A Holistic View of Solutions in Social Housing in São Paulo – Brazil: CO2 emissions, Performance, and Cost of Roof Compositions

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Abstract
This research aims to provide a holistic view of roofs in social housing in São Paulo - Brazil, focusing on a component solution with lower CO2 equivalent emissions, lower initial costs, and higher thermal performance. The three criteria analysis considered a representative low-income single-family housing unit of two bedrooms with a total area of 47.5 m². Two models were developed: the BIM, that supported GWP analysis, and BEM, that supported thermal performance. The cost analysis considered the Brazilian national database. The roof cases consisted of eight combinations of four roof tiles (fiber cement, ceramic, metal, and metallic sandwich) and two ceiling types (concrete and plasterboard with insulation). Overall, alternatives with plasterboard and insulation as ceiling presented good thermal performance, lower costs and GWP. However, the considered best solution for thermal performance presented the highest values of cost and one of the highest in terms of GWP.

Highlights
- The best thermal performance solution is not necessarily the best solution from a holistic point of view
- Multi-criteria approach enhances roof choice selection in low-income housing
- Light roof compositions achieve similar or better thermal performance results than the ones with concrete

Introduction
Social housing studies are crucial in developing countries. Most social housing stock has poor thermal performance, leading to health risks for the inhabitants due to increasing overheating (Holmes et al., 2016, Haddad et al., 2022). Frequently, the whole country applies the same design and envelope solution, which does not consider climate differences. It drives envelope-related deficiencies, such as inadequate materials to the climate conditions and poor solar orientation. Moreover, low-income families rely on self-construction, which may lead to a precariousness-housing situation.

Even with social programs, the Brazilian housing deficit in 2019 was more than 5.5 million units, representing 8% of the total residential stock (Procel, 2019). Furthermore, Bracht et al. (2022) present that, over time, the thermal performance in social housing tended to get worse due to climate change.

A Brazilian national survey regarding residential possessions and habits in 2019 shows that 46% of Brazilian homes do not have a ceiling between the roof tile and the interior room (Procel, 2019). The roof significantly impacts thermal performance in hot climates and even more in one-floor buildings. It is a key factor in thermal performance improvements regarding low-income housing.

Geraldí et al. (2022) analyzed Brazilian residential energy consumption and concluded that low-income houses had significant growth in consumption over the last few years. Similarly, Bavaresco et al. (2022) analyze the existence of roof ceilings and slabs in social housing and compare them to the energy consumption data. They conclude that houses without ceilings or slabs (only with roof tiles) are expected to have poor thermal performance, but at the same time, the energy consumption data did not present such a pattern.

Nonetheless, when considering ceilings, Souza et al. (2022) present that adding roof insulation is beneficial to prevent overheating, but other strategies, such as maintaining low absorptance, can be as important as insulation if considering ceiling finishing. When not considering internal finishing, Souza et al. (2023) present a social housing roof solution using Phase Change Materials as an alternative for thermal capacity in roofs, seeking to reduce the use of concrete slabs in construction.

Most social housing studies focus on the thermal performance of the envelope components, but in a developing country, prices are a key factor. Defining the best thermal performance solution is crucial, but high initial costs could make the construction unfeasible, aggravating the housing deficit numbers.

Bianchi et al. (2021) present a low-income housing study that evaluated the cost acceptance of three technologies from the residents’ perspective: conventional masonry, structural masonry, and light steel frame. The authors present that conventional technologies are preferred when presenting cost as the only factor. On the other hand, light steel frame enable shorter execution times and even present lower results of Global Warming Potential (GWP). Regarding the thermal performance analysis, the study only analyses the walls’ thermal transmittance. The authors reinforce the need for further studies in the area.
In addition, it is essential to understand the CO2 emissions of such components’ manufacture and then prioritize the choice of low-carbon productions to reduce the use of materials with high-embodied CO2 emissions and prevent climate change aggravation.

Apostolopoulos et al. (2023) present a study that analyses both cost and global warming potential through the life cycle of the building. They developed a tool and then tested it on a multi-family building, taking energy simulation into account. Key aspects of this study are that they were able to develop a tool with a focused national database based on materials costs and emissions.

From a Brazilian national point of view, studies in material production emissions are pretty recent and do not present a complete database yet. The SIDAC database still presents primary energy demand indicators and CO2 emissions only for a few materials. The SINAPI database has much information regarding material and construction costs but does not present the full envelope possibilities, such as steel frame pricing (CEP, 2021).

Thus, in order to push this type of analysis further and aim for the improvement of Brazilian social housing construction and refurbishment, more studies are necessary. A holistic view enables the choice of better roof composition with more detailed arguments, reducing the risk of misjudgment when considering long-term analysis.

This research aims to provide a holistic view of roofs in social housing in São Paulo - Brazil, focusing on a component solution with lower CO2 equivalent emissions (at the product stage), lower initial costs, and higher thermal performance.

Method

The example building consists of a representative low-income single-family housing unit of two bedrooms with a total area of 47.5 m², as shown in Figure 1, and takes place in São Paulo - Brazil. This model is widely used in Brazilian social housing research. It is based on the study of Triana, Lamberts and Sassi (2015), where they characterized the representative building typologies for Brazilian social housing. It was also the object of studies regarding the definition of thermal performance indicators for residential buildings in Brazil (Eli et al., 2021) and the exploration of the Brazilian standard NBR 15.575-1:2021 (Krelling et al., 2023). The Energy Efficiency in Buildings Laboratory from the Federal University of Santa Catarina - Brazil provides the EnergyPlus Input File of this example building to enhance and disseminate national studies concerning the Brazilian national Standard for residential buildings and social housing studies (LabEEE, 2023).

The authors conducted a previous analysis evaluating the more critical solar orientation regarding cooling needs. The one with the highest values was chosen as the case study: the living room was northwest and northeast-oriented (Figure 1).

The building was modeled using Revit 2023 and the Euclid 0.9.4.1 plug-in for SketchUp Make. Each model conducted a specific analysis: the first model (Building Information Model - BIM) supported the global warming potential analysis, and the second (Building Energy Model) supported the thermal performance study. Figure 2 represents them (view from the west direction).

Figure 1: The blueprint of the housing unit.

The following sections describe the model configurations, databases, inputs, and outputs.

Thermal performance

São Paulo has a humid subtropical climate (Cfa – mild temperature, fully humid with hot summer), according to the Köppen-Geiger classification, or a hot and humid climate (climatic zone 2A), according to the ANSI/ASHRAE Standard 169-2020.

According to the Brazilian Standard for Bioclimatic Zones and Building Guidelines for Low-cost Houses (ABNT, 2005), São Paulo belongs to Bioclimatic Zone 3, needing solar and thermal mass for heating in the winter and dehumidification (air renovation) and natural ventilation in the summer (ABNT, 2005).

For the thermal performance simulations, the EnergyPlus Weather File used was the TMYx 2004-2018 of São Paulo – Congonhas Airport (Crawley & Lawrie, 2022). Figure 3 represents the yearly variations of dry bulb temperature (DBT) and relative humidity (RH) of the EPW with the support of the web interface Data View2d. The daily averages range from 30% to 95% of RH and 10°C to 27°C of DBT. Figure 4 presents the same data, in blue, but...
applied to the psychrometric chart with the help of the web interface developed by Andrew Marsh. It implies the same information about bioclimatic design as presented by the National Standard (ABNT, 2005).

The building simulation model configurations comply with the Brazilian Standard for the Performance of Residential Buildings (ABNT NBR 15575). EnergyPlus version 9.0 performed the simulations, and Table 1 describes the default configurations in compliance with the Standard (ABNT, 2021).

Table 1: EnergyPlus configurations.

<table>
<thead>
<tr>
<th>Internal load</th>
<th>Living room</th>
<th>Bedroom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of people</td>
<td>4 people</td>
<td>Two people</td>
</tr>
<tr>
<td>Lights</td>
<td>5 W/m²</td>
<td>5 W/m²</td>
</tr>
<tr>
<td>Equipment</td>
<td>120 W</td>
<td>0 W</td>
</tr>
<tr>
<td>Activity Level</td>
<td>108 W</td>
<td>81 W</td>
</tr>
<tr>
<td>Occupation period</td>
<td>14h-18h: 2 people</td>
<td>18h-22h: 4 people</td>
</tr>
</tbody>
</table>

Also, the simulations have six timesteps hourly, solar distribution of FullInteriorAndExteriorWithReflections, the ground model uses the object Site:GroundDomain:Slab, are conducted for the whole year and do not consider sizing calculations.

The National Standard evaluation through the simulation method comprises two simulations: one with natural ventilation and one artificially conditioned (ABNT, 2021). Under natural ventilation conditions, the simulation uses the Airflow Network group and has the Zone Operative Temperature reported hourly as the output. The temperature to open the windows is 19°C, according to the Brazilian National Standard. In this case, the evaluated outputs are minimum and maximum operative temperature in each room during occupied hours (To,min and To,max, respectively), and the percentage of occupied hours within 18°C and 26°C is also analyzed (PHFT). Thus, the building does not use artificial conditioning in occupied hours from 18°C to 26°C, and the windows are open from 19°C. Only the results under natural ventilation conditions are accounted for in this case (ABNT, 2021).

Under artificial conditioning, the simulation considers the Zone Forced Air Units group with the ZoneHVAC:Ideal Loads Air System object and reports both the Zone Ideal Loads Zone Total Heating and Total Cooling Energy hourly. The heating setpoint is 21°C, and the cooling setpoint is 23°C, according to the Brazilian National Standard (ABNT, 2021). Nevertheless, the according to the Brazilian National Standard, the thermal load is only accountable in occupied hours, and the temperature is above 26°C (for cooling, - CgTR) and below 18°C (for heating, - CgTA). The occupied hours with a temperature above 26°C or below 18°C (hours not accounted for the PHFT) are considered using artificial conditioning. Only the results of the artificially conditioned simulation are accountable in this case.

Furthermore, the simulation method presents configurations of a reference model related to envelope characteristics. The window glass has a Solar Heat Gain Coefficient (SHGC) of 0.87, thermal transmittance (U) of 5.7 W/(m².K), and can not have any shading. Besides, slabs and internal and external walls are in concrete 10 cm (Co) (Table 2 presents the characteristics: d – thickness; λ – thermal conductivity; ρ – density; cp – specific heat; ε – emissivity). These parameters are fixed to all cases of this study.

Table 2: Concrete characteristics.

<table>
<thead>
<tr>
<th>ID</th>
<th>d [cm]</th>
<th>λ [W/(m.K)]</th>
<th>ρ [kg/m³]</th>
<th>cp [J/kg.K]</th>
<th>ε</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td>10</td>
<td>1.75</td>
<td>2200</td>
<td>1000</td>
<td>0.9</td>
</tr>
</tbody>
</table>

The roof cases consisted of eight combinations of four roof tiles (ceramic tile - Ce, fiber cement tile - Fi, metallic tile - Me, and sandwich panel tile - Sa) and two ceiling types (10 cm concrete slab – Cc, or plasterboard - Pb with 10 cm glass wool R = 2.38 m².K/W). All combinations have an air gap (not ventilated) between the roof tile and the ceiling with R = 0.21 m².K/W.

The present study considers the previous thermal performance analysis performed by Souza et al. (2022) and selects the roof combinations with the lowest solar and visual absorptances, as the authors concluded. The solar and visual absorptances are 0.4. Table 3 presents the material characteristics.

Table 3: Roof materials.

<table>
<thead>
<tr>
<th>ID</th>
<th>d [cm]</th>
<th>λ [W/(m.K)]</th>
<th>ρ [kg/m³]</th>
<th>cp [J/kg.K]</th>
<th>ε</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ce</td>
<td>1.5</td>
<td>1.05</td>
<td>2000</td>
<td>920</td>
<td>0.9</td>
</tr>
<tr>
<td>Fi</td>
<td>0.8</td>
<td>0.343</td>
<td>1690</td>
<td>840</td>
<td>0.9</td>
</tr>
<tr>
<td>Me</td>
<td>0.06</td>
<td>5</td>
<td>7800</td>
<td>460</td>
<td>0.9</td>
</tr>
<tr>
<td>Sa</td>
<td>3.13</td>
<td>0.02</td>
<td>189</td>
<td>1000</td>
<td>0.9</td>
</tr>
<tr>
<td>Pb</td>
<td>0.12</td>
<td>0.25</td>
<td>1000</td>
<td>1000</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Also, the Brazilian reference case, described in the National Standard, has a concrete ceiling with fiber
cement tiles but with solar and visual absorptance of 0.65. The study compared all eight cases with the Brazilian reference to account for output reductions.

**Initial costs**

The initial cost analysis employed the SINAPI database (National System for Research on Civil Construction Costs and Indexes) to measure the cost per area of the roof cases. The SINAPI database presents cost values in reais (BRL) that transformed into dollars (USD) considering values of November of 2022, 1 USD = 5.31 BRL.

The database provides prices regarding unit costs (i.e., estimated labor and material cost combined) or only the material cost. Composition values take into account whole spences: from screws and nails to the installation process and labor services. Thus, material prices take only the actual material cost into account. Table 4 presents the SINAPI code, each composition and material classification, and the price per area.

**Table 4: SINAPI cost survey.**

<table>
<thead>
<tr>
<th>Code</th>
<th>Type</th>
<th>Name</th>
<th>Total cost (USD/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>39745</td>
<td>Material</td>
<td>Glass wool</td>
<td>27.62</td>
</tr>
<tr>
<td>92260</td>
<td>Unit cost</td>
<td>Roof scissors</td>
<td>96.39 (each)</td>
</tr>
<tr>
<td>92539</td>
<td>Unit cost</td>
<td>Structure for ceramic tile</td>
<td>14.66</td>
</tr>
<tr>
<td>92543</td>
<td>Unit cost</td>
<td>Structure for Fiber cement, Metallic, or Sandwich</td>
<td>4.46</td>
</tr>
<tr>
<td>94195</td>
<td>Unit cost</td>
<td>Ceramic tiles</td>
<td>7.89</td>
</tr>
<tr>
<td>94207</td>
<td>Unit cost</td>
<td>Fiber cement tiles</td>
<td>8.55</td>
</tr>
<tr>
<td>94213</td>
<td>Unit cost</td>
<td>Metallic tiles</td>
<td>12.26</td>
</tr>
<tr>
<td>94216</td>
<td>Unit cost</td>
<td>Sandwich tiles</td>
<td>51.20</td>
</tr>
<tr>
<td>95955</td>
<td>Unit cost</td>
<td>Concrete structure</td>
<td>58.88</td>
</tr>
<tr>
<td>96109</td>
<td>Unit cost</td>
<td>Plasterboard ceiling</td>
<td>7.43</td>
</tr>
</tbody>
</table>

All roof cases are a combination of compositions or materials. Each case adds the respective ceiling, structure, and roof tile initial cost since they have the same other envelope configurations based on the reference model. Thus, the cost of the whole building is not necessary, and the initial cost of each final composition is transformed from BRL/m² to USD/m² and compared. Table 5 presents the combination of compositions and materials of the roof cases and the unitary costs of the assemblages.

**Global Warming Potential**

Since the SIDAC Brazilian National database only presents a few values of embodied energy and CO2 emissions, the GaBi database was applied in this study through the Tally (version 2022.04.08.01) plug-in for Revit 2023. Figure 2 (a) shows that the BIM is modeled with all envelope characteristics, but only the ceiling and roof compositions are considered in the analysis.

The eight roof types were modeled in Revit using the Design Option feature, varying the ceiling type, the tiles, and its structure (wood or metal) according to Table 4 description. Tally generated the Design Option Comparison by selecting the eight cases and applying the materials from the database.

**Table 5: Unitary costs of roof assemblages.**

<table>
<thead>
<tr>
<th>Roof</th>
<th>Composition</th>
<th>Type</th>
<th>Total cost (USD/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co_Ce</td>
<td>Tile</td>
<td>Ceramic tile</td>
<td>103.64</td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Roof Scissors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Structure above the tile</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceiling</td>
<td>Concrete structure</td>
<td></td>
</tr>
<tr>
<td>Co_Fi</td>
<td>Tile</td>
<td>Fiber cement tiles</td>
<td>93.50</td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Roof Scissors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Structure above the tile</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceiling</td>
<td>Concrete structure</td>
<td></td>
</tr>
<tr>
<td>Co_Me</td>
<td>Tile</td>
<td>Metallic tiles</td>
<td>102.76</td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Roof Scissors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Structure above the tile</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceiling</td>
<td>Concrete structure</td>
<td></td>
</tr>
<tr>
<td>Co_Sa</td>
<td>Tile</td>
<td>Sandwich tiles</td>
<td>138.83</td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Roof Scissors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Structure above the tile</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceiling</td>
<td>Concrete structure</td>
<td></td>
</tr>
<tr>
<td>Pb_Ce</td>
<td>Tile</td>
<td>Ceramic tile</td>
<td>78.30</td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Roof Scissors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Structure above the tile</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceiling</td>
<td>Plasterboard ceiling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceiling</td>
<td>Glass wool</td>
<td></td>
</tr>
<tr>
<td>Pb_Fi</td>
<td>Tile</td>
<td>Fiber cement tiles</td>
<td>68.16</td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Roof Scissors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Structure above the tile</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceiling</td>
<td>Plasterboard ceiling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceiling</td>
<td>Glass wool</td>
<td></td>
</tr>
<tr>
<td>Pb_Me</td>
<td>Tile</td>
<td>Metallic tiles</td>
<td>77.42</td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Roof Scissors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Structure above the tile</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceiling</td>
<td>Plasterboard ceiling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceiling</td>
<td>Glass wool</td>
<td></td>
</tr>
<tr>
<td>Pb_Sa</td>
<td>Tile</td>
<td>Sandwich tiles</td>
<td>113.50</td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Roof Scissors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roof structure</td>
<td>Structure above the tile</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceiling</td>
<td>Plasterboard ceiling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ceiling</td>
<td>Glass wool</td>
<td></td>
</tr>
</tbody>
</table>

**Output analysis**

The study compares the three criteria and seeks the best solution for São Paulo – Brazil. It lies in the case with the lowest total cooling and heating energy, the highest value of minimum operative temperature, and lowest value of maximum operative temperature, the highest PHFT, and the lowest value of both GWP and initial costs. Table 6 presents a summary of the research method.
The Brazilian roof reference has a solar and visual absorptance of 0.65, while all the roof cases have solar and visual absorptance of 0.4, as presented by Souza et al. (2022). Since the type of paint and colour (solar and visual absorptance) were not considered in the GWP analysis, and the only difference between case Co_Fi and the Brazilian reference was the colour of the fiber cement tile, Co_Fi case is the same as the Brazilian reference for GWP and cost analysis.

The concrete slab ceiling (Co) presents more GWP than the plasterboard with insulation (Pb) since its composition needs concrete and steel. However, when analyzing the roof tiles, the metallic (Me) presents the lowest value of GWP, while ceramic tile (Ce) presents the highest value, i.e., the combination of plasterboard and insulation with metallic tile (Pb_Me), even with a metallic structure, presents lowest values of GWP.

Further, the production of concrete and ceramic tiles presents higher kgCO2,eq emissions than plasterboard ceiling, metallic tiles, and glass wool.

Figure 6 presents the comparison of initial costs in percentage for each case. Regarding the ceiling, the concrete slab (Co) also represents the highest values for cost. On the other hand, ceramic (Ce) and fiber cement tiles (Fi) have lower values among the roof tiles. However, the wooded ceramic structure needs more elements and presents higher structure costs. Besides, the sandwich roof tile (Sa) can be five times more expensive than...
conventional roof tiles, making low-income construction unfeasible.

As presented, the sandwich roof tile with concrete slab combination (Co_Sa) increases the initial cost by more than 50% compared to the metallic roof tile with insulated plasterboard ceiling (Pb_Me). On the other hand, different roof tiles, combined with plasterboard ceilings with glass wool, can present lower prices than the Brazilian reference since the reference has a concrete slab as a ceiling. This analysis did not consider the increased costs associated with the higher weight of a concrete slab, which would have further raised the overall structure’s expenses. Even though the metallic roof tile with insulated plasterboard (Pb_Me) has the second lowest value for total heating and cooling energy, it presents the lowest values of initial cost (together with the ceramic tile variation (Pb_Ce)) but also the lowest value of global warming potential.

In summary, some roof solutions can present very similar thermal performance, even with different material compositions, but when analyzing initial costs and global warming potential, the more adequate solutions are different. Furthermore, roofs with plasterboard ceilings and insulation present better thermal performance and lower emissions and do not significantly increase the initial costs, unlike concrete slabs without insulation.

Figure 6: Global warming potential.

In a simplified manner, to analyze through a holistic view, the total cooling and heating energy becomes the comparison output for thermal performance. Figure 7 shows the global warming potential results compared to both initial costs and thermal performance. The Brazilian reference case is modeled and analyzed as the concrete ceiling with fiber cement roof tile (Co_Fi).

Figure 7: Three criteria results for the cases.

As shown, solutions with plasterboard ceilings with insulation tend to present reductions in cost and GWP. Total heating and cooling energy, in percentage, are not so expressive among cases. Also, even if the GWP

Figure 8: Order of preference.

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This research aimed to provide a holistic view of roofs in social housing in São Paulo – Brazil. The study searched for a solution with lower CO2 equivalent emissions, lower initial costs (in USD/m²), and higher thermal performance. The roof cases consisted of eight combinations of four roof tiles (fiber cement, ceramic, metal, and sandwich) and two ceiling types (concrete and plasterboard with insulation). The study analyzed the roofs through a representative low-income single-family housing unit of two bedrooms with a total area of 47.5 m².

Revit and Tally conducted the Global Warming Potential analysis using a Building Energy Model; the SINAPI National Database provided information regarding unit and material costs to roof compositions; EnergyPlus, through the Euclid plug-in for SketchUp, assisted the thermal performance analysis employing a Building Energy Model.

Results show that thermal behaviour was similar across the different solutions compared to the Reference, with Co_Sa proving to be the best alternative due to its higher inertia, better insulation, and lower absorptance. Overall, alternatives with plasterboard as ceiling presented good thermal performance.

When considering Global Warming Potential, alternatives with concrete slabs present higher CO2 emissions. However, the tile type shows the most significant differences and impact on total emissions, with metal tiles standing out as the best option, particularly the metallic roof tile with insulated plasterboard (Pb_Me) presenting the lowest total emissions.

Similarly, solutions with concrete slabs show the highest values when considering the cost. The cost of sandwich tiles is also considerably higher than other tile alternatives. A holistic analysis revealed that the metallic roof tile with insulated plasterboard (Pb_Me) presents the best alternative. It exhibits the second-best thermal-energetic behaviour, the lowest cost, and Global Warming Potential. This study highlights the importance of a holistic analysis to determine the best roofing solutions. Such an analysis is particularly important for low-income buildings, where cost is a significant factor.

Nonetheless, such analysis was enabled due to different software and analysis methods, such as a building energy simulation tool, a building information modelling tool and a national database cost. The need for different tools to approach a holistic study considering the three criteria can make this analysis less disseminated in the field, resulting in each criterion being analysed separately. As presented in the study, the thermal performance is insufficient to choose envelope solutions. Besides, solutions’ global warming potential is also a fundamental parameter to making decisions. Furthermore, the costs of such solutions can make it unfeasible, especially when considering social housing design.

Future studies should expand to evaluate different parts of the building envelope, especially the walls. Additionally, future studies could evaluate thermal behaviour over the building’s life cycle, considering the effects of climate change. Nonetheless, the study should be taken further to a whole building life cycle assessment and life cycle cost, also analyzing different envelope solutions.

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