An LCA Framework to Prioritize Carbon-Sensitive Measures in Residential Building Design

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Abstract
Building design involves numerous trade-offs between several design objectives that span multiple aspects with diverse effects on building subsystems. Hence, low-carbon building design requires a comprehensive understanding of varied factors and their range of impact on building emissions throughout the building life cycle. Previous research often focuses on one building component at a time. This research devises an LCA framework that provides a holistic overview of all building subsystems in the Whole Building Life Cycle Assessment. The methodology integrates a sensitivity analysis entailing conventional material selection and construction details for the building envelope, the heating/cooling system and the structure of the building. The methodology is demonstrated for a midrise residential building in the city of Vancouver. Results indicate that certain timber buildings both in structure and envelope have the lowest environmental impact and heat pumps are the most effective heating systems to provide comfort with the lowest whole building emissions.

Keywords: Sensitivity Analysis, Life cycle Assessment, Embodied emissions, Low-carbon building design.

1. Introduction
Climate change has intensified over the past decades and has turned into a threat to human life. Special attention has been placed on greenhouse gases (GHGs) since their accumulation in the atmosphere is the primary cause of climate change. In British Columbia, policies are set to cut greenhouse gas emissions by 40 percent by 2030 and to net-zero by 2050 (Toronto & Dulmage, 2018). AEC (Architecture, Engineering, and Construction) makes up to 25% of national emissions, therefore, construction and operation of buildings is an important contributor to global GHG emissions (Torabi & Mahdavinejad, 2021). In the field of low-carbon building design, building operations have historically been the largest contributor to GHG emissions; however, embodied emissions (EE) have been gaining in importance in recent years. This is mainly due to reductions in operational emissions (OE) achieved through the decrease in the carbon intensity of electricity and improvements in building energy systems. In British Columbia, the share of EE and OE in building whole life cycle emissions are roughly equal. EE has received scant attention in the research community as the top priority has been operational energy, therefore, there is a huge potential to mitigate buildings emissions by tackling EE, and it is growing to be more and more important (Engineering Net Zero, 2021.; Toronto & Dulmage, 2018).

In this study, firstly, the impact of building subsystems on EE is investigated. Secondly, as a building is defined as a system, changes in each component would impact other subsystems and result in the overall efficiency of the building. Therefore, no design decision can be evaluated correctly unless the impact on energy demands and building occupants is investigated. In this study, the most important contributor of building carbon footprint is investigated considering scenarios for structural and envelope design and heating options.

2. Background
Life Cycle Assessment (LCA) of buildings is a fast-growing research area with a number of publications that have more than doubled in recent years (Jusselme et al., 2020; Torabi et al., 2022). Historically OE was considered the most influential part of building emissions and consequently the research focus was drawn to tackling OE. In recent years however, with advances in in renewable energy extraction, efficient buildings and decarbonized energy sources, OE has been controlled significantly. This has results to steering attention towards the impact of EE in cutting whole building emissions, as there is huge potential in this overlooked issue.

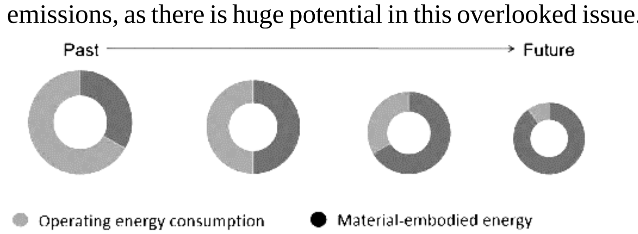

Figure 1- trend in life cycle energy/carbon in buildings from (Embodied Carbon in Construction, 2017)

Previous research shed light on the carbon footprint of a single components of the building individually. They have conducted an in-depth analysis of EE through variables in a subsystem. For example, to investigate EE of structure, DeWolf in a comprehensive study calculated structural emissions associated with different building archetypes. In her calculation, she considered different structural systems and materials according to local constructions. She also has reported the level of uncertainty associated with structural design in whole building emissions (De Wolf, 2017).

Similarly, in a research Schneider et al investigated the impact of structure on building environmental impact. They concluded that exchanging reinforced concrete for a wood structure reduces total GHG emissions by 25%, which emphasizes the importance of structure on building carbon footprint(Schneider-Marin et al., 2020). Similarly, the impact of Hvac systems in building EE has been addressed. Rodriguez addressed the EE associated with heating and cooling equipment and their distribution systems with a focus on the Northwest Pacific market (Rodriguez, 2019a). Similar research has been done in other regions (Kiamili et al., 2020).

The impact of envelope in whole building emissions is also investigated in several studies. In the study carried out at the Norwegian University of Science and Technology EE in single-family house was studied. Analysis was done according to the current standards in Norway (TEK 17), using an LCA approach. The study examines various insulation types and thicknesses in search of the most effective combination for lowering the lifetime emissions of the building. The study also identifies the part of the building envelope where additional insulation is most efficient in reducing the lifetime greenhouse gas emissions of the building. This study shows that the calculated GHG emissions vary inversely proportionally with the material quantities in building envelope. (Totland et al., 2019)

Although previous research clarifies emissions resulted from subsystems of a building in detail, they neglect multi-aspect, complex and interwoven impact of subsystem on one another and on whole building emissions. In other words, the goals of these fragmented studies are not mutually independent but closely related and interplaying with each other and some of them are even in a trade-offs. Therefore, a research gap is observed in addressing whole building emissions with a holistic approach.

To address this research gap, it is important to consider the impact of components on whole building emissions as one building with low EE can have high OE which over all dimmish all savings in manufacturing and construction phase. On contrary, all savings in OE through building life span might not justify huge EE of over-insulated passive building in design and construction phase. This shows the importance of adopting whole approach to EE modeling in LCA studies.

To adopt a holistic approach to whole building emissions, the initial is to identify the priorities. This can be defined as materials or systems that contribute the most to a building's emissions. Knowing the range of carbon-intensity associated with building components can help architects and engineers manage time, effort, and cost more effectively in projects and helps them to come up with better designs for lowering building total environmental footprint.

3. Methodology

The model for this research is developed in Rhino and Grasshopper and takes local data from Environmental Product Declarations (EPD)s as input data. All input data including thermos-physical characteristics of the materials, material EE, energy grid carbon intensity, and other required information are compiled and imported in an excel-sheet which in this report is called "Source Data File".

3.1. LCA Scope

The scope of this study is cradle to gate, covering stages A1-3, B6 of the building life cycle according to EN 15978 that encompasses production, manufacturing and building operation until end of life. The functional unit to evaluate scenarios is Kg or tonnes of CO_{2eq} and the life span of the building is 60 years. Figure.1 illustrates the LCA analysis scope.

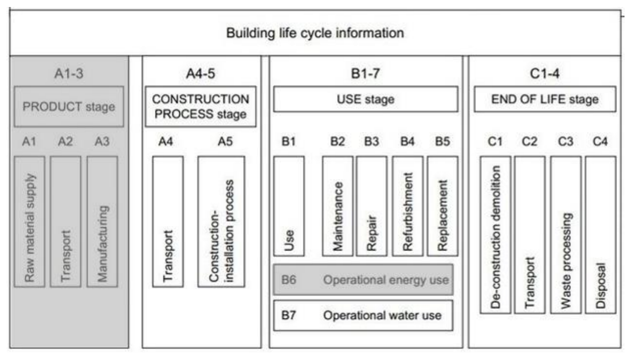

Figure 2- LCA Scope of this study from (CEN, 2011)

3.2. Modeling Framework

The model developed in this study to evaluate EE and OE is comprised of four modules to report emissions associated with building envelope, structure, heating system, operational energy consumption. As mentioned previously energy consumption and associated emissions is calculated to determine the impact of changes in building envelope and heating system on lifetime emissions. The figure below, illustrates 45 studied scenarios.

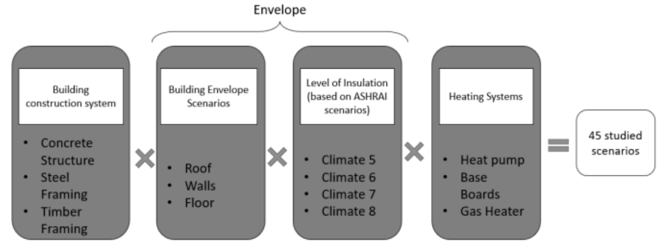

Figure 3- Scenario definition

3.2.1. Envelope

The envelope section of the model uses the construction details based on construction sets of ASHRAE 2019. The city of Vancouver is in climate 4, however, due to inclination to highly insulated buildings for new constructions in Vancouver, ASHRAE constructions from climates with higher heating demand were used for modeling in order to cover the higher level of insulation.

Table 1- Building envelope options

Envelope component	Studied ASHRAI Scenarios	Normalized EE ($KgCo_{2eq}/m^2$)
Wall	Typical Insulated Wood Framed Exterior Wall-R20	15
	Typical Insulated Exterior Mass Wall-R13	74
	Typical Insulated Metal Building Wall-R23	114
	Typical Insulated Metal Building Wall-R26	118
Roof	Typical Wood Joist Attic Floor-R48	12
	Typical IEAD Roof-R32	44
	Typical Insulated Metal Building Roof-R35	50
	Typical Insulated Metal Building Roof-R39	56
Floor	Typical Insulated Carpeted 8in Slab Floor-R5	63
	Typical Insulated Carpeted 8in Slab Floor-R8	65
	Typical Insulated Carpeted 8in Slab Floor-R10	68

3.2.2. Structure

The structure is estimated to be a concrete, steel, or wooden framing structure according to conventional structural systems in BC. In this study the result of a study on structure mass is used (Roynon, 2020). The concrete structure features in situ columns and flat slabs (400 mm), the steel option has composite decking (120 mm) with a steel frame, and the timber building uses a glulam frame with primary beams, secondary beams and CLT floors (100 mm). All designs include a concrete core and pad foundations.

The detail of structure mass for three structure systems is tabulated in Table2. The emissions were calculated using the LCI dataset (Hawkins et al., 2021; Oladazimi et al., 2020).

Table 2-Embodied energy and emissions of structural systems

Structural Material	Structure Emissions Intensity ($kgCO_{2eq}/m^2$)	EE ($MtCO_{2eq}$)
Concert	384	2.48
Steel	275	1.78
Timber	187	1.2

3.2.3. Heating system

For heating system systems, conventional heating systems were defined based on literature. To calculate the EE of heating systems, EE of equipment was calculated, as well as distribution systems (Planning, 2019). Emissions associated with equipment was calculated using the list of materials from EPDs and previous studies. Similarly, emissions for distribution system was calculated using a similar case study(Pease & Jayati Chhabra Zahra Zolfaghari Member ASHRAE, n.d.; Shah et al., 2008; Zheng et al., 2016).

Table 3- The components of the three heating and cooling systems

Heating system	Fuel consumption	Central appliances	Distribution system
Electric baseboard	Electricity	Baseboard	-
Residential Heat pump-no cooling	Electricity	Heat pump Fan coil unit	Ductwork
Gas heater	Natural Gas	Furnace	Ductwork

3.2.4. Operational Emissions

As mentioned previously, this research is focused on reducing WBLCA with a focus on EE; however, due to the significant impact of OE on WBLCA, this parameter is also simulated. To be more detailed as firstly OE comprises almost half of WBE, and secondly, it is deeply affected by the parameters forming EE, in a holistic approach to WBLCA both EE and OE should be monitored.

In this model, first model according to designated construction system, envelope and heating system is updated, then energy consumption for each scenario is calculated using EnergyPlus in honeybee. Lastly, emissions associated with energy consumption is calculated in grasshopper using carbon-intensity information provided by

BC Ministry of Environment (Ministry of Environment and climate change strategy, 2022). This information is embedded in model using "Source data file".

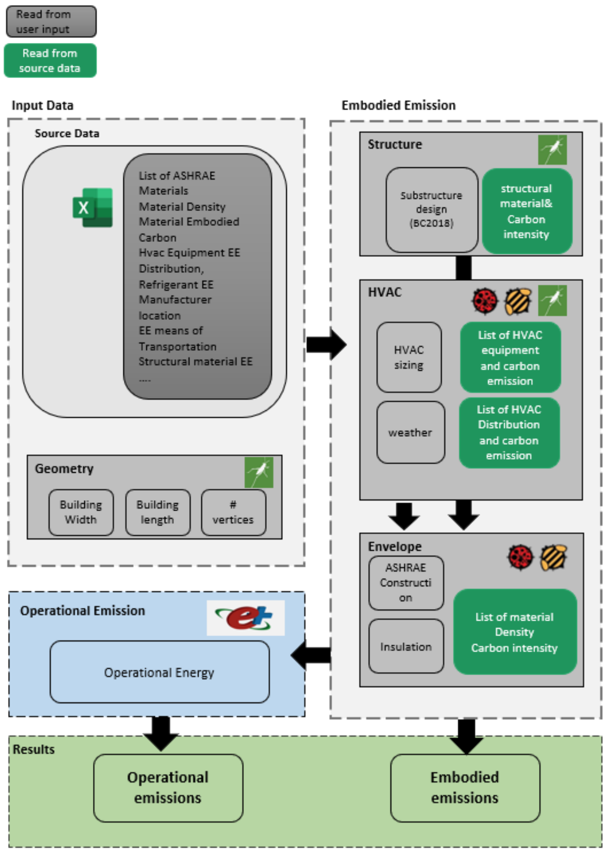

Figure 4- Modeling framework showing inputs and outputs of the four modules

The novelty of this research is mainly, in its holistic approach which aims to bridge the marked gap of disaggregated LCA studies in the literature. Outputs of this model shows the real impact of each design decision on whole life-time emissions of building which can help architects to make principal decisions in sustainable design consciously. Secondly, as this model is developed in parametric space, it can be best coupled with form finding modules in architectural software and provide accurate results on building environmental output instantly during early stages of design. Lastly, considering thermos-physical features of building in each design iteration, results of this modeling approach, shows the major carbon emitter in design alternative and shed light on next steps of back-and-forth process of design to reduce carbon footprint of the building.

3.3. Case Study

The case study building is a residential building in Vancouver. The building footprint is a 36*36 square with 4 residential units. The building enclosure has window-to-wall ratio of 20% on all facades. Building is facing south. The building has 5 storeys with spans of 9 m and an imposed loading of 5 kN/m^2 . For this building, 45 scenarios with different construction systems (defining structure and envelope layers) was modelled. Further, different level of insulation was investigated to including code minimum and better-insulated buildings. Finally, conventional gas and electricity-consuming heating systems was defined in

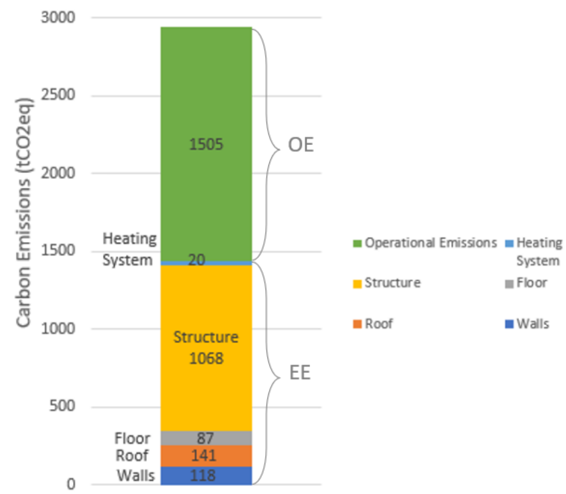

Figure 5-Average OE and EE of studied cases and main contributors

model. The EE of building was calculated and to monitor the impact of building component design on OE, energy consumption was also modelled coupling model to EnergyPlus. The EE, OE and whole building emissions is reported in Figure 8.

4. Results

British Columbia has one of the cleanest electricity grids in Canada, Therefore, the majority of buildings' carbon footprint is EE. Figure 5 illustrates the proportion of average EE versus OE for 45 studied scenarios of this study while Figure 8 shows the amount of EE and OE in each scenario. As the figure shows, due to the low carbon intensity of electricity in BC, average EE dominants OE, however, in some scenarios EE dominates OE and in some others, they share an equal share in building total emissions. It can be understood from the graphs EE associated with the structure is the main factor in building EE, which makes up for more than half of building EE. Envelope emissions is the second contributor to building EE, which is comprised of roof, wall and floor emissions. Wall EE grows to be more significant in highrise while in midrise and lowrise buildings the impact of the roof is more significant due to the high emissions of roof insulation, especially in colder climates.

4.1. Envelope and structure

Figure 8 reveals the result of carbon footprint in 45 studied scenarios in this study. As the figure shows OE in all scenarios are roughly similar with a 5% discrepancy, however, their EE can vary remarkably according to building characteristics and material selection. Buildings with concrete structures have noticeably higher EE than OE which is due to the high carbon intensity of reinforced concrete. Concrete structure buildings have also higher EE in comparison to buildings with steel and wooden framed structure. The difference between OE and EE amounts is minimum in buildings with wooden framing. Having lower EE for timber reduces buildings carbon footprint significantly.

4.2. Heating System

Figure 6 shows the energy efficiency of three studied heating systems in providing comfort conditions for the studied building. As it can be extracted from the figure, considering thermal behavior of building envelope due to varied insulation of building enclosure, scenarios with heat pumps for heating report less energy consumption and consequently lower OE. In the next place, electric baseboard and gas heater are reported with 13% and 17% increase in OE. It is worth mentioning that the ranks of heating systems in terms of EE is showing another pattern, with electric baseboards with the least EE followed by gas heaters and heat pumps with the highest EE. The reason can be found in the self-sufficiency of electric baseboards from the distribution system to convey hot fluid to the equipment, while heat pumps need distribution systems as well as transmission equipment such as fan coils that justify higher EE.

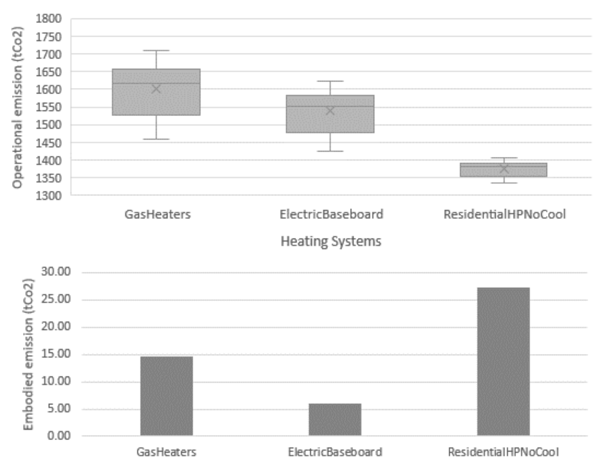

Figure 6- Comparison of Heating systems in terms of EE and OE

5. Discussion

The results of this study show the importance of structure in building carbon emissions in residential buildings. Studying the impact of structure on building EE shows that using high-carbon-intensity structural material can increase building emissions by up to 53%. Comparing the total emissions of the scenarios reveals that, timber framed structure not only provides a stable structure with lower emissions, due to high thermal resistance of wood, but these buildings also have better thermal performance and report lower energy consumption and OE. The results of this study show that wooden structures can be a good option for midrise residential buildings.

Similarly, envelope design and material selection play a significant role in building total emissions. Among the factors of the building envelope, walls and roof make up a noticeable portion of envelope emissions, which shows the priorities of building detailed envelope design in low carbon design to architects and engineers.

In terms of heating system, the scenarios show that electricity and gas consuming equipment and required distribution systems makes up 8% of EE. This amount might be significant using refrigerant based equipments and should be furthered investigated according to heating and cooling systems of the project. The comparison of EE and OE buildings according to heating systems shows that although heat pumps have remarkable higher EE in comparison to other options, due to its energy efficiency and lower OE it is the best option for residential heating system among studied scenarios.

Verification of results

In LCA studies, results cannot be evaluated using real data as real time emissions measurements are not possible. To be more detailed, as emissions factors for building material and equipment result from a chain of processes both within and outside construction project, it cannot be modelled in real condition (Ao et al., n.d.; Ciroth & Becker, 2006; Laurent et al., 2020).

Therefore researchers must verify results by first assuring the accuracy of model and calculations and then by using the results of similar studies for comparison. Therefore, to make the most reliable results of model, the calculations and outputs of modules where controlled separately and in conjunction. Secondly, the result of this study were compared to similar previous studies, each of which investigated EE of a single subsystem of the building (de Wolf, 2014; Hollberg et al., 2016; Rodriguez, 2019b). The results show good compliance to similar studies and therefore can be reliable for estimating carbon footprints of residential buildings in city of Vancouver and similar regions. The calculations for OE and EE are checked separately for correctness. The results can be checked in different layers, according to their objective and subject:

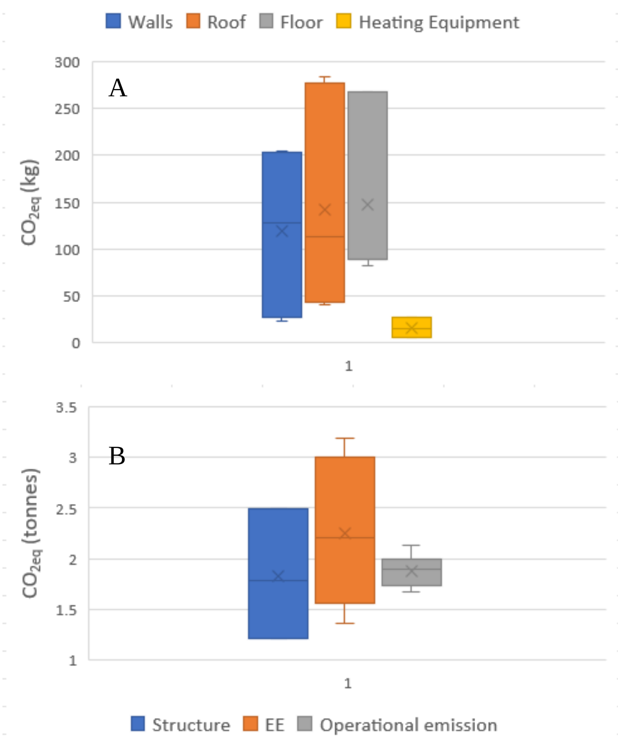

Figure 7-A) Deviation in EE of Envelope components and Heating systems. B) Deviation in EE of structure, EE, and OE in studied scenarios

6. Conclusions

In reducing building emissions through design, architects and engineers need to know the main contributors to dedicate time and effort to better decisions in those sections. Due to uncertainty in design and construction, there might always be changes. However, managing building emissions could be conducted easier and more effectively by determining the priorities in building emissions and the range of influence of each subsystem.

The result of this study reveals information on EE and OE of feasible construction scenarios for a typical residential building in Vancouver. The dependent variables are building structure options, envelope design, and conventional heating systems. The results show that with the benefit of low carbon energy use in BC, today EE is more important than before. Also, the structure is identified the most significant impact on building emissions and the lowest design solution for this case study is wooden frames building with the highest insulation and heat pump heating system. Total emissions can be increased to 53% in the scenario with concrete structure, lowest insulation, and gas heater.

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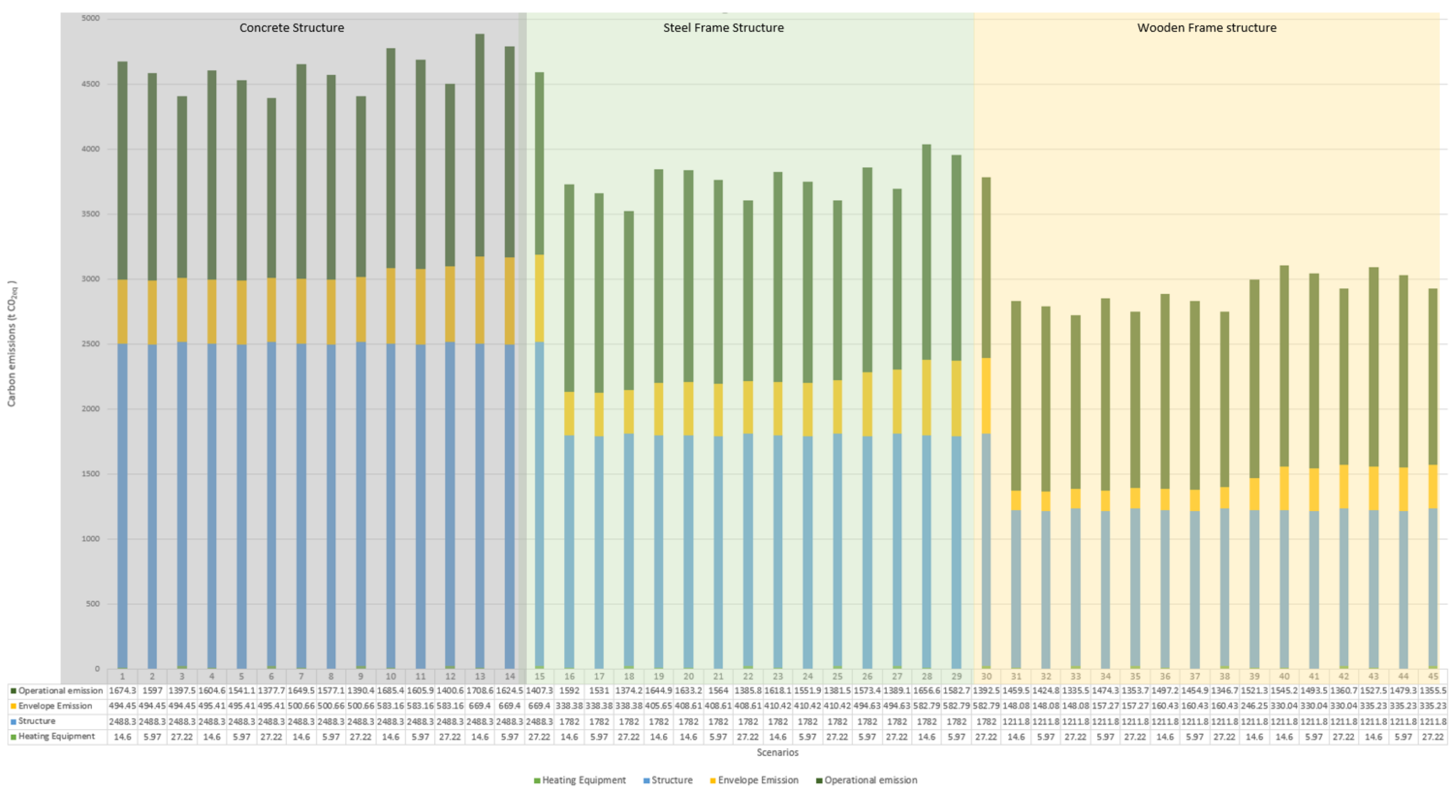

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Operational emission	1674.3	1597	1397.5	1604.6	1541.1	1377.7	1649.5	1577.1	1390.4	1685.4	1605.9	1400.6	1708.6	1624.5	1407.3
Envelope Emission	494.45	494.45	494.45	495.41	495.41	495.41	500.66	500.66	500.66	583.16	583.16	583.16	669.4	669.4	669.4
Structure	2488.3	2488.3	2488.3	2488.3	2488.3	2488.3	2488.3	2488.3	2488.3	2488.3	2488.3	2488.3	2488.3	2488.3	2488.3
Heating Equipment	14.6	5.97	27.22	14.6	5.97	27.22	14.6	5.97	27.22	14.6	5.97	27.22	14.6	5.97	27.22

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Operational emission	1592	1531	1374.2	1644.9	1633.2	1564	1385.8	1618.1	1551.9	1381.5	1573.4	1389.1	1656.6	1582.7	1392.5
Envelope Emission	338.38	338.38	338.38	405.65	408.61	408.61	408.61	410.42	410.42	410.42	494.63	494.63	582.79	582.79	582.79
Structure	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782
Heating Equipment	14.6	5.97	27.22	14.6	14.6	5.97	27.22	14.6	5.97	27.22	5.97	27.22	14.6	5.97	27.22

	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Operational emission	1459.5	1424.8	1335.5	1474.3	1353.7	1497.2	1454.9	1346.7	1521.3	1545.2	1493.5	1360.7	1527.5	1479.3	1355.5
Envelope Emission	148.08	148.08	148.08	157.27	157.27	160.43	160.43	160.43	246.25	330.04	330.04	330.04	335.23	335.23	335.23
Structure	1211.8	1211.8	1211.8	1211.8	1211.8	1211.8	1211.8	1211.8	1211.8	1211.8	1211.8	1211.8	1211.8	1211.8	1211.8
Heating Equipment	14.6	5.97	27.22	5.97	27.22	14.6	5.97	27.22	14.6	14.6	5.97	27.22	14.6	5.97	27.22

Figure 8- Embodied and operational emissions of studied scenarios

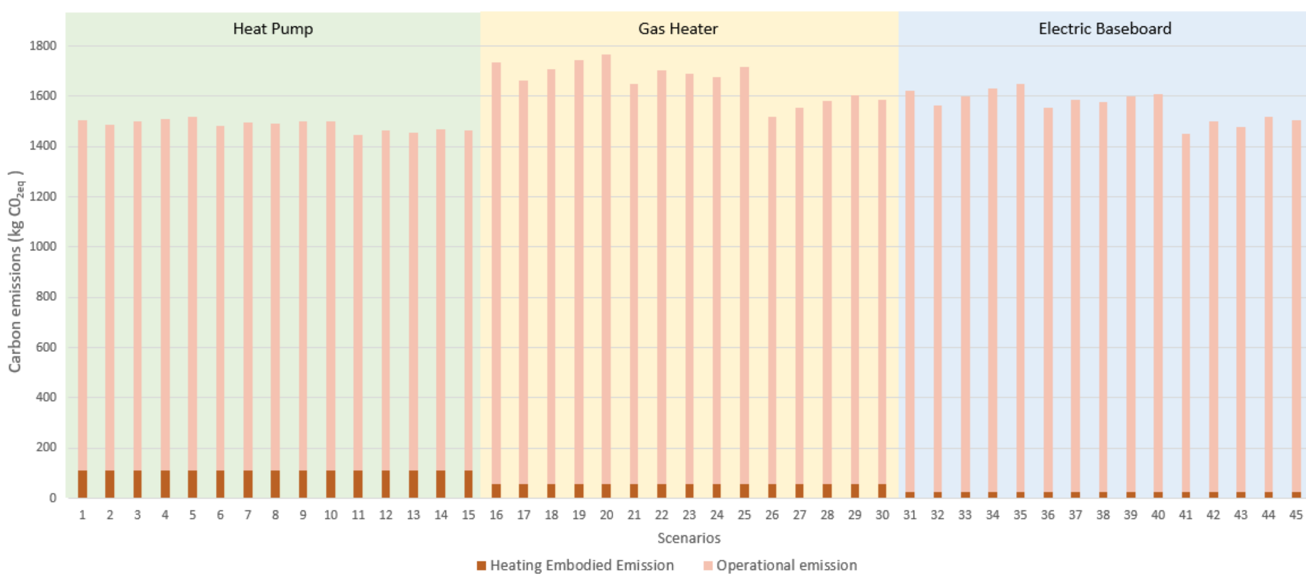

Figure 9- The impact of heating system on embodied and operational emission