Balancing carbon emissions and comfort: a comparative study of envelope materials in affordable housing projects

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Abstract

This study presents a comparative analysis of carbon emissions and thermal comfort in an Indian affordable housing project, employing two envelope materials: EPS core technology and brick-and-mortar construction. The study quantifies embodied and operational emissions through life cycle analysis to establish an emissions thermal comfort trade-off. Focused on the Bureau of Energy Efficiency design under the Pradhan Mantri Awas Yojana 2022 scheme in Bhubaneswar, Odisha, the study addresses the pressing need to track carbon emissions in this sector. Buildings contribute 39% of energy-related carbon emissions, gaining significance due to urbanisation and affordable housing projects. The study highlights a significant 10.16% reduction in operational carbon for EPS (Expanded Polystyrene) core technology compared to a brick wall assembly construction, driven by its superior thermal performance. But this comes at a cost of a much higher embodied carbon value. Despite higher embodied carbon, EPS achieves heightened comfort with fewer operational emissions over 50 years. Findings underscore the relationship between environmental impact, comfort congruence, and emissions. Results hold location-specific importance for informed decisions in diverse urban contexts across India.

Keywords - Carbon emissions, thermal comfort, life cycle analysis, embodied carbon, discomfort hours

1. Introduction

1.1. Background

Urban areas worldwide face multifaceted challenges, especially in developing countries like India. The challenges include population growth, increased informal settlements, limited urban services, concerns regarding climate change, and many others. India's economic growth and urbanisation are intertwined deeply. Indian cities create a pull factor for the human resources from rural areas towards urban areas in search of economic opportunities. This involuntarily creates a need to accommodate this workforce, which, if not catered to, results in the generation of informal settlements in the form of slums. Currently, the housing shortage in India is around 76.3 million units, of which 26.3 million are urban. [10]. The Government of India recently launched a campaign to provide housing for all citizens by 2022. The scheme known as Pradhan Mantri Awas Yojana (PMAY) 2022 aims to provide access to sustainable and affordable housing for every citizen. The Bureau of Energy Efficiency, under the Ministry of Power, has developed a set of designs for affordable housing units specific to the different climate zones of India. These designs are replicable and modular and have been designed in response to the climate [8]. The future of the affordable housing sector is thus expected to grow according to this roadmap. The government has also developed a set of construction typologies for different climate zones across India, which have been used worldwide to construct affordable housing units with relatively quicker construction time and minimal environmental impact. This has been done under the Global Housing Technology Challenge (GHTC), a sub-mission under the PMAY 2022. This study compares a business-as-usual construction scenario with an approved GHTC construction technology regarding environmental impact and thermal comfort.

1.2. Approach

The environmental impact of any product can be studied by conducting a life cycle analysis for both construction scenarios. A life cycle analysis is a tool to evaluate the environmental impact of any product during its whole life. Life cycle Analysis gives a cumulative numerical value of the

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emissions associated with that product. As per ISO14044 and 14040, a predefined functional unit should quantify the impact [14,15]. For the scope of this study, a functional unit of kgCO2eq has been used throughout [14,15]. This metric can account for all greenhouse gas (GHG) emissions regarding carbon dioxide equivalence. The study's second aspect is related to evaluating the state of thermal comfort inside the houses. For this, the range of operative temperatures is checked against the IMAC(Indian model for adaptive comfort) band of the city in India [23]. This results in estimating the discomfort hours of that space for the given set of conditions. This has been carried out with the help of energy simulations.

1.3. Scope

The scope of the study is limited to investigating and assessing one affordable housing project in Bhubaneswar, Orissa, India. The city falls under the warm and humid climate region of India. As per the GHTC, EPS core technology is proposed for the city of Bhubaneswar to construct affordable housing units. Therefore, the study's scope is based on comparing a business-as-usual case with the proposed solution. The emissions associated with the building are calculated for two different construction sets: A brick wall assembly construction and Expanded Polystyrene core technology. Following a similar order of business, thermal comfort has been evaluated for both scenarios. The U-value for Brick wall assembly is calculated to be 2.41 W/m²K; for EPS core technology, it is 0.5 W/m²K. This is based on the material study database prepared by CARBSE [22]. Figure 1 shows the typical floor plan selected for the study. The building is a four-storey structure with both sides open, as shown [8]. Figure 2 shows the proposed site plan for constructing these affordable housing units per the GHTC under the PMAY. Figure 3 and Figure 4 show the typical wall illustrative sections for both scenarios.

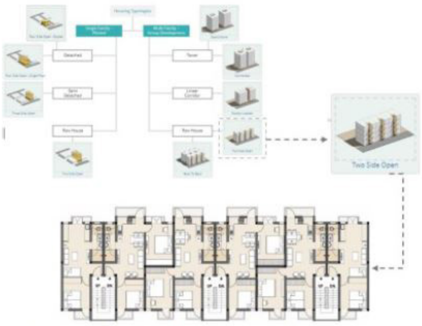


Figure 1: Building typical floor layout

Figure 2: Affordable housing site in Bhubaneshwar

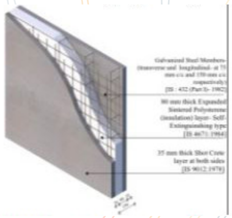


Figure 3: EPD core wall section

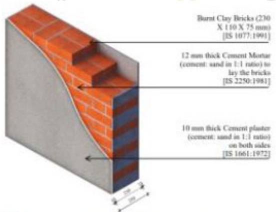


Figure 4: Brick wall section

2. Methods

2.1. Data collection

The outcomes of the study are mainly dependent on the quality of the Data. For the scope of this study, data collection has mainly two components, i.e., gathering data for conducting life cycle analysis and assessing thermal comfort. Most studies in the Indian context have gathered data from academic research papers and published reports [2,3], [17-21]. Some studies have also utilised EPDs(Environmental product declarations) of products in case it is relevant and available [19]. The studies conducted for the building sector in India use international data sources for performing the Life Cycle Analysis.

Further, embodied energy values are dynamic and region-specific, which may change according to the technology and transportation distances involved. Thus, to ensure the reliability of the results, the embodied carbon coefficient has been taken from various sources [1-3], [7,9,11,12], [16-21]. The architectural layout has been downloaded from the ENS replicable design tool on the ENS website [8]. For thermal comfort assessment, which requires energy simulations, the nearest weather station data is obtained with the help of a typical meteorological year weather file available online.

2.2. Data Analysis

As mentioned earlier, wherever possible, data is collected based on secondary sources such as academic research papers, technical reports and EPDs of products. This calls for a data quality check since each source brings a certain amount of uncertainty, and no single best value can be utilised to produce results [5,6,24]. Hence, a range of final carbon emissions has been produced to understand the possible emissions. All data sources have been scored based on a scoring system, as shown in Table 1 [14,15]. This clarifies the nature of each data source based on specific rules, as per ISO 14040.

Table 1: Pedigree matrix

Rule/score	**1**	**2**	**3**	**4**	**5**
Data Source	EPD of product	LCA database	Research paper/report	Other sources	-
Data Age	0-3yrs	3-5yrs	5-10yrs	10-15yrs	>20yrs
Technological completeness	A specific way of production	General industry methods	Innovation (pilot)	-	-
Geographical aspect	Sate specific value	Country-specific value	Continents specific	Globally used values	-
Functional unit	$kgCO_2/kg$	MJ/kg	kWh/kg	MJ/m^3	MJ/unit of material

Another layer of data quality check is usually done in a life cycle analysis to present a quantitative outlook. Uncertainty analysis is one such critical method of scientific research. It involves evaluating and quantifying the potential sources of uncertainty in data, models, and calculations used in a particular analysis. In life cycle analysis, uncertainty analysis plays a crucial role in assessing the environmental impacts of a product or process throughout its life cycle. It helps evaluate the robustness and accuracy of the results and enhances the credibility of the findings. Existing literature [16,19] used the classical statistical model to quantify uncertainty. In this, the uncertainty is expressed in terms of the standard deviation. The following equation has been used to quantify the uncertainty:

$$Uncertainty\ (u) = \sqrt{\frac{\Sigma[x_i - \mu]^2}{n(n-1)}}$$

Where,
x_i= i^{th} reading in the dataset
μ= Mean of the dataset
n= number of readings in the dataset
From the equation above, the percentage uncertainty is evaluated as follows:

$$Percentage\ Uncertainty\ (Pu)\ (\%) = \frac{u}{selected\ data\ point}\ x\ 100$$

2.3. Procedures

The procedure has been structured as per the required output from the study. The life cycle analysis of the selected stages has been conducted based on the data collected from various sources. This process helps give a range of possible embodied carbon values possible. The energy simulations help give the operational carbon emissions and state of the thermal comfort for the considered building. These results are then correlated and plotted against each other to understand the comparison between both construction scenarios for Bhubaneswar.

2.4. Life Cycle Analysis

As per ISO 14044 and ISO 14040, a life cycle analysis is conducted in a four-phase manner. First, the goal and scope of the study have been defined. The goal of conducting the LCA is to quantify the amount of CO2 emissions in the embodied and operational phases of a residential building. The System Boundary of the LCA is limited to the embodied and operational stages. The scope of the LCA is limited to one design typology (as per the ENS design tool for affordable housing [8]) for Bhubaneswar but for brick wall construction and EPS core technology. The inventory analysis is conducted where each product, in this case, each building material, is identified along with the quantities used. Each item is assigned its respective embodied carbon coefficient based on the data collection and analysis [16-21]. The quantity of the materials is calculated by creating a building information model based on the architectural layouts available. The impact assessment and interpretation of results are the last two phases of a life cycle analysis, discussed in Results and Discussion.

2.5. Thermal comfort assessment

The two different construction technologies in consideration have different thermal properties. Both envelopes have different materials with different physical and thermal properties. Therefore, both construction scenarios are expected to have different internal operative temperatures, resulting in different discomfort hours. An energy model is created based on the available drawings with all the necessary details to assess the situation. Data input in the energy model, such as schedules and internal loads, is based on assumptions and kept the same for both cases. Each flat in the building has at least one bedroom inside, modelled as a separate thermal zone, with the remaining other spaces as a different thermal zone. The model has been simulated for Bhubaneswar's four different available weather files. The results from the latest weather file are carried forward. The thermal zones assigned have been simulated as a naturally ventilated space to calculate discomfort hours.

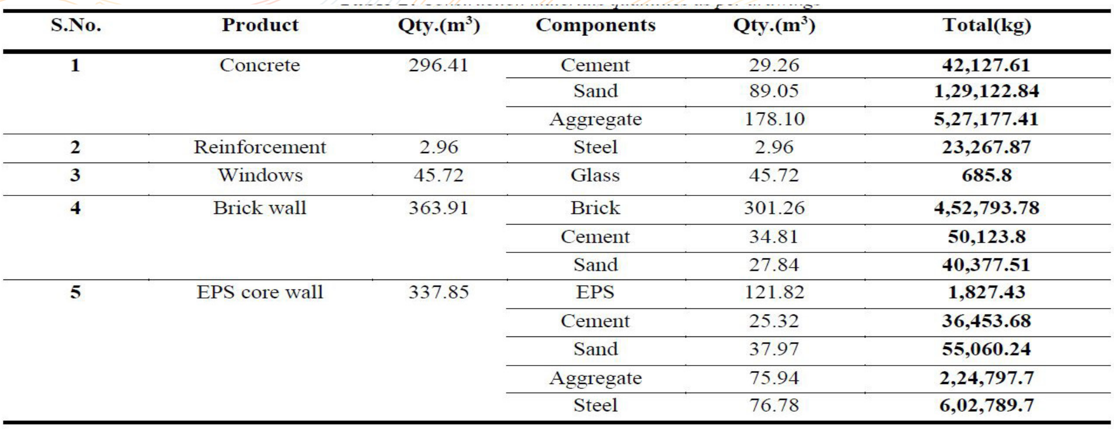
The natural ventilation logic provided is based on the set points provided as per the IMAC-R (Indian model for adaptive comfort-residential) model. The model is also simulated by inputting a packaged terminal air conditioning system with mixed-mode operation, meaning operating only when windows are closed. This is done by assigning the model a range of set points throughout the year. These set points have been calculated weekly for 52 weeks based on the IMAC-R. The AC operation is limited to inside the bedroom zones in all the flats. This is done to estimate the difference in energy consumption of the building and, hence, annual operational emissions for both construction scenarios considered.

3. Results

3.1. Uncertainty analysis and Embodied stage carbon calculations

Table 2 summarises the quantity and embodied carbon calculations for all the building materials based on the architectural drawings and various data points for embodied carbon factors. The quantity of each material has been estimated in kg. The embodied carbon factors have a unit of kgCO2/kg of material. Therefore, the quantities obtained are multiplied to obtain the embodied carbon emissions.

Table 2: Construction materials quantities as per drawings



S.No.	Product	Qty.(m^3)	Components	Qty.(m^3)	Total(kg)
1	Concrete	296.41	Cement	29.26	**42,127.61**
			Sand	89.05	**1,29,122.84**
			Aggregate	178.10	**5,27,177.41**
2	Reinforcement	2.96	Steel	2.96	**23,267.87**
3	Windows	45.72	Glass	45.72	**685.8**
4	Brick wall	363.91	Brick	301.26	**4,52,793.78**
			Cement	34.81	**50,123.8**
			Sand	27.84	**40,377.51**
5	EPS core wall	337.85	EPS	121.82	**1,827.43**
			Cement	25.32	**36,453.68**
			Sand	37.97	**55,060.24**
			Aggregate	75.94	**2,24,797.7**
			Steel	76.78	**6,02,789.7**

As mentioned earlier, the embodied carbon values for each material are obtained from multiple sources. At least six sources of data points were used for each material to calculate the uncertainty. Based on the uncertainty analysis, three scenarios have been created for reporting the total embodied emissions. Scenario 1 relates to total emissions when the data points with the slightest uncertainty have been multiplied by respective quantities of materials for total emissions. Scenario 2 is when the data points with median uncertainty have been multiplied with respective quantities of materials for total emissions. Scenario 3 relates to total emissions when the data points with maximum uncertainty have been multiplied with respective quantities of materials for total emissions. These scenarios make the emissions range possible within the maximum and minimum limits of correctness. Figure 5 shows the evaluation of embodied carbon values for both construction assemblies. The EPS core assembly has a significantly high embodied carbon value, with steel contributing to 96.7%, cement with 2.6% and EPS with 0.3%, respectively, of the total value.

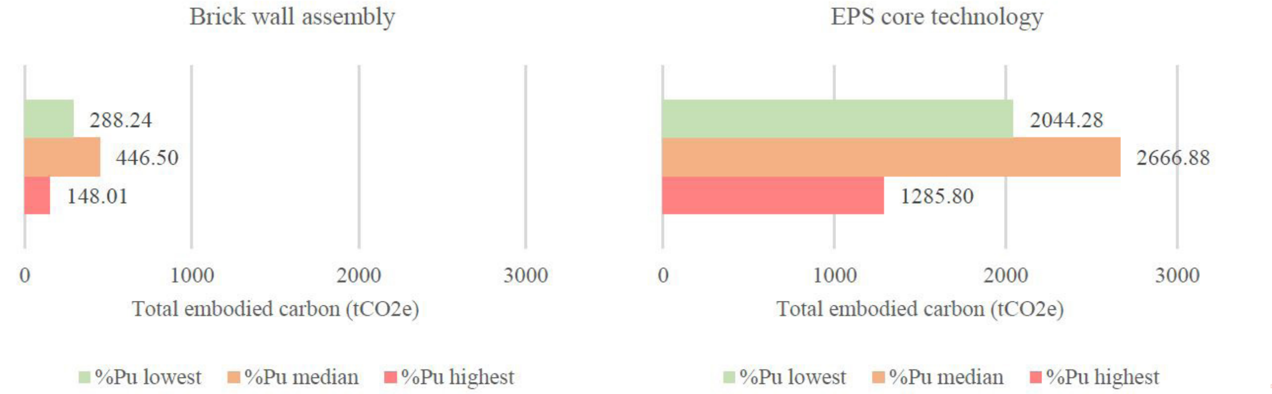


Figure 5: Brick wall assembly and EPS core technology embodied carbon

3.2. Thermal comfort and operational phase calculations

Figure 6 shows the degree of discomfort hours inside a single naturally ventilated zone in brick wall construction considered for the case. The upper and lower limits of the comfort band represent 90% acceptability rates for thermal comfort. The model has been provided with a set-point-based window operation logic based on the nature of outdoor ambient air temperature. From the graph, 2238 hours are uncomfortable throughout 8760 hours for the brick wall construction. Figure 7 shows the results of discomfort in the case of EPS core technology. For this case, a total of 1780 hours are uncomfortable throughout the year. The number of discomfort hours in EPS core technology is lesser due to better thermal performance. The additional insulation helps cut off heat gains and losses; therefore, internal temperatures are less frequently higher than Brick wall assembly. This also reduces the air conditioning load inside the space.

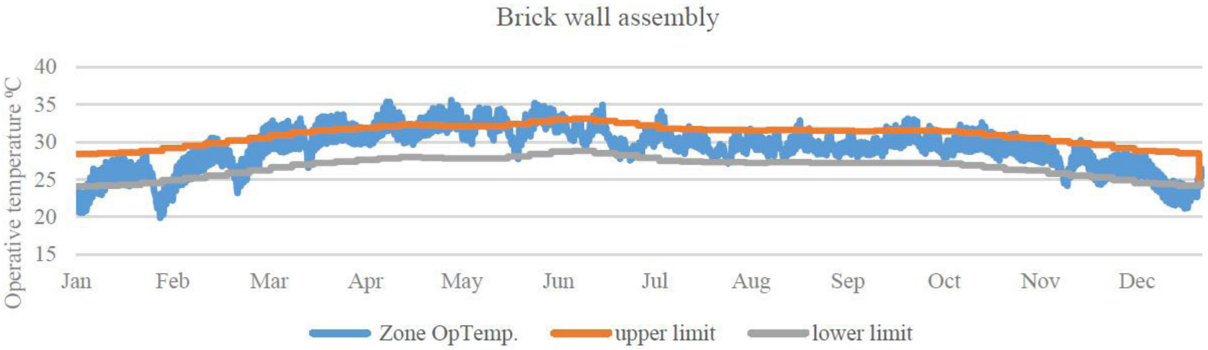


Figure 6: Operative temperatures for naturally ventilated space-Brick wall assembly

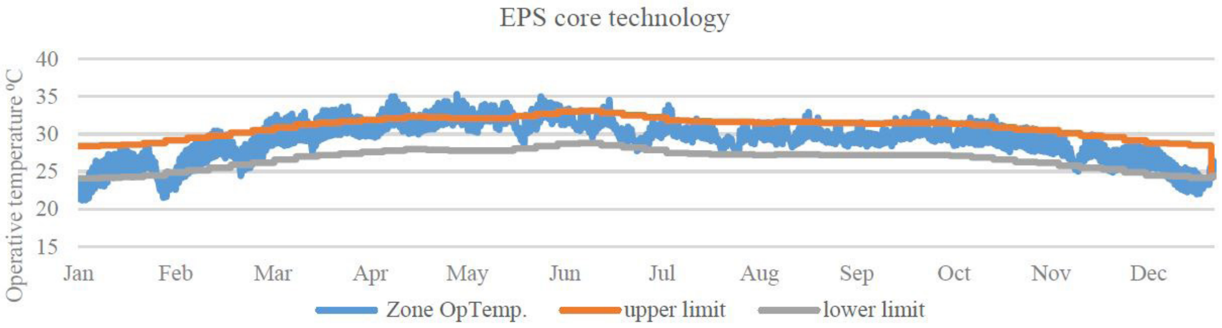


Figure 7: Operative temperatures for naturally ventilated space-EPS core technology

As discussed in section 2.5, the operational emissions are based on the operational electricity simulated based on the latest weather file selected for simulations. In India, electricity is majorly produced by burning fossil fuels such as coal. Coal-based electricity generation significantly contributes to building operational carbon emissions [4]. Therefore, to quantify the carbon emissions as part of the life cycle analysis, a characterisation factor denoted by kgCO2/kWh is required [4]. This factor varies geographically and technologically across the world. Central Electricity Authority of India (CEA) has compiled a database containing the necessary data on CO2 emissions for all grid-connected power stations in India [4]. As per the CEA, the national grid emissions are 0.91 kgCO2/kWh. However, this value might change in the future and might be an underestimation of the future emission scenarios, given that only coal-based power sources are used. Figure 8 shows the comparison of operational emissions between the two construction technologies. Brick wall construction has 11.32% higher emissions than EPS core technology. This is due to a lower thermal performance of the former envelope, resulting in higher cooling electricity consumption than the latter. As per the IPCC AR 6 report and India's commitment to achieve net-zero status, the years 2030, 2050 and 2070 are crucial [13]. Hence, the operational emissions have also been extrapolated for these three points.

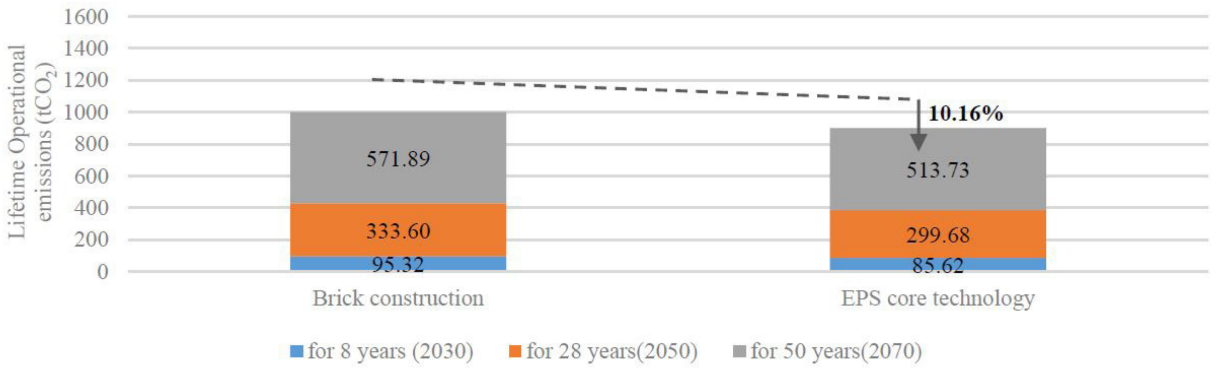


Figure 8: Lifetime operational emissions

4. Discussion

This section talks about the learning and findings of the study conducted by adopting a structured methodology and secondary data sources. The relation between thermal comfort and carbon emissions has been tried to understand from the results obtained. Figure 9 shows the obtained results from the simulation and life cycle analysis. At the cost of extra embodied carbon, the operational energy of the EPS core technology is less than a business-as-usual brick wall assembly. The discomfort hours have been calculated for a naturally ventilated space. The operational energy represents lighting cooling consumption with the air conditioner only in the bedroom in mixed-mode operation, with set points from IMAC-R. EPS core technology has a higher embodied carbon contribution, as compared to the embodied carbon of Brick, mainly due to the extensive amount of steel usage. The operational carbon emissions are lower for EPS core tech than Brick, owing to a better thermal performance of the envelope. The operational carbon for 50 years in the case of Brick is 98.8% more than its embodied carbon, indicating the necessity of using renewable energy sources for electricity generation for carbon offset purposes. The operational carbon has been calculated with the present emission factor available in the literature and data, which is projected to be a different value in the coming years based on technological changes.The discomfort hours are 25.73% less in the case of EPS core tech than in Brick, with 10.16% less operational carbon emission over 50 years. At the cost of almost seven times higher embodied carbon, EPS core tech is more thermally comfortable with less operational emissions than Brick Wall. The built-up area normalised embodied carbon for brick wall construction is 247.19 kgCO2/m², whereas, for EPS core construction, it is 1755.99 kgCO2/m². Similarly, the operational carbon for brick wall construction is 674.84 kgCO2/m², whereas, for EPS core construction, it is 606.21 kgCO2/m². These results are specific to Bhubaneswar since all the results are based on the climate profile of the city. The operational emissions and discomfort hours are expected to change for different locations across India.

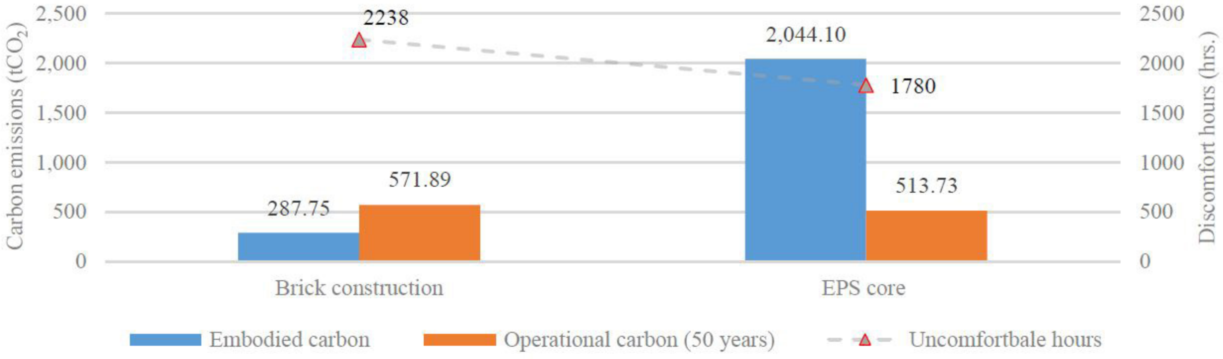


Figure 9: Relation between carbon emissions and thermal comfort

5. Conclusion

The findings of this study highlight the significance of considering multiple data sources with varying values to comprehensively present the results and understand the potential range of scenarios related to the outcome. Analysing data on embodied carbon values and operational emissions has provided a clear and valuable understanding of the situation within defined limits. However, it should be noted that life cycle analysis is susceptible to the quality of data used, and the results are critical in informing decision-making by stakeholders. This study's wide range of data sources has allowed for a more comprehensive analysis, considering potential inconsistencies. This approach has facilitated a more robust understanding of the research outcomes and their implications. Including data from diverse sources has ensured a more holistic assessment of the research problem and contributed to a more nuanced understanding of the complex relationships between different variables. These findings can serve as a valuable reference for policymakers, practitioners, and other stakeholders in making informed decisions about managing carbon emissions and sustainability efforts. This research study fills a critical gap in the existing literature by investigating the relationship between thermal comfort and carbon emissions in building materials, considering both embodied and operational emissions and showcasing a comparison between two different construction scenarios. The findings highlight the need to further study various materials and their thermal performance and carbon emissions to establish a direct correlation, if any, between thermal comfort and carbon emissions. Further research on studying more materials and considering other climate zones will help advance the understanding of carbon emissions and their link with comfort.

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