ANALYSIS OF MATERIAL AND ENERGY EFFICIENCY OF MEXICAN, PERUVIAN AND DUTCH DWELLINGS USING THE THREE-STEP-STRATEGY

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Summary

Buildings consume resources and produces emissions to the environment during their life cycle. They consume materials during their construction, maintenance and renovation activities, consume energy and water during their use, and produce waste at the end of their useful life. There are several sustainable building methods for environmental assessment; the results of these depend on the approach taken and therefore also on the objective or endpoint of the assessment. The most common strategies aim at reducing their impacts, but buildings will always have an environmental load. Therefore, to calculate the absolute damage of a building to the environment, as it is done in the Life Cycle Assessment may be considered inadequate for assessment when the objective is to improve the environmental performance of the building from design. The three step strategy is an option being a method that focuses on a different approach. This strategy establishes that for a sustainable use of resources, three steps are necessary: a) to reduce the need or use of resources, b) to use renewable sources to sustain the need and c) to be efficient with the remaining need. The method has advantages and disadvantages related to accuracy, data needed, output, and interpretation of results. In this research, the method is applied on case studies. Dwellings are analyzed to improve their environmental performance with the objective to point out at the limitation of the method in relation to its applicability and usability.

1. Introduction

Construction is considered one of the activities that contribute the most to the environmental burden. During its life cycle, a building consumes resources and releases emissions and waste into the environment having great responsibility for fossil fuel consumption and global warming (Edwards, 1996). The materials used in buildings also have a significant influence on the environment; concrete and steel having the greatest impact. In addition, these materials are the most intensively used on a global scale. Cement production emits greenhouse gases that contribute to global warming, while steel is one of the most energy-intensive materials (UNEP-IETC, 2002). The manufacture and final use of these materials is also water intensive.

The environmental burden and the quality of the building both depend on the interaction of the building with its surrounding environment. This interaction is defined from the design phase of the building. The type and quantity of resources used for the building, such as materials, energy and water are partly determined by design. In addition, the conditions of the indoor environment also depend on the design. Furthermore, the life cycle of the building is influenced by early decisions. The efficiency of maintenance, renovation and demolition activities will be defined by the potential of the building to allow such activities.

Design is an essential part of the construction process. If designed properly, dwellings can promote well-being of the occupants and ecological sustainability (Lawson, 1996). During this phase, environmental issues can be better incorporated. The design of the building determines the potential for good environmental performance during the entire life cycle (during maintenance, renovation and demolition activities).

An environmental assessment of the building is needed to determine the potential impact of the building on the environment. There is a great variety of environmental building assessment methods (Itard & Klunder, 2007), but these often have limitations that can cause uncertainty in the results or be ineffective in the assessment. These assessment methods, originally developed to calculate the environmental impact of buildings, are now used for design purposes (Ding, 2007). These methods can contribute to better understanding a building's impact on the environment, being most useful when the materials, construction processes and systems are chosen. Nevertheless, these methods may be unsuitable for a design analysis because they do not provide information on the choices made during the design of the building.

This study uses a method that allows analysis of the performance of the building in relation to design choices based on the Indicator Approach by Rovers (2005). This study was part of the Atlas Project (Rovers).

The impact of housing on the environment in three countries is assessed to point at the major environmental problems. Since this is a quantitative method, reference houses are needed. The reference houses were defined with the aid of demographic statistics and legislation. Reference houses were selected as representative of the average house. The reference dwellings provide examples of the most common building materials used. These examples are analysed focusing on materials and energy efficiency.

2. Methodology

2.1 The Approach

The approach followed for assessing the environmental performance is based on the Three Step Strategy. The strategy provides detailed information about building characteristics and has a direct relationship with design. The aim of the Three Step Strategy is to limit the inflow and outflow of resources and to retain for a longer time the incoming flows within the system (Hendriks, 2001). In order to decrease the environmental impact there are three steps that must be followed: reducing volume flows, using renewable sources, and being efficient with the remaining need. This is suitable for analysing the potential environmental impact of choices made during the design process because it provides detailed information about different aspects of the design of the building and point at the problems or areas for improvement. This study focuses on the resource efficiency of materials and energy.

2.2 Materials

An essential part of the design process is the selection of materials based on their sustainability (Jong-Jin & Rigdon, 2007). Materials possess characteristics that make them more or less sustainable in relation to the phases of the material's life cycle: pre-build, build, and post-build.

Hendriks (2001) and Jong-Jin and Rigdon (2007a) identified criteria for choosing construction materials according to their environmental sustainability. They group the criteria in the three phases of the life cycle of building materials: Pre-building, Building and the Post-building phase. The criteria for the Pre-building phase include the use of materials that produce a limited amount of waste and emissions during their manufacture, have low embodied energy, have a high content of recycled materials, and prevent depletion of natural stocks. The criteria for the Building phase are the use of non- or less toxic materials, with high durability, usability, reparability, safety, energy efficiency, and ability to withstand calamities. The criteria for selecting materials in relation to their performance in the Post-building phase are the use of materials with high potential for recycling and reuse, a low deterioration rate, and a long technical lifespan.

Most of the methods for determining the sustainability of materials (Hendriks, 2001) focus on the post-use or post-building phase of the life cycle of the building, Table 1 shows the methods and literature used. They are presented according to the steps of the Three-Step-Strategy.

Table 1 Summary of approaches to choose materials based on their sustainability

	Indicators		
	Material efficiency (2.2.1)	Renewability (2.2.2) and impact to environment (2.2.3)	Dismantling and reusability
Three Step Strategy	Step 1: Reduce need	Step 2: Use of renewables	Step 3: Increase efficiency
Hendriks	Avoid depletion of natural stock	Use materials with less emissions	Reuse materials Use materials with higher usability, reparability, and longer lifespan
Jong-Jin and Rigdon	Reduce waste	Reduce emissions Use materials with low embodied energy Higher recycled content Use of natural materials	Reuse materials Recycle material Use materials with longer lifetime
Design for recycling	Use fewer materials	Use of recycled materials	Design for dismantling Identification of materials

Sources: Hendriks (2001), Jong-Jin & Rigdon (2007)

Only the first two steps of the Three-Step-Strategy are considered in this paper. Therefore the objectives are to use fewer materials and to use renewable materials or materials with low embodied energy and emissions. In the present study, the following indicators are used:

2.2.1 Material efficiency: total embodied materials per useful living area. The quantity of embodied material consumption as a consequence of the design can reduce the demand on virgin resources and the production of waste, thereby reducing the environmental impact and energy and water consumption when needed for extraction and manufacturing (Jong-Jin & Rigdon, 2007a).

2.2.2 Renewability of materials: quantity of renewable materials. In a human perspective, a material is only considered renewable if it can be grown at a rate that meets or exceeds the rate of human consumption (Jong-Jin & Rigdon, 2007b). Non-renewable materials are materials that have a slow growth rate in relation to the consumption of the material for human activities.

2.2.3 High impact materials and low impact materials: embodied materials with high or low impact to the environment. Low impact materials have a low or no impact on the environment during their manufacture, requiring less processing and less embodied energy. High impact materials are those whose manufacture requires significant use of resources, high embodied energy and high production of emissions.

2.3 Energy

The design of the building plays an important role in energy consumption. The thermal properties of the building determine the energy use for heating and cooling. Another important characteristic of the building is the natural lighting of spaces; the better the natural illumination, the less energy is needed for artificial lighting.

According to the Three Step Strategy the steps needed are: reducing the use of energy, using renewable energy, and being efficient with the remaining need. This paper only focuses on step one. The energy indicators used are the following:

2.3.1Total energy consumption refers to the total consumption of energy per household. It includes energy used for artificial lighting, indoor climate, and for appliances, cooking and water heating. It is important to make a difference between primary energy and delivered energy. The efficiency of the generation of energy is given by the percentage of energy that is lost during the production and transport of energy. For this approach, only delivered energy is taken into account because the designer has little choice in the type of energy used, and therefore on the energy efficiency of the source (Rovers, 2005).

2.3.2 Energy used for heating or cooling: delivered energy used for heating or cooling per useful living area.

2.3.3 Energy use for artificial lighting: delivered energy used for artificial lighting per useful living area.

2.3.4 Energy used for appliances, cooking and heating water: delivered energy for appliances, cooking ans heating water per useful living area.

3. Reference dwellings

The goal of the international analysis is to place housing in a broader context for a better understanding of the situation. The dwellings used for the analysis are a Mexican reference house, a Peruvian reference house as defined in the Atlas Project (Wageningen University, http://www.iconwise.com/ue/), and a Dutch reference house.

The objective of the analysis is to determine the effects of different construction methods on resource consumption and sustainability. The institutional, cultural and social contexts are not deal with in the analysis. The goal of the analysis is to help to analyse housing design in relation to its context. Therefore the differences between the countries do not cloud the analysis but make it more useful. Nevertheless, the climate is an important factor affecting the performance of the dwelling therefore degree days are used to normalize the temperature in the three countries. The reference houses are introduced in next section. Table 2 summarizes the characteristics of the reference houses.

3.1 Mexican dwelling

In Mexico there is a great variety of climates due to its land extension, mountains and coasts. The climate in the selected area of study is semi-cold. Mexico City, Toluca, Tlaxcala, Puebla and Morelia are some of the cities with this climate. For the case study, the city of Toluca was chosen. The cold climate is due to its high altitude at 2,680m above sea level. During the night, temperatures can drop below 0^{o}C even in summer, and the maximum temperature rarely exceeds 27^{o}C.

Statistical data was used for the selection of the reference dwelling. The reference dwelling consists of a single-family row dwelling set over two floors. On the ground floor there is a living/dining room, separate kitchen, and toilet with sink. On the first floor there are three bedrooms and two bathrooms. The dwelling has continuous stone footing, confined masonry walls of fired clay units and reinforced concrete elements, reinforced concrete floor and roof, and a layer of gravel in roof as insulation.

Electricity produced in a thermoelectric plant is used for artificial lighting and appliances. For cooking and heating water the most common fuel used is gas. To calculate energy consumption in modern houses, a collection of data from a small sample of similar houses with different family composition was realized.

3.2 Peruvian dwelling

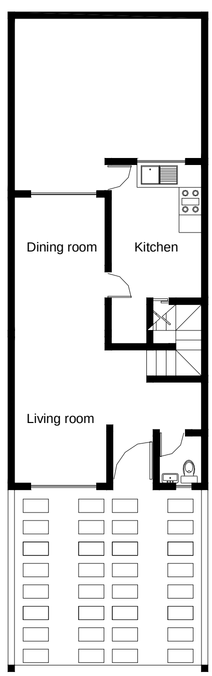
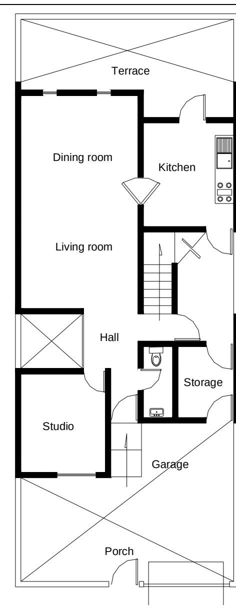
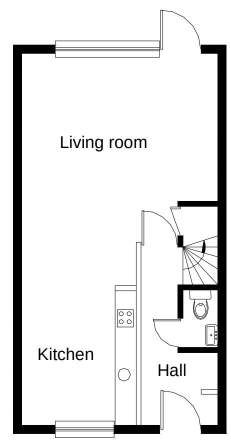
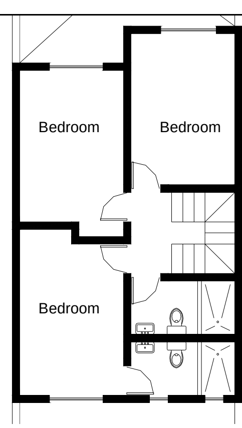
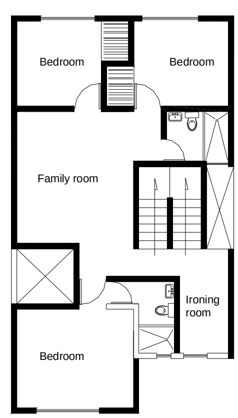
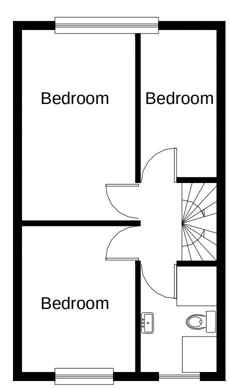
Most common type of construction in Peru is the self-build, carried out by the owners of the dwelling. The Peruvian case study and the data for the analysis was taken from Torres Mendez (2005), where a reference dwelling in the city of Lima was defined according to the typical construction processes, layout and construction procedures in the city. It is a three-level single-family dwelling with concrete with steel reinforcement footing, concrete with steel reinforcement beams and columns, walls of hollow clay and gypsum units. Energy consumption is based on a 5 person household.

3.3 Dutch dwelling

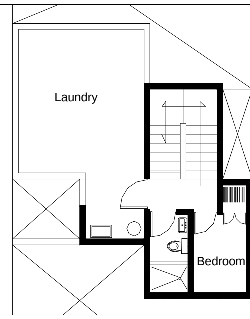
In the Netherlands, 70% of the housing stock consists of single-family dwellings. The Dutch case study was taken from the reference houses defined by the Agency for Sustainability and Innovation (Senternovem). In the Netherlands, reference dwellings have been defined and are widely used for comparative quantitative research. For this research, the “attached” house was chosen because it represents the average dwelling.

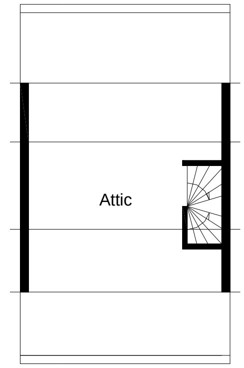
Data on energy consumption was obtained from the KWR survey (Ministry of VROM, Netherlands), and it represents the mean value for row houses with a four-person household. The dwelling consists of concrete and steel beams and poles footing, beams and columns made of concrete and steel, exterior walls made of double layer cavity gypsum walls with mineral wool or meranti insulation, interior walls made of gypsum walls filled with wool or fibre, wooden roof with concrete and ceramic tiles.

Table 2 Reference dwellings in Mexico, Peru and the Netherlands

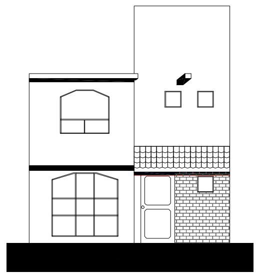
	Mexican dwelling	Peruvian dwelling (*1)	Dutch dwelling (*2)
Useful Living Area	108m^2	214m^2	111m^2
Average outdoor temperature	10^{o}C–15^{o}C	18^{o}C	5^{o}C–18^{o}C
Layout	Row single-family dwelling over two floors	Two levels and service area on third floor	Row single-family dwelling
Electricity	Electricity generated in thermoelectric plants	Electricity generated in thermoelectric plants	Electricity generated in thermoelectric plants
Water boiler	Low efficiency boiler (turned on all day)	Electric boiler (turned on for 2 hours per day)	High efficiency boiler
Energy for heating water	LPG	Electricity	Natural gas
Energy for cooking	LPG	Natural gas	Natural gas
Number of occupants	4	5	4
Kg/m^2 material	2126.92	1405.27	1068.87
MJ/m^2 energy per year	282.96	82.66	756.15 (*3)
Ground floor			
Second floor			

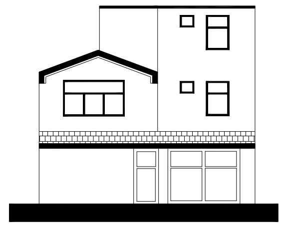
Second floor

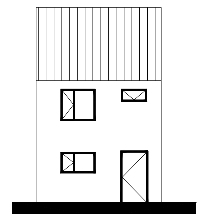




Facade







Sources:
(*1) Peruvian dwelling: Torres Mendez (2005)
(*2) Dutch dwelling: Senternovem (2005)
(*3) KWR Survey, Ministry of VROM

4. Analysis of material efficiency

4.1 Material efficiency and renewable, recovered and non-renewable materials

The Mexican reference dwelling is more material consuming than Peruvian and Dutch reference dwellings, the Dutch reference dwelling being the less material consuming. High impact materials are intensively used in all dwellings, due to concrete elements and ceramic bricks. All of the dwellings have a minimal percentage of renewable materials, which are mainly used in windows and doors. The Mexican reference house performs better than Peruvian or Dutch houses in terms of the origin of the material because of the higher percentage of low impact material from stone masonry footing used in Mexican dwellings (Figure 1).

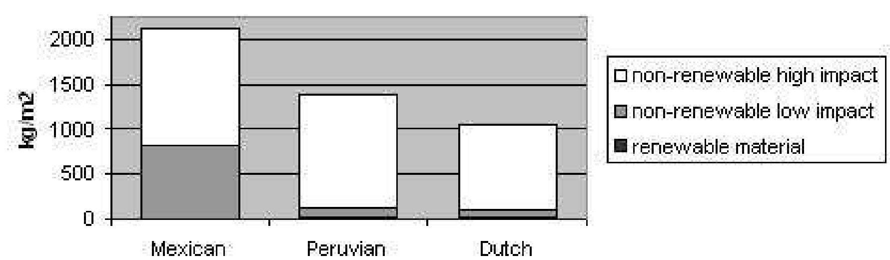


Figure 1 Percentage of renewable, non-renewable, high impact and low impact materials

4.2 Material efficiency of building elements

Figure 2 shows material use per useful living area per building element and the impact of the materials on the environment. Finishes are not shown in the graph.

Footing in Mexican housing is twice the weight of footing in Peruvian dwellings and more than triple that of Dutch houses because in Peruvian and Dutch dwellings, footing is made of concrete with iron reinforcement while footing in Mexican dwellings consists of continuous stone masonry along all walls, which increases the weight of the foundation.

Structural elements are more material consuming in the Mexican reference dwelling's walls than in the Peruvian and Dutch reference dwellings walls. Mexican vertical structural elements consist of confined masonry walls with horizontal and vertical reinforcement elements made from reinforced concrete. In addition, a higher percentage of walls in Mexican housing are structural walls. Materials used in structural walls in Mexican dwellings double the amount of materials used in walls in Dutch dwellings. The supporting elements in Peruvian housing consume half the quantity of material used in vertical structural elements of Dutch housing.

Non-structural elements in Mexican housing in comparison with Peruvian housing are lighter, given that a high percentage of walls in Mexican housing are structural. Nevertheless, non-structural walls are also made of solid brick with reinforced concrete confining elements. In Peruvian housing all the walls are non-structural; therefore consumption of materials for these elements is high. Non-structural walls in Dutch housing are very light in comparison to Peruvian non-structural walls. The weight of all vertical elements in Mexican housing is more than double that in Dutch housing and around 30% greater than in Peruvian housing. The large difference in weight between Mexican and Peruvian vertical elements and Dutch vertical elements shows that masonry structure accounts for a high percentage of material used in housing, while light walls, as in the Dutch case study, are more material efficient.

Materials in roof in the Mexican dwelling are lighter than in the Peruvian and Dutch dwellings because the roof tiles in Mexican housing do not need beams. Although Peruvian dwellings have concrete tiles like Mexican dwellings, roof tiles in Peruvian housing are hollow; therefore the use of beams increases the weight of roof tiles in Peruvian dwellings.

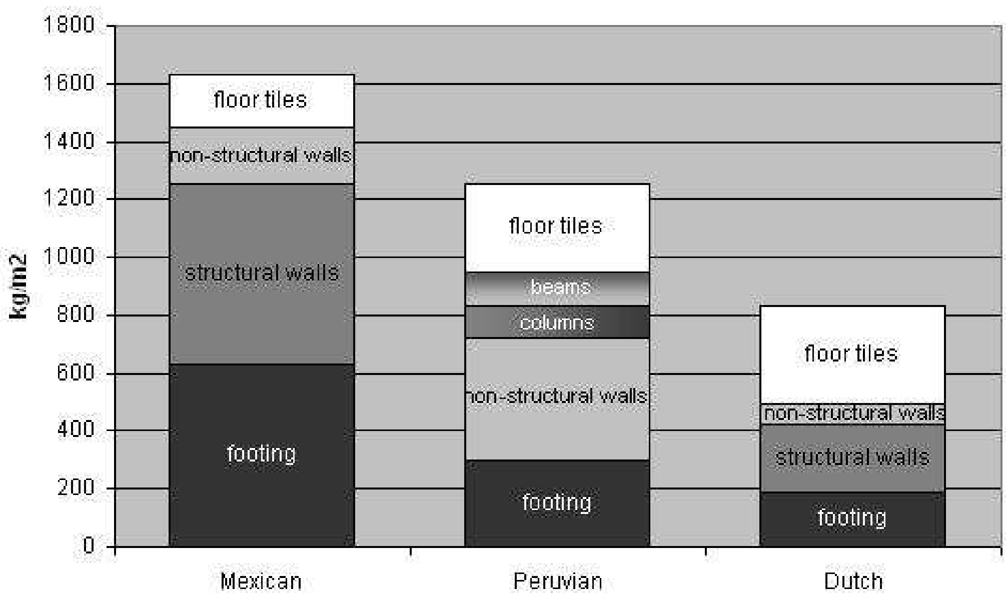


Figure 2 Material weights per useful living area per building element

4.3 Analysis of energy efficiency

Figure 3 shows the energy use for different purposes in the reference dwellings. Energy consumption in Peruvian and Mexican houses is visibly lower than for Dutch houses. Energy consumption for heating is high for Dutch housing, while in Peruvian and Mexican housing energy for heating or cooling is not used. This is because the weather in Lima is mild, and therefore, it is reasonable that energy is not used for heating or cooling. Nevertheless, Toluca is a city of cold nights, especially in winter, due to its altitude.

To test the relation between energy used for heating and the heating degree days per country, the energy consumed in Dutch houses is normalised with respect to the number of heating degree days in Mexico and Peru. Table 3 shows that in relation to the energy consumed in the Netherlands, energy in Peru is consumed according to its weather (real consumption is 0 while hypothetical consumption is 5.32 MJ), while in Mexico the energy consumed for heating is considerably lower than what is needed (real consumption is 0 while hypothetical consumption is 48.65 MJ). Nevertheless it is important to consider that the low temperature in Toluca is in the night when comfort is less needed.

Table 3 Energy consumption in the Netherlands according to degree days in different countries

	Netherlands	Peru	Mexico
Number of degree days	5328	566	3236
Hypothetical energy use in the Netherlands in relation to the degree days	80.11 MJ	5.32 MJ	48.65 MJ
Real energy use	80.11 MJ	0 MJ	0 MJ

Energy used for appliances, cooking, and for heating water in Mexican reference dwellings is higher than in Dutch and Peruvian reference houses. Energy used for cooking, heating water, and appliances in Peruvian houses equals about 80% of the total energy consumed. For Mexican houses this is about 75%. This shows a trend in Mexican houses of high consumption of energy for such activities.

Energy consumption for appliances, cooking and water heating in Mexican housing is higher than in Peruvian and Dutch housing, because of the large use of energy for heating water. The cause may be attributed to the type of boiler used in the majority of houses in the region, which is turned on all day.

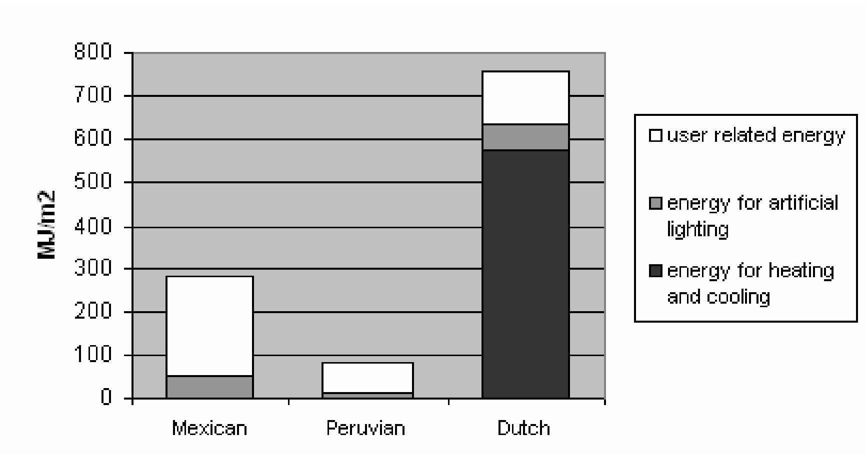


Figure 3 Energy use for different purposes

4.4. Conclusions

There is an intensive consumption of material in Mexico due to the use of continuous stone masonry footing along all the walls and due to the undifferentiated use of solid units in walls. Peruvian houses are lighter due to the use of hollow units. Dutch houses tend to have light interior walls, a factor that reduces the weight of the materials.

Non-renewable materials with high environmental impact seem to be intensively used in all dwellings due to the concrete elements and ceramic bricks. Renewable materials are almost not used with exception of the Dutch reference dwelling where wooden beams are used. The use of low impact materials makes the performance of the Mexican dwelling appear better in comparison to other countries but the amount of renewable materials is very low.

The performance of the reference dwellings could be improved by using more renewable materials in the structures such as in Dutch dwellings. The use of lighter walls in the interior of the dwelling reduces the use of material; as well as the use of hollow units.

Diminishing the quantity of materials by means of using different processes in foundations and walls would be a solution for material consumption in Mexican housing. Nevertheless, Mexican houses consume fewer high impact non-renewable materials than Dutch and Peruvian houses. This fact is attributable to the use of stone foundation.

Renewable energy is not used in any reference house, but in the Netherlands there is the possibility to choose sustainable sources. The energy consumption for artificial lighting is comparable in all dwellings, while energy for cooking and water heating seems higher in Mexican dwellings, followed by Dutch reference dwellings.

The high consumption of energy for heating water can be attributed to the use of low efficiency boilers in Mexico. Environmental performance in Mexican and Peruvian dwellings seems good in comparison to the Dutch reference house in relation to climate systems, because energy for air conditioning is not required. In Mexican housing there is no consumption of energy for cooling or heating in spite of the weather conditions in the region.

The low consumption of energy for air conditioning in Mexican houses in comparison with Dutch housing shows that comfort perception may be affected not only by the climate, but also by culture. An important consideration is that nowadays the dwellings do not have heating systems. It could be claimed that this is because of the lack of financial resources of Mexican households and that therefore this situation could change as soon as the economy of the country improves. Nevertheless, it is important to note that the use of heating systems nowadays does not depend on the finances of the households, because not even dwellings for high-income households have a heating system. Therefore, it could be that the level of comfort required in the indoor environment is more subjective than it seems.

5. Discussion

Sustainable building is acquiring more importance worldwide. The current situation of sustainable construction and housing in developed and developing countries is clearly different. Developed countries have reached a high level of quality in housing but consume more energy. The main problem that these countries face is maintaining the current level of quality of life while minimising environmental interventions. On the other hand, housing in developing countries still lacks the quality reached in developed countries, but energy use is still low. Nevertheless, material efficiency in developing countries appears to be lower than in developed countries.

The choice of indicators in the present study is based on the three step strategy and on needs identified from a designer perspective. From this perspective the use of LCA is not recommended, because it is not directly related to building design. In the present study, the level of the indicators was determined by literature and estimates. However, to determine quantitatively, or to determine if a material is low or high environmental impact, it would be better to use the LCA method, or at least parts of it, because it is the only widely accepted quantitative method to determine these characteristics.

The method gives a general idea of the situation regarding material an energy use within countries. For example we saw that materials in Mexican dwellings are more intensive than in Peruvian and Dutch dwellings and that energy use for heating is higher in NL and for heating water in Mexico. Nevertheless, factors dependent on the background of the countries should be considered before trying to apply a different solution for problems in a determined country.

References

Ding,G.. 2007, Sustainable construction. The role of environmental assessment tools. *Journal of Environmental Management* [Epub ahead of print].

Edwards, B. 1996, Towards sustainable architecture: European directives and building design, Oxford: Butterworth Architecture.

Hendriks, Ch.F. 2001, Sustainable Construction. Netherlands: Aeneas.

Itard, L, and Klunder, G. 2007, Comparing environmental impacts of renovated housing stock with new construction. *Building Research & Information,* Taylor & Francis, 35(3), pp.252–267.

Jong-Jin K, and Rigdon, B. 2007a, Introduction module. College of Architecture and Urban Planning, University of Michigan, National Pollution Prevention Center for Higher Education, Department of Architecture, University of Idaho. Available from: www.umich.edu/nppcpub/

Jong-Jin K, and Rigdon, B. 2007b, Sustainable Architecture Module: Quality, use and example of sustainable building materials College of Architecture and Urban Planning, University of Michigan, National Pollution Prevention Center for Higher Education, Department of Architecture, University of Idaho. Available from: www.umich.edu/nppcpub/

Lawson, B. 1996, Building materials, energy and the environment: Towards ecologically sustainable development, Red Hill: Royal Australian Institute of Architects.

Rovers R, 2005, reader Sustainable Building Module, Wageningen University, publication in preparation

Torres Mendez, R. 2005, Analyzing Peruvian Reference Houses and Improvement Proposal, MSc thesis. Wageningen University.

UNEP-IETC. 2002, Agenda 21 for Sustainable Construction in Developing Countries. The International Council for Research and Innovation in Building and Construction CIB and United Nations Environmental Programme, International Environmental Technology Centre. South Africa.