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A parametric study of the energy performance and carbon footprint of super-insulation in terrace constructions

A parametric study of the energy performance and carbon footprint of super-insulation in terrace constructions

Christofer Skaar, Jørn Emil Gaarder, Malin Sletnes
SINTEF Community

Corresponding author: christofer.skaar@sintef.no

Abstract. Energy requirements for buildings are continually tightened, as seen in the ambitions to introduce near zero-energy building (nZEB) requirements in Norwegian and European building codes from 2020. One consequence of this is an increased use of insulation. However, standard insulation may cause challenges in many circumstances, for example where increased wall dimensions lead to reduced daylight levels or where increased insulation leads to increased floor height. Super-insulation materials are a possible solution to these challenges. Although several super-insulation products exist on the market, there is still a need for proven system solutions that provide the required level of insulation, along with reduced thickness in the constructions. An additional challenge is that these solutions should also be cost-effective and carbon-effective. The economic benefits should outweigh the costs and the carbon footprint should ideally be reduced, but at least not significantly increased.

To analyse the potential of super-insulation, we have performed a parametric case study of terrace constructions based on super-insulation and compared these with a baseline solution. The terrace construction uses vacuum insulation panels (VIP) as the main insulation. The top plate insulation is tapered mineral wool, aerogel is used in the edges and on top of the construction there are wood tiles. The parameters that have been varied are i) terrace dimensions, ii) width of the edge with non-combustible aerogel, iii) the thickness of the VIP layer, iii) the slope of the tapering, and iv) the heat conductivity of the VIP panels.

To evaluate the benefits of the super-insulation an analysis of energy performance in the use phase has been done. As the energy efficiency of the super-insulation solution is improved, this gain can be used either to reduce thickness or to increase energy performance. Both these will have an impact on the costs. To evaluate the environmental performance of the solution a screening LCA has been performed, with focus on the carbon footprint. The results of the case study show under which circumstances the super-insulation solution has better performance than the baseline, and vice versa. Key parameters that drive energy performance and carbon footprint are identified, providing suggestions for further research.

1. Introduction

Improved energy performance has been a target ever since the national building act was introduced in Norway in 1965. This has resulted in a significantly reduced energy use in new buildings compared to the average [1] and the Norwegian and European ambition level is to require that all new buildings are nearly zero-energy buildings (nZEB) from 2020 [2]. One consequence of this is that there has been an increased use of insulation in buildings. However, standard insulation may cause challenges in many circumstances, for example where increased wall dimensions lead to reduced daylight levels or where increased insulation leads to increased floor height. Super-insulation materials are a possible solution to these challenges. Although several super-insulation products exist on the market, there is still a need for proven system solutions that provide the required level of insulation, along with reduced thickness in the constructions and with the additional challenges that these solutions should also be cost-effective and carbon-effective [3-5]. The economic benefits should outweigh the costs and the carbon footprint should be reduced both for the construction itself and for the building in a life cycle perspective.
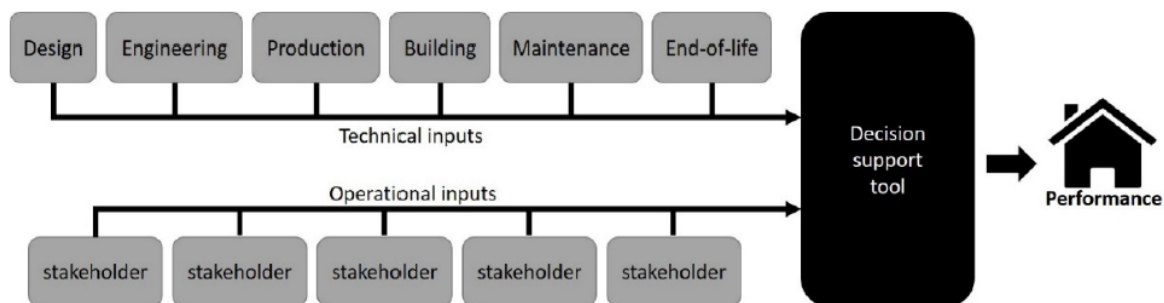

Fig. 1. An extended scope for performance-based design as a framework for a decision support tool

Figure 1: Decision support tool in a building context [6]

To reduce the carbon footprint, it is necessary to see the construction in a building context and with a life cycle perspective already from the design stage [7-11]. Figure 1 shows how performance-based design can be used as a framework for a decision support tool. This framework can be used from design stage to end-of-life stage, and it takes into account both the technical performance of the construction (e.g. U-value, load bearing capacity, etc.) and the operational performance (e.g. carbon footprint, life cycle cost, etc.) [6]. The main challenge is to provide reliable decision support early in the design process, where there is still flexibility to choose between different constructions, materials and processes. As there is a large range of options available, a parametric decision support tool will make it feasible to analyse several options. Such a tool can either be used to explore options manually or it could be integrated with optimisation tools [12]. Here we present the results from a case study of super-insulation in a terrace construction. The goal of the case study is to identify the key parameters driving energy performance and carbon footprint for the construction itself. The constructions are seen in a building context, but the scope here is limited to energy consumption in the use stage. Other potential consequences at the building level, such as reduced building height, increased daylight, are not addressed here.

2. Methods

The methodology in this case study is based on a combination of carbon footprint analysis and energy performance analysis. The calculation of the carbon footprint is based on life cycle assessment (LCA) and the calculation of the energy performance is based on calculating the U-value of the construction, shown in Figure 2 and Figure 3 respectively.
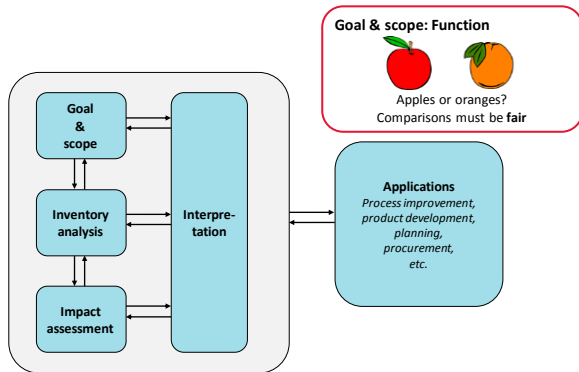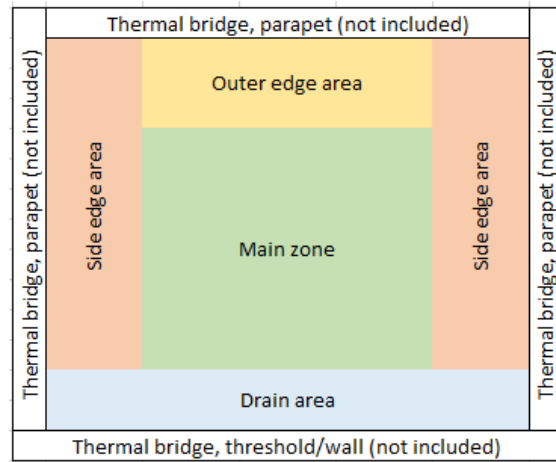
Figure 2: Life cycle assessment [13]

Figure 3: Calculation of U-value

There are four stages in an LCA: i) goal and scope definition, ii) inventory analysis, iii) impact assessment, and iv) interpretation [14, 15]. The first stage of an LCA defines the goal and scope of the study, including defining the purpose of the study, identifying the function of the system and defining the system boundaries. When comparing different solutions, it is necessary to ensure that the product systems meet the same functional requirements to ensure a fair comparison. This is based on first identifying the function and then defining a quantified functional unit. The system boundaries are defined using the modular approach as defined in EN 15978 for buildings [16] and EN 15804 for construction products [17]. The system boundaries are shown in Figure 4, with the included modules highlighted.

The second stage of LCA is to develop the life cycle inventory (LCI). To perform the analysis an adaptation of the tool developed in the ZEB research centre has been used [18]. The foreground inventory is based on work in the ongoing SuperIsol project [19]. The background inventory is based on a combination of data from ecoinvent 3.1. (using the system model *recycled content*) [20], scientific literature, and Environmental Product Declarations (EPD) [21-23].

The third stage of LCA is the impact assessment. Here this is limited to carbon footprint, quantified as global warming potential using the CML impact assessment methodology and in accordance with EN 15804 [17]. The fourth stage is the interpretation of the results. As LCA is an iterative process, this is done throughout the study. Finally, it should be noted that this analysis is not a full LCA, but it is a simplified approach based on the LCA methodology.

A1-3 Product Stage			A4-5 Construction Process Stage		B1-7 Use Stage							C1-4 End of Life					D Benefits and loads
A1: Raw Material Supply	A2: Transport to Manufacturer	A3: Manufacturing	A4: Transport to building site	A5: Installation into building	B1: Use	B2: Maintenance (incl. transport)	B3: Repair (incl. transport)	B4: Replacement (incl. transport)	B5: Refurbishment (incl. transport)	B6: Operational energy use	B7: Operational water use	C1: Deconstruction / demolition	C2: Transport to end of life	C3: Waste Processing	C4: Disposal		D: Reuse, recovery, recycling
x	x	x								x							

Figure 4: System boundaries according to EN 15978 and EN 15804 [16, 17]

The energy performance analysis is calculated for a building located in Oslo and based on the annual heat loss of the construction, with direct electric heating. Figure 3 illustrates the elements included in the calculation of the U-value for the constructions.

The results are presented both for the carbon footprint and for the energy performance analysis. The two methods are combined by applying a carbon footprint factor (kg CO_2-eq. per kWh) for the energy consumption in the use phase, and a simplified assumption that energy consumption is identical to electricity consumption. The choice of carbon footprint factor is an ongoing debate in Norway, and this is therefore a factor that has been included in the sensitivity analysis [24-26].

3. Case study

3.1. Functional unit, system and system boundaries

To analyse the carbon footprint and energy performance potential of super-insulation, we have performed a parametric case study of terrace constructions. The constructions using super-insulation are compared with a baseline solution using mineral wool. The purpose of the comparison is to analyse the scale of potential differences; it is not intended as a conclusive comparison between different materials. The functional unit is 1 terrace construction meeting the requirements in the Norwegian building code, over a period of 30 years.

The system boundaries are shown in Figure 4, showing that the included modules are the product stage (A1-A3) and the operational energy in the use stage (B6). The modules A4-A5, B1-B6, B8, C1-C4 and D are outside the system boundaries. This is a simplification based on two assumptions. The first is the assumption that the environmental impact of repair and maintenance are due to material consumption, and that these will correlate with the results for A1-A3. The second assumption is that the end-of-life stage is less significant when the impact assessment is limited to carbon footprint.

3.2. Terrace construction

Figure 5 shows a general illustration of the terrace construction using vacuum insulation panels (VIP) as the main insulation. The top plate insulation is mineral wool, the bottom plate insulation is tapered mineral wool, aerogel is used in the edges and a thin concrete plate constitutes the top layer. In the case study, only the insulation materials (VIP, aerogel and mineral wool) are included. This is because there is little variation for the other materials in the variants.
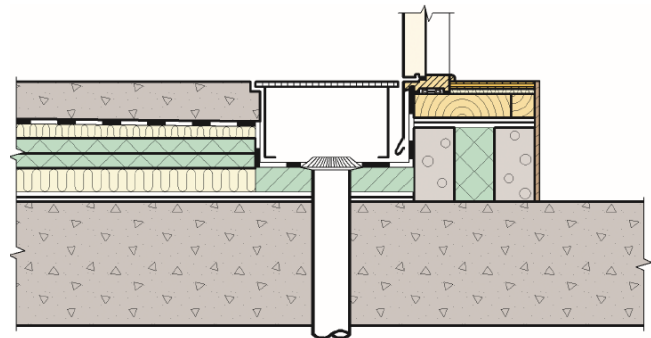
Figure 5: Terrace construction

The minimum performance requirements for the constructions is that they satisfy the requirements in the Norwegian building code. Examples of performance requirements are thermal conductivity, load bearing and safety in case of fire. For load bearing, it can furthermore be relevant to distinguish between uniformly distributed loads, line loads and concentrated loads, as each material will have different properties in this regard.

It should be noted that there is a significant difference in height between the mineral wool and the base case super-insulation construction is 183 mm. This difference can have consequences at the building level, e.g. reduced floor height.

3.3. Parametric variation

The selected parameters are those that typically can be varied when designing a terrace construction. In addition, the heat conductivity of the VIP panels is a significant parameter to include, to address the possibility of degradation of the VIP panel over time (e.g. due to aging effects or damage). The parameters are shown in the list below, with values for each variant shown in Table 1. The standard

VIP solution is shown in the column labelled *base case*. The VIP solutions are compared with a traditional construction using mineral wool. Here the parameters are identical to the base case with VIP, but the volume of materials are different. The parameters that have been varied, are:

i) terrace dimensions
ii) width of the edge with non-combustible aerogel
iii) the thickness of the VIP layer
iv) the slope of the tapering
v) the heat conductivity of the VIP panels

Table 1: Parametric variation of terrace construction and corresponding material volumes (parameter variation is shown in green).

		Mineral wool	Base case VIP	A	B	C	D	E	F	G	H	I	J
Parameter	Dimensions [m x m]	4x4	4x4	3x3	6x6	4x4	4x4	4x4	4x4	4x4	4x4	4x4	4x4
	Edge [mm]	-	600	600	600	300	900	600	600	600	600	600	600
	VIP thickness [mm]	-	60	60	60	60	60	30	90	60	60	60	60
	Slope [-]	1:40	1:40	1:40	1:40	1:40	1:40	1:40	1:40	0	1:100	1:40	1:40
	VIP heat conductitity [W/mK]	-	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.005	0.011
Volume	VIP [m3]	-	0.52	0.23	1.47	0.69	0.20	0.2604	0.7812	0.52	0.52	0.52	0.52
	Aerogel [m3]	-	0.44	0.31	0.69	0.33	0.76	0.2196	0.6588	0.44	0.44	0.44	0.44
	Mineral wool [m3]	5.02	1.42	0.68	4.15	1.42	1.42	1.4245	1.4245	0.74	1.0138	1.42	1.42

3.4. Energy performance

The energy performance is here defined to be identical to the heat loss of the construction, and any other energy consumption is not considered here. The annual heat loss for each variant is calculated based on the location of Oslo, with a constant indoor temperature of 20 °C and a heating demand in October—April. The heat is supplied with direct electric heating, where 1 kWh of heat loss is equal to 1 kWh supplied electricity. Table 2 shows the energy performance of all variants, as well as the base case VIP and the traditional construction using mineral wool.

Table 2: Parametric variation of terrace construction and corresponding energy performance

	Mineral wool	Base case VIP	A	B	C	D	E	F	G	H	I	J
U-Value, VIP [W/m2K]	0.119	0.119	0.132	0.103	0.109	0.128	0.171	0.116	0.139	0.130	0.107	0.138
Heat loss (Oct-Apr) [kWh]	192	120	120	373	176	206	275	187	224	209	172	222

3.5. Carbon footprint

The carbon footprint has been calculated for each of the variants of the construction, taking into account the amount of key materials to build the terrace and the energy performance of the construction in a 30–year time perspective. 30 years has been selected as an estimate of the reference service life of the terrace. Only the materials VIP, aerogel and mineral wool have been considered in these solutions. For energy, two variants have been included.

The sources for the GWP values have been found in EPDs and scientific literature. It should be noted that there is a high level of uncertainty for the carbon footprint calculations for VIP and aerogel. This is due to the low number of life cycle assessments and Environmental Product Declarations (EPD) for these materials, as they are novel compared to mineral wool. This is a key uncertainty and is addressed in the following section.

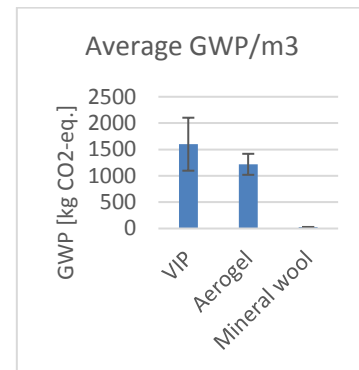*Figure 6: Average GWP per m³, with 95 % confidence limits (A1-A3)*

3.6. Sensitivity and uncertainty analysis

The sensitivity of the design is covered through the parametric variation described above. The GWP factor for electricity is a value-based choice and is often debated. The sensitivity of the results related to the choice of GWP factor for electricity is therefore evaluated, with two different factors. The first factor is for the current Norwegian physical grid mix and the second is the based on a scenario analysis (the ZEB factor, [25]). The factors used here are 24 g CO_2-eq. per kWh and 130 g CO_2-eq. per kWh, respectively.
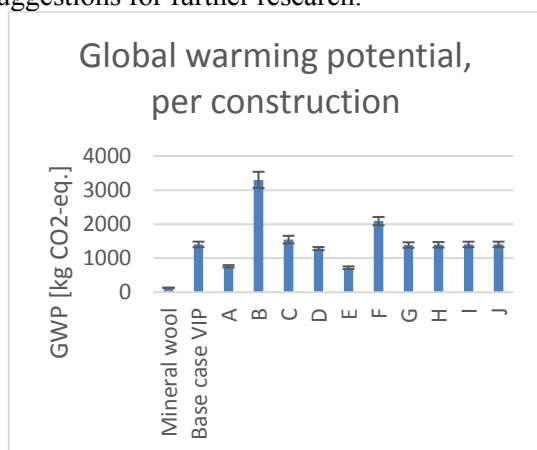
There are several potential suppliers for each of the materials that make up the constructions. The uncertainty of supplier selection is estimated using for each material with values from relevant EPDs or from scientific literature. Based on this, the average value and the 95 % confidence interval are calculated. This provides an average result for each construction, with an estimate of the uncertainty. However, it should be noted that there are three challenges with this approach. The first is that it assumes a normal distribution, the second is that the sample size is small (it is limited to relevant products with an EPD or documented in scientific literature), and the third is that there is a risk of sampling bias as it can be assumed that it is more likely for producers with a good environmental performance to have an EPD.
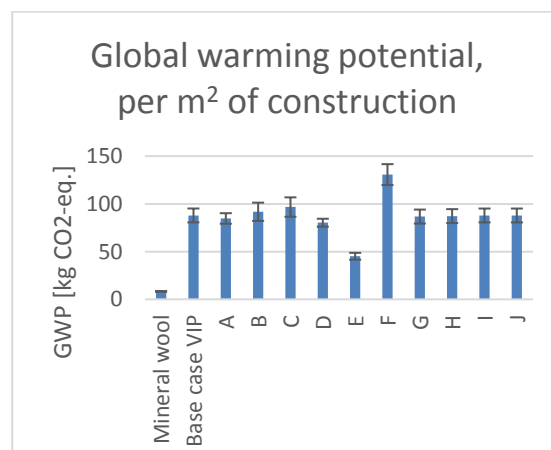
4. Results and discussion

To evaluate the benefits of the super-insulation an analysis of energy performance in the use phase has been done. As the energy efficiency of the super-insulation solution is improved, this gain can be used either to reduce thickness or to increase energy performance. Both these will have an impact on the costs. To evaluate the environmental performance of the solution a screening LCA has been performed, with focus on the carbon footprint. The results of the case study show under which circumstances the super-insulation solution has better performance than the baseline, and vice versa. Key parameters that drive energy performance and carbon footprint are identified, providing suggestions for further research.

Figure 7: GWP per construction, with 95 % confidence limits (A1-A3)

Figure 8: GWP per m² of construction, with 95 % confidence limits (A1-A3)

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Figure 7 shows the total carbon footprint (cradle-to-gate, A1-A3) for each variant of the terrace construction and Figure 8 shows the carbon footprint normalised per m^2 of terrace construction. The first figure shows that the most significant parameter for the total carbon footprint is here—as expected—the dimensions of the terrace. However, even when we normalise the results per m^2 of terrace—as shown in Figure 8—an increase in the terrace dimension will only lead to a slight increase of the carbon footprint per m^2. The reason for this increase is that edge will have a relatively lower share of the area. This is also reflected in variants C and D, where the edge is decreased and increased. For variants I and J there are no differences, as these solutions have the same amount of materials as the base case. The change in these two variants is in the heat conductivity of the VIP panels, which is not reflected in the cradle-to-gate footprint.
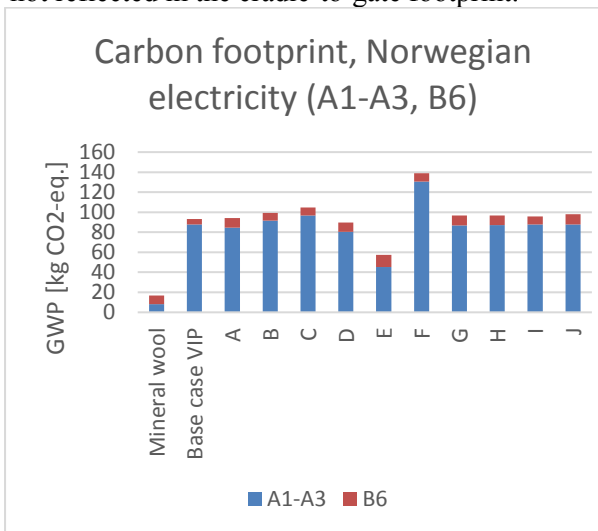
Figure 9: GWP per m2, Norwegian electricity (A1-A3 + B6)
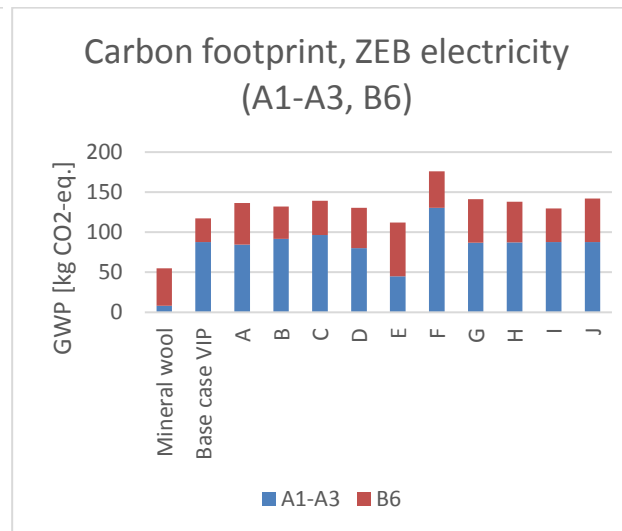
Figure 10: GWP per m2, ZEB electricity (A1-A3 + B6)

If we include the electricity consumption in the use phase, the different energy performance of each construction can be analysed. Figure 9 and Figure 10 shows the carbon footprint both for the production of the materials (A1-A3) and the electricity consumption in the use phase (B6). Here two different CO_2-factors for electricity have been used, first with today's Norwegian physical mix and the second with the ZEB factor. Both figures show that it is the carbon footprint of the materials that has the main contribution to the total carbon footprint, especially for the scenario with the Norwegian electricity. However, we also see the importance of having a life cycle perspective, e.g. when we compare A and B (differences in heat loss changes the conclusion when we include the use phase) and I and J (damaged VIP panels will here lead to 25–30 % increased heat loss). For A, the reduced carbon footprint comes at the expense of worse energy performance. The improved energy performance of B far outweighs the difference in carbon footprint for the materials. For the VIP solutions, only the solution E (with decreased VIP thickness) has a better performance than the base case. The solution with the highest carbon footprint is F, where the VIP thickness is increased from 60 to 90 mm. None of the VIP solutions outperform mineral wool, when we look at the terrace construction alone. However, one argument for using super-insulation is that it may have advantages in a building context. E.g. reduced thickness can lead to reduced floor height in the building or the possibility to add an extra floor within regulatory restrictions.

To provide an estimate of how large these advantages would need to be in a building context, we can compare the increased carbon footprint from the terrace construction (A1-A3 + B6) with the carbon footprint for low-carbon concrete. The maximum carbon footprint for low-carbon class A concrete (B30, M60) is 200 kg CO_2-eq. per m^3 concrete [27]. For the scenario with Norwegian

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electricity mix, a 4x4m terrace would need to provide a saving of 0.65 m3 low-carbon concrete. For the scenario with the ZEB electricity factor, the saving would need to be in the magnitude of 3–10 m^3 of low-carbon concrete. When we know the difference in height between the mineral wool and base case super-insulation is 183 mm, it is likely that a saving can be achieved at the building level.

These results indicate that super-insulation in terrace constructions can lead to a reduction in carbon footprint, but only if the advantages at the building level outweigh the higher carbon footprint of the construction itself. It should be noted that there is high uncertainty in the GWP calculations for VIP and aerogel, as these are relatively novel materials with less available documentation than mineral wool.

5. Conclusions

The results of the case study of a terrace construction show that if super-insulation simply replaces traditional insulation it will likely lead to a higher carbon footprint. However, if there are additional benefits in a building context (e.g. reduced floor height), super-insulation may lead to reduced carbon footprint for the whole building. The most significant parameters for the VIP solution are terrace dimensions, thickness of VIP, and increased heat conductivity due to damage. A key recommendation for further work is to investigate the effect at the building level of using VIP in constructions.

6. Acknowledgements and declaration of interests

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