A BIM-based Framework for Quantifying Embodied Emissions from MEP Systems in Building Life Cycle Assessments

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Abstract. Embodied emissions from Mechanical, Electrical, and Plumbing systems (MEP) in buildings contribute substantially to the carbon footprint of buildings. Because of lack of standardized methods, reliable data, and environmental product declarations (EPD), MEP systems have typically been excluded from Life Cycle Assessments (LCAs). With increasing emission reduction efforts for other building components, the share of embodied emissions for MEP will rise if not focused on. This research fills the gap by introducing a comprehensive framework for quantifying embodied emissions for Mechanical and plumbing systems (MP). Our approach includes three main components: a BIM based embodied emissions calculation methodology, an EPD database, and guidelines for estimating emissions in data gaps. Seamless integration into the building information model (BIM) tool Revit, allows MEP designers to access real-time emissions data and engage in iterative design for reduced carbon footprint. Testing of the framework on a building in the design-stage indicates that emissions from replacement of components can constitute up to 50% of total material emissions for MP during the calculation period, that the emissions from MP can be in the order of 8-20 % of the total emissions from material use in a new office building and that ventilation, heating and fire suppression constitute the largest contribution to the total. Optimization of MP-solutions appears to offer substantial emission reduction.

1 Introduction

Mechanical, Electrical, and Plumbing systems (MEP) are substantial contributors to greenhouse gas emissions within the context of building construction and operation. Despite their considerable environmental impact, MEP systems have often been omitted from comprehensive sustainability assessments. This omission is likely largely due to the lack of a structured approach for quantifying their embodied emissions, the scarcity of reliable data regarding the environmental performance of MEP components, and the absence of specialized Environmental Product Declarations (EPDs) for these systems.

As global efforts intensify to reduce emissions across all facets of construction and building operation, the relative significance of embodied emissions associated with MEP systems will grow, unless focused on. Therefore, there is a growing urgency to establish a systematic methodology for evaluating and mitigating the environmental impact of MEP systems.

In response to this imperative, our research endeavors to provide a thorough framework for the assessment and reduction of embodied emissions linked to Mechanical and Plumbing

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systems (MP) i.e., not including electricity commonly included in the MEP definition. While previous studies have highlighted the importance of addressing MEP-related emissions, our work distinguishes itself by introducing a comprehensive and methodical approach. This framework encompasses three essential components; a structured methodology for the calculation of embodied emissions from MEP, a curated EPD database to address the data gap specific to MP components, and guidelines for estimation when specific data is lacking, enabling a more holistic assessment.

To make this framework practical and accessible for building design processes, we have seamlessly integrated it into the Building Information Modelling (BIM) tool Revit [1]. This integration empowers MP designers to access real-time information on embodied emissions and engage in iterative design processes, e.g., through system design choices, aimed at reducing the carbon footprint associated with MP.

It is our aim to address a critical knowledge gap in the field of sustainable building design by providing a systematic framework for assessing and mitigating embodied emissions from MP. And to empower designers to make informed decisions that can lead to substantial reductions in carbon emissions associated with MP.

2 Related studies

The environmental impact of buildings is normally assessed through the framework of Life cycle analysis. Life cycle analysis, often referred to as life cycle analysis (LCA), is a systematic method for evaluating the environmental and social impacts of a product, process, or service throughout its entire life cycle, from resource extraction to disposal. It quantifies various factors such as energy use, emissions, and resource consumption to help assess and improve the sustainability of a product or system. While there is increasing interest in the application of LCA on buildings, most studies focus on structural elements of buildings and relatively few studies have included parts of or entire MEP or other technical installations in the scope of analysis.

According to a review on LCAs conducted on buildings in Norway from 2009-2020 only 7 % of the examined analysis included parts of MEP [2]. Where MEP systems were included in the scope of analysis there was strong indication that the material components and products of these systems contribute significantly to the carbon footprint of buildings. Furthermore, as operational emissions are likely to decrease with improved operational energy performance, embodied GHG emissions, including those associated with MEP, become more important to both the relative and absolute carbon footprint of buildings [3]. Research into the embodied carbon of MEP can therefore highlight areas where optimizations in materials and/or solutions could be effective in reducing the overall carbon impact of buildings. Several such case studies have conducted analysis on the carbon footprint of MEP.

Kiamili et al. [4] conducted a detailed assessment of embodied emissions in heating, ventilation, and air conditioning systems in a Swiss office building using a BIM model and calculated the embodied carbon footprint of the systems to be 79 kg CO_2-eq/m^2 (A1-A3) and 102 kg CO_2-eq/m^2 (B4). Compared to the total embodied emissions for office buildings in Switzerland, this constitutes between 15% and 36%. A key finding in the study is that component replacements have a significant impact on the overall embodied emissions. This is supported by Hoxha et al [5] who found that technical and electrical equipment represented 18 and 19 % respectively of embodied carbon in research and office facility. Similar numbers have been found in a Swedish case study on an office building based on site specific data [6], while a Norwegian master thesis found that technical installations including solar panels represented 46 % of embodied carbon in an office building in Norway [7].

Previous research indicates that MEP systems contribute significantly to the embodied carbon footprint of buildings. While the methodology for the assessment of the environmental performance of buildings has been standardized (e.g., EN 15978 [8]), methodological decisions regarding assessment scope of included building parts and life cycle stages covered vary significantly. This makes interpretation and comparisons of results challenging. Clearer methodological guidelines and standardized documentation requirements are therefore needed.

3 Methodology

3.1 Extracting relevant MP data from BIM

Current MP Building Information Modelling (BIM) standards feature models with intricate levels of detail, typically including nearly all components in the systems. This in theory provides an opportunity to compute the embodied emissions associated with each individual component, provided that the BIM object has the necessary information. MP BIM models commonly encompass a substantial number of components, averaging between 17,000 to 20,000 for a midsized building, based on our empirical assessments. Each component represents the geometric and parametric attributes of its real-world counterpart. However, the precision of the representation is varying.

Regrettably, data on the embodied carbon emissions for these components are generally absent. Also, parameters such as weight and material composition are often absent, making it difficult to effectively calculate emissions. Moreover, the absence of unique identifiers like the Global Trade Item Number (GTIN) [9] for components poses a significant hurdle in establishing a standardized approach for their identification, adding complexity to the carbon emission computation process.

However, the nomenclature or type-name of a component tends to remain consistent, within the framework of each MEP BIM tool e.g., MagiCAD Connect [10] within Revit [1]. These can be leveraged to construct a database with the information needed for computing the embodied carbon emissions of the system or other relevant factors such as weight or GTIN. Although plausible, this methodology is challenging due to the many variations in sizes within each type, necessitating a comprehensive database addressing each variation.

Manual input of each component in the database per variation in the model is a labor-intensive task. Leveraging the Revit application programming interface (API) facilitates the development of custom code capable of individually modifying specific parameters of each component. Iteratively accessing and aligning the parameters of each component with the database enables the computation of carbon emissions associated with every component in the model. Notably, a database entry is necessary for a match; absence thereof results in an unassigned value.

Assigning specific carbon emission values to each component and visualizing variations in the model empowers users to identify high-emission contributors, thereby enabling informed decision-making, regarding optimalization and which components have negligible impact on total emissions. In Norway it is customary to assign 2-3 digit code to each component, according to the structure given in NS 3451:2020 *Table of building elements and table codes for systems in buildings with associated outdoor areas*, streamlining sorting processes within user interfaces and programs [11].

Our add-in aggregates three distinct metrics—length, cubic meters, and number of pieces—to quantify components. Length quantifies pipes and ducts, volume encapsulates insulation, and number of pieces counts most other MP components. Notably, certain duct and pipe parts such as fittings that have overlapping components e.g., elbows, often lack accurate geometry. To circumvent this each connection of pipe fittings and ducts is evaluated and translated into an equivalent length of the connected pipe/duct.

The result of this process is a comprehensive list of unique components within the model and their respective quantities. These lists, typically comprising 200 to 400 unique components per project, are then the basis for calculation of environmental parameters.

3.2 Environmental data for components

The analysis of the carbon footprint of MP in buildings require the identification and application of emission factors for components in the systems. Environmental data are typically available through EPDs accessed via EPD program operators, through specialized LCA software, or even from suppliers' own websites. A lack of EPDs for technical components requires the application of proxy-data, allowing for the analysis of all or most components and closing data gaps but reducing the accuracy of the calculations. As an increasing volume of EPDs for technical components become available, this problem will probably be reduced over time. To track the use of product-specific EPDs and proxy-data a numeric data quality indicator (DQ 1-3) is applied where:

- DQ 1 represent a product specific EPD that is used for its actual component in the model.
- DQ 2 represents the use of a product specific EPD that is used as proxy for a similar but not identical component in the model.
- DQ 3 represents the use of a generic emission factor for a material (e.g., galvanized steel).

The environmental data in our database therefore consist of a conglomerate of data, where some products are very specifically represented based on an EPD for that specific product, others on similar products that have EPDs that we have evaluated to have similar environmental impact based on both qualitative and quantitative factors, and lastly data that is generic where we have curated a list of generic data from EPDs that is suitable for use in Norway. We have endeavored to uphold the utmost quality in all procedures. However, the absence of product-specific data inevitably imposes an element of error into the assessment.

The embodied carbon of technical installations is distributed (unevenly) across the products life cycle stages from initial raw material extraction and product manufacturing (A1-A3), transportation from manufacturing site to construction site (A4), installation (A5), use stage (B1-B5) and the end-of-life stage (C1-C4). While calculated emissions in life cycle stages A1-A3 and C1-C4 are mandatory under EN 15804+A2, emissions in other life cycle stages (e.g., A4, B4) can contribute significantly to components overall embodied carbon. Through using specialized LCA-software like One Click LCA it is possible to calculate the embodied emissions from the complete life cycle (cradle-to-grave) using assumptions about transport distances and the components service life in the building.

MP components from BIM are paired with emission factors using the data quality principles outlined above. An emissions factor database is thus constructed, and the factors are retrieved by the add-in to Revit described below.

The workflow for constructing the EPD database following the steps described above is illustrated on figure 1.

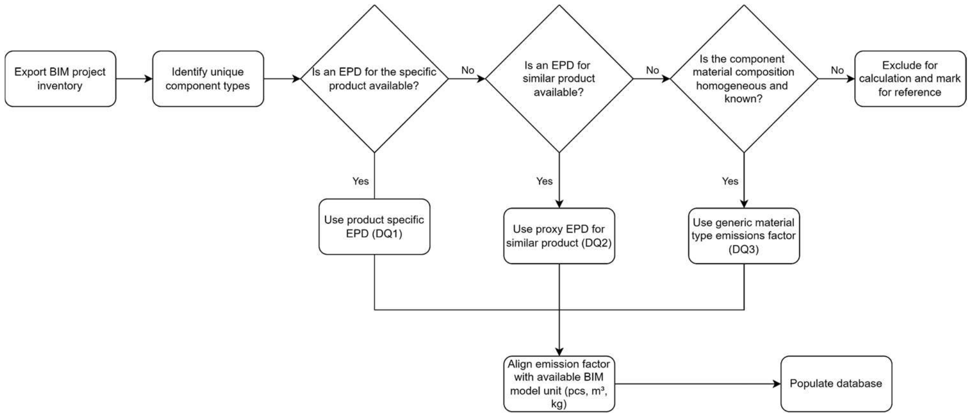

Fig. 1. The workflow for constructing an EPD-database for the BIM workflow, including assigning quality classes (DQ 1-3), and aligning emission factors with BIM units.

3.3 The tool itself

The methodology for extracting data from BIM models, searching for each component in the EPD database, determining component type and assigning emission values is implemented in an addon to Revit. The workflow within the app itself is found on figure 2.

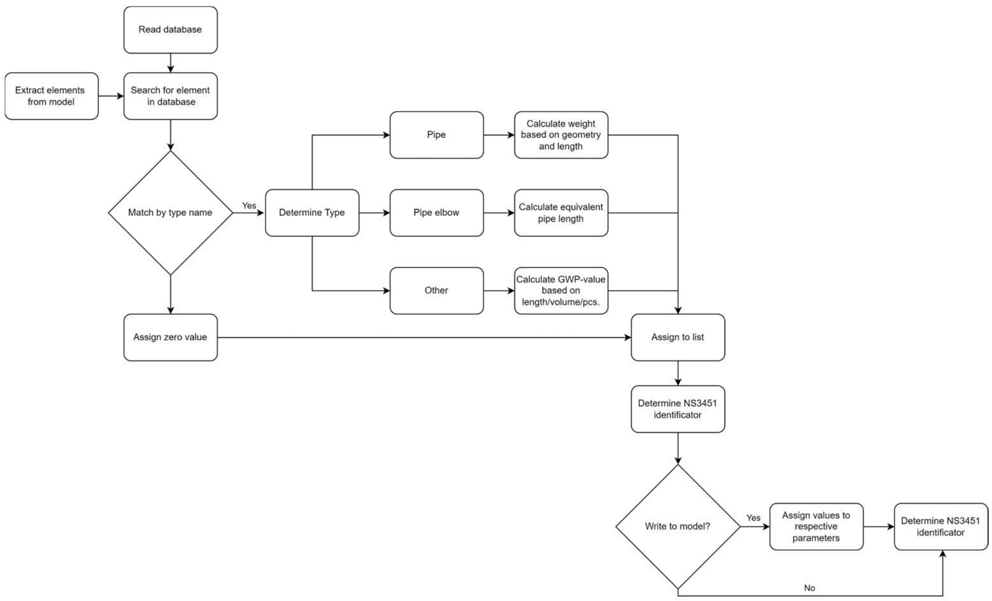

Fig. 2. The workflow within the add-in.

The addon is meant to be used by MP designers, with no prior experience with environmental calculations. Thus, facilitating outsourcing of the environmental optimalisation of MP systems to the MP consultant, which is best positioned to evaluate possibilities and consequences of changes made. To lower the threshold of use the tool has an easy-to-understand graphical user interface (GUI), for each step of the process. An example of the GUI, in Norwegian, is shown in figure 3.

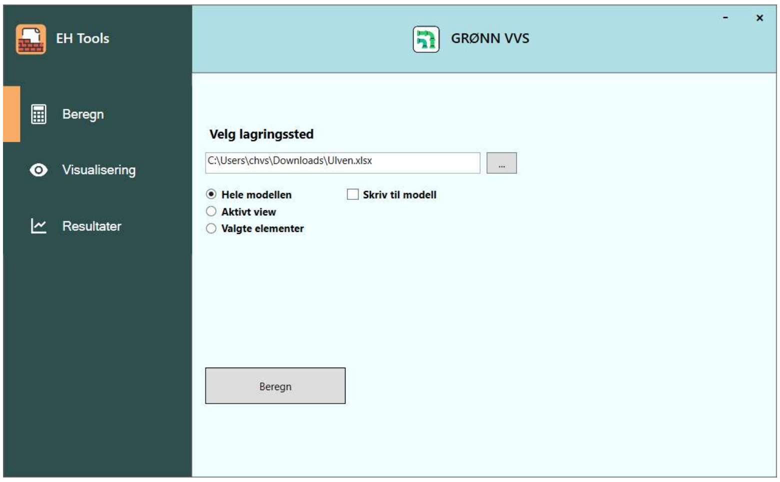

Fig. 3. Graphical interface in the tool.

At the end of the workflow in figure 2, the user can choose to export the results as a report or assign values to BIM objects in the model. The exporting of report is typically used when one wants to post process the data for visualization or presentation of the result. While the option of assigning values to BIM objects, enables the user to work visually with emissions in the model. Figure 4 illustrates an interface where BIM objects are colored according to their emissions.

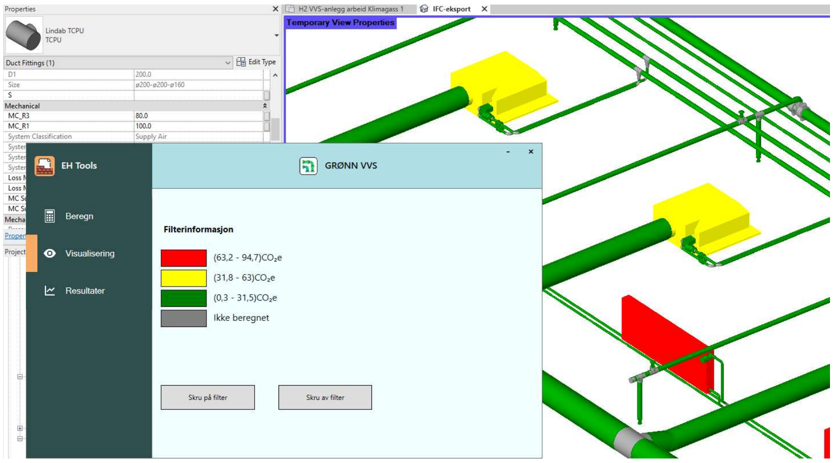

Fig. 4 Graphical interface of the emissions class visualization per object in the BIM model.

4 Further development

Enhancing the add-in to perform calculations on a broad range of buildings is vital. As the calculation of embodied carbon emissions depends on the component's presence in the database, expanding the database remains a necessary ongoing task. With each project calculated requiring an addition of approximately 300-1000 unique components to the database, this manual update process is a recognized limitation. We are exploring various solutions, including allowing the tool to source data on components from other resources.

At present, we lack a precise method to determine the percentage of elements calculated, as there are no readily available parameters for evaluation. The current assessment quality measure, checking the percentage of computed components, can be deceiving. Some components, like the HVAC unit, might be critical regardless of their count, while others may not have significant impact irrespective of their quantity. Currently, we manually ensure all crucial components are evaluated in each case, a process that demands expertise and time. Hence, there's a need to explore a more accurate representation of hits, perhaps based on each component's volume.

Another avenue worth exploring is to utilize the components' geometric representation to a greater degree. This could enable the calculation of a component's weight without requiring an exact match in the database, by approximating it based on similar components already in the database.

Addressing these challenges necessitates further work, and we aim to concentrate on these aspects in our forthcoming endeavors.

5 Case

To showcase the tool, a BIM model of an office landscape in an office building in Oslo has been modelled. The model consists of five different air conditioning and heating options, the climatization principles are shown in Table 1. Case alternatives analyzed using the tool.

All configurations have the same fire sprinkler protection system, and indoor climate calculations have been performed to ensure that the function unit i.e., a m^2 of climatized office, is the same. All alternatives are modelled in the BIM software Revit with the MEP specific addon MagiCAD. A 2D representation of the models is shown in figure 5.

All BIM components in the models are included in the database, and the add-in therefore succeeds in calculating 100 % of the components. A calculation that outputs only a report takes 2 seconds, while a calculation that writes the result back to the BIM objects in the model takes 8.5 seconds. Although this is a relatively small model with only 1231 components, we consider this a satisfactory result for this early phase of design.

Table 1. Case alternatives analyzed using the tool.

Nomenclature	Description of the climatization concepts
A	Comfort modules for cooling and waterborne radiators for heating
B	Comfort modules for cooling and heating
C	Displacement ventilation and waterborne radiators
D	Active air diffusors and TABS
E	Active air diffusors and local electric heating

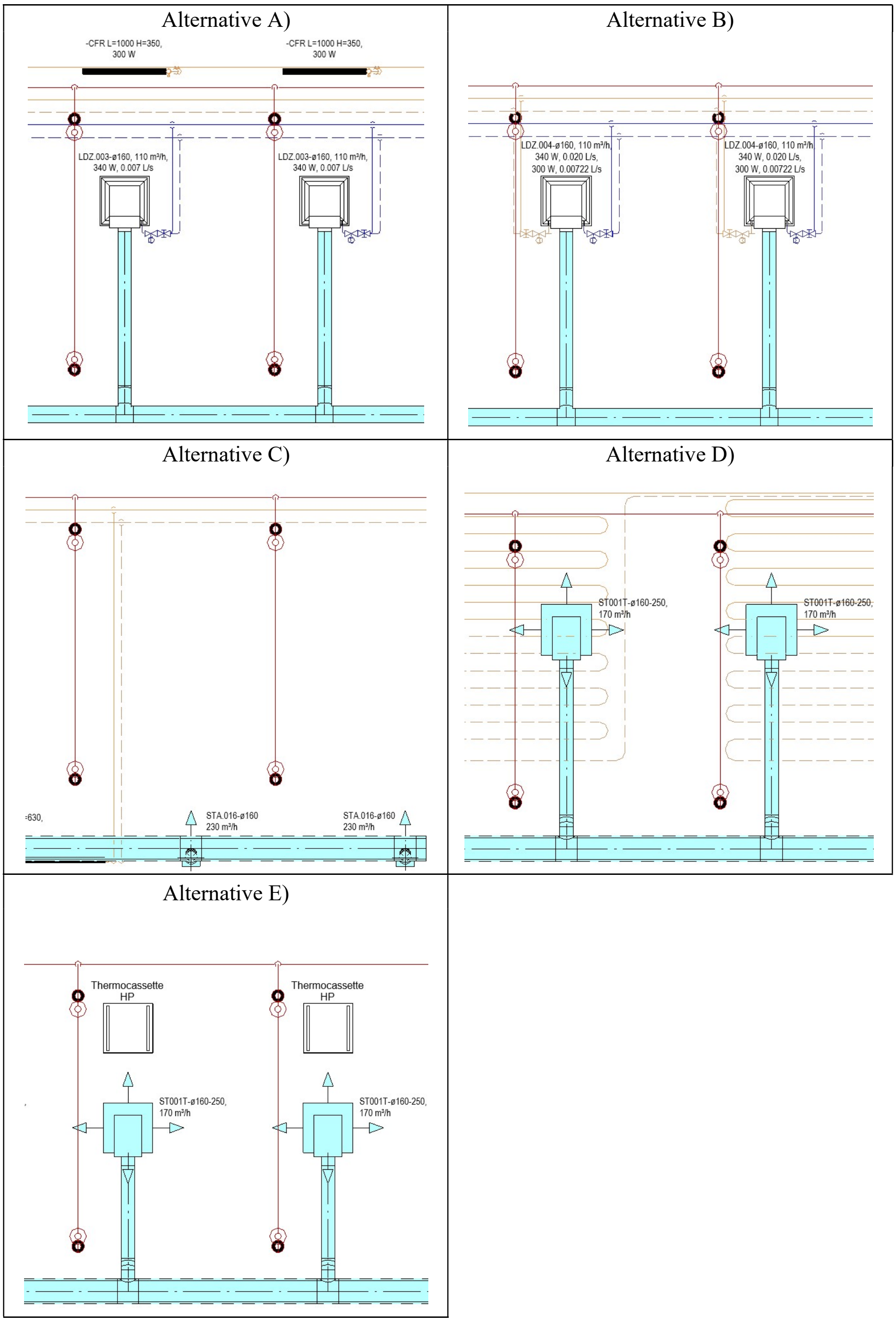

Fig. 5 Geometry of the cases studied. See table 1 for description of the alternatives.

6 Results

The embodied carbon emissions from material use throughout the calculated lifetime for the alternatives studied is shown in figure 6. Emissions in the figure are presented for each MP-system; Heating, Ventilation, Fire suppression and Cooling.

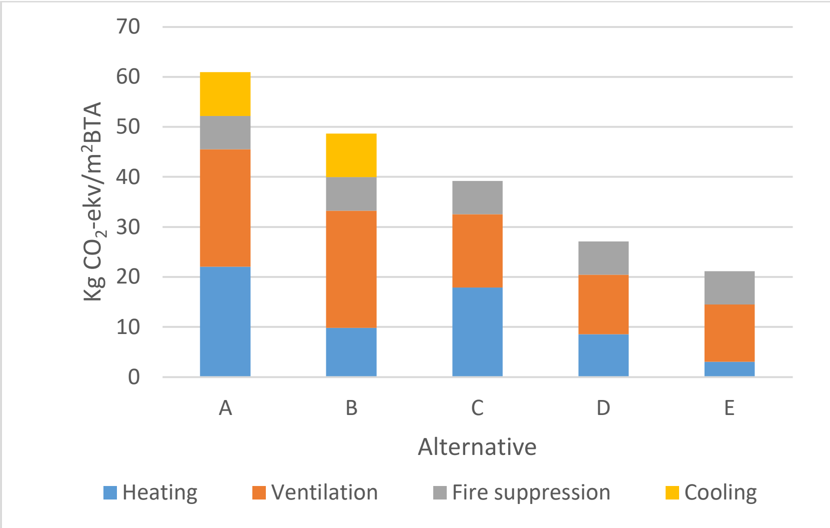

Fig. 6 Embodied emissions (A1-A3, A4, A5, B4, C2-C4) by alternatives studied over a calculation period of 50 years. The results are presented for each MP-system; Heating, Ventilation, Fire suppression and Cooling.

Emissions were calculated over a time period of 50 years. Embodied emissions by life cycle module including replacement and end-of-life (A-C according to [8]) are shown in figure 7. Embodied emissions from replacement of components contribute significantly to overall embodied emissions for all evaluated systems indicating that the service life of materials is a crucial factor for embodied emissions from MP in buildings. While embodied emissions in structural building parts were not assessed in this case-study, embodied emissions (A1-A3+B4) for MP constitutes between 8-20 % of embodied emissions of structural building elements in office buildings found in a large Norwegian meta-analysis [2].

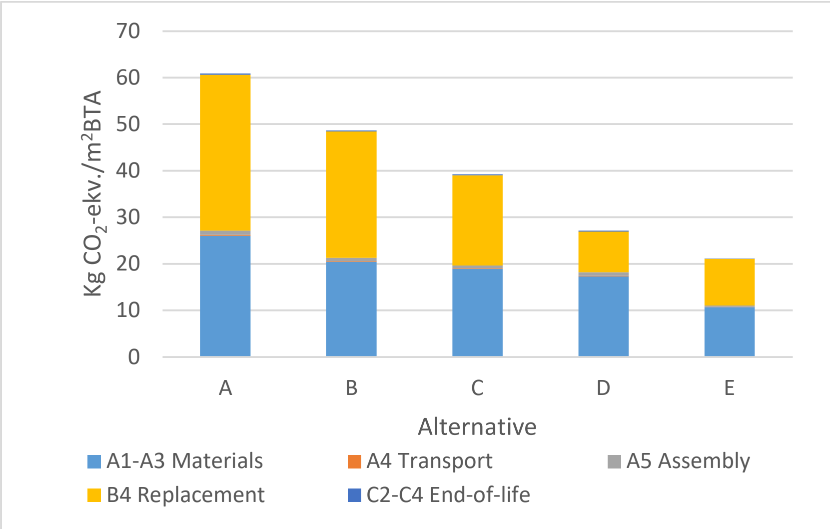

Fig. 7 Embodied emissions by life cycle module and alternatives studied over a calculation period of 50 years.

7 Discussion

The main objective of this article is to describe a methodology for calculating the emissions from MP, despite the general lack of EPD data, and a total lack of BIM models that include the necessary information for the calculation.

The methodology for mapping MP components and compiling a database with emission factors that can handle varying degrees of data quality is described. A database with approximately 250 data points has been established using EPD-data and proxy-data. The use of proxy-data for components in lieu of product-specific EPDs is a short-term solution to close data gaps while there is a substantial lack of EPD-data for MP components. It also allows for early-stage calculations where specific products have not been chosen and are therefore unknown.

The BIM models themselves, generally represent geometry with an acceptable precision. But there are some exceptions, especially for components with overlapping features i.e., piping & ducts. The quantification of these components is converted from number of pieces to equivalent length of pipe/duct, using conversion factors that are custom made for each type of system and component. This is a necessary workaround due to lack of specific EPD-data and insufficient geometry quality.

To showcase the methodology implemented in an addon to the BIM-toolset, the addon is successfully tested on five different alternative climatization methods for a small landscape office. The main takeaways for the systems themselves are:

- The main sources of embodied emissions in all cases are ventilation, heating, and fire suppression systems.
- Case E that uses airborne cooling and heating, has the lowest embodied emissions, indicating a potential for similar solutions.
- Comparison of the alternatives indicate that substantial reduction of emissions can be achieved by choosing low emitting alternatives, and without compromising the defined function.

- It is plausible that further reductions can be achieved through additional optimizations, such as replacing materials like galvanized steel in piping with materials with lower impact.
- A substantial proportion, in the order of magnitude 33-50 % of the emissions are due to the replacement of components during the calculation period. This emphasizes the importance of increasing the lifetime data quality, and that improving lifetime of components can have a large positive impact.

The area studied in this case is a small portion of a building, and the total emissions can therefor vary substantially with result from a whole building analysis. Yet the case indicates that there might also be significant differences between solutions for a whole building. Comparing the calculated emissions for the systems with the median emissions from meta-analysis of office buildings in Norway of 250 kg/CO2-eq/m^2, indicates that the emissions from MP can be in the order of 8-20 % of the total emissions from material use in a new office building depending on solutions [2].

Calculation of emissions from MEP systems in general is a young engineering field, where this study represents both a state-of-the-art and a hands-on approach. Our work shows that there is a lot to learn from these early results, and much more information will be gathered by applying the methodology in future projects.

8 Conclusion

The significance of embodied emissions from Mechanical, Electrical, and Plumbing systems in the construction industry's carbon footprint appears to be evident. These emissions, although substantial, have long been overlooked in sustainability assessments due to the lack of structured methodologies, reliable data, and Environmental Product Declarations (EPDs) tailored to MEP systems. However, in a world increasingly focused on mitigating emissions across all building components, the proportional impact of MEP-related embodied emissions is poised to grow.

Our research contributes to fill a critical gap in the field by introducing a comprehensive framework for quantifying and mitigating embodied emissions from Mechanical and Pumping systems. Offering a systematic approach that encompasses three key elements: a structured methodology for calculating embodied emissions, a database of available EPD data, and guidelines for estimating emissions when data is unavailable.

Moreover, our commitment to practicality has led us to seamlessly integrate this framework into the widely used Building Information Modeling (BIM) tool, Revit. This innovation empowers MP designers to access real-time information about embodied emissions, enabling them to make informed decisions and engage in iterative design processes aimed at reducing their projects' carbon footprint.

The results from our extensive testing across multiple building projects have illuminated a startling reality: emissions from MP equipment replacement can constitute in the order of 50% of total material emissions during the calculation period, that emissions from ventilation, heating and fire suppression systems are the dominant emission, and that optimization appears to offer substantial potential without compromising indoor climate quality significantly. This underscores the urgency of including MP systems in Life Cycle Assessments (LCAs), as their impact reverberates throughout a building's overall environmental profile.

In summary, our research has addressed a critical knowledge gap within the realm of sustainable building design by providing a systematic framework for assessing and mitigating embodied emissions from MP systems. By seamlessly integrating this framework into widely used BIM tools like Revit, we empower MEP designers to make informed decisions that yield substantial reductions in carbon emissions associated with building construction and renovation. This approach represents a pivotal stride toward achieving more sustainable and environmentally responsible building practices, a matter of paramount importance as we confront the growing concerns of climate change.

Acknowledgement

This work was supported by the project: *Helhetlig vurdering av miljøpåvirkning av VVS-installasjoner i bygg – Grønn VVS* financed by The Research Council of Norway (project nr. 327867). The partner group includes a variety of industry partners from the Scandinavian Building industry as well as representatives of NMBU and OsloMET.

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