Regionalizing the Environmental Impact of Bamboo-Based Buildings by Integrating Life Cycle Assessment with Geographic Information Systems. A Comparative Case-Study in Colombia.

E. Zea Escamilla[1]*, G. Habert[1]

1. Institute of Construction and Infrastructure Management, Chair of Sustainable Construction, Federal Institute of Technology (ETHZ), 8093 Zürich, Switzerland

* Corresponding author. Tel.: +41 44 633 71 14. E-mail address: zea@ibi.baug.ethz.ch (E. Zea Escamilla). Postal address: ETH Zürich. Institute of Construction and Infrastructure Management. Chair of Sustainable Construction. HIL, Room F 28.2; Stefano Franscini Platz, 5; 8093 Zürich, Switzerland

Abstract

The present research aimed to develop a methodology to regionalize the environmental impact associated with the production of bamboo-based buildings by integrating life cycle assessment methodologies and geographic information systems for a case study in Colombia. The data were regionalized at three levels: Global –representing three levels of production efficiency of the materials; Regional – resenting the type of electricity mix used in the production and national transport distances at the country level; and Local – representing factors such as seismic and wind risk zones at the city level. The functional unit for the LCA was defined as an 18 m^2 core shelter unit considering only its structural elements. The life cycle inventories for five designs were calculated, each using a distinctive construction material: bamboo, brick, concrete hollow block, ferro-cement panels, and soil stabilized bricks. The results showed that under certain conditions, the environmental impact of a low performance bamboo house can be achieved by a high performance block house. The effect of the external constraints (earthquake and wind) were analysed, and their effect on the whole life environmental impact was assessed. The results show that in most cases, the buildings with high technical performance can achieve high environmental performance. It is possible to conclude that the use of GIS enables the development of regionalized LCA data for buildings with a high degree of consistency. Moreover, the proposed approach was able to accurately represent the range of production practices encountered. Finally, the use of the proposed methodology can allow the assessment of building design in the early stages where the uncertainty is the highest, identifying the improvement potential of each design and recognizing the structural needs for specific locations.

Keywords: LCA, Bamboo, GIS, Buildings, Transport Distance, Regionalization

Introduction

In recent decades, life cycle assessment (LCA) was developed and established as the main methodology to quantitatively assess the environmental impact of goods and processes throughout their entire lives. The models used in LCA propose a cause-effect relationship between the environment and human activities and highlight their impacts and consequences(Hellweg and Mila i Canals 2014). LCA has been used to assess the environmental performance of buildings and construction materials for more than 20 years (Fava 2006);however, its application has been limited to Europe. LCAs of non-load-bearing, bamboo-based construction materials (BBCM), such as flooring (Vogtländer et al. 2010), and loadbearing materials in bamboo based buildings(Murphy et al. 2004), supporting structures(van der Lugt et al. 2009), and load bearing bamboo walls (Zea Escamilla et al. 2013)have been conducted. These studies have shown the potential that bamboo-based construction materials have to produce environmental savings. The results can also be related to the potential that these materials have to sequester and store CO_2 emissions (Archila-Santos et al. 2012; Riaño et al. 2002; Vogtländer et al. 2013). The main challenge of these LCA studies had been data quality and availability. To address these challenges, several studies have proposed the regionalization of data using Geographic Information Systems (GIS)(Gasol et al. 2011; Liu et al. 2014; Mutel et al. 2011).

The LCA of buildings presents many complexities; for example, LCAs should be conducted at the early design stages when it is still possible to make substantial changes to the design(Hellweg and Mila i Canals 2014) but at the cost of higher uncertainty of which construction materials will be used, the performance of production and the distance they need to be transported. Moreover, the LCA of buildings is influenced by external environmental constraints, such as earthquakes and wind, that influence the whole life environmental impact of a building directly. All of these factors create a complex yet very local setup for the assessment of the whole life impact of building designs. The present paper explores the use of GIS on the regionalization of the life cycle assessment of buildings, proposing a methodological approach to account for local variations on production efficiency, electricity mixes, transport distances and external environmental constraints by integrating the life cycle assessment impacts of construction materials and buildings on a geographic information system. To achieve this, LCA datasets were developed for bamboo-based construction materials (BBCM) to represent the global diversity of production practices (Zea Escamilla and Habert 2013). Furthermore a methodological approach to use these datasets was developed to conduct the LCA of buildings worldwide, including the possibility to assess the environmental savings potential from the use of bamboo and other construction materials in buildings (Zea Escamilla and Habert 2014). The present paper expands this approach, placing special emphasis on the impact associated with construction materials' transport distances and how different transport regimens affect the whole life environmental impacts of buildings for a case study in Colombia.

Data and Methods

The proposed case study is a comparative LCA in which five house designs were assessed at twelve locations in Colombia, South America (Figure 1). This country was selected for several reasons; first the locations of the production centres for bamboo, cement, and steel are well documented. Second, the size of the country and its regional administrative units are large enough for the proposed methodology to produce meaningful results. Finally, the building codes in Colombia include bamboo-based construction and regulate its application and design (AIS 2004).

Figure 1 Colombia -- Case study geographical location

The functional unit for the LCA was defined as an 18 m^2 core shelter unit considering only the load carrying elements in the assessment. This approach is used to reduce the uncertainty produced by elements such as doors and windows, of which the selection and use is not connected to the type of construction material used. This core shelter is the minimum housing unit defined by the International Federation of Red Cross Societies (IFRC 2013). The functional unit's main dimensions are presented in Figure 2.

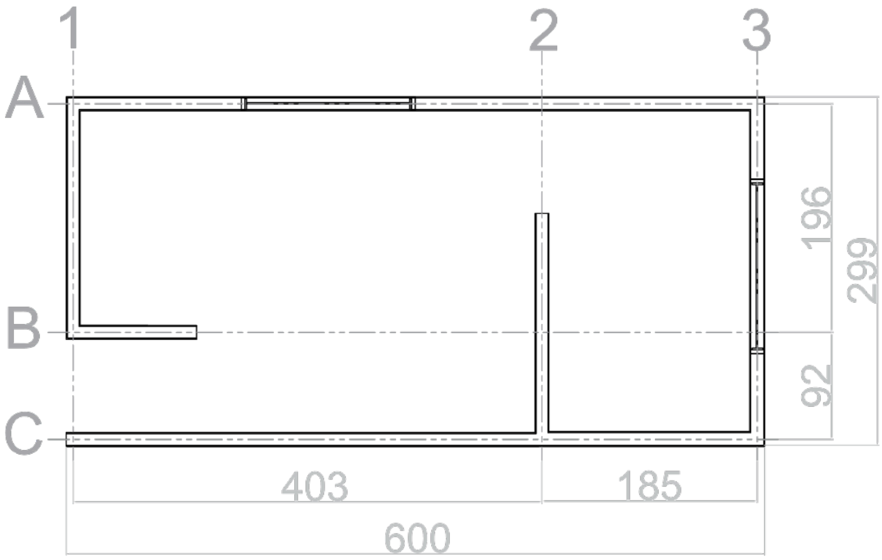
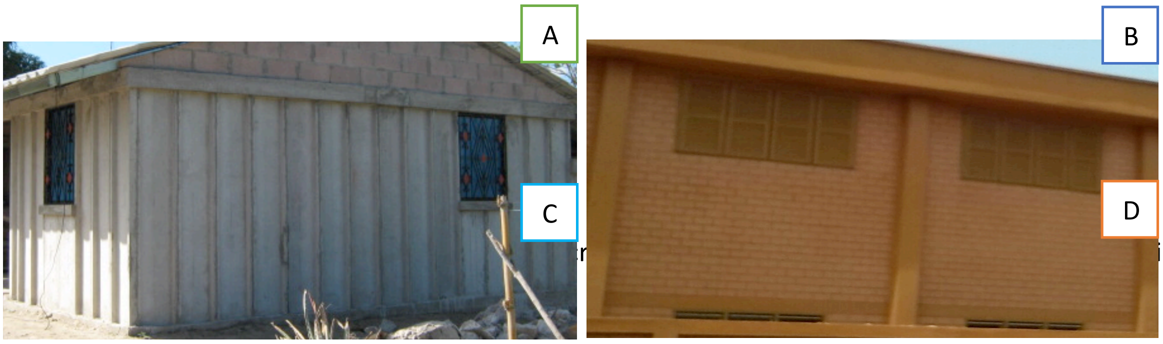


Figure 2 Functional Unit -- General Floor Plan. All measurements in cm.

The life cycle inventories (LCI) for five house designs were calculated based on the functional unit, each using a distinctive structural construction material: bamboo frame (Bahareque), brick, concrete hollow block, ferro-cement panels, and soil stabilized bricks, as seen in Figure 3.



The life cycle inventories (LCIs) showing the material demand for the erection of each house design are presented in table 1.The calculation of the life cycle impact assessment (LCIA) data was performed using the evaluation method IMPACT2002+(Jolliet et al. 2003) and the software SIMApro7.3 (Pre-Consultants 2012).

Table 1 LCIs of the five house designs

Materials	**Block House**	**Bamboo House**	**Brick House**	**Ferro-cement House**	**Soil-cement House**
Bamboo pole	0.0	160.0	0.0	0.0	0.0
Flattened bamboo	0.0	397.8	0.0	0.0	0.0
Brick	0.0	0.0	5307.0	0.0	0.0
Concrete block	3816.0	120.0	0.0	0.0	0.0
Ferro-cement panel	0.0	0.0	0.0	3002.7	0.0
Soil stabilized brick	0.0	0.0	0.0	0.0	5605.1
Reinforcing steel CN	1604.4	524.9	893.8	798.1	690.2
Concrete	2878.3	8800.0	2878.3	2878.3	6397.7

Source: Authors

Three levels of geo-referenced data were developed: global, regional, and local, as seen in Figure 4. The global level represents data that are valid worldwide, such as the amounts of material per functional unit and the range of production efficiencies of construction materials. The regional level contains data that can be linked to the specific country or administrative unit of study, such as the electricity mix and transport distances for construction materials from their production centre to the target city. The local level represents data of seismic risk zones and wind risk zones where the buildings can potentially be built. The approach to operationalize the methodology contains three interconnected steps: regionalization of the LCIA; the building's LCA; and identification of seismic and wind risk zones (Fig.4).

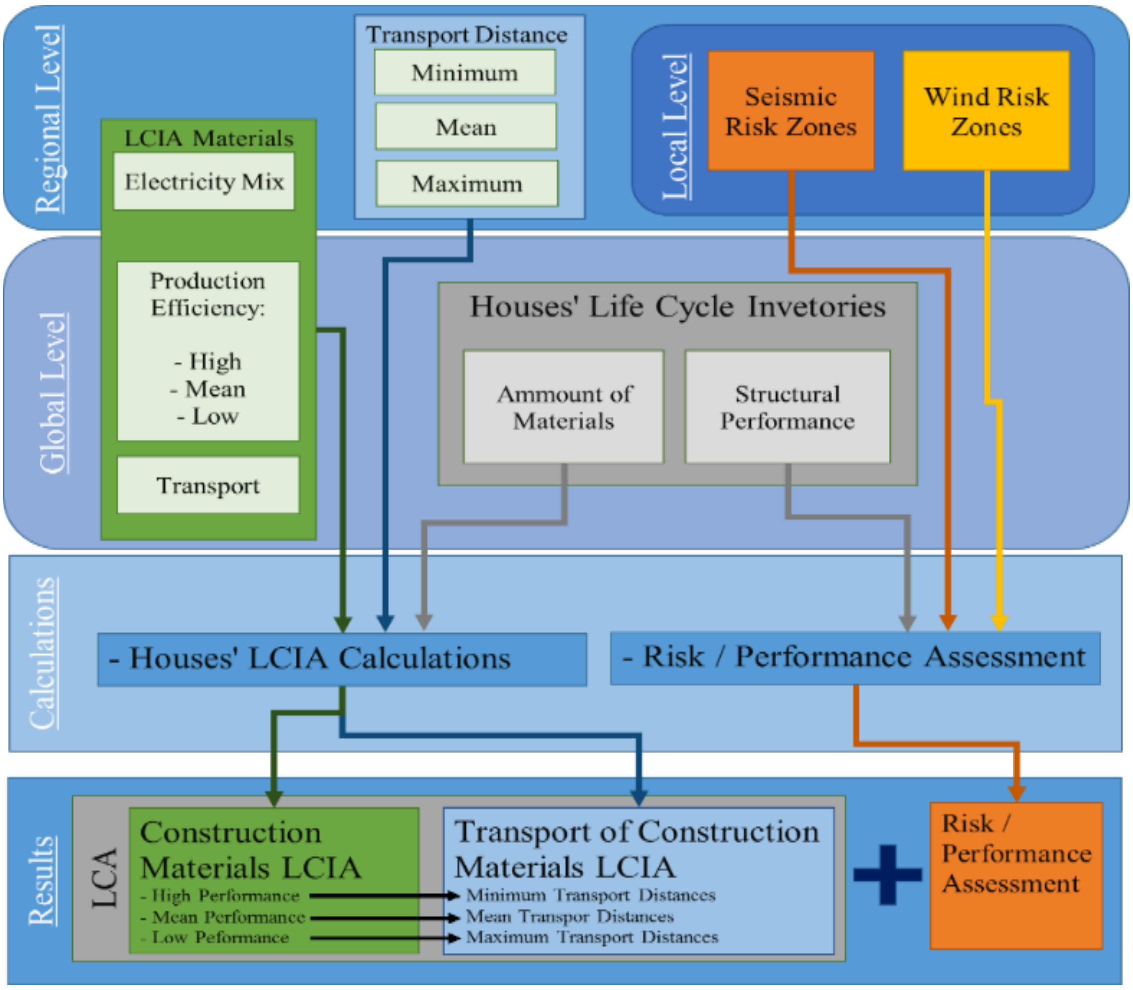


Figure 4 Methodology's conceptual framework.

3.1. Regionalization of LCIA

The first step in the regionalization of the life cycle impact assessment (LCIA) data was to calculate the environmental impacts under three scenarios for a construction material's production efficiency: high performance, mean performance and low performance, using the specific electricity mix for Colombia. Furthermore, the work of Zea et al.(2014) identified the transport of construction material as a major contributor to the environmental impact of buildings. These impacts were related to the size of the country, but they generated a high level of uncertainty in the results. To reduce the uncertainty, in this project, the transport distances were calculated specifically to the centres of the production of bamboo, cement and steel in Colombia. These centres were identified and geo-referenced using the GIS software ArcMap. Using the spatial analyst features, the geodesic distances between the target city and the production centres was calculated. This approach provides only an approximated value, but it is more cost effective than solutions based on transport network analysis. Furthermore, the transport distances for other construction materials considered as local were calculated based on the size of the *department* on which the target city was located. With this information, three ranges of transport distance were established for each house design (Figure 5): minimum (closest production centre), median (production centre in the middle) and maximum (farthest production centre). The transport distances of construction materials have a high degree of uncertainty. Nevertheless, the present research proposed a consistent method to relate the area of the country or administrative unit and the potential transport distances occurring within their borders. This approach is not 100% correct, but it reduces the uncertainties related to transport distances significantly.

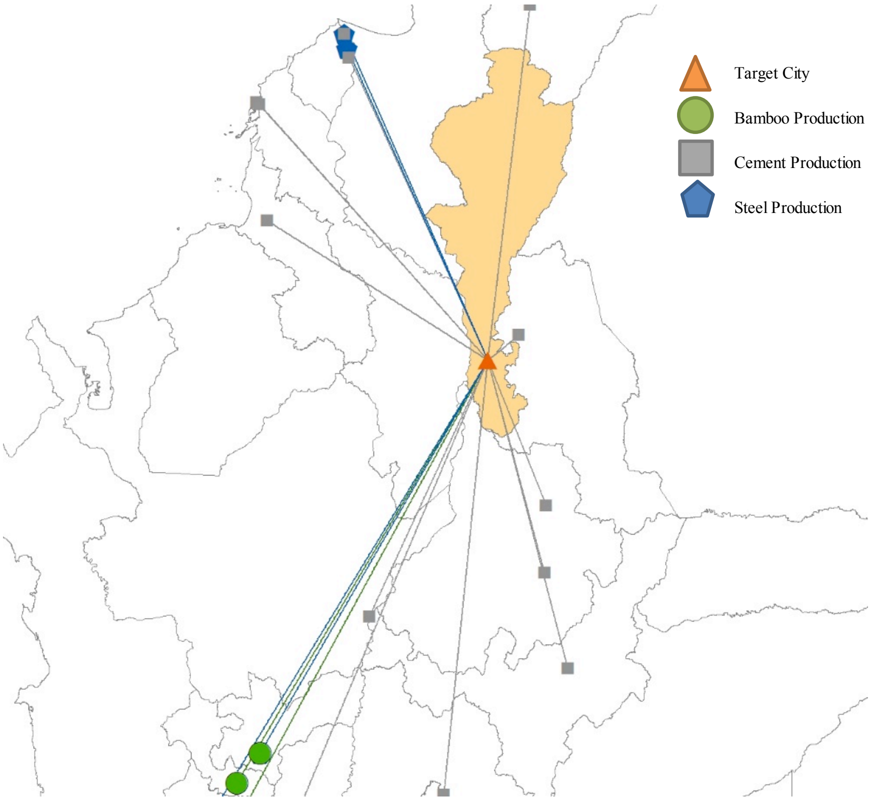


Figure 5Transportdistances – example.

3.3. Building's LCA

With the values for the impact from transport and the regionalized impacts from the production of construction materials, the life cycle impacts we reassessed by adding the regionalized environmental impacts of materials per functional unit and the environmental impacts from the transport of materials from their production centres to the target city. Three values were produced. Low performance considered the maximum transport distances and the lowest production efficiency. Mean performance considered the median transport distances and the mean production efficiency results. High performance considered the minimum transport distances and the high efficiency production of construction materials.

3.4. Identification of seismic and wind risk zones

The final step in the calculations was to identify the seismic risk and wind zones on which the studied city was located. This calculation was achieved using spatial analysis tools and geo-information from the database. Based on this information, an external environmental constraint factor was defined for each location and further compared with the structural performance of the studied house. Then, the difference between the external constraint factor and the structural performance was calculated. If the factor was equal to the performance of the house, it was considered that such structure would perform appropriately for the external constrains (earthquake and winds). If the factor was larger than the performance, then the structure would be at risk of collapsing under the external loads, requiring a revision of the structural design or the selection of an alternative design. Finally, if the factor was smaller than the performance, it was considered that the house would withstand the external loads but would over perform.

Results

The LCAs of the five proposed house designs were calculated in 12 locations in Colombia, considering three levels of production efficiency and three transport distance ranges, and the results are shown in Figure 6. The three scenarios of production diversity of construction materials of high, mean and low performance were represented by a band (Fig. 6), with the high performance being the lower line and the low performance the higher line. The X-axis represents the total tons of construction materials times the total transport distance in kilometres (t*km). From these results, it is possible to see that with short transport distances, the variation in the results is smaller than with higher transport distances. In the cases with the largest transport distances, the variation in the results is mainly driven by the impact of the transport of the materials (Fig.6). Not only is the level of impact influenced by the transport distances but also the difference between these impacts. This means that in some cases, the "bamboo house" has a higher impact than the "concrete hollow block house", and the difference between their impacts also changes depending on the transport distance range.

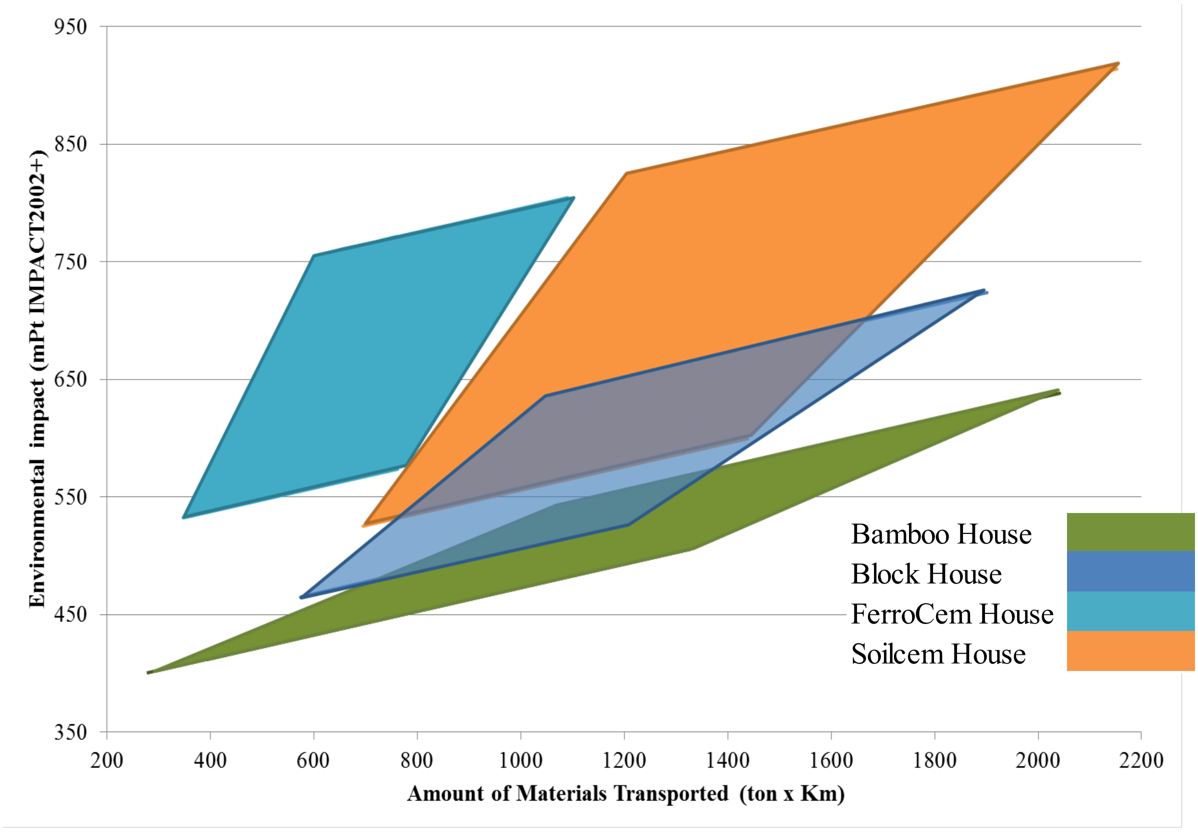


Figure 6Environmental impacts at different transport regimes.

The "brick house" has the highest impact and was excluded from the results to improve the readability. The results of the bamboo, concrete hollow block and ferro-cement houses are in a similar range, indicating that under certain conditions, the environmental impact of a mean performance bamboo house can be achieved by a high performance block house. Thus, the environmental performance of a given construction technique cannot be directly correlated to the use of specific construction materials but to its appropriated use at the specific location, the efficiency of production and the transportation of construction materials. This can be seen in Figure 6, where the bands for bamboo and concrete hollow block overlap between ca 700t*km and 1300t*km.

To better understand these results, the contribution to the environmental impact of the five house designs was calculated (Fig.7); this Figure shows the average values for the 12 locations, representing all transport distance ranges and production efficiencies. These results show that the construction materials contribute approximately 70% of the impact, whereas the transport of the construction materials represents between 15% and 30% of the impact, depending on the house design. Moreover, in most houses, the reinforcing steel is the main contributor to the environmental impact of 30% to 40%. This result suggests that special attention needs to be paid to the possible transport ranges that might occur in a project (transport distances) and also to the external environmental constraints of seismic risk zones and wind loads (structure reinforcement).

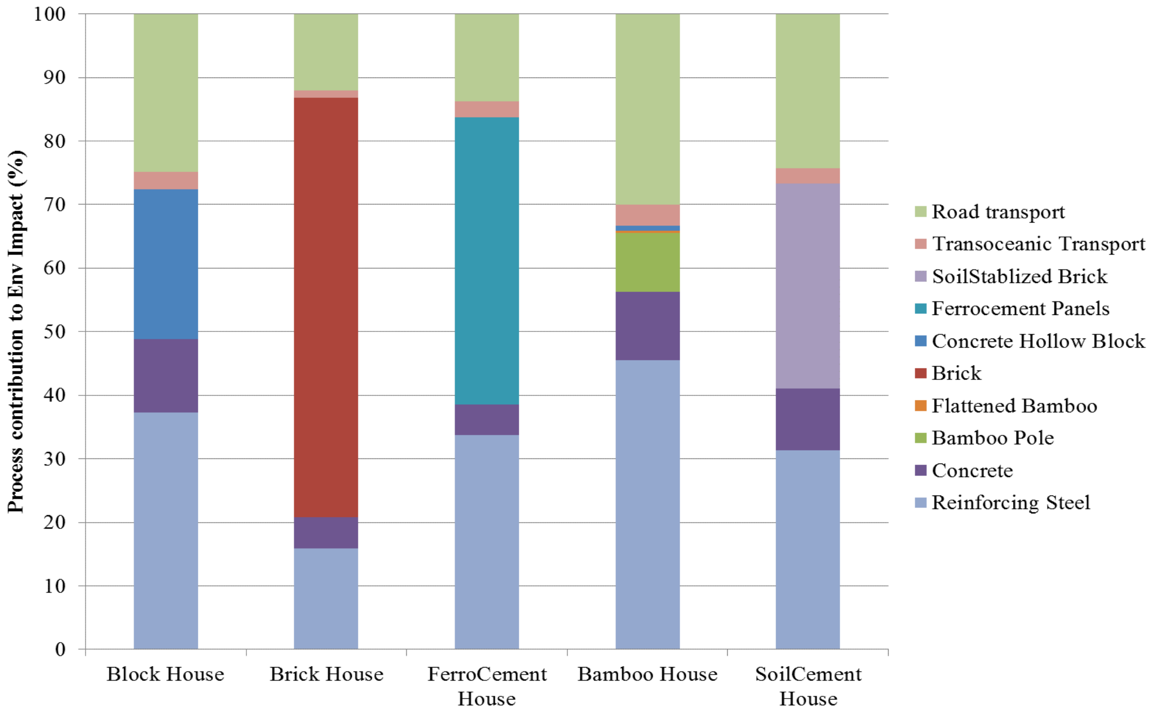


Figure 7 Contribution to environmental impact.

The analysis of the contribution to the impact showed that the impact of transporting the construction materials increased from approximately 10% at short transport distances to 30% for the ferro-cement and brick houses, 45% for the block house and 55% for the bamboo house. In all cases, the components of concrete contribute the most to the impact of transport.

Finally, the effect of the external environmental constraints was analysed. Each location has its distinctive requirements for both earthquakes and wind loads. A colour range from red to green was used to identify the performance as seen on Figure 8. Red indicates that a given house design would underperform for the seismic/wind demands of the location. Yellow is used to represent an appropriate performance where the house will withstand the external environmental constraints. Finally, green represents a house that would over-perform at a given location. The “bamboo house” has often both a lower environmental impact and a better structural performance. However, in some cases, its impact is much higher than the benchmark design and still has better structural performance. This feature can support the decision-making process when choosing appropriate constructive systems and house designs for specific locations, allowing a decision maker/designer to prioritize between environmental impact and structural performance, depending on the local conditions.

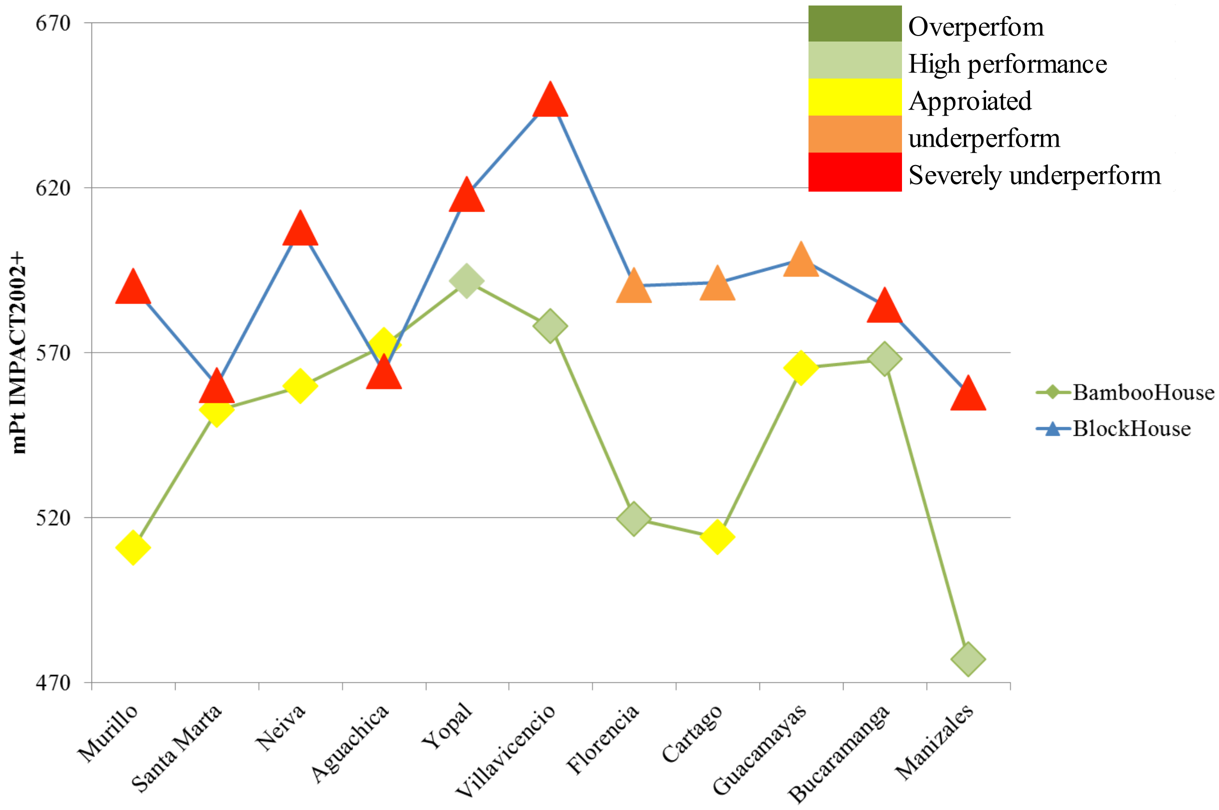


Figure 8 Environmental and structural performance at different locations.

Conclusions

The proposed methodology represents the local granularity considering country-specific transport distances from centres of production to target cities. Furthermore, the proposed approach was able to accurately represent the range of production practices encountered in the case study. The results showed that under the high performance scenario, the bamboo house presents the best environmental performance, independent of the transport distance. Finally, the use of the proposed methodology can allow for the assessment of building designs in the early stages, where the uncertainty is the highest, identifying the improvement potential of each design and recognizing the structural needs of specific locations.

1. Acknowledgements

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