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Spatial life cycle energy model of dwellings within a bioregional context

Initial steps

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ABSTRACT: A bioregional approach to Life cycle energy analysis provides an opportunity to balance the hegemonic role of international standards over ecological principles in order to establish more appropriate sustainable indicators of building materials in housing. The use of Input-Output based hybrid method for the calculation of the Embodied Energy includes accurately energy intensities of national economies, while a Bioregion also sustains the environmental framework of local realities in terms of related socio economic and cultural value which can be incorporated in process analysis. Using life cycle energy analysis and taking a house as an entire system, this research adopts a multi-method systems approach that in turn requires an integrated model to perform its function. This paper will present the first stage of a Spatial Life Cycle Energy Model (SLCEM) based on Geographical Information Systems (GIS) to merge scientific and local values in order to provide a common language through the analysis of thematic maps. A cradle-to-cradle system boundary is considered in this research. The feasibility of this approach is shown in this paper with the selection of a case study in a Mexican bioregion.

Keywords: Life Cycle Energy, Bioregions, GIS, Building Materials, Embodied energy

INTRODUCTION

The construction industry requires 60% of the total raw materials used worldwide. These materials follow different processes during their manufacture until their final use in buildings, and buildings consume 40% of the annual global energy in their life cycle stages [1]. The energy involved in these processes is called the embodied energy for manufacturing a product and operational energy for that used by users. Both energy approaches attempt to measure the energy consumption and the environmental impact of greenhouse gas emissions associated with them. In order to fulfil this function, Life cycle assessment (LCA) which is based on international ISO 14040 standards is currently one of the most popular tools used by researchers within the environmental management. However, its complexity and limitations have been challenged when socio cultural values and place-making are not taken into account [2, 3].

A more comprehensive and holistic strategy is required which considers both quantitative and qualitative approaches. Hence the inclusion of a bioregional concept into Life cycle energy analysis which provides an opportunity to balance the hegemonic role of international standards over ecological principles in order to establish more appropriate sustainable indicators of construction materials in housing.

The aim of this study is to present initials steps towards the calculation of the embodied energy of building materials and the potential process of mapping their intensities based on Geographical Information Systems (GIS) at a bioregional scale [2]. This approach allows the identification of energy patterns related to local manufacturing processes and dwellings construction activities in order to minimize their impact.

BACKGROUND

The choice of a case study in a Mexican bioregion is based on the high demand of new housing, where close to one million homes are built every year [4]. Until now policies in the built environment of that country attempted to reduce the operational energy by improving the housing thermal performance based on local energy efficiency norms, NOM-008-ENER-2001, NOM-018-ENER-2011, NOM-020-ENER-2011. However, there is still not criteria for the selection of building materials in terms of their embodied energy.

A bioregion represents an ecological approach in sustainability and is considered as a “large area defined by its natural physical characteristics, not by man-made political boundaries.” A bioregion can be also defined based on natural patterns within a specific area with geographic and topography features, climate, native plants and animals, soils; landforms and watersheds where people live [5]. Although the watershed is a key ecological criteria in bioregionalism, there is no general agreement about how define its boundaries. However, in spite of this inconsistency, regional scales are considered as appropriate “for natural resource management and progressing sustainability where ecological functioning and human activities most intensely interact" and where the influence of decision makers and community participation can be best applied in this case [6].

Within the built environment, bioregionalism has the potential to complement current national distribution of building materials extending the perspective of regional land use and local economic development [3]. Furthermore, taking into account cultural factors, the use of local natural resources, the need to reduce transportation of building materials, the adaptability of local construction typologies and their potential for re-use or recycling will naturally ensure a selection of lower energy building materials in that area. Bioregionalism could also help to reduce energy consumption in housing, although this approach has not been well developed. Some supporters state that only local knowledge is required to understand this concept. However, the potential integration with science can provide the neutral approach that a sustainable assessment based on bioregionalism needs [7]. Some background understanding follows to help locate this approach in relation to passive low energy housing.

Life cycle energy analysis (LCEA) represents a systems approach towards sustainability. It is a calculation procedure to consider all energy inputs during all stages of the building lifespan. LCEA is considered to be a simplified version of LCA and is used to quantify the environmental impact of buildings taking energy as the only indicator to assess CO_2 equivalent emissions. It is underpinned by the embodied energy concept.
Embodied Energy (EE) is considered as the total consumption of primary energy over the life cycle of a building material, where the different stages for its production are broken down for specific analysis. Extraction of raw materials, manufacture, and transportation are the most common stages of this process, also known as a Cradle to Gate system boundary [8]. Embodied energy is gaining interest in the built environment but, there is still not agreement on its calculation methods, suggesting that analyses based solely on EE are not reliable yet.

One main method for embodied energy calculation is;
Process based analysis. This method collects selected data for a product analysis in order to identify the system boundaries and requirements of direct and indirect energy involve in its process [9]. In order to know these requirements the process analysis follows a classification well-known by researchers of energy levels (Upstream stages) established by the International Federation Institute for Advanced Studies [10]. However, in spite of the capability of this method several studies showed that even extensive process based analysis does not achieve enough completeness for embodied energy analysis where time consumption and truncation errors present significant limitations [11, 12]. Input-Output analysis (IOA) relies in the usefulness of national data for planning and decision making. IOA has been accepted worldwide in economics because of its comprehensiveness. In the built environment, this economic theory relies on Input-Output tables from national accounts that turn economic data into energy flows by applying energy tariffs. Hence, the Embodied energy is calculated by "multiplying the cost of the product by its energy intensity resulting in MJ or GJ/(£,$, etc. national currencies) [13].

Despite the apparently completeness of Process and IOA methods, these traditional approaches have shown considerable limitations. More recently, hybrid methods have been incorporated as a more accurate approaches to compensate weaknesses and shortcomings associated with traditional process and IOA [14]. The two main variations of hybrid approaches are Process based hybrid analysis and Input-Output based hybrid analysis which is considered "nearly perfect" in the study of low carbon buildings life-cycles, although it is known that no method available is entirely accurate, [13].

METHODOLOGY

Given the complexity of a LCEA and taking a house as an entire system, this research has adopted a multi-method system approach to analyse the embodied energy which in turn requires an integrated model to perform its function.

Given the lack of data, to calculate the embodied energy of a house located in Mexico an initial question was raised where to start when no data is available at all to carry out a life cycle energy analysis of Mexican building materials? Should embodied energy coefficients from databases such as the Inventory of Carbon & Energy (ICE) or New Zealand building embodied energy be used? These databases provide very useful parameters for the initial consideration of some building materials. However, they do not represent the realities of construction activities as they are calculated using only a cradle to gate system boundary. This does not reflect the entire life cycle of the Mexican housing, which includes transportation and recycling.

Hence, rather than use external sources, an IO based hybrid methodology was selected for this study to identify the most important energy paths of the Mexican construction sector which will be used later for a more detailed process analysis. The following three initial steps represent the current developing of a spatial life cycle energy model of dwellings within bioregional area in Mexico.

1. Identification of the most commonly used building materials in the Mexican construction sector: for the selection of the bioregion case study and life cycle energy inventory, the first step taken was to identify the most used construction materials through the national territory of Mexico. Statistical data from a survey carried out by INEGI [15] was taken and turned into maps with ARCGIS 10 software in order to display spatial representation in terms of quantity and proportionality.

2. For representation of materials within the national territory according to the bioregional criteria of watershed, topography, ecology, climatic, cultural and socioeconomic, a case study area was defined within the Morelia region. This bioregion is located at Michoacán state in central Mexico and has an area of 3831.75 km^2. Given that bioregional areas are not political boundaries, a Kernel density analysis with spatial analyst tools from ARCGIS was used to calculate its population and the total number of houses in the case study area. Later in this research these data will be used to statistically calculate the operational stage of the life cycle energy analysis. The bioregional area was also used to identify activities related the construction sector. These activities represent processes of socio economical local practices which will be incorporated at a later stage within the IO model during the further development of this research. Simultaneously a survey of people's building material preferences is ongoing to incorporate cultural values within the model proposed.

3. The first stage of the LCEA is the derivation of initial embodied energy intensities which were calculated through excel spreadsheets, based on the Input-Output based hybrid model developed by Treloar [16]. This model required the developing of IO analysis using the symmetric Input-Output tables from the Mexican national economy accounts [17]. The input-Output tables from the Mexican economy were calculated and mapped proportionally using the code scheme of the North American Industry Classification System, (NAICS). USA, Canada and Mexico adopted this common system in 1997 to allow statistical comparison between countries. These tables are published by the National Institute of Statistics and Geography (INEGI). The latest version uses 2003 as a base year.

The code scheme represents economical activities of the different aggregation levels of a sector. For embodied energy calculations, this code scheme identifies energy flows of the industrial sectors and calculates their total energy intensities TEI (equation 2) through the derivation of direct and indirect requirement coefficients DEI (equation 1). In this research we adapted this coding system to extract data from the (I-O) model and export them to GIS for the mapping process.

(Equation 1)

$$\varepsilon_n = \sum_{e=1}^{E} D_{en}\ x\ tariff_e\ x\ PEF_e$$

Where if n is an energy supply sector, then $\varepsilon_n = 0$, and;
ε_n= the direct energy intensity of the target sector, n;
E= is the number of energy supply sectors, n;
D_{en} = the direct input of each energy supply sector into the target sector, n;
$tariff_e$= the national energy tariffs in units of energy per \$MX peso, and;
PEF_e= the primary energy factors

(Equation 2)

$$X_n = \sum_{e=1}^{E} T_{en}\ x\ tariff_e\ x\ PEF_e$$

Where if n is an energy supply sector, then $\varepsilon_n = 0$, and;
X_n= the total energy intensity of the target sector, n;
E= is the number of energy supply sectors, n;
T_{en} = the total requirement coefficients for inputs from energy supply sectors;
$tariff_e$= the national energy tariffs in units of energy per \$MX peso, and;
PEF_e= the primary energy factors

(Equation 3)

$$X_n = \varepsilon_n \sum_{i=1}^{N} D_{in}\left[\varepsilon_i + \sum_{j=1}^{N} D_{ji}\left[\varepsilon_j + \sum_{k=1}^{N} D_{kj}\,[\varepsilon_k + \ldots]\right]\right],$$

Where *n, i, j* and *k* are any stage 0, 1, 2, and 3 sectors respectively, and;
X_n= the total energy intensity of the target sector, n;
ε_n= the direct energy intensity of the target sector, n, and so forth (for *i,j* and *k*);
N= the number of sectors (equal for *n,i,j,* and *k*); and
D_{in}= the primary energy factors

The extraction of energy paths (equation 3) from the IO tables is the main contribution of Treloar's research. This algorithm allows the modification of energy paths within the IO model with more detailed data from process analysis at any stage of the calculation without affecting its completeness [16]. This study identified that the codification scheme of NAICS can be used along with equation 3 for the mapping representation of energy intensities at any upstream stage of the different sectors.

RESULTS

The results presented in this paper only show the initial process for mapping embodied energy intensities of construction materials. Full analysis of the bioregion approach inclusion into LCEA will be presented later in a more detailed way.

1. The following thematic maps display the spatial representation of building materials in terms of quantity and proportionality in the Mexican territory.

Construction materials are broken down according to structural housing components for the mapping process; Walls (Fig. 1), Roofs (Fig. 2), and Floors (Fig. 3).

For walls, the results (Fig. 1) showed that solid; Brick, Block, Concrete and stone are the predominant construction material across the country (86%), while adobe (6%), wood (5%), reed, bamboo, and metallic sheet materials are used less.

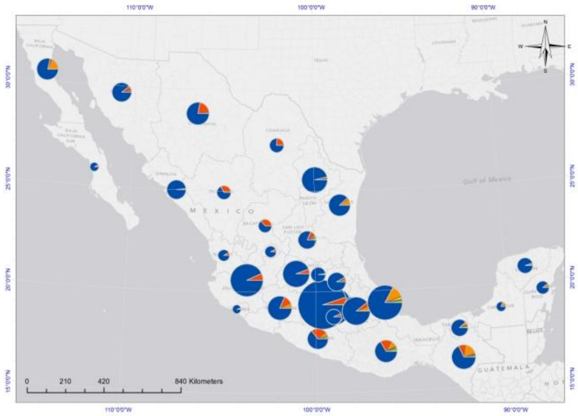

Figure 1: Wall materials distribution and use proportionality

For Roofs, the results (Fig. 2) again showed that reinforced concrete is the prime material (71%). Metallic Sheets is the second most used material (13%), while asbestos sheets are still in use (5%) despite potential toxicity. Wood (3%), cardboard sheets (2%), and Palms and rammed earth (1% each) are minimal in use.

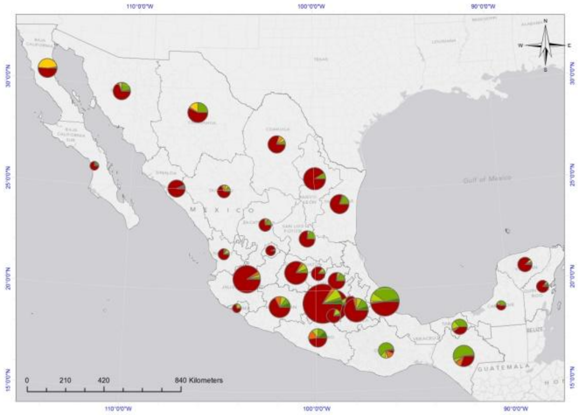

Figure 2: Roof materials distribution and use proportionality

Finally, the Floor results (Fig. 3) showed that concrete slab and cement floors predominated (53%). Wood, ceramic tiles and other covering make up (41%), interestingly rammed earth still represents (5%) of flooring within the national territory.

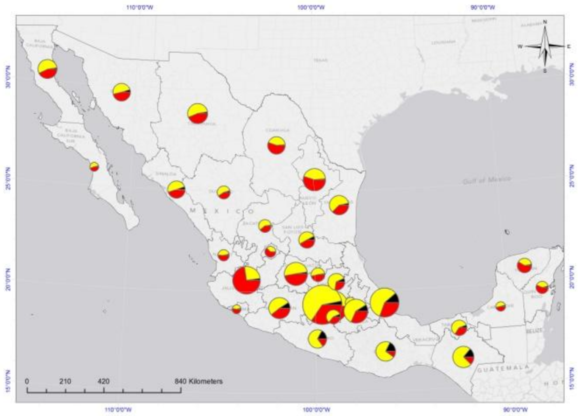

Figure 3: Floor materials distribution and use proportionality

2. Bioregion; the bioregional selection showed a population density for the case study area of 267.43people per km^2, with a total of 1,024,751 million inhabitants, while in housing the total number is 364,483 with a density of 95 dwellings per km^2, however, most of these houses are located in Morelia city, See (Fig. 4).

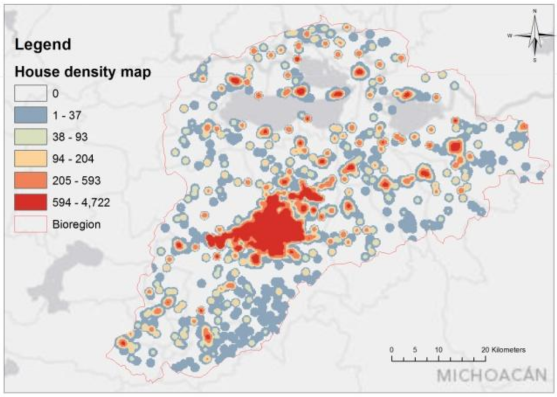

Figure 4: Bioregion Housing density map

The bioregion case study also identified and codified, with georeferenced precision a total of 5,295 economical activities related with the residential sector. These activities also represent potential factors for the inclusion of a more detailed process analysis, indicative of local and socio economical values that will be incorporated within the Spatial Life Cycle Energy model as displayed in (Figs. 5 and 6). Both maps show embodied energy intensities of brick clay and concrete production based on results of the (I-O) model.

3. Embodied Energy; the initial IO analysis showed the proportion of the total energy intensities (TEI) of 76 Mexican industrial sub-sectors (2 supply energy sectors; Electricity and Gas, are excluded). EE was calculated

using equation 2, while Direct (DEI) and indirect energy intensities were calculated using equation 1.

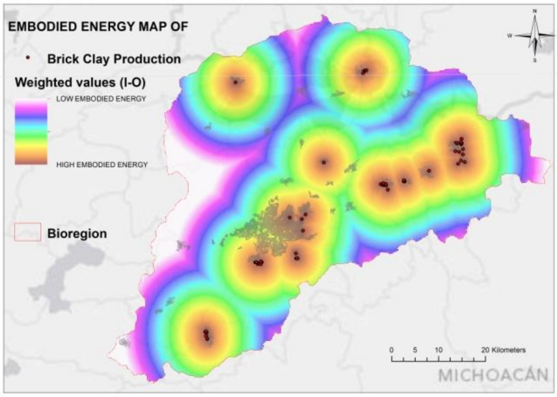

Figure 5: Embodied energy weighted representation of brick clay production within the bioregion

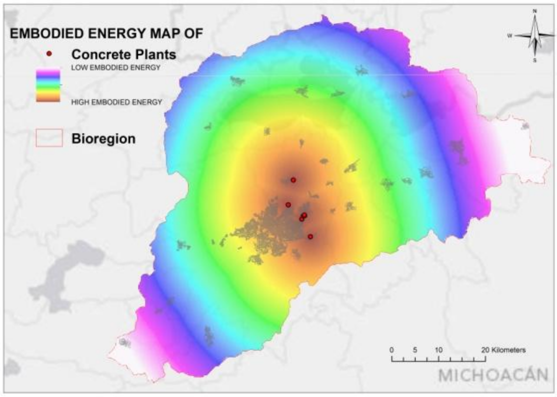

Figure 6: Embodied energy weighted representation of concrete plants production within the bioregion

The line graph (Fig. 7) shows a column on the right which correspond to codes of some of the 76 Mexican industrial sub-sectors according to the North American Industry Classification System (NAICS). The black line (code 236) represents the construction sector of the Mexican economy. It shows the embodied energy in the five main upstream stages to build a house, from the extraction of raw materials to the construction phase [10]. This means that only 29.30% of the total energy was used in a direct way during the construction, and the rest is the invisible (embodied energy) that was used for the production of the different building materials or components from which the house is built.

As a reference of this study, a different pattern can be found in the Australian residential sector as shown in (Table 1). This is because of the way of input-output tables are made and the way energy is used in construction processes en each country.

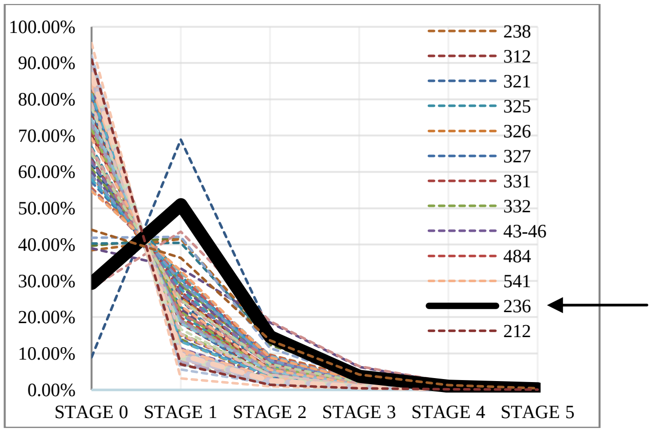

Figure 7: Proportion of the total embodied energy of the Mexican residential sector.

Residential housing (Embodied energy upstream stages)							
	DEI	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage n
Mex	29.30%	51.20%	14.64%	3.67%	0.98%	0.27%	.....
Aus	17.0%	43.8%	26.6%	7.9%	2.9%	1.1%	

Table 1: Embodied energy comparison between Mexican and Australian residential sectors based on IO analysis.

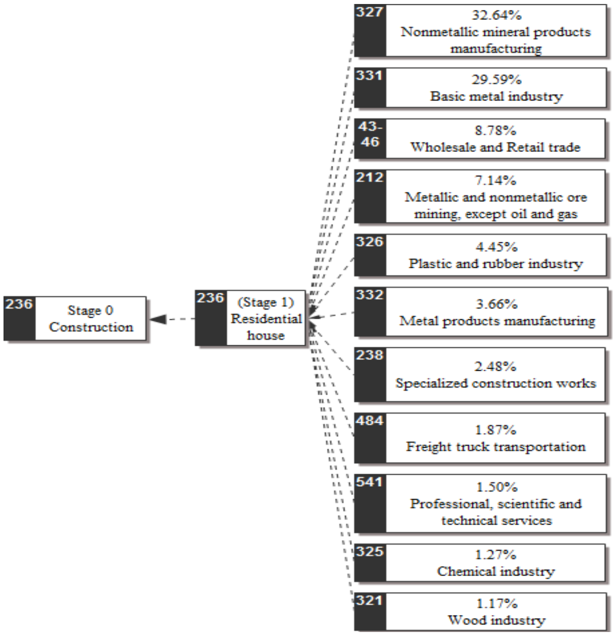

Figure 8: Top energy paths of the Mexican construction sector at Stage 1

In order to find which building materials contribute the highest energy intensities to the residential sector in Mexico and in the bioregion specifically, equation 3 was used. In this upstream stage 1, the top 11 sub-sectors that are involved directly were identified from the total of the 76. For example (Fig. 8) shows that the sector 327 (Non-metallic mineral products manufacturing) significantly represents 32.64% of this invisible energy with products such as concrete, cement, brick, glass among others. To calculate any component or a single material, the same process has to be repeated until stage 5, which according to results showed in (Fig. 7) and Treloar's research, an Embodied energy analysis beyond this stage is not necessary [16].

CONCLUSIONS

Given that this is ongoing research, this paper only shows the initial steps developed in order to uniquely perform a LCEA of the Mexican construction sector. The inclusion of a bioregion scale rather than a national or urban is an innovation in LCEA of dwellings and the results of this adaption will be showed forward in a more detailed way. However, it is expected that natural boundaries will present a significative effect for a better localisation and use of local resources, cutting down on unnecessary transport that conventional methods of LCEA cannot perceive to ensure the selection of lower embodied energy materials to build a house.

The literature review showed that analysis based solely on EE methods is not reliable yet because of the inherent weaknesses in their methodologies. However, according to the process presented here, it is feasible that the bioregional approach could enhance its potentiality as a more tailored sustainable indicator.

This study also identified and suggested the potential to encode the energy path algorithm developed by Treloar to display georeferenced energy intensities of products and activities in a namely bioregion. Here it is also suggested that Geographical information systems GIS might fulfil this function where an ecological approach such as Bioregion and a system thinking such as LCA could be merged to help low carbon building designers specify more appropriate materials in relation to embodied energy.

The fact that the embodied energy of goods and services is invisible to the human eye represents a challenge to scientists, mapping embodied energy intensities in all the system boundaries of a house, represents a bridge for science communication between experts and stakeholders in terms of decision making and participatory processes, which is the ultimate goal to reduce o mitigate CO_2 emissions associated with the built environment.

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