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The effect of insulation thickness on lifetime CO₂ emissions

Totland M, Kvande T and Bohne R A

Norwegian University of Science and Technology

marietot@stud.ntnu.no

Abstract. This paper assesses the total carbon emissions of a single-family home designed and built for Norwegian conditions, according to current standards (TEK 17), using an LCA approach. Various combinations of insulation thicknesses are assessed to identify which combination is most efficient in lowering the lifetime emissions as well as in which part of the building envelope additional insulation is most efficient in reducing the lifetime greenhouse gas emissions of the building. Overall, increased insulation resulted in lower lifetime emissions; the increased embodied emissions generally being outweighed by the energy savings resulting from the increased insulation thickness. The location of the insulation is the factor that was found to have the largest impact on the lifetime emissions. When increasing the insulation thickness from 100-500 mm, changing only one component at a time, the operational emissions were most sensitive to the insulation thickness in the walls, with a 26 % decrease compared to 7% and 3% for the roof and floor respectively. The most efficient cases tended to have little insulation in the floor (100 - 150 mm) and relatively high insulation thickness in the wall (350 mm). The most variable component was the roof, varying from 150 to 400 mm.

1. Introduction

According to the IPCC 19% of the global CO₂ emissions, and 32% of the final energy consumption in 2010 could be accounted to the building sector[1]. Due to the long lifetime of buildings, the efforts made to reduce these emissions can affect the world in decades to come. In recent years there has been an increasing focus on reducing the carbon footprint of buildings, which in colder climates like in Norway, focuses on reducing heat loss and thus lowering the operational energy consumption. Increasing the insulation thickness, ensuring airtightness and eliminating thermal bridges are steps taken to bring the use phase energy consumption down. These measures are indeed reducing the lifetime energy use and emissions, but at what cost? The solutions to reduce the carbon footprint of buildings are increasingly "engineered", relying on more materials to further reduce the emissions. Increasing the insulation thickness will potentially reach a limit where adding more material can not further decrease the energy use without it affecting the user-friendliness or increasing lifetime emissions.

The overall objective of the study is to investigate the effect of insulation thickness on lifetime greenhouse gas emissions. This is done through the case study of a single family home located in Norway. Life-cycle assessment (LCA) methodology is used to analyse the GHG emissions and to answer the following research questions:

- (i) To what extent will increased insulation thickness reduce the lifetime GHG emissions?
- (ii) In which part of the building envelope is additional insulation most efficient in reducing the lifetime GHG emissions of the building?



To assess the environmental impact of buildings, the embodied emissions; impacts that are "built into" the building, are separated from those coming from the use phase of the building, also called the operational emissions. Traditionally, when the buildings were less insulated, the operation phase constituted between 70-90 % of the total environmental impact[2]. As the buildings have improved the operational energy consumption has been reduced, which increases the relative importance of the embodied emissions. For buildings of passive house standard the embodied emissions can constitute almost 50 % of the total emissions[3]. The impacts of the operational and embodied emissions are highly dependent. The choice of materials used in the construction can for instance decrease the heating requirements of the use phase, but increase the need for transportation or emissions related to the production of the materials[4].

2. Method

2.1. Case study

The case study for this project is a small, residential building designed by Norgeshus, called Trend 2. The house will, for the purpose of this analysis, be considered as a detached, single family house, but the design is also compatible as several adjacent units as a row house, and can therefore easily be scaled for further investigation.

The main part of the building has a rectangular shape with two stories and a flat roof. In addition there is a carport attached to the long side of the building, also serving as a terrace with access from the second floor.

The construction is placed on a concrete perimeter foundation, with timber frame walls insulated with mineral wool, and a flat, compact roof on glulam beams. The original house is built according to current Norwegian standards, TEK 17. The details and thermal properties of Trend 2 are presented in Table 1.

Table 1. Trend 2 building properties

Property	Value
U-value External wall [W/m ² K]	0.207
U-value Ground floor [W/m ² K]	0.092
U-value Roof [W/m ² K]	0.14
U-value Windows [W/m ² K]	0.81
Airtightness, n ₅₀ [1/h]	0.9
Heat recovery efficiency	85%

2.2. LCA methodology

Life-Cycle Assessment (LCA) is used to analyse the environmental impacts of a product or service during their entire lifetime [4]. The International Organization for Standardization (ISO) publishes standards for Principles and Framework - ISO 14040 [5] and Requirements and Guidelines - ISO 14044 [6] for life-cycle assessments, and the procedure for the LCA of this paper follows these standards.

The goal of this study is to investigate the effect of increased insulation on the lifetime GHG emissions and identify hot spots, components that contribute more than others to the life-cycle emissions. For this reason, only the impact category global warming potential (GWP) is assessed. According to NS-EN 15643 [7] the embodied emissions correspond to A1-A3 and the operational emissions to B1. The lifespan of the building is considered to be 60 years. Materials with a shorter lifespan than 60 years were multiplied with a lifetime factor to be included in the embodied emissions.

The functional unit is 1 m² heated floor area. A complete life-cycle inventory of Trend 2 as designed was performed based on a material list provided by Norgeshus, using a combination of EPDs from EPD

Norway and the Ecoinvent v3 database. The operational energy use was calculated using the energy calculation software SIMIEN. Trend 2 uses a combination of electric heating and biofuel (wood burning fireplace). The electricity mix is assumed to emit 132 g CO₂/kWh[8] and 22 g CO₂ eq/kWh for the biofuel [9].

Initially, two combination methods were used in the case study for the insulation thicknesses, hereafter called Case A and Case B. In Case A all insulation thicknesses were assumed to be identical, e.g. 100 mm insulation in the wall, the roof and the floor. Case B is a parameter study, where all values were kept as they were designed for Trend 2, and only one component was changed at a time. As the work progressed, it became apparent that other combinations of insulation thicknesses should be investigated, which became Case C. A total of 126 combinations were assessed with various combinations of insulation thicknesses, but for the purpose of this paper only the most efficient are presented in detail.

A sensitivity analysis was performed with regards to lifetime (± 30 years) and electricity mix ($\pm 30\%$).

3. Results

The life-cycle impact analysis of the building body of Trend 2 yielded an embodied emission of 25176 kg CO₂ eq, corresponding to 194,56 kg CO₂ eq/m².

The LCIA revealed that concrete was the greatest contributor to embodied GHG emissions despite the relatively small amount used in the construction. Concrete is used only in the perimeter foundation, yet constitutes almost 16 % of the total embodied emissions, emphasising the carbon intensity of the material. Insulation is the third most carbon intensive material in the construction.

The variations in embodied emissions for the case study was calculated for each case, and the difference is mainly due to the change in insulation quantity. Polystyrene insulation (EPS and XPS) is more carbon intensive than mineral wool. EPS provides a GWP of 2.2 kg CO₂ eq/m² for phases A1-A3, whereas Glava mineral wool provides 0.43 kg CO₂ eq/m². For Trend 2, insulation contributes 11 % of the total carbon emissions, including the mineral wool, XPS and EPS. For the most insulated case (A.500), the insulation accounts for 19 % of the total embodied emissions.

Table 2. Embodied and operational emissions

Insulation thickness [mm]	100	150	200	250	300	350	400	450	500
Case A: Same insulation thickness in all components									
Operational emissions [kg CO ₂ eq/m ² year]	18.7	15.7	14.2	13.2	12.5	12.1	11.8	11.6	11.4
Embodied emissions [kg CO ₂ eq/m ²]	184	188	191	194	198	201	204	208	211
Case B: Varying insulation thickness for single component, others unchanged									
Embodied emissions [kg CO ₂ eq/m ²]									
Wall	192	193	195	196	197	199	200	201	203
Roof	193	194	194	195	195	195	196	196	196
Floor	188	190	191	193	195	196	198	199	201
Operational emissions [kg CO ₂ eq/m ² year]									
Wall	17.0	14.9	13.9	13.2	12.7	12.4	12.2	12.0	11.5
Roof	14.8	14.3	14.1	13.9	13.7	13.7	13.6	13.5	13.5
Floor	14.5	14.2	14.1	13.9	13.9	13.8	13.8	13.8	13.8

The results for the embodied and operational emissions for cases A and B are presented in Table 2. For all insulation thicknesses in both cases the embodied emissions increase with the increased insulation,

and the operational emissions decrease. The operational emissions were most sensitive to the insulation thickness in the walls. Thin walls (100 mm) resulted in lifetime emissions 15.2% higher than Trend 2 and when the walls had 500 mm insulation the lifetime emissions decreased with 14.9%. With the same insulation thicknesses in the roof and the floor the lifetime emissions varied from +5.1% to -1.5% and from +2.8% to -0.1% respectively. It is likely that this distribution is partly affected by the area difference, as the wall surface area is more than double those of the roof and floor and thus allows for more heat transmission.

Overall, the lifetime emissions decrease as the insulation amount increases, this applies for almost all case variants. Table 3 shows the results of Case A, displaying variations regarding lifespan and emission of the electricity mix. The baseline results, with a lifespan of 60 years, and 132 gCO₂ /kWh are shown in the middle. The difference between the least and most insulated cases increases as the electricity mix becomes more carbon intensive and as the lifetime increases. The size of the reduction of lifetime emissions as the insulation increases from 100 to 500 mm depends on the electricity mix (reduction of 25-38% for least and most carbon intensive electricity mix respectively) and expected lifetime (reduction of 26-31%).

Figure 1 shows the lifetime GHG emissions for Case B with a lifespan of 60 years. The insulation thickness in the wall has the greatest effect on the lifetime emissions. The lifetime emissions are less affected by the insulation thickness of the roof and floor, the greatest difference occurring when going from 100 to 150 mm in both components. The wall provides the most significant decrease in lifetime emissions per mm added insulation, with a 26 % decrease compared to 7% and 3% for the roof and floor respectively when the insulation is increased from 100 - 500 mm at a lifetime of 60 years.

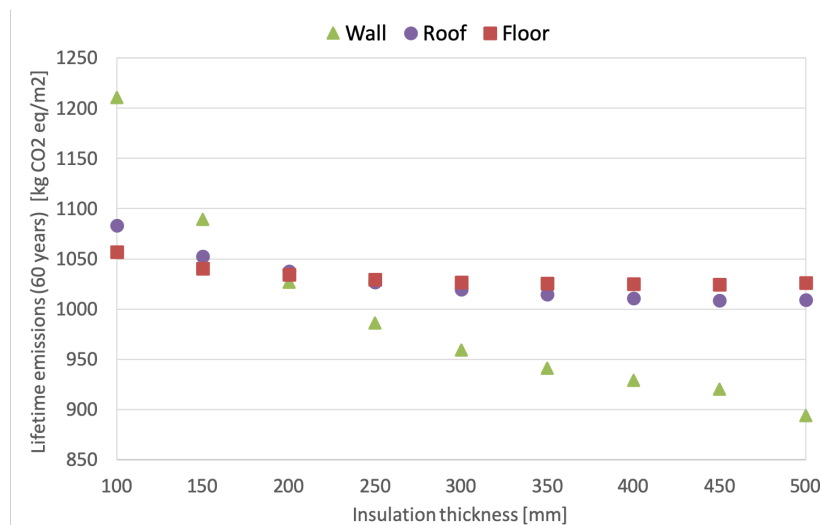
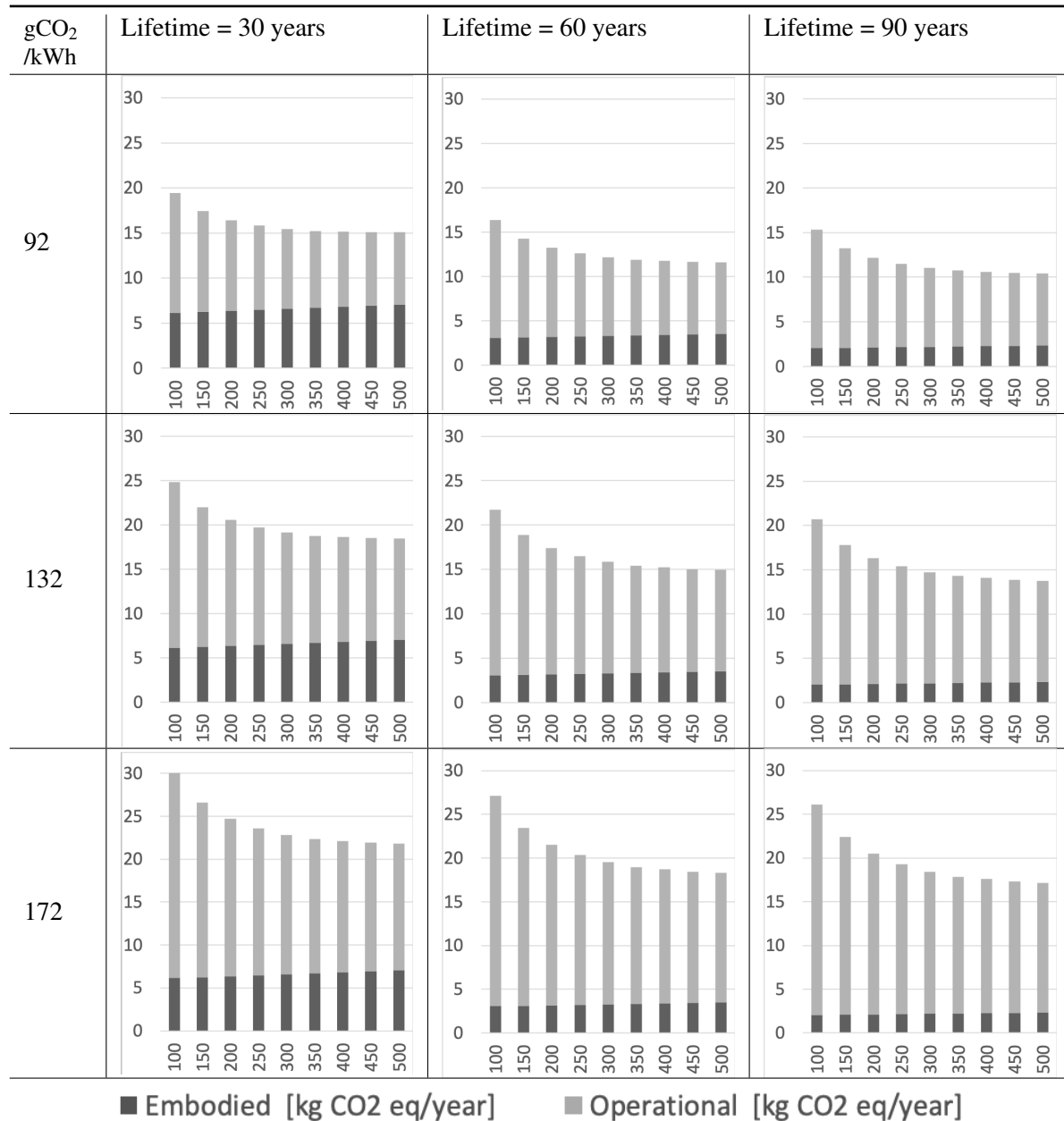


Figure 1. Case B Lifetime emissions (60 years) for the various insulation thicknesses changed in single component

Figure 2 shows the relationship between the lifetime embodied and operational GHG emissions with a life span of 60 years for all the assessed cases. The frontier along the leftmost data points in the figure is called the Pareto frontier. Pareto efficiency is a concept that stems from economics, describing an allocation that makes some individuals better off, and no individual worse off [10]. In the case of optimising insulation thickness, the Pareto frontier represents cases where the operational emission is as low as possible for a given embodied emission. Cases to the right of the frontier therefore have the same operational carbon emissions, but higher embodied emissions, and are thus less efficient than a case on the frontier. The simulations of Trend 2 and the three versions of the Norwegian building standards

Table 3. Annual CO₂ emissions for the Case A variants (insulation thickness in mm) as functions of different lifespans and electricity emissions

(TEK17, TEK07 and TEK 97)¹ all result in data points to the right of the Pareto frontier.

The insulation thicknesses and lifetime emissions of the cases on the Pareto front are presented in Table 4².

¹ TEK17 is the current standard, TEK07 and TEK97 are past standards, included to see the effect of the evolution of the insulation requirements

² The values are sorted alphabetically according to Case ID and the order does not represent Pareto efficiency

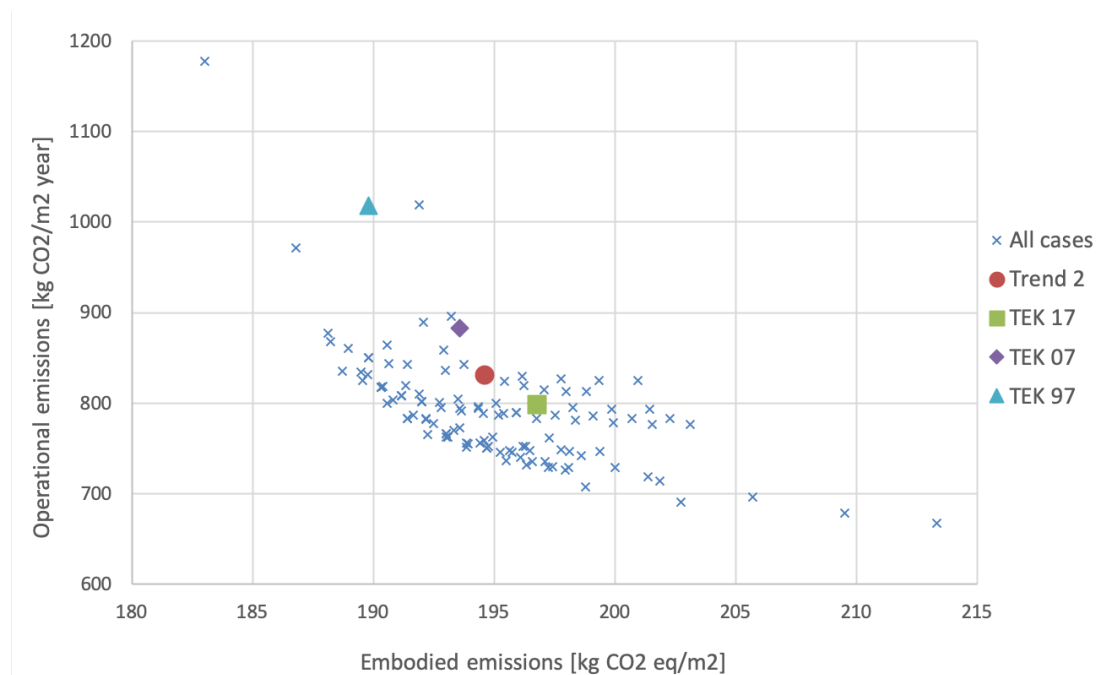


Figure 2. Relationship between embodied and operational carbon emissions

Table 4. Cases on the Pareto frontier with insulation thicknesses [mm] and lifetime emissions [kgCO_2/m^2]

Case ID	Insulation Roof	Insulation Wall	Insulation Floor	Operational	Embodied
All 100	100	100	100	1177,8	183,0
All 450	450	450	450	679,0	209,5
All 500	500	500	500	667,6	213,3
C.2.250	200	250	150	190	817,9
C.3.400	250	400	150	195,2	746,1
C.3.500	250	500	150	197,9	726,7
C.4.500	300	500	150	707,3	198,8
C.6.100	200	250	100	835,6	188,7
C.7.100	250	250	100	189,5	825,4
C.9.100	200	350	150	783,2	191,4
C.10.150	150	350	100	800,1	190,6
C.10.250	250	350	100	765,1	192,2
C.11.200	400	350	150	762,7	193,0
C.11.250	250	350	150	751,4	193,8
C.11.300	300	350	150	750,3	194,7
C.11.350	350	350	150	736,5	195,5
C.11.400	250	350	150	732,2	196,3
C.11.450	450	350	150	732,2	196,3

4. Discussion

The results are based on a theoretical framework, which can lead to discrepancies based on factors outside of the scope of this study. Some uncertainty is to be assumed as the study does not consider all phases of

a life-cycle assessment. The sensitivity analysis with regards to lifespan in table 3 is especially uncertain as it is a purely theoretical analysis. When exceeding the original lifespan of 60 years no additional maintenance, repair or replacement is assumed, meaning that in reality the embodied emissions would increase as well as a possible change in operational emissions. Furthermore, the insulation thicknesses assessed in this study might exceed what is practical or economically feasible, however these aspects have not been considered for the purpose of this study.

The environmental impact of a building can vary greatly based on the geographical location, both as a result of the electricity mix used, both in use and for the material production, as well as transportation of the materials to the building site. As shown in Case A, the choice of electricity mix makes a significant impact on the lifetime emissions. The sensitivity ratio (SR) was calculated according following standard methodology [11], the results can be seen in Table 5. The results are clearly more sensitive to variations in lifespan and CO₂ factor, than the insulation variations studied, which corresponds to the findings in Table 3. The building sector might not be able to control the CO₂ factor from the grid, but it can affect the lifetime of the buildings. The findings show that no matter how optimally insulated the building is the annual CO₂ emissions will decrease for longer lifespans, so it is important to ensure that the building is robust enough to last for as long as possible.

Table 5. Sensitivity analysis

Parameter	SR
CO ₂ factor	0.76-0.81
Lifespan	0.78-0.82
Insulation - roof	0 - 0.12
Insulation - wall	0.07 - 0.37
Insulation - floor	0 - 0.07

The results of this study are representative of a house built in Norway or the Nordic region, as most of the materials (and thus EPDs) considered are provided by Norwegian manufacturers.

Case B showed that the roof and the floor insulation did not contribute significantly to the decrease of lifetime emissions compared to that of the wall insulation. At around 200-250 mm, the slopes level out. Even though the lifetime emissions are decreasing after this point, the return on investment will be slight. If the electricity mix becomes less carbon intensive over time, this added insulation might even contribute to an increase in lifetime emissions. This study suggests that it is not given that the solution to reducing the carbon footprint of buildings can rely solely on adding more material. In passive houses it is not uncommon for the insulation thicknesses in the roof to exceed 400 mm and 300 mm in the floor. As Figure 1 shows, the slope of lifetime emissions has evened out long before reaching these thicknesses. It might therefore be beneficial to reconsider the amount of insulation used in these components.

The results of this study indicate that it is not necessarily beneficial to increase the insulation thickness uncritically and expect it to yield lower lifetime emissions. Trend 2 has 250 mm insulation in the roof, 200 mm in the walls and 300 mm in the floor. For this particular building, the results show that the insulation in the floor does not have a significant impact on the lifetime emissions, yet in the original building, the floor is the component with the most insulation. EPS insulation, which is used in the floor construction, is also more carbon intensive than mineral wool, used in the wall and the roof. For Trend 2 it would therefore be recommended to decrease the insulation in the floor construction, and increase it in the walls. Changing the insulation thicknesses to 150 mm in the roof, 350 mm in the walls and 100 mm in the floor leads to the same amount of delivered energy as a building with TEK 17 recommended insulation thicknesses, but with embodied emissions of 191 kg CO₂/m², 6 kg CO₂/m² less than the original. In total, this is actually less insulation than in the TEK 17 version. It is therefore possible to use less material, yet still achieve the same or even better energy performance.

5. Conclusion

The study concludes that overall, the calculated GHG emissions vary inverse proportionally with the material quantities - more insulation leads to lower operational emissions, and overall lower lifetime emissions. Although more insulation increases the embodied emissions, it generally does not outweigh the energy savings of the increased insulation.

The location of the insulation is the factor that was found to have the largest impact on the lifetime emissions. For this particular building, when changing only one component at a time, the operational emissions were most sensitive to the insulation thickness in the walls. Thin walls (100 mm) resulted in lifetime emissions 15.2% higher than Trend 2 and when the walls had 500 mm insulation the lifetime emissions decreased with 14.9%. With the same insulation thicknesses in the roof and the floor the lifetime emissions varied from +5.1% to -1.5% and from +2.8% to -0.1% respectively. It is likely that this distribution is partly affected by the area difference, as the wall surface area is more than double than those of the roof and floor and thus allows for more heat transmission.

While the increased embodied emissions generally is outweighed by the energy savings resulting from the increased insulation thickness, it is desirable to ensure that the embodied emissions are as low as possible for a given level of operational emissions. A Pareto distribution comparing the embodied to the operational emissions for each case was created to identify the most efficient combinations of insulation thickness. The most Pareto efficient cases tended to have little insulation in the floor (100 - 150 mm) and relatively high insulation thickness in the wall (350 mm), some cases having more and less. The most variable component was the roof, varying from 150 to 400 mm.

It is clear from the findings of this study, that increasing the insulation thickness uncritically does not necessarily yield an optimal solution for lowering the lifetime GHG emissions of a building. It can be enough to increase only one component (in this case the insulation in the wall) while keeping others constant or even decreasing them to lower the lifetime emissions.

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