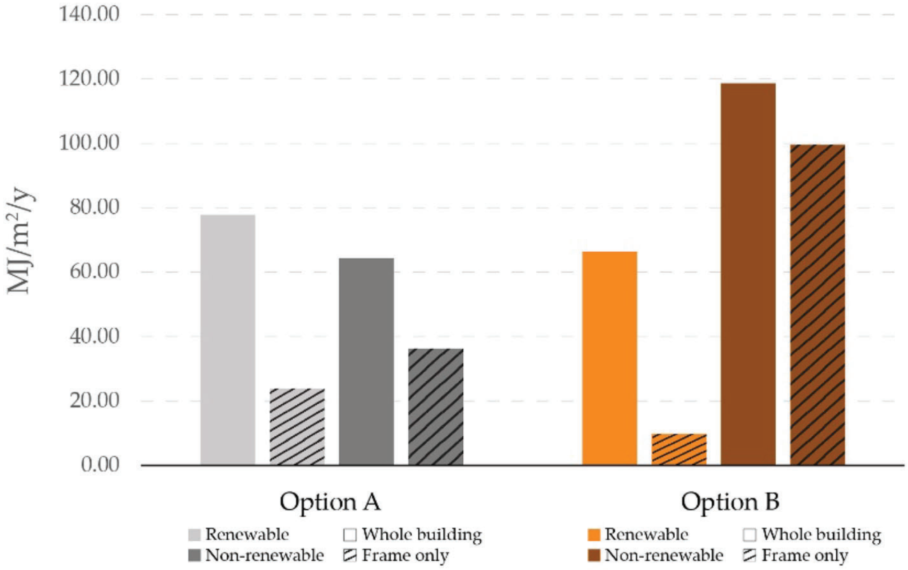


Fig. 16. Embodied impacts in terms of the use of primary energy.

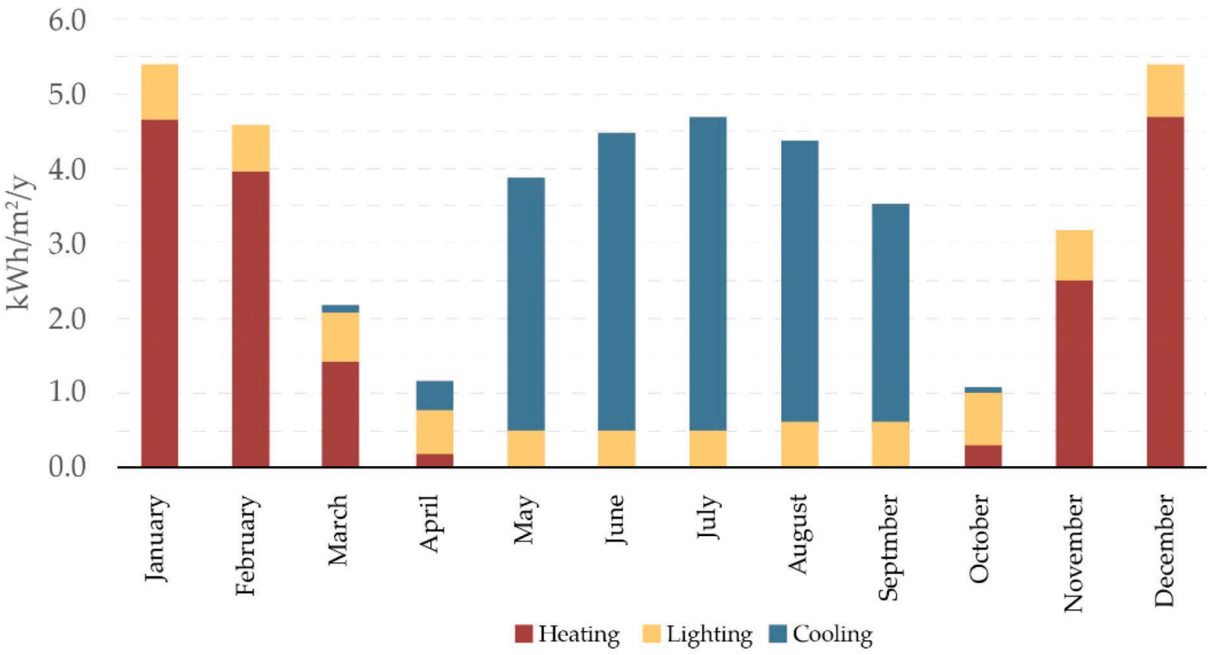


Fig. 17. EUI, expressed in kWh/m^2/y, calculated for each month for the case study.

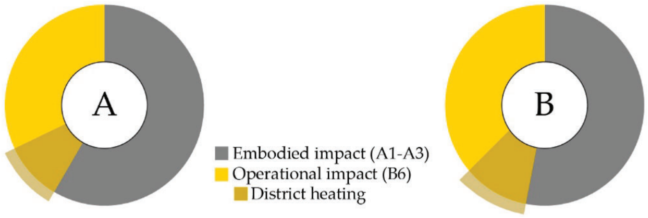


Fig. 18. Embodied impacts against operational impacts in terms of GWP (kg – CO_2 eq.).

eq./m^2/y) of the embodied impacts and 46.9% (4.1 kg – CO_2 eq./m^2/y) of the operational energy (considering that the operational energy is the same for both variants).

3.4. End-of-Life (C stages)

As part of the end-of-life stage, the following modules were included: waste transportation to a processing facility (C2), and waste processing for reuse, recovery, and recycling (C3). For both options, the total impact is very low, respectively 1.3% on the total CO_2 emissions or 0.15 kg – CO_2 eq./m^2/y for Option A, and 1.7% or 0.16 kg – kg – CO_2 eq./m^2/y for Option B. Among all (C) modules, all materials and transportation, as well as products and their associated energy and water consumption, are aggregated as one. Hence, taking into account, for example, the main materials used in the two scenarios, in Option A, the concrete would be crushed to aggregate, and the steel reinforcement bars would be transported to a landfill, whereas in Option B, the CLT panels would be reused as a material. Disassembly, adaptation, and reuse of Option B (CLT) is the best disposal option at the end of its potential service life. However, in this study, the end-of-life stage impacts are considered marginal compared to the embodied and operational ones.

4. Conclusion

An analysis of sustainable residential tower construction has been presented in this article with regard to BIM-LCA integration during the early stages of design. For a single residential tower in Aalborg (DK), two different building structural frame types, one traditional RC structure (Option A) and one CLT structure (Option B), were compared in terms of their environmental impact, assuming a service life of 50 years and the building's envelope and its energy performance to be the same in both scenarios. For the purposes of evaluating the environmental impact of the building materials of both variants, a BIM software, Autodesk Revit, was employed to calculate the BoQ. DesignStudio was used to simulate the operational energy demands for heating, cooling and lighting. Life cycle assessment, normalisation, and weightings achieved through One Click LCA were used to compare the environmental impacts. The cradle-to-grave evaluation aimed to reflect the impact of each structural frame type on the overall building impact.

Not surprisingly, the results of the study demonstrate that the traditional Option A has a greater environmental impact than Option B, primarily in terms of embodied emissions (production phase) due to the large amount of concrete and reinforcement bars that were produced. However, the scope of the study included focusing on evaluating the contributions and role of the different parts of the building when alternative solutions are under investigation. Therefore, the point is not the result itself, but rather the outcomes of the proposed methodology that can be used as objective elements on the basis of which to discuss the advantages or disadvantages of certain design decisions.

The operating energy was considered to be the same for both options since the main difference between them was the structure, which does not directly affect the energy performance as an envelope would. This study emphasized the embodied and operational effects of the product over the end-of-life stage.

The ever-increasing diffusion of timber-based solutions as a consequence of more sustainable and energy-efficient approaches requires a wider set of assumptions, requirements and performance targets to be taken into account when design concepts and decisions are explored. Awareness of the differences between building typologies is required, while pre-defined positions should not be taken about the supposed effectiveness. This has to be discussed according to scientifically oriented methods and evidence-based outcomes.

In the rush to timber mass high rise, the sections of hyperstructures and the profiles may become so large to become uneconomical or may impact the floor surface usability to compromise the architectural and functional brief.

The study presented here does not provide a definitive answer on how to choose the most appropriate solutions but adds a step forward by including some useful indicators and data – among the many other criteria – in support of strategic decision-making at an early design stage in the design process.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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