SUSTAINABLE URBAN AREAS

16

# Environmental indicators for building design

## Development and application on Mexican dwellings

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Delft Centre for Sustainable Urban Areas

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# Contents

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# Preface

The ultimate goal of building and construction – in relation to environmental issues – is to construct in an environmentally neutral way; or, as the Brundtland Report states, to consume in such a way that our children have the same choices that we have. Construction will always be needed, and will always consume resources. But in accordance with the conditions of the Brundtland Report, we should move construction into a direction that does not deplete resources, and does not worsen living circumstances through harmful indoor or outdoor environmental effects.

Improving our efficiency in resource consumption is the only way in which we will be able to continue our current way of life. Ernst Ulrich von Weizsäcker in particular has given meaning to this task by adding targets to this strategy. His book Factor Four has placed the issue at the forefront of the international agenda. It has been calculated that in order to (only) maintain the world average lifestyle a factor 4 of improvement in efficiency of resource consumption is necessary, based on global resource availability, effects on climate change, and coping with growing welfare for developing countries.

Measuring a factor x improvement heavily relates to the chosen benchmark. In the Netherlands we have reduced consumption from an average of 3.500 $m^3$ natural gas for housing stock heating (1970s) to 1.700 $m^3$, which is an improvement of factor 2 (for heating, not for the building). However, if we compare this 1.700 $m^3$ against fuel consumption for the heating of a pre-1900s house, the result is higher energy consumption today. At that time only one room in the house was heated for just a few hours each day, while today the whole house is heated throughout the day, meaning that we have made improvements in terms of comfort, not in energy consumption. Therefore the setting of benchmarks is an important issue.

Building activities will always require some environmental load: the mere fact of living already implies use of earthbound resources, so it is generally not very efficient to calculate emissions and other effects in an absolute way. The ultimate target is not to avoid resource use at all, but to use only “reproductive resources” (“regrowable, renewable and replaceable”) to create a balanced situation. When this is achieved, we will still use resources, but usage will be sustainable: it can be maintained well into the future. The concept of Closing Resource Cycles lies at its basis (Rovers, 2007).

In developing an approach for assessing sustainable building, the Three Step Strategy (in the Netherlands named Trias Ecologica) has proven to be useful. The first step in this principle is to reduce the need or use of anything. The next step is to use renewable sources to supply the need. And if 1 and 2 are not sufficient to cover the activity, the third and final step must be applied, which is to supply the remaining need as efficiently as possible.

When adapted to energy, for instance, this leads to a significant reduction in demand (via insulation, efficient ventilation, daylight optimisation, etc.), the introduction of renewable energy (solar collectors, passive solar gains by design, solar electricity, etc.) and as last step: very efficient use of fossil fuels for any remaining need. These steps must be applied in that order. The same approach can be used for materials, water consumption, and even for maintenance or installations.

The natural progression of the Three Step Strategy approach leads to a closed cycle approach, where all needs are taken care of in steps 1 and 2, and step 3 is eliminated. At that point, non-renewable resources are no longer needed, and there will be a balanced situation for the activity. An approach of "adding measures" will not be sufficient to create this optimal situation: innovative and creative concepts are needed to accomplish this. Of course, this cannot be implemented in one day or one year, at least not on a wide scale. Nevertheless, the concept should be clear, and any choice to establish part of the concept should be made in a way that does not exclude realisation of the entire concept at a later stage.

When using the Three Step Strategy it is important not to combine the different performances (energy, materials, etc.) into one figure: there should be progress on all topics separately. This has led to measuring a building's performance by means of easy indicators, such as total mass and the percentage of renewable and recycled materials used. If this equals 100, the ideal situation has been achieved. This futuristic ideal aside, it is an easy and honest way to benchmark progress: in the Netherlands, the amount of renewable and recycled materials in an average house is around 8%. It is now easy to define a factor to improve the performance of the house, for example a factor of 4 (32%), to be realised either by reducing the mass and/or by increasing the amount of renewable and recycled materials used. The same can be done for other environmental issues.

This principle approach has been the basis for the ATLAS project: documenting houses and buildings along these indicators as a benchmark for future improvements. The initial study presented in this book was part of Wageningen University's ongoing ATLAS project. The study has documented Mexican housing according to this approach, using comparisons with similar studies of other countries' housing performance. It has shown to be an effective way to reveal main areas of improvement, and can be broadly applied to start analyses. In this research, Olivia Guerra Santín has extended the set of indicators to a more detailed level and has applied it to the case of Mexico, partly during her work at Delft University of Technology's OTB Research Institute.

Although we are still improving the approach, I hope this can act as an example for others to build on a global overview of documented housing, as is the intention of the ATLAS project.

Ronald Rovers
Wageningen University, Urban Environmental Group

# 1 Introduction

Construction is 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. Two of the most important impacts of the construction industry are the consumption of energy and the emission of greenhouse gases into the environment. The consumption of energy in the building sector accounts for 40% to 50% of energy consumed in the developed world. Buildings are responsible for a large share of fossil fuel consumption and global warming (Edwards, 1996). The design of the physics and services of the building influences directly the consumption of energy and therefore the release of $CO_2$ into the environment. In developed countries energy used to heat spaces accounts for the largest share of energy consumed in dwellings. Increasing insulation, making airtight buildings and improving ventilation systems have been key objectives in reducing the energy consumption of buildings. The materials used in buildings also have a significant influence on the environment; with 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. Another problem caused by buildings is construction and demolition waste. The highest rate of waste is known to come from Portland cement and ceramic brick. The extraction and displacement of raw materials both disrupts ecosystems and causes land degradation; the transport and production of building materials requires large quantities of energy and water.

Housing is considered to be one of the most fundamental needs of human beings. Its quality is important for the development and well-being of individuals. To reduce the environmental impact of construction activities while ensuring the good quality of a building is not an easy task. Housing affects the environment in different ways, such as the consumption of resources and production of emissions before and during construction, interventions during the use of housing, and the impact caused by maintenance or renovation and disposal.

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 (for natural illumination or indoor temperature) and water (e.g. number of bathrooms) are partly determined by design. In addition, the conditions of the indoor environment (e.g. ventilation) 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.

Sustainable building is the approach used to solve this problem. Environmental agendas have been set in several countries, and policies and regulations aimed at reducing the environmental burden of buildings are already in place in developed countries. Meanwhile, in some developing countries, regulations and policies are in the process of formulation and design, such as in Mexico (CONAFOVI, 2006). Nevertheless, the situation in these countries is very different from the situation in developed countries. The urban environment of these countries is still under construction and therefore the environmental impact of developing countries is probably greater than the impact of developed countries. Developing and developed countries have different building agendas. In developed countries the green agenda is concerned with over-consumption, while the focus of the brown agenda of developing countries is on poverty, underdevelopment and unequal distribution of resources; therefore a proper approach for sustainable building in developing countries is needed (UNEP-IETC, 2002).

The objective of this book is twofold. The first goal is to develop a method to assess the design of buildings for their improvement through a more environmentally sustainable design aimed at decreasing environmental impact and increasing sustainability potential during the building's life cycle. The second goal of this research is to present possible strategies to improve the environmental performance of Mexican housing using the methodology based on the Atlas approach (Rovers 2005) and further developed in the book.

In order to improve design from a sustainable building approach, guidelines are developed in this book based on sustainable building strategies. In order to pinpoint strategies to improve design, an environmental assessment is conducted to recognise the environmental impact of current housing design. The degree of the impact of housing on the environment in (one region of) Mexico is assessed to point at the major environmental problems. For this evaluation, an analysis of the factors that influence the performance of housing design in the perspective of environmental sustainability was realised.

The assessment is carried out by analysing construction trends in the area of study. Two levels are used for the assessment: a) analysis of dwellings through time and socioeconomic levels to show the trend that building has followed in the region, and to show the differences in environmental interventions between socioeconomic levels; and b) international analysis to give insight into the position of Mexican housing (in the selected region) within housing with similar minimum and maximum temperatures, and with similar socioeconomic and cultural backgrounds. The international case studies are from the Netherlands and Peru.

The reference dwellings provide examples of the most common building materials used. These examples are analysed, taking into account their impacts on the environment and on the future performance of the dwelling. The analysis of the reference dwellings demonstrate the use of the environmental assessment method for design with a view to improvement.

The analysis is made between reference dwellings within the national and international context. The results produced from the analysis are then used to identify the major benefits and shortcomings of dwelling design in order to study alternatives for its improvement. For the analysis, indicators are developed in accordance with the approach of the research. Proposals for improving a case study are based on the results of the study. The proposals are based on two sustainable building approaches: dematerialisation and material substitution.

The research questions of this study are the following:

1. How can the environmental performance of housing design be assessed?
   - 1a. What are the factors that affect the environmental performance of a dwelling from a design perspective?
   - 1b. What indicators can be used to evaluate the environmental performance of the design of a dwelling?
2. How can the environmental performance of Mexican housing be improved?
   - 2a. What is the environmental performance of Mexican housing?
   - 2b. How can the performance of Mexican housing be improved with sustainable building strategies?
3. What are the aspects of design that can be improved in Mexican housing?

This book comprises 7 chapters. The second chapter addresses research question 1, establishing the approach and indicators used for the analysis. Chapter 3 introduces the reference houses to be analysed, and the fourth chapter consists of the analysis of housing within a national and international context, answering the second research question. Chapters 5 and 6 address research question 3, containing recommendations for improving Mexican housing. Conclusions are presented in Chapter 7.

# 2 The approach

## 2.1 The Three Step Strategy approach

The environmental performance of a building depends on the type of construction, materials and characteristics of the dwelling that affect its interaction with the surrounding environment. This interaction is determined from the early stages of construction, such as urban development and building design. Design is an essential part of the construction industry. 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 into the design. The design of the building determines the potential for good environmental performance during the entire life cycle (during maintenance, renovation and demolition activities). The focus of this research is on the performance of the design of a dwelling, considering aspects such as layout, materials used and construction processes.

When comparing products, it is nearly always necessary to consider the entire chain or life cycle of a product to ensure that problems are not simply shifted elsewhere (Hendriks, 2001). Considering a building as a product, it comes through different phases during its service life: construction, use and demolition. Extraction of raw materials, manufacturing and transport of construction materials are also considered when the focus is on materials instead of buildings. Each of these phases has several factors that must be taken into account in order to assess their impact.

An environmental assessment of the building is needed to determine the potential impact of the design 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 to asses the impact 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 what choices should be made during the design of the building. For example, the Life Cycle Assessment tells us the environmental impact of a building, but the opportunities for possible improvements of design are not visible in the output. Therefore, an assessment method that allows analysis of the performance of the building in relation to design choices is further developed in this study, based on the indicator approach by Rovers (2005).

To develop the assessment method, the approach followed is based on the Three Step Strategy. The Three Step Strategy is used because it 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 out-flow of resources and to retain for a longer time the incoming flows within the system (Hendriks, 2001). This strategy establishes that 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 strategy is suitable for analysing the potential environmental impact of choices made during the design process because it provides detailed information (e.g. environmental impact, potentials) about different aspects of the design of the building and point at the problems or areas for improvement.

The goal of the first and third steps of the Three Step Strategy can be fulfilled by means of dematerialisation. The goal of a dematerialisation strategy is to fulfil needs while decreasing resource consumption. There are two schools within the dematerialisation literature. The first is concerned with measuring environmental impact in terms of quantity of materials displaced. The second is concerned with measuring impact in terms of the environmental effect of the material flows (Riele *et al.*, 2000). Taking into account both schools, the aim of dematerialisation is the reduction of the environmental impact of material flows. This supports the reduction of kilograms as a possible strategy: less mass indeed means less environmental effect (Riele *et al.*, 2000). The principles of dematerialisation (Geiser, 2001) are closing the materials loop by keeping materials actively within the economy, increasing the intensity of materials use, and substituting products for services. For sustainable building, these concepts can be applied as follows:

a. *Closing the materials loop* can be achieved by means of designing for dismantling in order to reuse or recycle. Reusing is better than recycling because reuse of materials slows their flow from extraction to disposal; meanwhile, recycling may make the flow run more frequently and rapidly, keeping the materials within the cycle. This approach integrates the concept of Design for Demolition (DfD), taking into account the possible reuse of elements and materials. DfD is easy to plan by designing for reusing, but it is uncertain whether it will be achieved; reuse or recycling of materials is difficult to plan because it involves cultural patterns, policy and economic factors, but it is easy to measure whether it has been achieved in the design of a building or not. This strategy is related to recoverable elements and materials, but not to building lifespan. The concept originates from the idea that short lifetime buildings may be more sustainable than others due, amongst others, to rapid changes in lifestyle and the possibility of using short lifetime renewable materials. The goal of this concept is to recover all materials and construction elements for new buildings. Of course, combining this strategy with extending the life cycle of the building is a much better solution.
b. *Increasing the intensity of materials use* can be better achieved from the design of the building. The goal is to increase the value (e.g. service) per unit

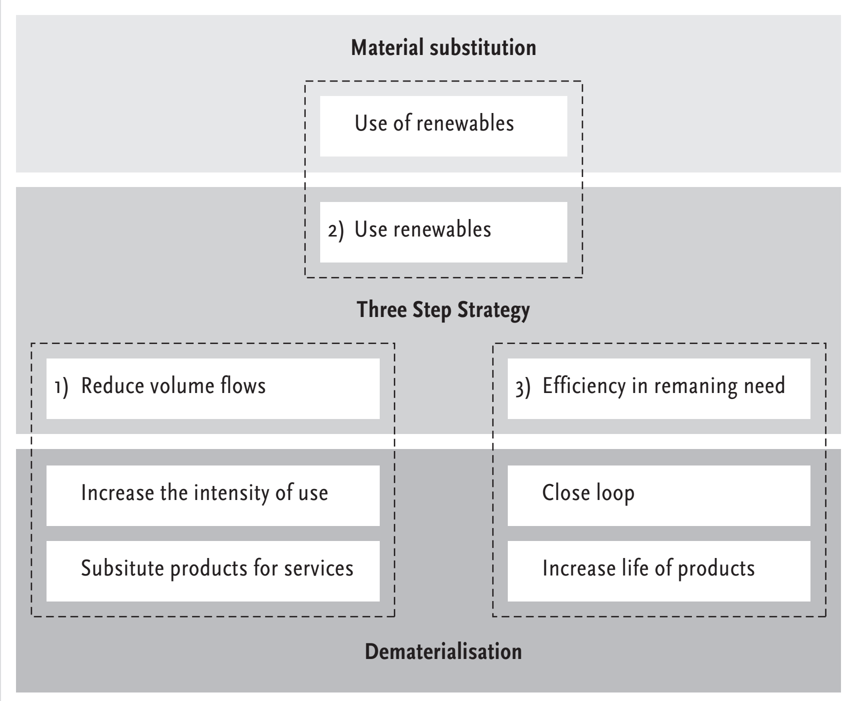
of material used (i.e. using less material to provide the same level of service). One way to increase the intensity of the materials is to make smaller and lighter products made from lighter, stronger and more durable materials (Geiser, 2001). Decreasing the amount of materials used for satisfying a need not only increases the value of service per unit of material, but also decreases the amount of energy and water used per unit of service. For example, reducing the quantity of materials used in construction also reduces the quantity of water and energy used in the process of extraction, production and transport of the materials. Regarding housing, some aspects of design can also accomplish this objective, for example, reducing the number of bathrooms, or reducing the size of non-habitable areas such as corridors and storage.

c. *Extending the life cycle of the product* maximises the value of the product during its useful life. It reduces the need for new products and slows the rate of discarding (e.g. demolition). This can be achieved by designing buildings with the potential to adapt to the future needs of the user, or the future user. This approach is related to the reusability of the building. To achieve it, the building must have high flexibility in terms of space, options for growth, and its elements or materials must be removable and recoverable. The main goal is to increase the time-use of the building, which is considered to be the best option because short lifetime buildings do not perform better than normal lifetime buildings of 75 years (Klunder, 2005). For this approach, the goal is to improve the reusability of a dwelling. The best option for this approach is the use of prefabricated structural elements. This would improve the flexibility of the dwelling and make it easy to dismantle the elements in order to locate them in a different place.
d. *Substituting services for products* in buildings could be achieved with new communication technologies. One example of this strategy is promoting working at home instead of using large office buildings.

The second step of the Three Step Strategy can be accomplished with the Material Substitution approach. It consists of increasing the amount of renewable materials in the design. Material substitution aims at reducing the burden on the environment by using resources with low embodied energy, and with low impact. In addition, this strategy also aims to limit the amount of hazardous materials used in order to procure a better indoor environment.

In order to clarify the use of the indicators, Figure 2.1 shows the relation between the Three Step Strategy and the principles of dematerialisation and material substitution. Use of renewables, one of the objectives of material substitution, is also the second step of the Three Step Strategy. Reduce volume flows and efficiency in remaining need, the first and third steps of the Three Step Strategy, can be achieved by means of the dematerialisation principles: the first step can be accomplished by increasing the intensity of use

**Figure 2.1 Relation between Three Step Strategy, dematerialisation and material substitution**



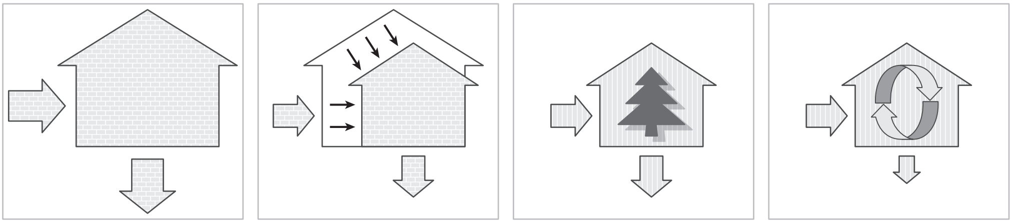

and substituting products for services; efficiency in the remaining need can be accomplished by closing loops and increasing the life of products.

## 2.2 Choosing the right materials

The importance of material consumption is shown in the Trias Ecologica (R. Rovers, oral communication, 2003) or Three Step Strategy, where the first and therefore the most important step is to minimise the consumption of resources (Figure 2.2).

An essential part of the design process is the selection of materials based on their sustainability (Jong-Jin & Rigdon, 2007b). Choosing the right material is an important aspect of sustainable building. Materials possess characteristics that make them more or less sustainable in relation to others. The main characteristics are those of the material itself, which are related to the renewability of the source, the possibility of reprocessing, and the origin of the material (i.e. new, reused). The secondary characteristics that can affect the level of sustainability of the materials are external: these are the local availability of the material and the existence of market and labour (construction workers trained to work with the materials). Such selection should be done carefully, taking into account all the phases of the material's life cycle: pre-build, build, and post-build. The sustainability of a material is sometimes relative and de-

**Figure 2.2 Three Step Strategy of materials**



A dwelling consumes resources and produces waste

1. Reduce consumption: by decreasing the consumption of materials, the waste also decreases

2. Use of renewable materials: by using renewable materials, the consumption of materials and the waste has less impact on the environment

3. Efficiency in remaining need: by using materials efficiently, the waste produced by the building decreases

pends on a specific location or situation. For this reason a detailed analysis is essential before choosing materials.

Two additional factors increase materials consumption: waste production during the construction, which tends to increase the environmental burden of the building; and the materials necessary for the construction that do not form part of the building. For example, during the construction of concrete elements, materials are wasted during the process and casting is required and eventually also wasted.

Pre-building activities such as extraction, manufacturing and transport of materials do not belong to the life cycle assessment of the building but to the life cycle assessment of the building materials or elements (Rovers, 2005). In the approach chosen in this book, the impact of these activities is taken into account in an aggregated way (component level).

The first activity in the manufacturing of materials is the extraction of raw materials. When quantifying the material volumes, a factor that is important to take into account is that during the extraction of the desired material, some other materials must be extracted as well. This increases the quantity of resources actually used for construction. For the method developed in this book, materials which require a large quantity of other material to be displaced during their extraction are considered as high-impact.

Raw materials are later on processed to create construction materials. Not all materials go through this phase and the intensity of the process varies depending on the material and its future use. Besides the environmental emissions, the impact on society and the economy must also be analysed. This phase has an important impact on society and the economy because it is related to labour, trade, the market and economic issues in general. For example, if a given material is banned because of its negative impact on the environment, it could have a negative social or economic repercussion. Therefore, the stakeholders in this phase are not only the manufacturers or material corporations, but also the government and workers in the manufacturing sector.

The third activity is the transport of the construction materials and ele-

**Table 2.1 Summary of approaches to choose materials based on their sustainability**

| Three Step Strategy | Dematerialisation | | | |
|---|---|---|---|---|
| | Reduce need | Increase efficiency | | |
| Indicators ▸ / ▾ Author | Availability of raw materials | Dismantling | Reusability | Durability |
| **Hendriks** | Avoid depletion of natural stock | | Reuse materials | Use materials with higher usability, and reparability, and longer technical lifespan |
| **Jong-Jin and Rigdon** | Reduce waste | | Reuse materials<br>Recycle material | Use materials with longer lifetime |
| **Delft's ladder** | | | Reuse materials<br>Recycle material | Use materials with longer lifetime<br>Reuse building |
| **Design for recycling** | Use fewer materials | Design for disman-tling<br>Identification of materials | | |
| **Design for disassembly** | | Design for disassembly | | |
| **Degradation factor** | | | Reuse materials<br>Recycle material | Reuse building |

ments. This includes transportation from the extraction field to manufacturing sites and transport to the place of construction. Using local materials decreases the energy and environmental impact ($CO_2$ and pollution emissions) required for transport. Often, local materials are better suited to climatic conditions because their development is linked to traditional architecture. Their use can also support the economy of the region (Jong-Jin & Rigdon, 2007b). Transport has a significant impact on the consumption of resources, especially of energy fuels. The quantity of energy consumed for transportation has an effect on the right decision about the type of material to use. For example, by using a renewable material the environmental burden created by the extraction and manufacturing of the material could be reduced on the one hand, but this may be increased on the other hand because the material is not available in the area and transport is therefore needed. Social impact in these activities is related to the mobility of resources on a local level. This means that the social and economic benefits of constructing in the locality would be reflected within it. For instance, if the materials are from the same location as the construction, the activities for extraction of materials, manufacturing and construction will be conceived for the people of the area. As said before, policy plays a fundamental role. This may take the form of restricting regula-

| Material substitution | | |
|---|---|---|
| Use of renewables | | |
| **Environmental impact** | **Embodied energy** | **Hazardous materials** |
| Use materials with less emissions | | Use safe and healthy materials |
| Reduce emissions | Use materials with low embodied energy | Use of non-toxic materials |
| Higher recycled content<br>Use of natural materials | | |
| | | |
| Use of recycled materials | | |
| | | |
| | | |

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

tions or subsidies when using local materials. This is not an easy task, and to be able to implement any transport policy, the characteristics of the region, the availability and renewability of materials and the possible use of them in the area must be known. This would have to be done for each locality, complicating the process even more.

Hendriks (2001) and Jong-Jin & 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 Prebuilding 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 (Hen-

**Table 2.2 Environmental impact and potential of materials**

| | Availability of raw material (1) | Impact on environment (1) | Embodied energy efficiency (1) | Durability (1) | Potential for Reuse (1) | Dismantling | Hazardous material |
|---|---|---|---|---|---|---|---|
| **Wood** | Very good | Low | Very good | | Reuse | Dismantling | Non-hazard |
| **Hardboard** | Very good | Low | Fair | Good | Recycle | Dismantling | Non-hazard |
| **Plastics** | Good | High | Good | Very good | Recycle | Dismantling | Hazard |
| **Bitumen** | Good | High | Good | Very good | Recycle | Dismantling | Hazard |
| **Foam** | Good | High | Good | Very good | Recycle | Non-dism. | Hazard |
| **PVC** | Good | High | Good | Very good | Downcycle | Dismantling | Hazard |
| **Adobe** | Very good | Low | Very good | Good | Recycle | Non-dism. | Non-hazard |
| **Earth** | Very good | Low | Very good | Good | Reuse | Dismantling | Non-hazard |
| **Sand** | Very good | Low | Very good | Good | Reuse | Dismantling | Non-hazard |
| **Stone** | Good | Low | Good | Very good | Reuse | Non-dism. | Hazard |
| **Clay** | Very good | High | Very good | Excellent | Recycle | Semi-dism. | Non-hazard |
| **Ceramic bricks** | Very good | High | Very good | Excellent | Recycle | Semi-dism. | Non-hazard |
| **Concrete** | Good | High | Very good | Excellent | Recycle | Non-dism. | Hazard |
| **Glass** | Good | High | Good | Excellent | Recycle | Dismantling | Non-hazard |
| **Steel** | Very good | High | Fair | Very good | Recycle | Dismantling | Non-hazard |
| **Aluminium** | Very good | High | Poor | Excellent | Recycle | Dismantling | Hazard |
| **Copper** | Fair | High | Fair | Excellent | Recycle | Dismantling | Hazard |
| **Lead and zinc** | Fair | High | Fair | Excellent | Recycle | Dismantling | Hazard |

Source: (1) Bill Lawson (1996)

driks, 2001) focus on the Post-use or Post-building phase of the life cycle of the building, and on the “increase efficiency” step of the Three Step Strategy. In the method presented in this book, all steps and all phases are included. Table 2.1 shows the methods and literature used to develop material indicators. They are presented in relation to the Three Step Strategy, the dematerialisation and the material substitution strategies. From Lawson (1996), construction materials are categorised in Table 2.2 according to the way they score on different sustainability issues. It is important to add that the sustainability of materials depends in most cases on external factors such as weather, availability of the materials in the region, quality, manufacturing process, and installation of the materials among others. Therefore, the categories of sustainability used in this book should be taken with precaution, as they may be only valid in a determined region.

## 2.3 Indicators for environmental assessment

In this chapter, the indicators to be used for the environmental assessment of the dwellings are defined. These express the characteristics of resources such as water, energy, materials and land during the life cycle of the building. In order to reduce the environmental load in construction, the different phases of the life cycle of a building as a whole must be taken into account: building, use and demolition. The origin of the materials is important and is taken into account by including the characteristics of the materials in terms of origin and recoverability studied in Section 2.2. In this section, the indicators used for the assessment method are introduced for each phase of the building life cycle: Building and construction, Use, and Demolition.

Some of the indicators are area normalised. These indicators are used to compare the performance of different houses, eliminating differences in culture or socioeconomic level. The normaliser in this case is the Useful Living Area and refers to the total square metrage of the dwelling with the exception of external spaces (such as balconies or terraces), storage areas, stairs and areas with a height of less than 1.5 metres. The criteria chosen for this concept are based on the fact that only the necessary spaces of the dwelling should be considered for analysis because the objective of housing is to satisfy human needs related to protection, comfort, stability and health. Unnecessary spaces for basic human needs are considered to be a luxury and those spaces tend to vary according to culture and economic issues. Nevertheless, resource consumption for those spaces is considered because even though they depend on cultural factors, they increase the environmental burden of the dwelling. In addition, spaces that are necessary because they are related to the design of the house, such as stairs or low height areas, are not considered to be part of the useful living area.

### 2.3.1 Building and construction phase

The indicators in this phase can be divided into four categories: the first is related to the characteristics of materials; the second is related to construction process; the third is related to land use; and the fourth is related to costs The environmental factors that have implications on the performance of the building in this phase relate mainly to materials and land.

**Materials**

*Total material consumption or resource efficiency (D-B1)*

Raw materials procurement methods, the manufacturing process itself, and the distance from the manufacturing location to the construction site all have environmental consequences. The quantity of 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). This indicator measures the quantity of material embodied in the building; this is useful to analyse the design of the dwelling by showing the quantity of material needed to fulfil a necessity. It is defined as the sum of all the material embodied in the building, including renewable, recovered and non-renewable materials. Auxiliary materials are not included in this indicator.

*Origin of materials*

The origin of the materials shows the impact of the material related to the renewability of the source, and to the consumption of other resources during its production. This categorisation is useful to define the environmental performance of the embodied materials of the building, and of auxiliary materials and waste produced during its construction. The material characteristics concerned here are renewability, recovered content and environmental impact. Therefore, for the purposes of this research, three indicators of sustainability were defined: renewable materials, recovered materials and non-renewable materials.

*Renewable materials (D-B2)* are those that can be artificially or naturally replenished at a rate that exceeds the lifetime of the material used for a specific activity. Harvestable materials like wood are considered as renewable resources and their extraction causes less damage to ecosystems than other resources. However, 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). Materials that belong to this category are wood, shells, cotton and wool.

*Recovered materials (D-B3)* are those that have been reused, recycled or downcycled after previous use in a different building or industry (Rovers, 2005). These materials make it possible to avoid the use of virgin materials, present a reduced environmental impact, and are therefore highly favourable. Within recovered materials, the grades of recovery show the positive environmental impact that is already present in the building. The categorisation of the materials depends on each individual case study; therefore, it is not possible to show the categories of materials in this section. The three levels of recovery identified are the following:

a. *Reused materials (D-B3.1)* are those that are used again for the same original purpose with only light processing. There is therefore no extra consumption of resources and the products are not degraded. One example is a door that has been reused after resizing.
b. *Recycled materials (D-B3.2)* are those that have been reprocessed in order to be used for their original purpose in a new construction.
c. *Downcycled materials (D-B3.3)* are those that have been reprocessed in order to be used again for a lower quality purpose, for example, iron from concrete structures that can be recycled but cannot be used for structural elements.

Non-renewable materials (D-B4) are materials that have a slow growth rate in relation to the consumption of the material for human activities. The environmental performance of the materials not only depends on the origin of the material but also on the impact that the manufacturing process has on the environment. Non-renewable materials can be divided into two categories, depending on the environmental impact during the production of the materials.

a. *Non-renewable low impact materials (D-B4.1)* are those that are not renewable but that have a low impact or no impact at all on the environment during their manufacture. In this way the contribution to energy and water consumption and emissions is minimal although the contribution to material depletion is still significant. Natural materials require less processing than artificial materials. Less processing leads to less embodied energy and toxicity, and less damage to the environment. The embodied energy of a material refers to the total energy required to produce that material (Jong-Jin & Rigdon, 2007b). For example, traditional adobe bricks are made of non-renewable material but due to the fact that they are sun-dried, there are no emissions or consumption of resources during their manufacture. Stone, adobe, earth, sand and pebbles belong to this category when they are not manufactured for construction products (e.g. sand used in concrete manufacture does not belong to this category) (Spiegel & Meadows, 1999).
b. *Non-renewable high impact materials (D-B4.2)* are those whose manufacture requires significant use of resources, high embodied energy and high production of emissions. In addition they contribute to material depletion. The materials considered in this category are mainly metals and plastics, due to the high environmental impact that they present in their manufacture. This indicator is based on Van der Voet *et al.* (2003), who presented the "top 20" high impact materials for different environmental impact categories (Global warming, Land consumption, Resources depletion, Solid waste, and Aquatic ecotoxicity). Examples of these materials are: aluminium, wallpaper, copper, iron, textile, zinc, foam, glass, concrete, PVC, steel, gypsum, paint, ceramic, plastic and bitumen (Van der Voet *et al.*, 2003; Jong-Jin & Rigdon, 2007a).

*Material efficiency (D-B5)* is the ratio of renewable plus recovered materials to raw materials (Rovers, 2005).

*Waste and auxiliary materials during the construction process*

An important environmental factor during the building and construction phase is waste production during construction activities. This refers to the waste generated during the construction processes of the building. Some processes produce more waste than others depending on the manoeuvrability and flexibility of the material. In the case of auxiliary material for construction activities, the most common example is casting for concrete elements.

For example, in Mexico, although steel is sometimes used for casting, for the production of individual houses it is not efficient, because of the differences in design. This leads to the use of wooden casting, which is made of medium quality wood, often new. Wood for casting is reused three times for the same purpose; a percentage of nails and other steel elements are reused as well. In addition, casting also produces waste. This is important for the analysis because some materials or processes can produce more waste and consume more resources than others, even when they are based on the same design.

These indicators are related to the total amount of material use, including auxiliary materials and waste. The characteristics of each material are important in drawing conclusions about the performance of the construction process related to the real amount of material consumption. To determine the real impact of the process, it is also important to analyse characteristics of the materials such as reusability, recyclability or downcyclability of the waste produced, the origin of the material and the renewability of their sources.

*Total waste (D-B6)* concerns only the waste during the construction process on site, including auxiliary material. Materials embodied in the building are excluded from this indicator.

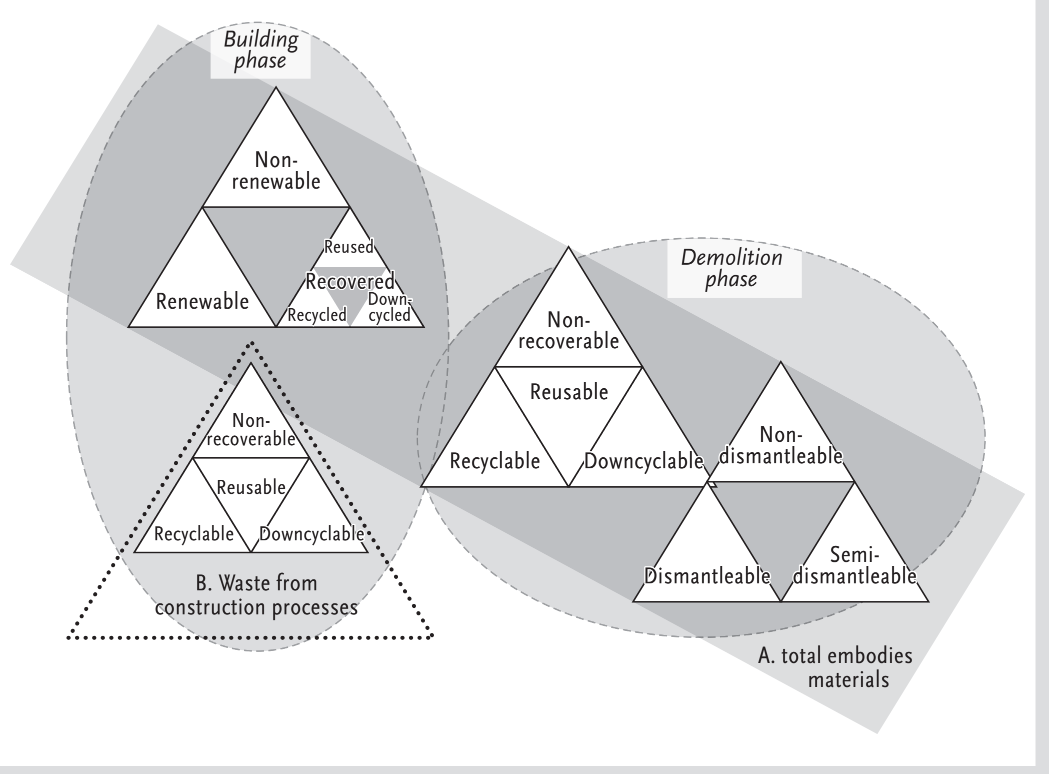
*Recoverability of waste from construction processes (D-B7)*

There are several factors that influence the reuse or recycling of waste materials from construction processes. These factors are related to the degree of mixture of materials with others, their fragility and the possibility of reusing or reprocessing them for further use (recyclability).

a. *Reusable waste (D-B7.1)* can be reused in its original form without needing to be reprocessed; these waste materials have the best performance due to the fact that there is no need to use more resources to reintegrate them into the cycle.
b. *Recyclable waste (D-B7.2)* needs processing in order to be used again.
c. *Downcyclable waste (D-B7.3)* refers to those materials that may or may not require a process to be reused for a different purpose due to their fragility or lack of flexibility.

It is important to note that this indicator is also used for embodied materials in the demolition phase of the building; the difference lies in the phase where the effect is allocated (i.e. construction waste and demolition waste). Figure 2.3 shows the differences between embodied materials indicators (A) and waste indicators (B). The materials embodied in the building are represented by the series of indicators inside the grey box (A). The indicators for embodied materials are categorised for each phase of the building life cycle. Within the building phase we find the "origin of materials" indicators: non-renewable, renewable and recovered. Within the demolition phase we find the "recoverability" and "dismantleability" indicators, which are defined in next

**Figure 2.3 Differences between embodied materials (A) and waste indicators (B)**




section. The "recoverability" indicators are also used for the waste from construction processes. These indicators can be seen in the triangle (B) outside of the "embodied materials" area. Waste from construction processes is not considered part of the embodied materials and therefore it is categorised differently to the indicators during the demolition phase, where the embodied materials are categorised as demolition waste.

**Land**

Land is a fundamental element for construction. A main factor determining the quality of housing is location. A neighbourhood determines access to services and infrastructure. This is, in most cases, established by economic and social factors. The price of the land and social segregation can influence the quality of life of the inhabitants of the houses.

Furthermore, besides social issues, the type of land used also has environmental implications. The type of land can refer both to its ecological and urban planning categorisation. With these categorisations it is possible to approximate the level of sustainability of land use. The use of fertile land for building is less sustainable than its use for agriculture, since the reutilisation of urban land is more suitable for construction activities, and the reutilisation of urban land for agricultural activities is nearly impossible. The surface used for building and the percentage of green area are the indicators considered in this phase.

*Total land use (D-B8)* refers to the ratio of the useful area of the house to the total land area; total land area being the area of the plot. It shows the efficiency of land used: the smaller the percentage of land use, the better the efficiency.

*Total green area (D-B9)* refers to the percentage of green area in relation to the useful living area of the construction. The larger the percentage of green area, the more efficient the use of land.

**Hazardous construction processes**

Construction is a highly dangerous activity for workers (Toole & Gambatese, 2007). Therefore, a decisive factor affecting the performance of the dwelling during the building and construction phase is the health and safety of construction workers. This is determined by the hazardousness of materials and construction processes. The hazardousness of materials during construction activities is determined by the particle emissions that they produce (e.g. dust). Hazardous processes are those that represent a danger for construction workers due to the complexity or location of the process.

According to Toole & Gambatese (2007), there are four trajectories in which Designing for Construction Safety (DfCS) is likely to evolve. Based on these trajectories, methods for procuring less hazardous occupational environments in the construction industry can be divided into four categories: use of prefabricated systems, use of less hazardous materials, application of engineering principles and spatial investigation and consideration.

*Use of prefabricated systems*

The use of prefabricated systems reduces hazards in two ways. Firstly, it relocates the works from the construction site to an environment with fewer hazards (Gambatese *et al*., 1997); for example, to a lower height where there is a lower risk of dangerous falls. Secondly, these elements are assembled in factories, where automated equipment and appropriate ventilation reduces the hazards (Toole & Gambatese, 2007).

*Use of less hazardous materials*

Use of less hazardous materials can be achieved by providing more information on the specification of the materials. Such specifications should be taken into account by the designer to provide a healthy environment for construction workers. According to Weinstein *et al.* (2005), paint, adhesives and cleaners are associated with low air quality, flammability and skin hazards.

*Application of engineering principles*

Proper application of engineering systems can ensure a safe environment for workers by means of better temporary structures, fall protection anchorage points and temporary load analysis (Toole & Gambatese, 2007).

*Spatial investigation and consideration*
Spatial investigation and consideration refers to the analysis of the spaces needed for good construction activities. Examples are the distance to power lines and adjacent structures.

The hazardousness of a construction site and construction process is specific to each case and it is therefore difficult to define categories for indicators. This should be done for each case study analysis. In general, hazardous and non-hazardous processes can be classified as follows:

*Hazardous processes (D-B10)* are processes that are considered to be dangerous to construction workers, such as construction processes done at dangerous locations, using heavy elements such as some steel elements, or applying toxic materials.

*Non-hazardous processes (D-B11)* are processes that normally do not present danger to construction workers: light metals or parts in small pieces, wallpaper, installations, carpets, (non-toxic) paint, walls on lower floors, etc.

*Cost of dwelling*
Economy is an important factor in any activity. For construction, the cost of the land, materials and labour determine the size, quality and infrastructure of the dwelling. For example, there are low-income families that would look for land far away from the city because it is cheaper or even “free” (irregular settlements). These areas are often in places where it is very difficult to provide infrastructure, causing problems for the government and poor quality of life and poor sanitation for the inhabitants. The cost of materials influences construction activities because they are chosen in accordance with the resources of the owners influencing the origin of the materials; if in a different region the materials are cheaper and the cost is not increased too much by their transportation to the construction site, they might be chosen instead of local materials which could benefit local people (i.e. labour). Therefore, an indicator has been developed in relation to the cost of the building.

*Cost of dwelling per square metre (D-B12)* includes all direct and indirect costs of the dwelling normalised per useful living area. This indicator is used for the purpose of eliminating economic differences between households when comparing dwellings from a different socioeconomic level. The concept refers to the cost of the house expressed in times minimum salary in the region. This normaliser is useful for analysing the environmental and social impact of economy factors. Times minimum salary (TMS) consists of dividing the total cost of the house by the minimum salary per year in a given country. It is presented as cost per square metre per TMS.

So far, the building and construction indicators have been introduced. This indicators are summarised in Table 2.3.

**Table 2.3 Indicators for the building phase**

| Key | Name | Definition |
|---|---|---|
| D-B1 | Total material | Totality of embodied materials per useful living area |
| D-B2 | Renewable materials | Renewable embodied materials per useful living area |
| D-B3 | Recovered materials | Recovered embodied materials per useful living area |
| D-B3.1 | Reused materials | Reused embodied materials per useful living area |
| D-B3.2 | Recycled materials | Recycled embodied materials per useful living area |
| D-B3.3 | Downcycled materials | Downcycled embodied materials per useful living area |
| D-B4 | Non-renewable materials | Non-renewable embodied materials with low environmental impact plus non-renewable materials with high environmental impact, per useful living area |
| D-B4.1 | Low impact non-renewable materials | Non-renewable embodied materials with low environmental impact per useful living area |
| D-B4.2 | High impact non-renewable materials | Non-renewable embodied materials with high environmental impact per useful living area |
| D-B5 | Material efficiency | Renewable plus recovered materials in relation to raw materials |
| D-B6 | Total construction waste | Total construction waste weight per useful living area |
| D-B7 | Recoverability of construction waste | Recoverable construction waste during construction activities per useful living area |
| D-B7.1 | Reusability of construction waste | Reusable construction waste per useful living area |
| D-B7.2 | Recyclability of construction waste | Recyclable construction waste per useful living area |
| D-B7.3 | Downcyclability of construction waste | Downcyclable construction waste per useful living area |
| D-B8 | Total land use | Ratio between the useful area of the house and the total land area |
| D-B9 | Green area | Percentage of land that is left free |
| D-B10 | Hazardous construction processes | Hazardous processes during construction activities |
| D-B11 | Non-hazardous construction processes | Non-hazardous processes during construction activities |
| D-B12 | Cost of dwelling per square metre | The cost of housing per useful living area |

### 2.3.2 Use phase

This phase is the longest in the life cycle of the building and therefore it is of great importance in the environmental impact of a building. Water and energy consumption have a high impact during the use phase of a house.

The environmental factors for analysis in the use phase are largely related to the design of the house. A good design will provide sufficient natural light, thermal insulation, good ventilation and heat from solar radiation. This means that the energy required to maintain an acceptable level of comfort in the building will be minimal.

Adaptive reuse is also considered within this phase, but only from the point of view of the potential for renovation of the dwelling. Adaptive reuse is the process of changing a building's function to accommodate the changing needs of its users while preserving the integrity of architectural space (Jong-Jin & Rigdon, 2007a). Adaptive reuse is required when the dwelling no longer

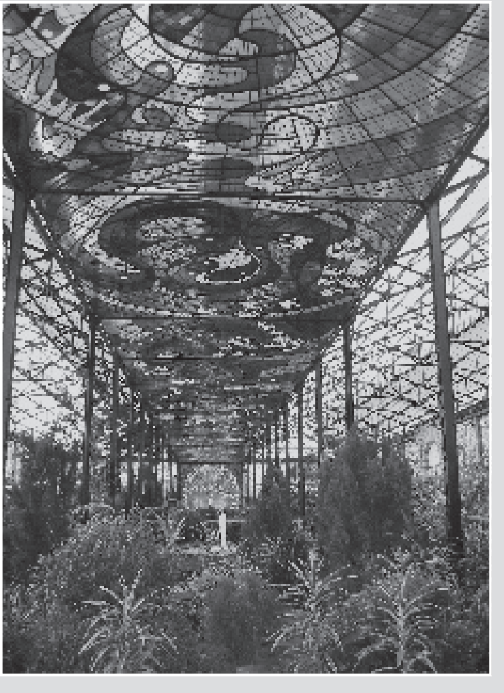
Figure 2.4 Market in the city of Toluca (Mexico) transformed into a botanical garden

satisfies the needs of the user. It offers numerous opportunities for minimising impact and for developing more sustainable renovation practices; furthermore, it extends the service life of buildings. For adaptive reuse, adaptable structures are needed. Characteristics of adaptable structures include simple form, low density and height, generous interior and exterior open space, separable parts, and durable construction (Lynch, 1990). Flexible buildings with open plans and easily removable partitioning have the best potential for reuse (Jong-Jin & Rigdon, 2007a). Figure 2.4 and 2.5 show a market in the city of Toluca that was adated for use as a botanical garden.

Another way to increase the sustainability of a building is by maximising the building's use and function while minimising its size. Simplifying the building's shape, using standard material modules, reducing circulation space, and increasing flexibility increase materials efficiency by design (Jong-Jin & Rigdon, 2007a).

Research has shown that renewal activities in comparison to new construction activities show a reduction of 50% in material consumption and 80% in waste production (Klunder, 2005). In addition, after the renovation has been carried out, the consumption of water and energy during the use of the house can be reduced significantly. There are several factors to

Figure 2.5 Interiour of the transformed market in the city of Toluca (Mexico)



consider when renovating a house. There are several approaches to reducing the environmental burden of a building that can go from the highly technological approach to the dematerialisation approach. Each of these approaches, as explained by Klunder (2005), has its advantages and disadvantages. An improvement in one aspect can cause disadvantages in other aspects. Klunder recommends combining the approaches to obtain the maximum level of efficiency.

The factors affecting this phase are related to the durability of the materials, the flexibility of the building, the quality of indoor air, and the characteristics of design that affect the consumption of resources. In addition, indicators related to occupant behaviour are included because they greatly affect the consumption of water and energy during the use phase of the building.

**Materials**

*Durability*

It is difficult to know the lifespan of a dwelling because of the complexity of its composition and its importance to the quality of life of its users. The life of a building may be determined by technical, social and cultural factors (Lawson, 1996). The durability of a material determines its required maintenance and replacement. In general, materials with high embodied energy are more durable. Stone, masonry and concrete are considered durable materials that require minimal maintenance (Jong-Jin & Rigdon, 2007a). Three categories of durability have been defined according not only to the characteristics of the materials but also to their use in the building. *Excellent durability (D-U1) materials* include clay, ceramic bricks, concrete, glass, metals, stone and plastics (Lawson, 1996). *Very good and good durability (D-U2) materials* are wood, adobe, earth and sand (Lawson, 1996). *Fair durability (D-U3) materials* are mortar, paint, textile and wallpaper (Lawson, 1996). It is important to clarify that this classification is not applicable to all cases. Depending on their quality, the weather or other conditions, some materials can last a longer or shorter time. Therefore, the context of the dwelling to be analysed has to be considered in order to classify the materials.

*Hazardous materials*

Hazardousness characteristics in materials refer to the presence of toxic materials during the life cycle of the building. For the categorisation of hazardous materials, volatile organic compounds (VOCs), radon and radiation emissions were taken into account; Meijer *et al.* (2005a; 2005b) present the materials in Dutch reference houses that have the greatest effect on human health. *Non-hazardous materials (D-U4)* are materials that do not produce toxic emissions in the indoor environment (e.g. radon, radiation, suspended particulates, VOCs) and that do not have high environmental interventions (e.g. toxic emissions). These materials are: wallpaper, glass, clay, ceramics, iron, wood, mortar, steel, earth, sand, shells, pebbles and adobe (Meijer *et al.*, 2005a; 2005b). *Hazardous materials (D-U5)* are those considered to produce high emissions in the outdoor environment during their production or those materials that emit toxic substances into the indoor environment: aluminium, copper, plastic, textile, zinc, paint, foam, gypsum, bitumen, PVC and stone with high radon emissions (Meijer *et al.*, 2005).

*Layout*
The layout of the building determines the flexibility of the building to be adapted in the future. The layout also influences the way the dwelling is used and can affect the usability of the building.

*Flexibility*
The aspect that has most influence on the possibilities for renovation is flexibility; the structure, space, the component's materials and the urban layout are the determinants.

The location of structural elements and the space between them contribute to the flexibility of the building because of the possibilities for redesigning the layout of the dwelling without having to remove structural elements (Figure 2.6). This avoids structural problems and waste production for structural elements, which are considered to be the most waste-intensive building elements when they are disposed of (Klunder, 2005).

Materials of construction elements influence the flexibility of the dwelling for two important reasons. The first is associated with the process of removal and reprocessing of the material or element as mentioned before. The second refers to the possibility of reusing the elements of the building.

The urban layout of a neighbourhood can have implications on the flexibility of a dwelling. This is related mainly to the accessibility of the house and to the possibility of opening extra windows or doors onto the exterior. A building with a high level of accessibility can be easily transformed into a building for a different purpose, and offers the possibility of merging and splitting dwellings.

Flexibility in terms of piping and electrical installations as well as blocks of services (e.g. kitchens or bathrooms) offers more possibilities for efficient renovation. Flexibility in services implies a good location, depending on the layout of the plan (for example, they could be in a central space or near staircases) and easy access, for example in ducts for maintenance (Figure 2.7).

The layout of the building is also important for flexibility. A design that can be adapted to the needs of the household through time can also increase the lifespan of the dwelling; for example, a house with the potential to adapt a room on the ground floor for use as a bedroom in the event that one occupant cannot use the stairs (Figure 2.8). Because this research does not take into account wiring and piping, the indicators in this research are limited to

**Fugure 2.6 Design with little flexibility (top) and a flexible design (bottom)**

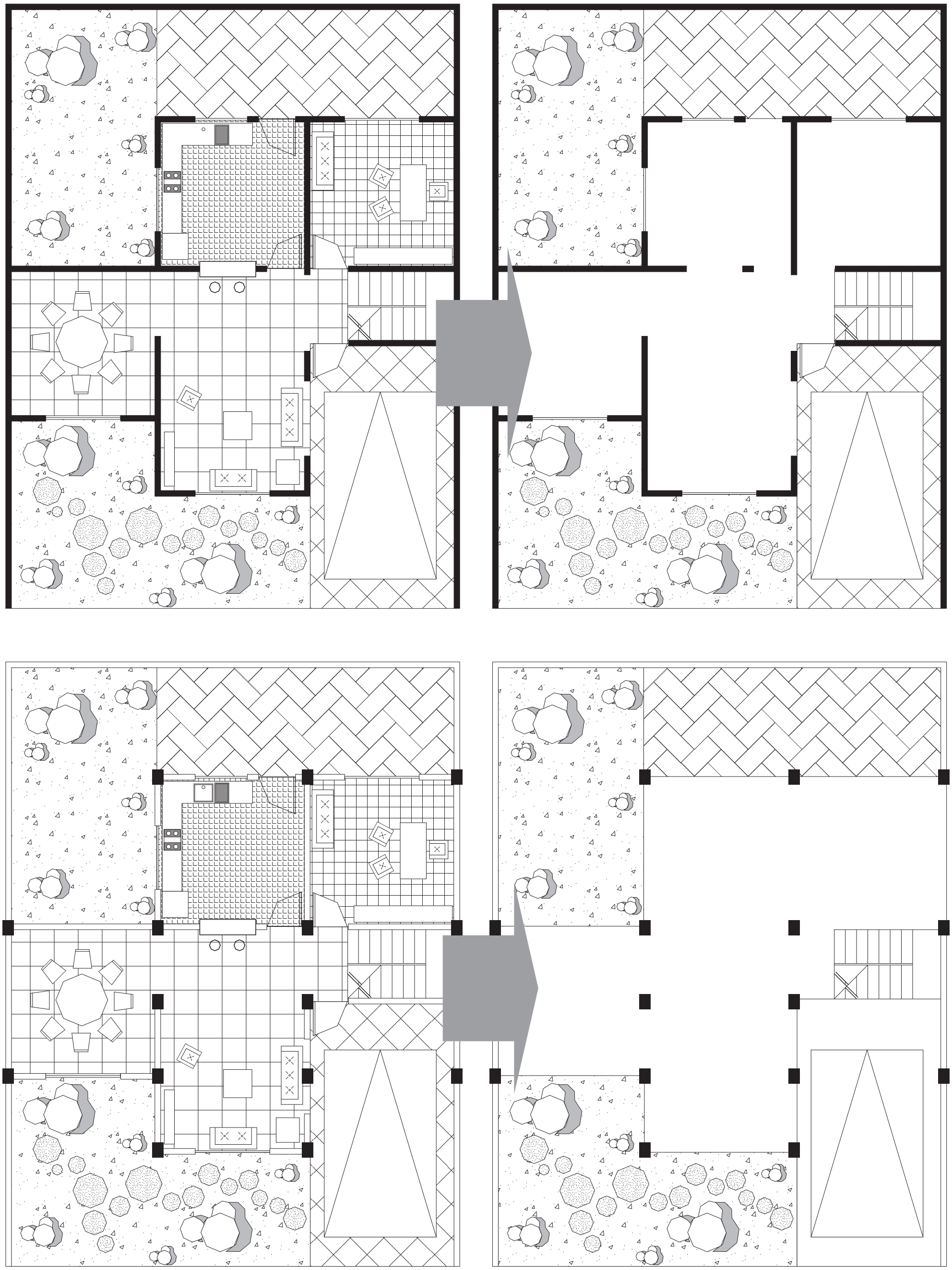
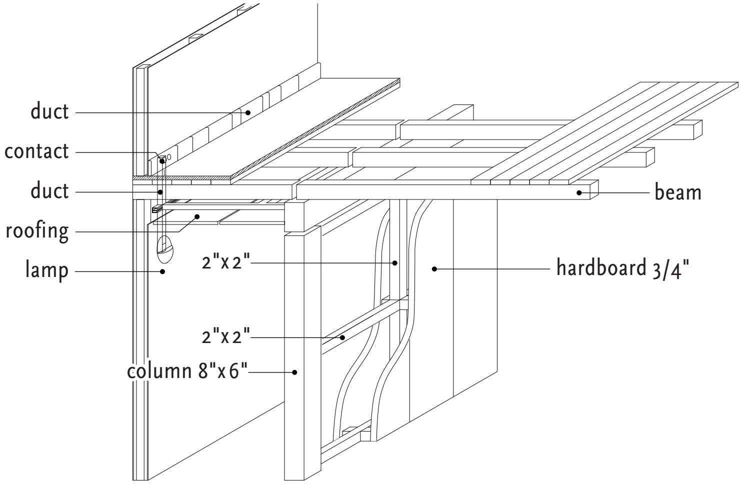


**Figure 2.7 Flexible installations**




the amount of structural walls in the layout of the dwelling.

*Interior structural walls (D-U7)* refers to the percentage of interior structural walls. *Exterior structural walls (D-U8)* refers to the percentage of exterior structural walls. The purpose is to evaluate the flexibility of the building. Internal structural walls reduce the possibilities for redesigning the layout of the plan. An open plan with load bearing walls in the outline of the building is more flexible than a house with internal structural walls. Sometimes, the type of material and construction process used determines this choice.

*Privacy*

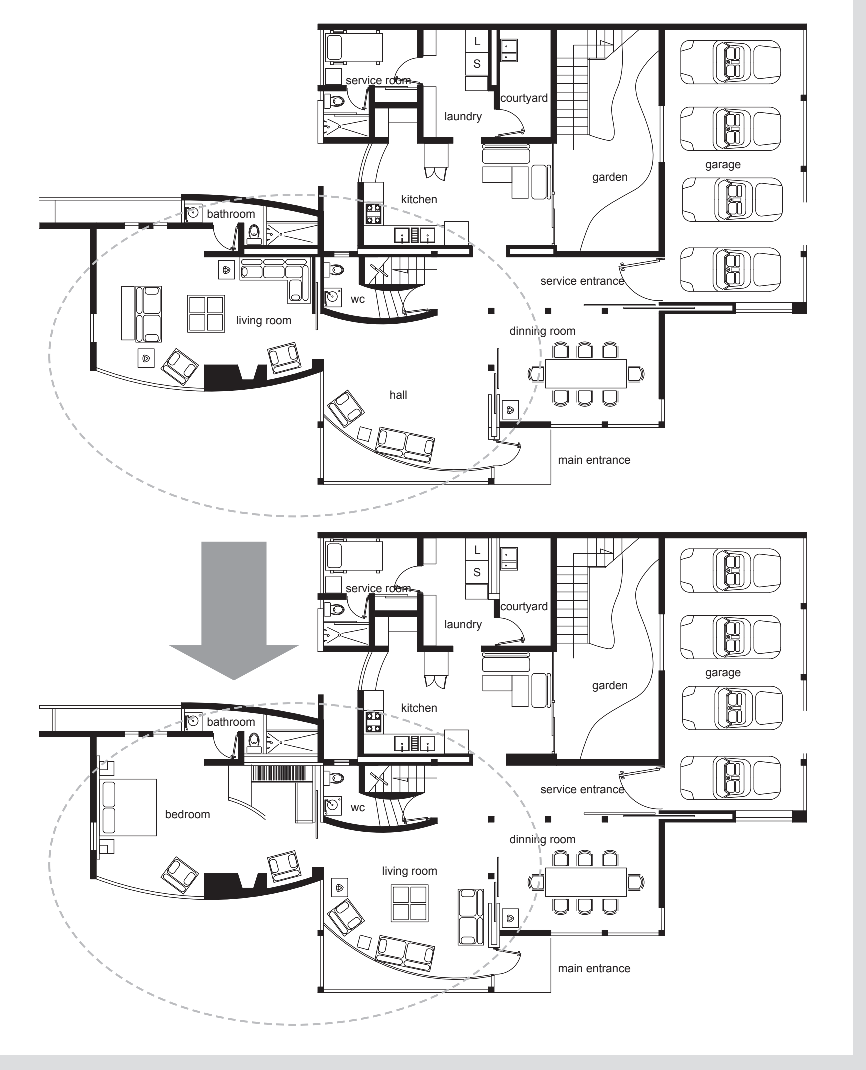
Among the factors that impact on the use of the house are those that involve the size of the household. Two similar houses will have a different performance if one of them is inhabited by a couple without children and the other by a family of six. Families are in a state of constant change: their members grow, come and go, which leads to different needs in different conditions.

Privacy is a fundamental necessity for personal development; therefore it is important to take into account the quantity of inhabitants in a dwelling. The following indicators can be useful to assess the degree of density of the dwelling. *Persons per bedroom (D-U8)* indicates the level of privacy in the house. *Useful Living Area per Person (D-U9)* is used to compare the need satisfaction per person when comparing dwellings.

## 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. Passive energy design can improve the energy per-

**Figure 2.8 Flexibility of spaces**



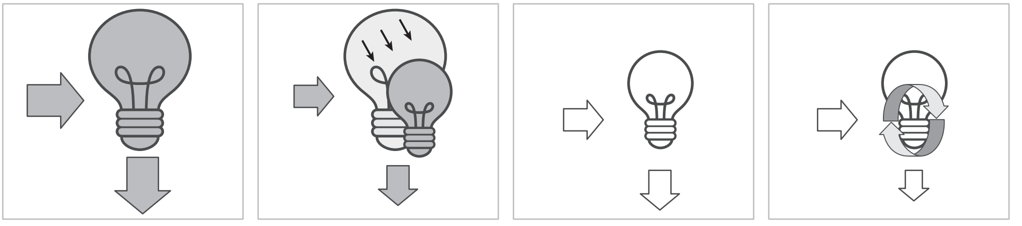

formance of a building. For example, in the United Kingdom, semi-detached houses consume 25%-33% more energy for heating than terraced houses (Edwards, 1996).

The energy performance of the building is also determined by the type of energy production in the area. Environmental problems such as climate change and acidification occur during the extraction, storage, distribution and conversion of energy (Hendriks, 2001). However, this is not a choice made by developers, construction companies or architects.

The approach followed in this research is the Trias Energetica (Three Step Strategy), which consists of three steps: reducing the use of energy, using renewable energy, and being efficient with the remaining need.

For the analysis of energy performance, two categories are used. These are:

**Figure 2.9 Three Step Strategy for energy**



A dwelling consumes energy, and energy production produces emissions

1. Reduce consumption: by decreasing the consumption of energy, emissions also decrease

2. Use of renewable energy: by using renewable energy, the production of energy has less impact on the environment and there are fewer emissions

3. Efficiency in remaining need

origin of energy (renewability of energy sources and energy recovered) and final use of energy (see Figure 2.9).
*Total energy consumption (D-U10)* 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. In this indicator, only purchased energy is considered.

*Origin of energy sources*
In this category, sources of energy – depending on their origin – can be renewable, recovered and non-renewable. *Renewable energy (D-U11)* is produced from continuous streaming resources such as solar radiation, water, wind, air, geothermal and geysers. *Recovered energy (D-U12)* refers to the capacity of producing energy from a product considered to be waste. An example from this category is energy produced as a by-product from material or waste, such as energy from biomass (when produced from waste). *Non-renewable energy (D-U13)* is energy produced from non-renewable sources, including oil, gas, coal, brown coal and nuclear.

*Final use of energy*
It is important to make a difference between primary energy and purchased or 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 example, the generation of electricity from coal is 30% efficient, because 70% of the energy contained in coal is lost before the delivery of the electricity (Lawson, 1996). 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). The uncertainty in the accuracy of the data may be considered acceptable since the purpose of this research is not to evaluate the environmental impact of the dwelling, but to improve the design. The indicators for final energy use are Climate related, Artificial Lighting and energy used for appliances, cook-

ing and water heating. *Climate related energy (D-U14)* use refers to the energy used for heating, cooling and ventilation by artificial means. The distinction is made with the intention of showing the amount of energy used for heating and cooling of the dwelling, and at the same time to analyse dwellings from different climates. In addition, it shows the energy reductions that could be achieved with a better design. *Artificial Lighting energy consumption (D-U15)* shows the impact of natural lighting in the design. The consumption of energy for *appliances, cooking and water heating (D-U16)* tends to vary according to the needs and culture of society; it can therefore be considered as a social indicator.

*Energy efficiency (D-U17)* is the ratio of renewable and recycled energy to climate related energy. It shows the quantity of sustainable energy used for keeping the house at a comfortable temperature (Rovers, 2005).

**Water**

Following the Three Step Strategy, the first step for the sustainable use of water is to reduce the quantity of water that enters the cycle (i.e. reduce consumption). The second step is related to the use of renewable sources of water. The third step refers to keeping the water within the system for a longer time by, for example, reuse and recycling of greywater (Figure 2.10).

The strategies for sustainable use of water using the Three Step Strategy are as follows (Hendriks, 2001): steps on the IN side of the system are: (1) prevent unnecessary use, (2) use renewable sources, and (3) use non-renewable sources carefully, cleanly and with high output. Steps on the OUT side of the system are: (1) prevent wastewater, (2) reuse wastewater, and (3) use wastewater carefully, as cleanly as possible and preserve for later use.

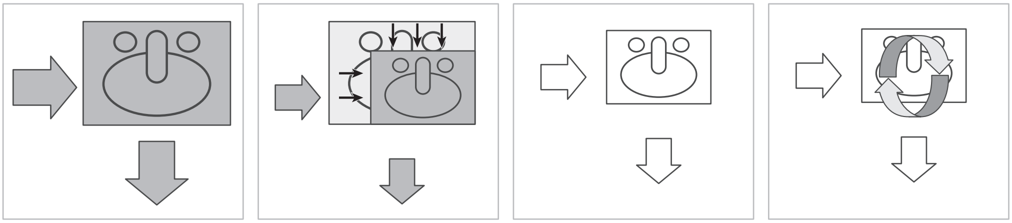
*The Total water consumption per person (D-U18) indicator* in this phase is related mainly to the quantity of water consumed. It shows the amount of water consumed per person. Its purpose is to help to understand the differences in cultures and societies that lead to differences in water consumption. This indicator is occupants-normalised to the average household size in the country. It is needed to analyse the design of spaces and changes in culture.

Closing cycles for resources is important, especially for water. Studies have shown that an efficient water system is one in which the distances from the water source to the water treatment plant and buildings are shorter (Ewijk, 1998). Nevertheless, the effectiveness and sustainability of the system depends on local characteristics.

Performance in this category is determined by the origin, quality and future treatment of the water, and the size of the water system cycles. The quantity of taps and bathrooms can be used for the analysis of cultural and societal trends. There are four categories that define water system efficiency, as follows:

a. Source or origin: rainwater, ground water, surface water or treatment plant.

**Figure 2.10 Three Step Strategy for water**



| A dwelling consumes water and releases wastewater | 1. Reduce consumption: by decreasing the consumption of water, the wastewater also decreases | 2. Use of renewable water: by using rainwater, the need for treated water decreases | 3. Efficiency in remaining need: reusing greywater keeps the water within the cycle for a longer time |
|---|---|---|---|

This characteristic affects the system efficiency because of the consumption of resources in the extraction of water from its source.

b. Off-site or on-site treatment: the size of the cycle has an important effect on the performance of the system. On-site treatment consumes fewer resources than off-site treatment because the first does not require a large amount of infrastructure, as is the case for off-site treatment. In addition, water treated on-site is easier to redistribute and reuse to the final consumer.
c. Quality of delivered water: this affects the consumption of resources for treating the water and it can be drinkable, treated (second grade water) or untreated. Delivery of drinkable water is considered better because it is healthier for consumers. However, when talking about system parts, the delivery of treated water could be more efficient. This is because not all the water used in a household is for drinking, so resources are used for treating water to a drinkable level when only treated water is needed.
d. Wastewater treatment depends more on the urbanisation than on housing level. The different types are: recycling on-site, treatment plant, or discharging without treatment.

In this approach, which is based on the design of the building, only the source of the water is considered.

*Source of water*

The origin of the water source is important to determine not only the characteristics of the water system but also the environmental impact of water consumption. Depending on its origin, water can be renewable, recovered or recycled. *Renewable water (D-U19)* is when the water source is a continuous stream, such as rainwater collected in the area of the house or neighbourhood. *Recovered water (D-U20)* is when it is reused without a treatment process; for example, the use of greywater for flushing toilets. *Recycled water (D-U21)* is when the treatment point is at the same location as the consumption point. In the context of this research this means the same house in the same neighbourhood.

**Table 2.4 Indicators for the use phase**

| Key | Name | Definition |
|---|---|---|
| D-U1 | Excellent durability of materials | Materials with high durability per useful living area |
| D-U2 | Good durability of materials | Materials with medium durability per useful living area |
| D-U3 | Fair durability of materials | Materials with low durability per useful living area |
| D-U4 | Hazardous materials | Hazardous materials per useful living area |
| D-U5 | Non-hazardous materials | Non-hazardous materials per useful living area |
| D-U6 | Interior structural walls | Percentage of internal structural walls out of the total |
| D-U7 | Exterior structural walls | Percentage of external structural walls out of the total |
| D-U8 | Persons per bedroom | Number of inhabitants divided by the number of bedrooms in the dwelling |
| D-U9 | Useful living area per person | Useful living area divided by the number of inhabitants in the dwelling |
| D-U10 | Total energy | Sum of renewable, recovered and non-renewable energy or climate related, artificial lighting, and energy used for cooking, water heating and appliances |
| D-U11 | Renewable energy | Renewable energy per useful living area |
| D-U12 | Recovered energy | Recovered energy per useful living area |
| D-U13 | Non-renewable energy | Non-renewable energy per useful living area |
| D-U14 | Climate related energy | Energy used for heating and cooling of the dwelling per useful living area |
| D-U15 | Artificial lighting energy consumption | Energy used for artificial lighting per useful living area |
| D-U16 | Energy used for cooking, water heating and appliances | Auxiliary energy needed to run a house per useful living area (cooking, heating water, appliances) |
| D-U17 | Energy efficiency | Renewable and recycled energy to climate related energy |
| D-U18 | Water consumption per person | Water consumption per number of inhabitants |
| D-U19 | Renewable water | Renewable water per useful living area |
| D-U20 | Recovered water | Recovered water per useful living area |
| D-U21 | Recycled water | Recycled water per useful living area |
| D-U22 | Water efficiency | Renewable, recovered and recycled water in relation to water consumption |

*Water efficiency (D-U22)* is the ratio of renewable, recovered and recycled water to the water consumed (Rovers, 2005).

The design indicators for the use phase are summarised in Table 2.4.

### 2.3.3 Demolition phase

When talking about sustainable building, demolition should no longer be considered a phase in the life cycle of a building. It should be considered only as a last resort. There is sufficient evidence that the only way towards a truly sustainable construction sector is through the management of building stock (Rovers, 2004; Van der Flier & Thomsen, 2006; Wassenberg, 2006). It is generally more cost effective to recycle than demolish and rebuild. The conservation of buildings not only saves resources and energy, but ensures that the infrastructure of our towns and cities continues to be used (Edwards, 1996). Nevertheless, there are cases in which a building has to be demolished, for example, when the structure cannot be repaired or when social problems in the area cannot be solved in any other way. Figure 2.11 shows a case in Duindorp (a neighbourhood in the city of The Hague, the Netherlands) in which social and structural problems led to the demolition of several dwellings; in contrast, Figure 2.12 shows a church in Maastricht (also in the Netherlands) that was adapted as a bookshop. This is why demolition activities should still be considered from the conception of the design. For this research, demolition indicators do not mean that the demolition phase is considered in a building's life cycle, but that the design should consider the maximal environmental efficiency of a dwelling, even in extreme conditions.

The indicators in this phase are related to the process of removal and reprocessing of materials. In addition, the type of materials (renewable, non-renewable) and the total quantity of resources in volume and weight are important factors when considered in terms of waste. Furthermore, a building can be demolished not only by human decision but also as a consequence of natural or human-caused disaster; in these cases the characteristics for removal of materials from the building would be neglected, and the possibilities for separation of waste would be considered the main factor that would determine the effectiveness of the process. Dependent on this would be whether some materials could be recovered for energy production, and the volume of waste that would have to be disposed of without energy recovery.

**Materials**

The factors that influence performance during demolition activities are related to the process of dismantling and recovering elements or materials (Sassi, 2002). To increase the possibilities for sustainable demolition, a Design for Recycling strategy can be used. This is a strategy that takes into account characteristics of the materials that allow better recycling methods. The characteristics that are considered are: homogeneity, dismantleability, identification and recycled content. Homogeneous materials are more easily recycled than composite materials, which require more processing in order to be reused. By using materials that can be easily dismantled and with identifiable parts, the process of dismantling and sorting becomes more efficient.

*Dismantleability*

Design for Disassembly is a strategy that facilitates the recycling of materials. Though it is difficult to predict the future use of the building, or the capabilities of the building industry and market to recover and recycle materials, conservative disassembly can be simplified by designing the building in such

Figure 2.11 Duindorp: demolition due to social and structural problems

a way that the elements and materials can be recovered. Conservative disassembly means dismantling the building into simpler elements. This type of disassembly is labour-intensive, costly and often dangerous, but the recovered materials have a higher value and quality (Jong-Jin & Rigdon, 2007a). There are mechanical technologies for sorting demolition debris, but they produce low-grade materials.

Dismantleability refers to the process of removal during maintenance and renovation activities. Efficient dismantleability means an effective dismantling process, in which materials can be easily removed from their place without excessive effort, danger or time. A high level of dismantleability can be achieved through accurate drafting and labelling of materials, easy and safe access to the element or material to be removed, minimal machinery requirements, use of mechanical fixing methods, use of homogeneous materials, and minimising the use of hard materials for fixing units (e.g. bricks) (Sassi, 2002; Lawson, 1996).

The indicators of dismantleability are defined according to the strategies of Lawson (1996) and Sassi (2002). *Dismantleability of materials or elements (D-D1)* refers to the property of materials for being dismantled during demolition activities. It includes dismantleable and semi-dismantleable materials.

a. *Dismantleable materials or elements (D-D1.1)* are those for which the information needed is minimal (i.e. it is already known by construction workers); there is easy and safe access to it (e.g. only normal anchorage is needed); and it can be performed with small hand tools. Examples from this category are mechanical fixed elements such as aluminium frames, bitumen from roofing, wallpaper, carpets, wooden elements, glass, installation materials

**Figure 2.12 Maastricht bookshop situated in an old church**


such as copper, plastic, steel, cast iron, galvanised iron, PVC and zinc, and filling elements such as earth, pebbles, sand and shells.

b. *Semi-dismantleable materials or elements (D-D1.2)* are those in which some of the abovementioned requirements are not satisfied but the removal process can be carried out without excessive damage to the material or element, and the removal process is not dangerous for construction workers. Examples from this category are clay or ceramic tiles and sometimes masonry that can be removed and reused for a different purpose, for example roads.

*Recoverability*

There are several factors that influence the reuse or recycling of the materials in a product. For buildings an important factor is their long service life. When considering the recyclability or reusability of materials, potential recoverable materials were considered based on the guidelines for recoverability of materials by Sassi (2002) and Lawson (1996). The difference between recovered materials of the building and construction phase as defined in Section 2.3.1, and recoverability of materials defined in this section, is that the first refers to materials already used and the second refers to the potential of the materials. The guidelines for reprocessing or recovering materials or elements are: no contamination of materials by other materials, durability of materials ensures the quality of reprocessing, and elements with mechanical fixing are reprocessed more efficiently than elements fixed with chemical processes.

*Recoverable materials (D-D2)* are those that have the potential to be recovered. They include reusable, recyclable and downcyclable materials.

a. *Reusable materials or elements (D-D2.1)* are those that can be reused in their original form with little reprocessing; these materials have the best performance because there is no need to consume many more resources in order to integrate them into the cycle one more time. Reusability is a function of the age and durability of a material (Jong-Jin & Rigdon, 2007b). For example, doors are easy to dismantle and adapt to another building, even though they require processing in order to be reused. Examples of these materials are: wood from elements, textiles like carpets, and stone from foundations (Jong-Jin & Rigdon, 2007a).
b. *Recyclable materials or elements (D-D2.2)* are those that require more complex processing in order to be used again. Recycling has many benefits: keeping the materials in the cycle for a longer time, reducing the consumption of new resources, conserving the embodied energy of materials (Jong-Jin & Rigdon, 2007b), reducing transportation and therefore energy and emissions related to transportation, and reducing construction waste. Nevertheless, recycling sometimes requires a lot of energy and may not be the most environmentally-friendly option (Hendriks, 2001). Therefore recycling must ensure that the energy and resources saved are greater than those needed to make a fresh product. The cost and benefits of recycling vary from one material or component to another. Examples of materials are: aluminium frames, wallpaper, glass, copper from installations, plastic elements, steel structural elements (not embodied in concrete elements), iron (on installations), gypsum from plasters and zinc (installations) (Jong-Jin & Rigdon, 2007a).
c. *Downcyclable material or elements (D-D2.3)* refers to those materials that need reprocessing to be used again though not for the same purpose. The limitation for recycling materials is due to difficulties of adaptation related to size or low quality. The quality of the materials can drop so much that they can no longer be used for the same application (Waal, 2002). Examples are: clay from tiles, bitumen from roof tiles, ceramic from tiles, and foam from insulation. Concrete is considered here as a downcycling material because when recycled it has been weakened by previous exposure to weather, traffic and structural stress, and it is not as strong or durable as virgin concrete (Jong-Jin & Rigdon, 2007a).

**Hazardous demolition processes**

The indicators considered in this phase are defined similarly to those presented for the building and construction phase. *Hazardous demolition processes (D-D3)* are demolition processes considered to be dangerous to construction workers. *Non-hazardous demolition processes (D-D4)* are demolition processes that normally do not present a danger to construction workers.

The design indicators for the demolition phase are summarised in Table 2.5.

**Table 2.5 Indicators for the demolition phase**

| Key | Name | Definition |
|---|---|---|
| D-D1.1 | Dismantleable materials | Dismantleable materials per useful living area |
| D-D1.2 | Semi-dismantleable materials | Semi-dismantleable materials per useful living area |
| D-D2.1 | Reusable materials | Reusable materials per useful living area |
| D-D2.2 | Recyclable materials | Recyclable materials per useful living area |
| D-D2.3 | Downcyclable materials | Downcyclable materials per useful living area |
| D-D3 | Hazardous demolition processes | Hazardous processes during demolition activities per useful living area |
| D-D4 | Non-hazardous demolition processes | Non-hazardous processes during demolition activities per useful living area |

## 2.4 Relation between indicators and Three Step Strategy

### 2.4.1 Choice of indicator

In order to ascertain which type of indicator to use, the definition of the endpoint of the assessment is essential. Endpoints are the final impacts to be analysed and depend on the objective of the research. Table 2.6 shows the endpoints of the approach followed in this book and the related indicators. Because the approach taken in the assessment is based on the Three Step Strategy, the endpoints are developed from this strategy.

Some indicators introduced in the last section are normalised for comparability reasons. Normalisation reveals the size of effects in relative terms (percentages). Other indicators are expressed through indicatory concepts, such as people, square metres, etc. Normalisation allows comparability, taking into account the characteristics of the place, design, or size. The indicators help us to assess the environmental performance of the design of the dwelling for each phase of the cycle. For the analysis the indicators are not in the same order than the Three Step Strategy; they are categorised according to the life cycle of the building. Some indicators help us to assess the effect of occupant behaviour on the environmental performance of the dwelling. Table 2.7 shows the indicators for each phase of the building.

### 2.4.2 Relation within the indicators

Figure 2.13 and Figure 2.14 give an overview of the relation within the indicators used for assessing the environmental performance of the dwelling. Figure 2.13 shows materials indicators. In the building phase, three types of materials make up the total quantity depending on their origin; these are: renewable, recovered and non-renewable. Within recovered materials there are three categories: reused, recycled and downcycled. Non-renewable materials can also be high impact or low impact for the environment. During the use phase materials can be hazardous and non-hazardous. In the demolition phase of the building, the total quantity of material is measured according to its recover-

**Table 2.6 Indicators and endpoints**

| Three Step Strategy | Endpoint (objectives) | Categories of indicators | Indicators |
| --- | --- | --- | --- |
| Step 1 Reduce consumption | Reduction of intensity in the use of resources (economy of resources) | Total consumption of material | Total material (D-B1) |
| | | Total consumption of energy | Total energy (D-U10)<br>Climate related energy (D-U14)<br>Artificial lighting energy (D-U15)<br>Energy for cooking, water heating and appliances (D-U16) |
| | | Total consumption of water | Water use per person (D-U18) |
| | | Total consumption of land | Total land use (D-B8)<br>Green area (D-B9) |
| Step 2 Use renewables | Increase use of renewable and recovered resources | Use of renewable and recovered materials | Renewable materials (D-B2)<br>Non-renewable low and high impact (D-B4) |
| | | Use of renewable and recovered energy | Renewable energy (D-U11, 13)<br>Recovered energy (D-U12) |
| | | Use of renewable and recovered water | Renewable water (D-U19)<br>Recovered water (D-U20,21) |
| | Reduce emissions | Waste production | Total waste (D-B6)<br>Recoverability of waste (D-B7) |
| | Improve health in indoor environment and during construction | Hazardous materials<br>Hazardous processes | Hazardous materials (D-U4, 5)<br>Hazardous construction processes (D-B10-11)<br>Hazardous demolition processes (D-D3, 4) |
| Step 3 Increase efficiency | Increase efficiency during construction and use | Efficiency of resources | Material efficiency (D-B5)<br>Energy efficiency (D-U17)<br>Water efficiency (D-U22) |
| | Increase efficiency in maintenance, renovation and demolition | Possibility of material reprocessing (reusability) | Recoverability of materials (D-D2.1, 2.2)<br>Recovered materials (reused, recycled, downcycled) (D-B3) |
| | | Possibility of material removal (dismantling) | Dismantleability of materials (D-D1.1, D-U1.2) |
| | | Possibility of reuse of building (flexibility) | Structural walls (D-U6-7)<br>Persons per bedroom (D-U8)<br>Useful living area per person (D-U9) |
| | | Increase durability of materials | Durability of materials (D-U1-3) |

ability (reusable, recyclable, downcyclable and non-recoverable) and dismantleability (dismantleable, semi-dismantleable and non-dismantleable).

Figure 2.14 shows energy indicators. During the use phase, energy can be classified according to its origin: renewable, recovered and non-renewable. Energy during this phase can also be classified according to its final use: for air conditioning (climate related), artificial lighting, or for appliances, cooking and heating water. Climate related energy can therefore be non-renewable, for example. The sum of the three types of energy according to its origin account for the total energy consumed in the dwelling (in one year) as does the sum of the three final uses of energy.

**Table 2.7 Resource characteristics and indicators for each life cycle phase**

| Resources | Indicators per phase of the life cycle | | | | | |
| --- | --- | --- | --- | --- | --- | --- |
| | **Building and construction** | **Indicators** | **Use** | **Indicators** | **Demolition** | **Indicators** |
| **Materials** | Total materials | D-B1 | Durability | D-U1,2,3 | Dismantleability | D-D1 |
| | Renewability | D-B2 | Hazardous materials | D-U4,5 | Recoverability | D-D2 |
| | Impact on the environment | D-B3,4 | Flexibility | D-U6,7 | Hazardous processes | D-D3 |
| | Waste | D-B6,7 | | | | |
| | Hazardous processes | D-B10, 11 | | | | |
| | Material efficiency | D-B5 | | | | |
| **Energy** | | | Total energy | D-U10 | | |
| | | | Renewable | D-U11 | | |
| | | | Recovered/re-used | D-U12,13 | | |
| | | | Climate energy | D-U14 | | |
| | | | Artificial lighting | D-U15 | | |
| | | | Cooking, water heating and appliances | D-U16 | | |
| | | | Energy efficiency | D-U17 | | |
| **Water** | | | Total water | D-U18 | | |
| | | | Renewable | D-U19 | | |
| | | | Recovered/re-used | D-U20,21 | | |
| | | | Water efficiency | D-U22 | | |
| **Land** | Quantity | D-B8 | | | | |
| | Green areas | D-B9 | | | | |
| **Others** | Cost of housing | D-B12 | Persons per bedroom | D-U8 | | |
| | | | Useful living area per person | D-U9 | | |

Figure 2.15 shows the differences and relationship between material indicators. In the example, a door made of wood is renewable on account of the sustainable origin of the wood, non-hazardous for the occupants of the dwelling, reusable because it can be reused as a door, and dismantleable because it can be dismantled easily and without damage.

Some indicators have been developed in relation to aspects in which the behaviour of the occupants influences the environmental performance of the dwelling. The effects of these factors are seen during the use of the building.

**Figure 2.13 Materials indicators**

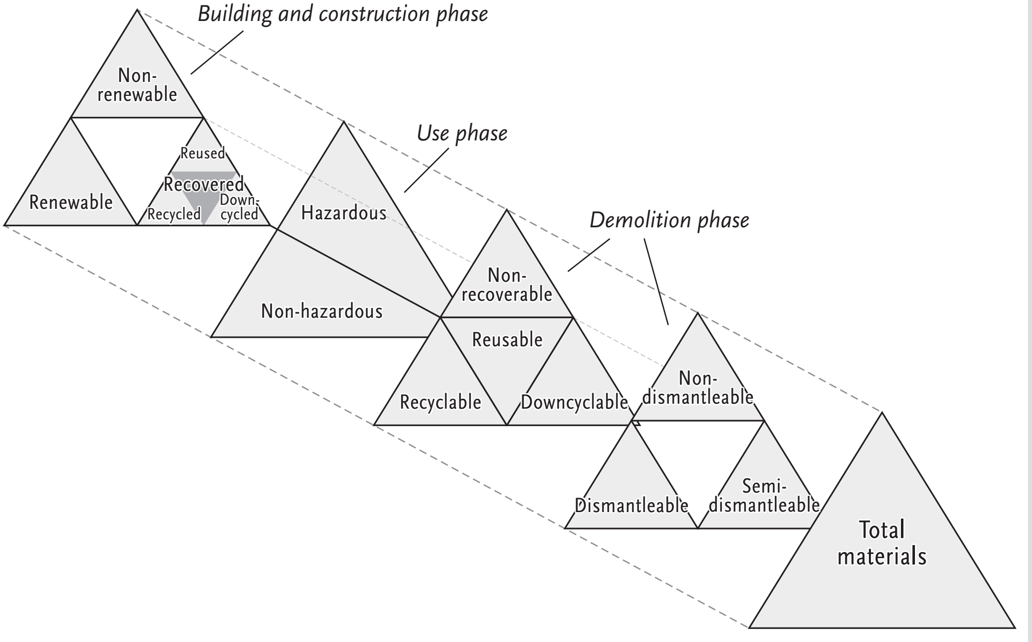



**Figure 2.14 Energy Indicators**

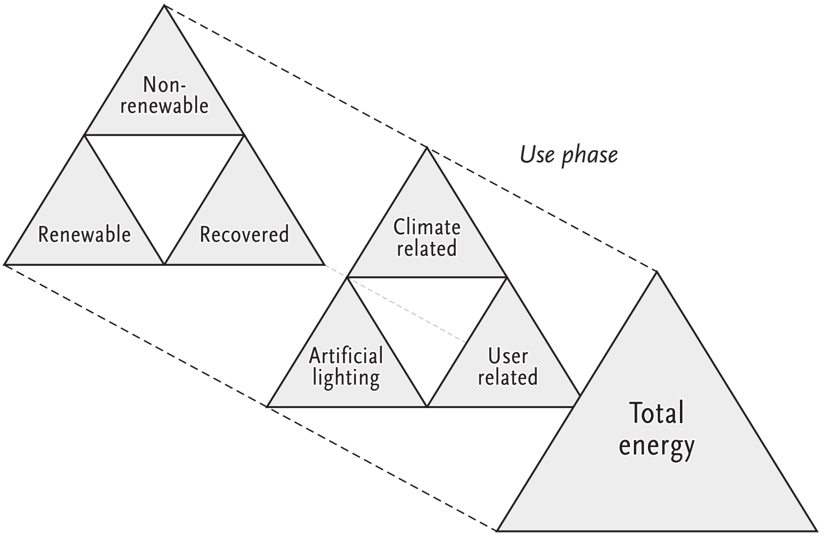
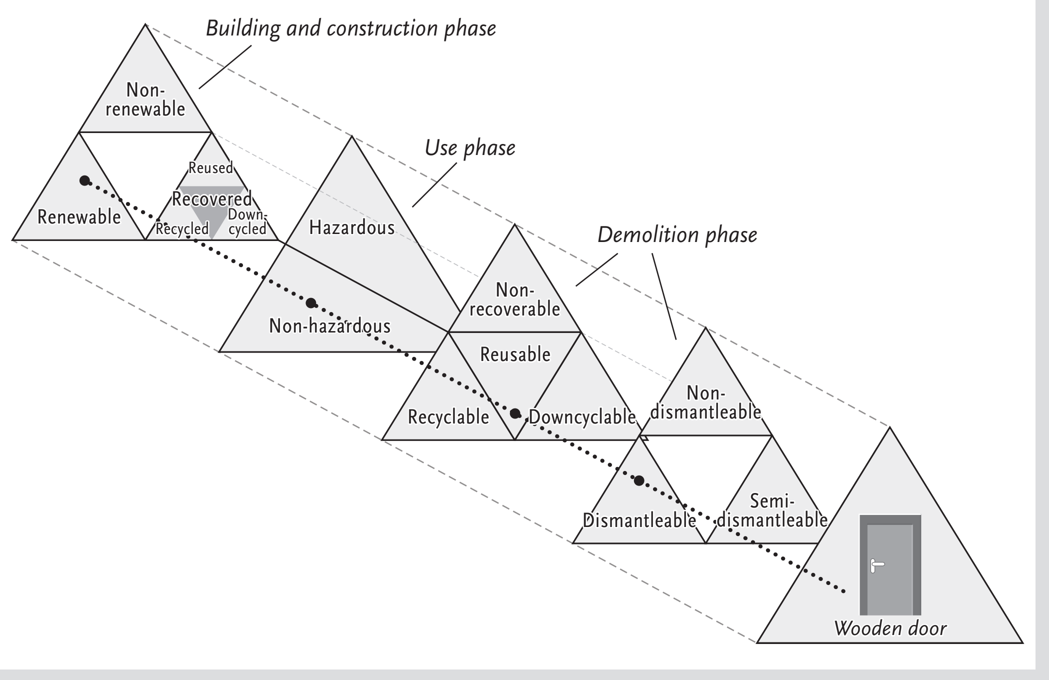


**Figure 2.15 Relation between dismantleability and recoverability**



# 3 Reference dwellings

## 3.1 Introduction

The indicators defined in the previous section are used to analyse housing at two different levels: national and international. The goal of the national analysis is to analyse trends in policy and use of materials with the idea of transferring best practices from one dwelling to another. The goal of the international analysis is to place Mexican housing in a broader context for a better understanding of the situation.

In this section, Mexican housing is analysed next to reference houses in two other countries, Peru and the Netherlands. The first step of the evaluation is to establish the dwellings to be analysed. The characteristics of the building, the type of materials used, the energy consumption and the construction processes tend to vary within the country due to the diversity of climates in Mexico. Therefore, this study is focused on one region of Mexico, which will be introduced in the next section.

For the Mexican case study dwellings, an analysis of the state of Mexican housing was realised with the support of statistics and legislation. Three reference houses were selected, keeping in mind that they only represent the average house in the region of study. The houses were selected in the following categories: traditional, modern middle level, and modern social housing. In this way, the relative effects of socioeconomic factors could be studied to a certain extent. The dwellings used for the international analysis are a Peruvian reference house, as defined in a study similar to this book (Torres Mendez, 2005), and a Dutch reference house.

Comparisons of the international reference dwellings are limited by diverse factors, such as different climates and cultures. Therefore, only technical and design aspects are taken into account. Social aspects of housing are not compared. Climate is an important factor affecting the performance of a dwelling; therefore, degree days are used to normalise the temperature in the three countries.

In order to conduct a comparison analysis it is necessary, according to Oxley (2001), to define precisely the object and the purpose of the comparison. In this study, dwellings are analysed in terms of design and use of resources with the purpose of determining the situation in Mexican dwellings in relation to houses in other countries.

The questions defined for this analysis are as follows:

a. Do Mexican dwellings consume more or fewer resources in comparison to international reference dwellings?
b. Is the Mexican dwelling's design more or less sustainable in terms of maintenance, durability and flexibility?

The goal of the analysis is to determine the effects of different construction methods on resource consumption and sustainability. The institutional, cultural and social contexts are therefore not covered in the analysis, with the exception of cost of dwelling and water consumption per person.

The analysis of Mexican dwellings against the Dutch dwelling can provide insight into the differences between developed and developing countries, while the analysis against Peruvian housing can give insight into the use of materials in countries with a similar background but with different climates. The goal of the analysis is not to transfer knowledge or construction procedures from one country to another, but to help to analyse housing design in relation to its context. The intention is that the differences between the countries do not cloud the analysis but make it more useful.

The housing situation in Mexico is studied in Section 3.2. The characteristics of Mexican houses are defined in Section 3.3 of this chapter. Three Mexican dwellings are then selected, taking into account the most common characteristics of housing in the region for each of the categories named above. Sections 3.4 and 3.5 of this chapter present the national and international case studies and the analysis of the reference houses. The analysis of housing is carried out in Chapter 4.

## 3.2 Housing situation in Mexico

Nowadays, there is a tendency in Mexico towards sustainable construction, as shown in a number of laws, plans and studies (CNA 2005; SENER 2006; CONAFOVI 2006), although providing good housing to the population is still a major issue. Statistics show that a large proportion of the population lives in poverty or in extreme poverty. Roughly 7% of households live on less than the minimum salary, and 26% live on between one and two times the minimum salary. The minimum salary is considered to be the necessary amount of money for the “basic basket”, which consists of the products and services needed to cover the basic needs of a household (SEDECO 2007). On average, the minimum salary is MXN 52.59 per day (SAT, 2008). At the current exchange (2008) rate this is equivalent to EUR 3.27. With these figures it is unsurprising that a large part of the population does not have access to good housing.

### 3.2.1 Housing market

The population in Mexico is still growing, even though the number of children per family is decreasing, being in 2000 the average family of 4.4 members, and in 2005 4.04 persons per family (INEGI, 2007). Therefore, the demand of new housing in Mexico is still high.

High demand and low offer of dwellings characterises the housing market in Mexico. The lack of housing is not the only housing-related problem in Mexico. Migration from the countryside to cities causes poverty and marginality.

Migrants tend to establish themselves in the periphery of the cities, often in dangerous or protected areas. These illegal establishments are characterised by a lack of infrastructure and basic services. Even though eventually the government may provide the necessary infrastructure, it may take some years to happen. These houses are made of non-permanent materials. Social problems are frequently seen in poor or deteriorated neighbourhoods where houses or apartments are small and badly designed causing lack of privacy and overcrowding.

The housing market in Mexico is divided into three sectors, depending on the mechanisms of financing, subsidies and income of the target population.

1. Housing for high-income families (more than ten times the minimum salary) has as the main characteristic its high overall quality.
2. Housing for middle-income families has been the sector that institutional programmes or credits are aimed at.
3. Housing aimed at low-income families tends to be situated in high-density locations without the required infrastructure and services. Land and construction is often illegal. The population that belongs to this range is typically unemployed, self-employed or part employed. Therefore these families do not have a fixed income or social security.

### 3.2.2 Overview of housing policy

Housing policy in Mexico has evolved through a series of different phases. The obligation of employers to provide housing for their employees was established in the constitution of 1917. In 1943, the Mexican Institute of Social Security (IMSS) was founded, which provided housing for its affiliates. In 1963, a financial foundation for housing (Fondo de Operación y Financiamiento Bancario a la Vivienda, FOVI) was created within the Bank of Mexico to promote construction and social housing improvement through private loans.

Since 1972 employers have been obliged to pay into a national housing fund aimed at providing accessible credit for the acquisition of housing, known as the National Housing Fund for Workers (Fondo Nacional para los Trabajadores, INFONAVIT). In the same year, the ISSSTE fund for housing (FOVISSSTE) was also founded with the objective of giving housing credits to workers.

Until the 1980s, housing policy was implemented through the direct intervention of the government through development, construction, financing and subsidies. From 1990, national housing organisations began to assume a predominately financial role.

Nowadays, there are four national financial housing organisations: INFONAVIT, the Fondo Nacional de Vivienda del ISSSTE (FOVISSSTE), FOVI, and FONHAPO. In the period 1995-1999 these public organisations covered 44.7% of credits. Commercial credits covered only 14% for middle-income and high income housing.

In 1997 the social security system in Mexico was reformed, modifying the pensions structure from collective to individual; this led to modifications in credits for housing.

Nowadays housing objectives aim to (CONAFOVI, 2007):

- coordinate actions between national and regional governments;
- clarify credit and subsidy systems;
- decrease indirect costs by improving logistics;
- decrease direct costs with the help of new applicable technologies; and
- increase construction of popular and social housing.

Problems in Mexican housing are due to socioeconomic and political factors, including the following (CONAFOVI, 2007):

- Unequal distribution of income, difficulties for the majority of the population to access financial mechanisms, lack of private stimulation for housing.
- Economic crisis, poor distribution of income, poor application of subsidies, lack of incentives by legislation, inefficiency of construction processes, demography, migration from countryside to cities and inadequate financial mechanisms.
- A significant proportion of the population does not have access to good housing because they do not have the required income.
- Housing policy in Mexico consists of creating financial mechanisms that are accessible to those sectors that do not have sufficient resources.
- Those sectors that are not capable of acquiring good housing tend to accept housing spaces that do not comply with the minimal requirements for providing good quality of life. Others squat or illegally purchase communal land in dangerous places.
- Tolerance by authorities to illegal settlements is related to political factors such as gaining votes in elections, and involvement in political acts.
- The response of the government to housing problems since the Mexican Revolution has been directed towards those groups committed to the political system or that have threatened their permanence. Therefore, housing policy has been focused on political criteria.

### 3.2.3 Water and energy in Mexico

**Water**

Like in many developing countries, the main goals of water policy are related to its quality, distribution, losses in the piping system, and treatment of wastewater. The main goals of the CNA (National Water Commission) are to increase the percentage of the country's inhabitants who have drinking water and sewerage, and to increase the volume of wastewater treated. In Mexico, only 89.5% of the population have access to drinkable water, and only 77.5%

**Table 3.1 Consumption of water per person (litres/day) in Mexico**

| | Consumption by socioeconomic level | | |
|---|---|---|---|
| Average temperature | High-income | Middle-income | Social income |
| > 22°C | 400 | 230 | 185 |
| 18 to 21.9°C | 300 | 205 | 130 |
| 12 to 17.9°C | 250 | 195 | 100 |
| < 11.9°C | 250 | 195 | 100 |

Source: CNA (2005)

have sewerage systems (CNA, 2007).

According to the CNA, the opportunity areas for water saving in the country are as follows:

- setting of tariffs that reflect the real costs of water provision and treatment;
- decrease of water consumption per household;
- reuse of greywater;
- use of rainwater.

A high percentage of water is lost during distribution. Due to water losses during distribution, which account for 40% (CNA, 2004), norm NOM-002-CNA-1995 was established to reduce losses caused by technical failures in the system.

On average, consumption of water in the country per person is higher than in developed countries. Nevertheless, water consumption within the country varies according to the climate and socioeconomic level (Table 3.1). Information campaigns for decreasing the consumption of water have existed for several years. In general, the rates (cost of water) are progressive, which means a higher rate per cubic metre of water for higher consumption of water (CNA, 2004). In practice, this system is not always applied, such as in the municipality of Toluca, where the water rate is fixed per household regardless of the size of the household or the consumption of water.

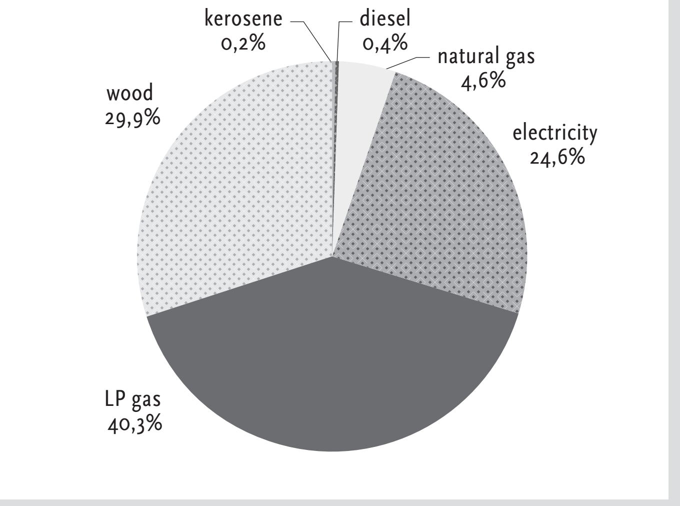
## Energy

In Mexico, buildings consume 20% of the total energy produced in the country; 85% of this percentage is consumed by housing. From the total consumption of energy, 75% is produced from hydrocarbons (non-renewable sources) (SENER, 2006). In housing, commerce and the public sector, the major sources of energy are derived from oil (LP gas) and wood. Figure 3.1 shows the percentages of consumption per energy source in this sector.

In Mexico, four main types of energy source are used in housing: gas derived from oil, wood, electricity, and natural gas. Wood is the principal energy source for approximately 19 million people living in rural areas (CONAFOVI, 2006). Roughly 13% of the population lacks electricity, using candles, petroleum, wood or LP gas for artificial illumination. LP gas and natural gas are used for heating water and cooking. Figure 3.2 shows these percentages.

On average, energy consumption in housing is related in the first place to cooking, in the second place to heating water and artificial lighting and in

**Figure 3.1 Percentages of energy consumption per source in the public sector in Mexico**




Source: SENER (2006)

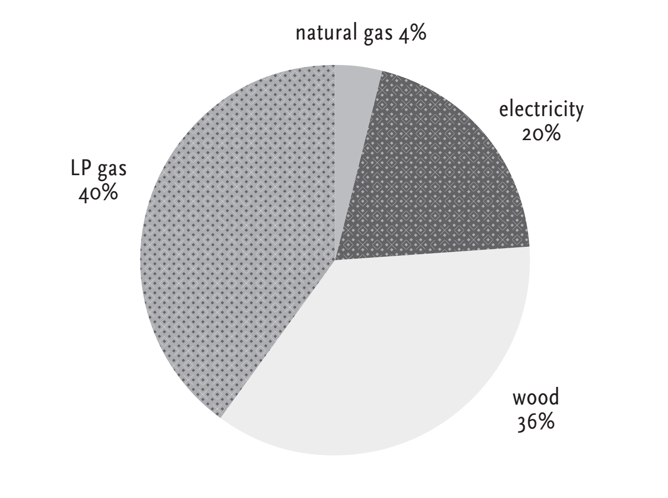
the third place to air conditioning and electrical appliances. In the north and on the coast, energy consumption for air conditioning (cooling) takes second place.

## 3.3 Selection of reference houses

### 3.3.1 Location

**Mexican dwellings**
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, with temperatures averaging 10°C to 15°C and relative humidity within and below comfort limits. During the nights and in winter the wind is cold. In general, the region presents two seasons: rain in summer and dry the rest of the year. Mexico City, Toluca, Tlaxcala, Puebla and Morelia are some of the cities with this climate. Due to the variety of conditions in the country, the reference house only reflects the characteristics of housing in this region. For the case study, the city of Toluca was chosen. Toluca is an industrial city and the state capital of the State of Mexico, 63 km from Mexico City. The metropolitan area of Toluca is the fifth most populated area in Mexico. The cold climate is due to its high altitude at 2,680 m above sea level. During the night, temperatures can drop below 0°C even in summer, and the maximum temperature rarely exceeds 27°C.

**Figure 3.2 Type of energy consumption in Mexican housing, in percentage of households**




Source: SENER (2006)

## 3.3.2 The approach for selection of Mexican dwellings

Using statistical information from censuses, a traditional reference house and two modern reference houses for two different socioeconomic levels were chosen. The characteristics taken into account are: size, number and type of rooms, type of materials and construction processes. Statistical information is available for Mexico from 1950, when the first census was conducted.

**Traditional reference house**

The data for the traditional house were obtained from a case study and the analysis of the trend in housing materials observed in the census. This case study is located in Metepec, a city next to Toluca. These data, in addition to observations in the locality, provided the characteristics for the traditional reference house.

At the beginning of the last century, the majority of the population lived in the countryside. For the purposes of this research a city dwelling is considered due to the fact that countryside houses would differ too much from modern houses and the analysis would lose sense. In addition, even though in some places these types of houses are still being constructed, this is only in very poor locations and it is not considered as a good practice to follow.

*Size*

Dwellings used to be larger than modern dwellings due to the low cost of land, the need for storage space, and family size. Traditional houses have a central open space with rooms around it and storage on the second floor.

**Table 3.2 Wall materials in housing in the region of study (Estado de Mexico) from 1960 to 1990, in number of houses**

| Walls | 1960 | 1970 | 1980 | 1990 |
|---|---|---|---|---|
| Adobe | 22,047 | 22,671 | 19,909 | 16,699 |
| Wood | 142 | 298 | 252 | 341 |
| Fired clay brick | 4,881 | 15,920 | 40,563 | 74,210 |
| Stone masonry | 95 | – | – | – |
| Paperboard | – | – | 463 | 208 |
| Bamboo, palm | – | – | 21 | 9 |
| Hollow units | 18 | – | – | – |
| Stone | 8 | – | – | – |
| Other | 92 | 618 | 1,477 | 1,145 |

Source: INEGI (2000)

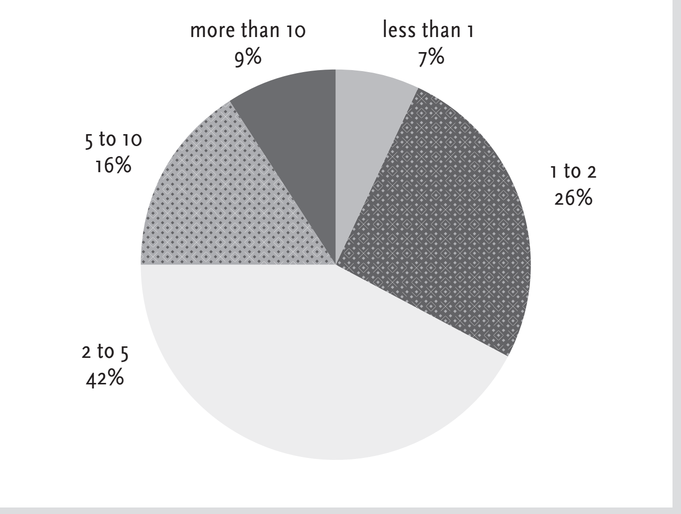
*Materials*
Traditional houses in the region have masonry foundations, masonry adobe walls, wooden columns and beams, and a terrado roof. Statistical data from the censuses show that this type of construction was common in the region. Table 3.2 shows that in 1960 the percentage of housing with adobe walls was over 75%; in 1970 it was over 50%. This shows a decreasing trend of 25% per decade. Following this trend, we can trace back the predominant material in walls in 1900, like adobe. The increase of modern materials is due to two facts: demolition of old dwellings and new construction. In 1960 the number of houses with adobe walls was 22.047, while in 1990 it was 16.699. Figure 3.3 shows the trend in roof tile materials. In 1970, roof tiles made of clay were used about 10% more often than concrete tiles. Since this decade, the percentage of clay tiles has decreased while the percentage of concrete tiles has increased. Therefore, we can conclude that at the beginning of the 20th century, most roof tiles were made from clay.

**Modern reference house**
Census data was also used for the selection of a modern reference house. The factors that are taken into account are: socioeconomic level, size of dwelling, number of rooms, materials and construction processes, type of energy used in the region and water treatment.

Due to the fact that in Mexico there are big differences in income and lifestyle, two reference houses are chosen with different socioeconomic characteristics. The legislation of Human Settlements of the State of Mexico states the characteristics of housing depending on the socioeconomic level to which they belong; these are presented in Table 3.3. The most common type of houses are social progressive, social and popular housing, being followed by medium level housing.

In Figure 3.3 the percentages of the population in each socioeconomic level are presented. As shown, the most representative levels for Mexican housing are social and middle level housing. Therefore, these will be the levels that will be considered in the research. In addition, construction for the social level (both social and popular in Table 3.3) and in some cases the middle level is closely related to policies and plans because financing programmes are normally aimed at social and middle economic levels. After choosing the socioeconomic level of the reference houses, their characteristics were determined with the help of statistical information and other documentation.

**Figure 3.3 Percentage of households per income category (times minimum salary)**




Source: Ley de Asentamientos Humanos del Estado de México (Legislation of Human Settlements of the State of Mexico)

**Table 3.3 Salaries by level of housing, in Mexico**

| | Social progressive housing | Social housing | Popular housing | Medium housing | Residential housing |
|---|---|---|---|---|---|
| Income (times minimum salary) | Less than 2.0 | 2.0 to 5.0 | 5.0 to 10.0 | 10.0 to 29.9 | More than 30.0 |
| Percentage of demand | 28% | 28% | 28% | 13.0% | 3.6% |

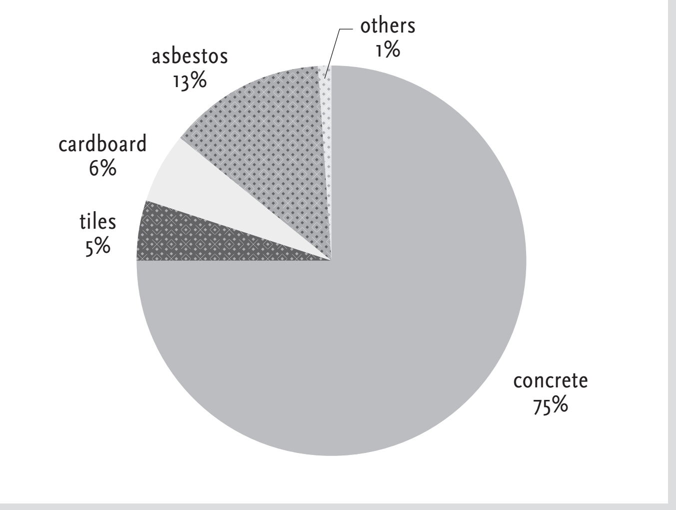
Source: INEGI (2000)

*Size*
The legislation of Human Settlements of the State of Mexico indicates the requirements for surface areas and characteristics. These characteristics are presented in Table 3.4. Therefore for the social reference house, a dwelling with land area between 72 and 90 square meters was chosen, and with construction surface of around 56 square meters.

*Materials*
Table 3.2 and Figure 3.4 show that the most commonly used materials nowadays are concrete for roof tiles and masonry walls.

**Energy and water**
*Energy*
In the Toluca area energy is produced in a thermoelectric plant. For activities such as artificial lighting and appliances, electricity is considered to be the

**Figure 3.4 Materials used for roof tiles in Mexican housing from 1970 to 1990**




Source: Ley de Asentamientos Humanos del Estado de México (Legislation of Human Settlements of the State of Mexico)

**Table 3.4 Surface area and minimal construction surface by level of housing, in Mexico**

| | Social housing | Popular housing | Medium housing | Residential housing |
|---|---|---|---|---|
| Minimal surface of land by law ($m^2$) | 72 | 90 | 100 | 180 |
| Minimal construction surface ($m^2$) | 20 to 56 | 56 to 75 | 75 to 150 | More than 150 |

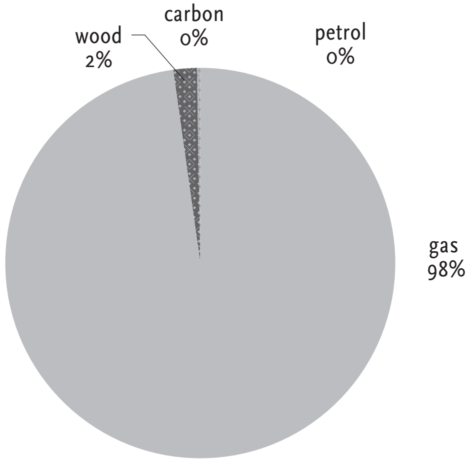
Source: Ley de Asentamientos Humanos del Estado de México (Legislation of Human Settlements of the State of Mexico)

average energy type used. Figure 3.5 shows that the fuel most used is gas. In order to calculate energy consumption in modern houses, a collection of data from a small sample of similar houses with different family composition was realised in order to obtain an overview of artificial lighting energy consumption and energy for cooking, water heating and appliances. The calculation for artificial lighting was realised by calculating the number of bulbs in the house and the hours spent by an average family per room; the remainder of the electrical consumption was assigned to appliances. To quantify the amount of energy used for cooking, average hours for cooking in an average house were calculated and checked against the calculation for water heating consumption for an average family. In order to estimate energy consumption related to appliances, statistical information was used, containing type of appliances and percentages of use in Mexican housing per economic level (see Appendix 1).

*Water*

Water consumption in Toluca is not metered. The payment is a fixed tariff per

**Figure 3.5 Percentages of overall use of energy sources in the Toluca area, Mexico**




Source: INEGI (2000)

household. Mexican legislation considers that the average water consumption per person is about 100 litres per day (Gob.Mex, 2004). Table 3.1 shows the average personal consumption of water per economic level according to the CNA (Consejo Nacional del Agua).

## 3.4 Mexican reference houses

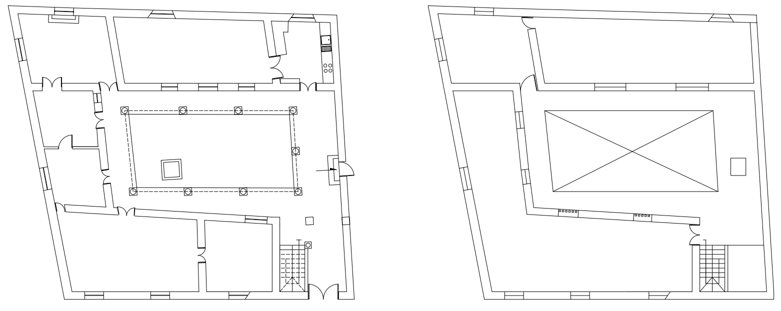
In this section a short description of the reference houses, their construction technology and their urban context is presented. Section 3.4.1 introduces the traditional dwelling; Section 3.4.2 introduces the medium modern dwelling, and Section 3.4.3 the social modern dwelling. In Section 3.4.4 a technical review of the three dwellings is carried out.

### 3.4.1 Traditional dwelling

The case study consists of an approximately 100 year old house in the city of Metepec. It has a typical layout from the colonial era with a garden or patio at the centre and rooms surrounding it. This system has the advantage of having windows in two walls of every room, even when houses are built in a row. The ground floor was used as the living area with a total of 5 rooms and a kitchen, the first floor was used only as storage space. In the original design there was no bathroom; the toilet was near to the stables, an area that is not considered for this project. The kitchen is in front of the main entrance and has its own entrance from the garden-patio and a second leading to the dining room (see Figure 3.6 and Figure 3.7).

For the analysis, data on the traditional reference house is based on its

Figure 3.6 Ground floor (living area) and first floor (storage area) of a Mexican traditional reference dwelling



current use. The owners have made some recent modifications to the original layout. Four bathrooms have been added to the house, one on the ground floor next to the main bedroom, and three on the first floor. The first floor was divided in three rooms.

**Construction technology**

Through field observation, a number of conclusions were drawn about the construction process in the region. Walls are made from sun-dried clay masonry units laid directly on top of a layer of mortar with no reinforcement or other fastening method. The structure is made from wooden columns and wooden beams. The roofs are made of sun-dried clay tiles with a 5% gradient on top of the wooden beams and lintels. The construction of the roof is identical to the construction of the floor with a parapet made of the same materials. Even though the summer season is humid, the roof is flat with a minimal pendent. The finishes, which are mainly plaster and paint, are lime-based. Doors and window frames are made of wood (see Figure 3.8).

**Urban context**

The streets are laid out in a grid pattern, typical of colonial times. This city still maintains the look of a traditional town. Some streets are still without pavements (only stones). In addition, most of the houses are traditional and the new ones have been built in the same style. For the analysis, urban context is not taken into account.

### 3.4.2 Modern medium level dwelling

The selected modern medium level dwelling is a single-family row dwelling set over two floors (Figure 3.9). 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 full bathrooms. The front garden is used as a parking area for two cars and there is a back yard for laundry and drying (see Figure 3.10).

**Figure 3.7 Interior and exterior facades of a Mexican traditional reference dwelling**

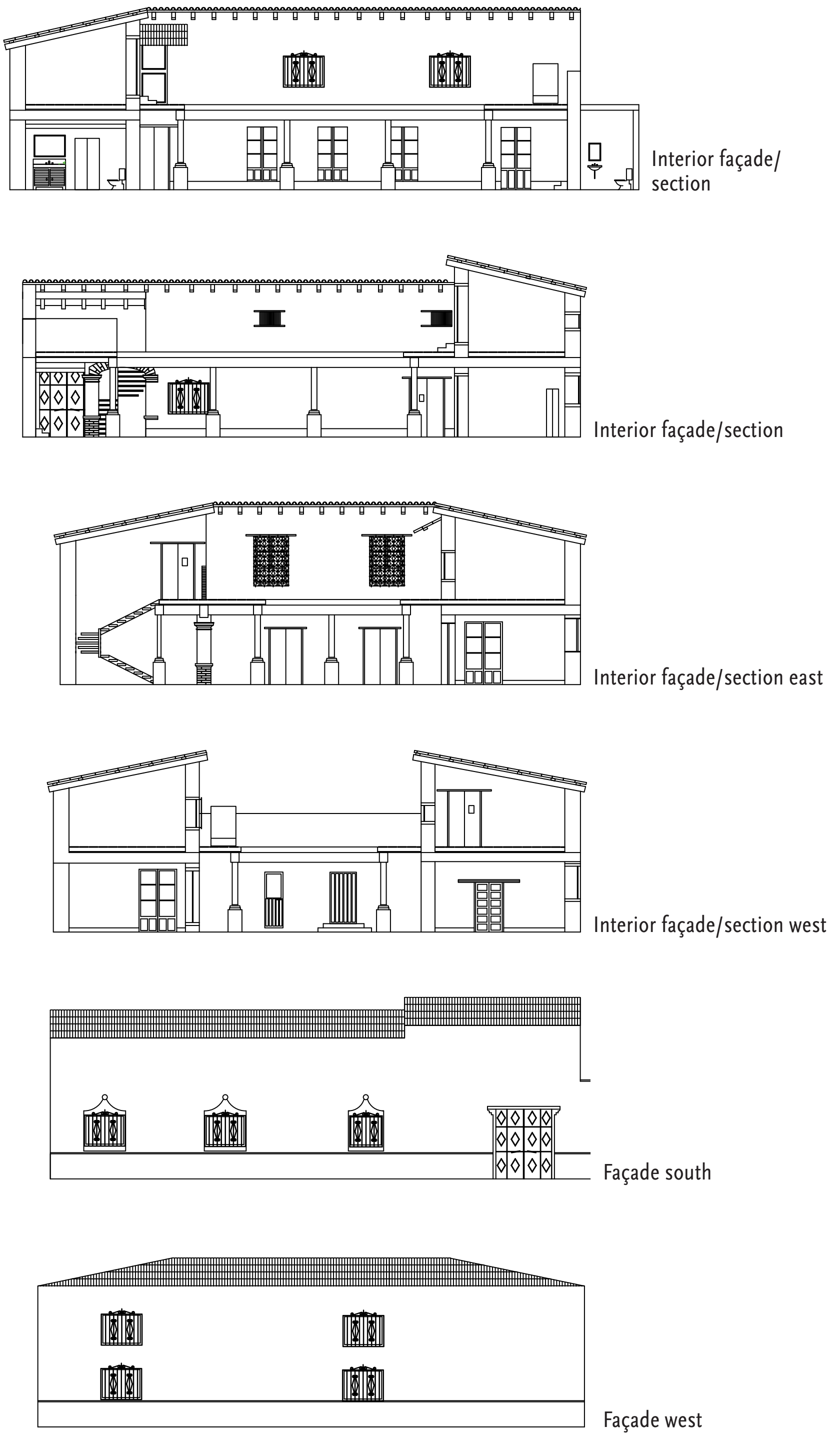
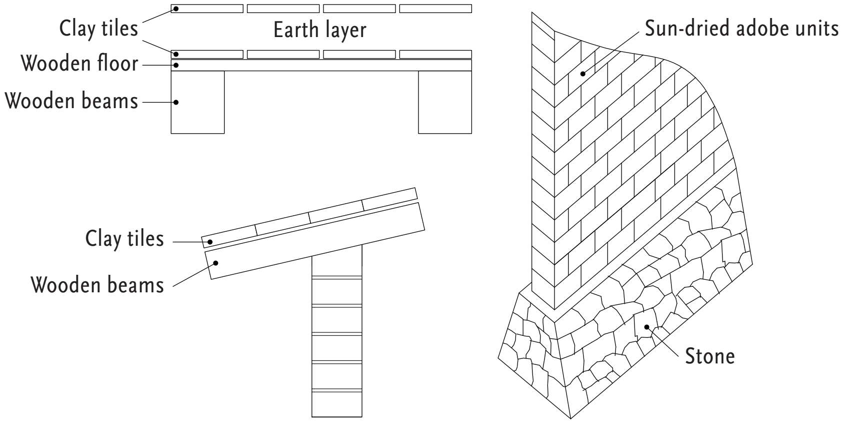


**Figure 3.8 Details of floor tile 'terrado', roof tile (add tiles) and foundation and walls of a Mexican traditional reference dwelling**




**Construction technology**

Confined masonry (see Figure 3.11, middle drawing) is the construction process that is most commonly used in the region nowadays. The foundation consists of a continuous footing with a base about 0.6 m below grade, made of large rocks interspersed with small rocks and sand and cement mortar. The structure is made of unreinforced masonry walls confined by horizontal and vertical reinforced concrete elements. Masonry panels are made of solid units of fired clay, laid with mortar between courses. The concrete elements are placed horizontally and vertically at jambs of openings and intersections. Floor and roof tiles are made of reinforced concrete; a layer of gravel is laid over the roof tile for waterproofing. The finishes are ceramic tiles and carpet on the first floor and gypsum plaster in the ceilings and walls. Windows are single glazed and the frames are made of aluminium (see Figure 3.11).

**Urban context**

The trend in urbanisation in the region nowadays is to build horizontal condominiums. These are groups of houses within a semi-closed space that share the ownership of common areas and streets. This is not only on account of security reasons but also for social status. In these condominiums all houses have the same design and share common areas, the extent, quality and services of which depend on the socioeconomic level at which they are targeted. These condominiums share the characteristic of providing healthy and respectable housing for their inhabitants and providing spaces for social development, in spite of differences between socioeconomic levels.

### 3.4.3 Social dwelling

The characteristics of this house are similar to the medium level dwelling. The main difference is the size of the spaces within the dwelling. In addition,

Figure 3.9 Medium level dwelling in Mexico

on the first level there is only an open kitchen, living/dining room and a bedroom; and on the second floor there are only two bedrooms and a complete bathroom. Another difference between the houses is the quality of the finish (see Figure 3.12).

**Construction technology**

The same characteristics as for the medium reference house apply for this house, with the exception of the use of ceramic tiles on the second floor instead of carpet. As above, the quality of the finish is the main difference between the houses (see Figure 3.11).

**Urban context**

Social houses nowadays are built in the form of horizontal condominiums to provide more security and better quality of life to their inhabitants. As far as

Figure 3.10  Ground floor, first floor and façade of a Mexican medium level reference dwelling

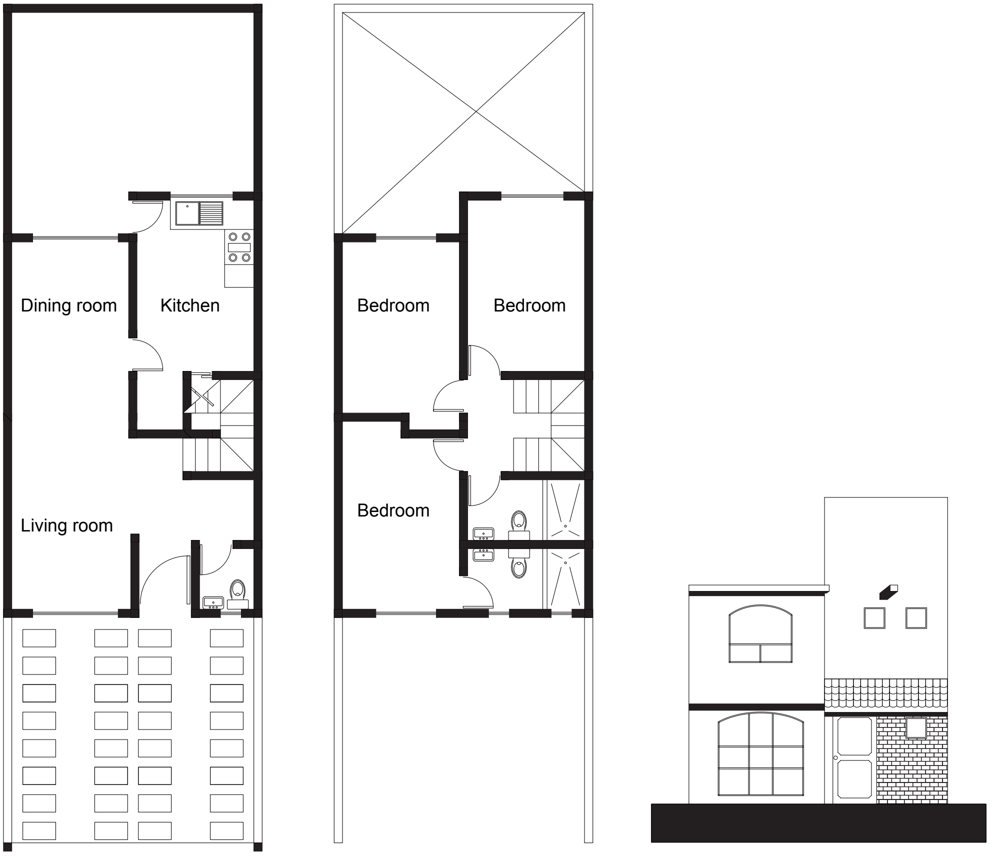



Figure 3.11  Foundation, walls and floor tile of a Mexican medium level reference dwelling

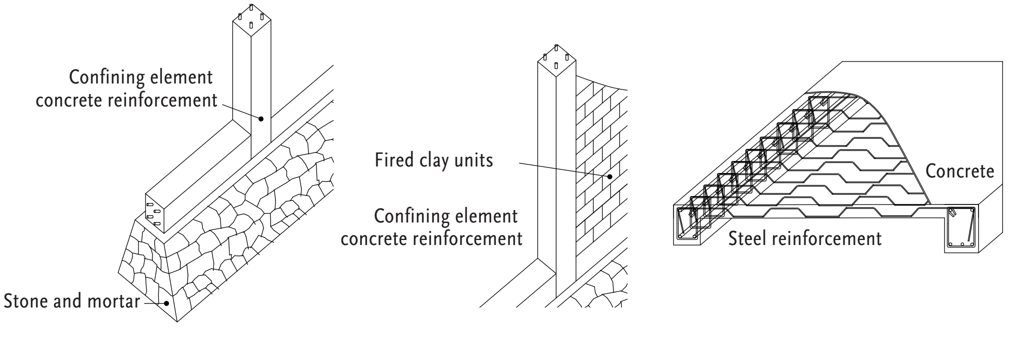


**Table 3.5 Summary of characteristics of Mexican reference houses**

| | Traditional housing (high level) | Modern medium level housing | Modern social level housing |
|---|---|---|---|
| Useful Living Area (ULA) | 360 $m^2$ (current use) | 108 $m^2$ | 68 $m^2$ |
| Layout | Colonial layout: rooms surrounding garden | Single-family row dwelling over two floors | Single-family row dwelling over two floors |
| Ground floor | • 2 bedrooms<br>• Living room/dining room<br>• Kitchen<br>• 1 bathroom | • Living/dining room<br>• Kitchen<br>• Toilet<br>• Front garden/parking<br>• Back yard for laundry and drying | • Living/dining room<br>• Open kitchen<br>• Front garden/parking<br>• Back yard for laundry and drying<br>• Bedroom |
| First floor | • 3 bedrooms<br>• 3 bathrooms | • 3 bedrooms<br>• 2 bathrooms | • 2 bedrooms<br>• 1 bathroom |
| Fuel for cooking | • Natural gas | • Natural gas | • Natural gas |
| Technology | • Continuous stone footing<br>• Masonry walls of sun-dried adobe units<br>• Wooden columns<br>• Terrado roof: clay tiles on top of wooden beams and lintels, with a 10 cm layer of earth and finished with clay tiles | • Continuous stone footing<br>• Confined masonry walls of fired clay unit and reinforced concrete elements<br>• Reinforced concrete floor and roof<br>• Layer of gravel in roof for insulation | • Continuous stone footing<br>• Confined masonry walls of fired clay unit and reinforced concrete elements<br>• Reinforced concrete floor and roof<br>• Layer of gravel in roof for insulation |
| Finishes and frames | • Lime-based plaster and paint<br>• Clay tiles<br>• Wooden frames in windows<br>• Wooden doors | • Ceramic tiles on ground floor<br>• Carpet on first floor<br>• Gypsum plaster in the ceilings and walls<br>• Single glazed<br>• Aluminium frames<br>• Wooden doors | • Ceramic tiles<br>• Gypsum plaster in the ceilings and walls<br>• Single glazed<br>• Aluminium frames<br>• Wooden doors |
| Embodied materials (in kg/$m^2$) | 2,570.47 | 2,126.92 | 2,943.54 |
| Energy use per year (in MJ/$m^2$) | 95.02 | 282.96 | 189.35 |
| Water use per year (in litres) | 365,000 | 284,700 | 146,000 |

the building is concerned, the difference between economic levels for urban context concerns the quality of the finish and the size of areas. One of the most important factors is the location of the condominium, which is determined by the cost of land.

A summary of the characteristics of the Mexican reference houses is shown in Table 3.5.

**Figure 3.12 Ground floor, first floor and façade of a Mexican social reference dwelling**


### 3.4.4 Technical review of Mexican housing

In the region, construction has not changed as much as the type of materials over time. Footing and walls are still made of masonry, with the difference that reinforced concrete elements are now used for masonry confinement. The area of construction that has seen the greatest change is the process for floor tiles. Floor tiles were traditionally made of wooden beams and terrado roof (clay tiles on top of wooden beams and lintels, with a 10 cm layer of earth and finished with clay tiles). Nowadays floor tiles are made of concrete with steel reinforcement. Both processes have advantages and disadvantages, which are presented in Table 3.6.

## 3.5 International reference houses

In this chapter, the reference houses for Peru and the Netherlands are intro-

Table 3.6 Advantages and disadvantages of traditional and modern construction processes

| | Advantages | Disadvantages |
|---|---|---|
| **Traditional construction** | • Fewer environmental interventions due to the light manufacturing and processing of materials<br>• Less difficult to reprocess after recovery<br>• Non-specialist labour needed<br>• Non-hazardous materials and processes | • Due to the lack of mortar and reinforcement, walls need to be considerably thicker than those of modern processes and are not as strong as confined masonry (Klingner, 2005) |
| **Modern construction** | • Flexibility increased by higher structural resistance<br>• More flexibility provided by the thickness of walls and concrete vertical elements | • More hazardous processes and materials<br>• The mixing of materials causes a reduction in the recoverability of materials<br>• Higher level of environmental interventions |

duced. In Section 3.5.1 the characteristics of the Peruvian dwelling are described, while Section 3.5.2 introduces the Dutch reference dwelling.

### 3.5.1 Peruvian dwelling

The Peruvian house is located in Lima, at 137 m above sea level. The average temperature is 18°C. The most common type of construction in Peru is the self-build, carried out by the owners of the dwelling.

In the second half of the last century, Lima was characterised by a rapid peripheral migration from the Andes due to the availability of land, mild climate and flexible housing policies (Fernández Maldonado, 2007). There are two types of housing system: formal development led by the real estate market, and informal development organised by the low-income part of the population. These informal settlements are known as Barriadas (Fernández Maldonado, 2007). In Lima, 54% of the population live in informal settlements (UNEP-IETC, 2002). Dwellings in Barriadas are often built without technical assistance, leading to low quality. In addition, not all dwellings are immediately finished.

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 (auto-construction) in the city. It is a three-level single-family dwelling. On the ground floor there is a living/dining room, studio, kitchen and toilet. The second floor consists of three bedrooms and two bathrooms. The service area is on the third floor, where there is a small bedroom and bathroom (Figure 3.13). The dwelling has a reinforced concrete structure and masonry walls of hollow gypsum units. The finishes are wood and ceramic tiles on floors, mortar and latex paint in walls and ceilings, and wooden window frames and doors.

The use of this reference dwelling is appropriate because it is in accordance with statistical information from Lima. In Lima, the most common type of dwelling is the single-family unit as shown in Table 3.7 (INEI, 2007). The roof in almost 50% of dwellings is made of reinforced concrete, almost 65% of dwellings have masonry walls, and more than 50% of dwellings have concrete floors (see Table 3.8).

**Table 3.7 Types of dwelling in Lima**

| Type of dwelling | Units | % |
|---|---|---|
| Single-family dwelling | 1,565,488 | 77 |
| Cabin | 3,299 | 0.1 |
| Apartment | 311,792 | 15 |
| Multiple-family dwelling | 28,650 | 1.4 |
| Provisional | 57,708 | 2.8 |
| Other | 64,729 | 3.1 |
| Total | 2,031,666 | 100 |

Source: Instituto Nacional de Estadística e Informática (http://www.inei.gob.pe/)

**Table 3.8 Materials in Peruvian housing**

| Roofs | % | Walls | % | Floors | % |
|---|---|---|---|---|---|
| Reinforced concrete | 48.6 | Adobe | 22.1 | Concrete | 52.8 |
| Wood | 3.1 | Clay or concrete brick units | 64.7 | Asphalt or vinyl | 4.4 |
| Non-durable material | 12.7 | Wood | 6.4 | Tiles | 9.5 |
| Zinc ore | 29.5 | Other | 3.4 | Wood | 4.4 |
| Tiles | 6.1 | Stone and clay | 1.2 | Polished wood | 7.5 |
| | | *Quincha* (cane and clay) | 2.2 | Earth | 21.1 |
| | | | | Other | 0.3 |
| **Total** | **100** | **Total** | **100** | **Total** | **100** |

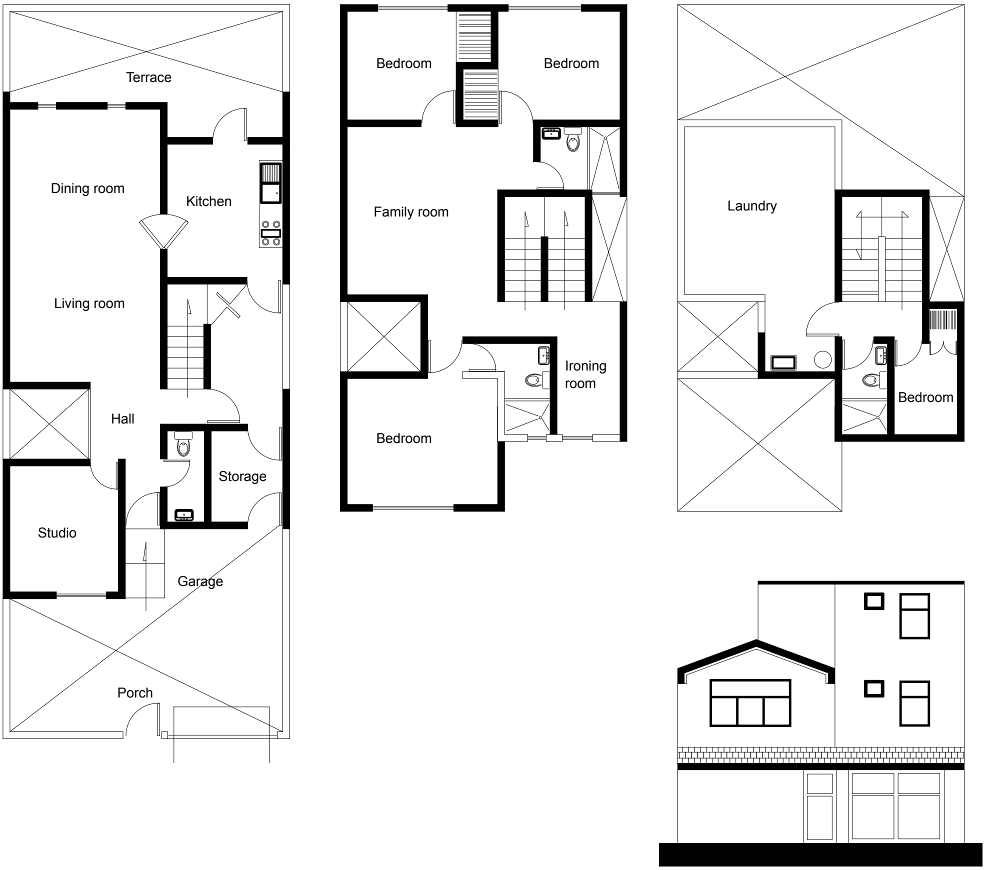
Source: Instituto Nacional de Estadística e Informática (http://www.inei.gob.pe/)

Lima has always had problems with its water supply; a situation that is worse in peripheral Lima, and the quality of the water delivered to houses is not drinkable. Around 60% of the electricity in the country is produced hydroelectrically. The remaining 40% is generated from petroleum (Torres Mendez, 2005). Houses in Lima do not have cooling or heating systems. Propane gas is used for cooking, and electricity is used for heating water (Torres Mendez, 2005).

### 3.5.2 Dutch dwelling

The altitude of the Netherlands varies from 7 m below to 322 m above sea level. The average temperature ranges from 5°C to 18°C. The characteristics of the housing sector are very different to the characteristics of developing countries. In the Netherlands, 70% of the housing stock consists of single-family dwellings, 23.3% are multi-family buildings (apartments) and 6.7% are high rise buildings (more than 5 floors) (VROM, 2007). The share of rental properties is large (46%) in comparison to other European countries. Social rental housing represents around 75% of the rental stock and 35% of the housing

**Figure 3.13 Ground floor, first floor second floor and façade of a Peruvian reference dwelling**




sector. In the country, social rental housing is generally owned and managed by housing associations. Housing is constructed by private developers, housing associations and private builders to a lesser extent (VROM, 2007).

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. It consists of a single-family row dwelling. On the ground floor there is a living room, open kitchen and toilet. On the second floor there are three bedrooms and a bathroom. The dwelling also has an attic (see Figure 3.14). The structure of the dwelling is made of concrete and steel. The exterior walls are made of double-layer gypsum walls with mineral wool insulation. The roof is made of wood and ceramic tiles. The finishes are wood, ceramic tiles floors, gypsum ceilings, Meranti wood frames

**Figure 3.14 Ground floor, first floor, attic and façade of a Dutch reference dwelling**


and wooden doors. Double glazing is used in windows. Data on energy consumption was obtained from the KWR survey (Ministry of VROM, the Netherlands), and it represents the mean value for row houses with a four-person household. Table 3.9 shows the characteristics of the Peruvian and Dutch single-family dwellings.

**Table 3.9 Reference dwellings in Mexico, Peru and the Netherlands**

| | Mexican medium level | Peruvian house (*) | Dutch house (**) |
|---|---|---|---|
| Useful Living Area | 108 $m^2$ | 214 $m^2$ | 111 $m^2$ |
| Location | Toluca | Lima | Reference |
| Average temperature | 10°C-15°C | 18°C | 5°C-18°C |
| Layout | • Row single-family dwelling over two floors | • Two levels and service area on third floor (see Figure 3.13) | • Row single-family dwelling (see Figure 3.14) |
| 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 |
| Technology | • Continuous stone footing<br>• Confined masonry walls of fired clay unit and reinforced concrete elements<br>• Reinforced concrete floor and roof<br>• Layer of gravel in roof for insulation | • Concrete with steel reinforcement footing<br>• Concrete with steel reinforcement beams and columns<br>• Walls of hollow clay and gypsum units | • Concrete and steel beams and poles footing<br>• Beams and columns made of concrete and steel<br>• Exterior walls made of double layer cavity gypsum walls with mineral wool or meranti insulation<br>• Interior walls made of gypsum walls filled with wool or fibre<br>• Wooden roof with concrete and ceramic tiles |
| Finishes and frames | • Ceramic tiles on ground floor<br>• Carpet on first floor<br>• Gypsum plaster in ceilings and walls<br>• Single glazed<br>• Aluminium frames<br>• Wooden doors | • Wood and ceramic tiles on floors<br>• Mortar and latex paint for walls and ceilings<br>• Wooden window frames<br>• Wooden doors | • Wood or ceramic tiles on floors<br>• Gypsum for ceilings<br>• Meranti frames<br>• Double glazed<br>• Wooden doors |
| Household size | 4 | 5 | 4 |
| Embodied materials (in kg/$m^2$) | 2,127 | 1,405 | 1,069 |
| Energy use per year (in MJ/$m^2$) | 283 | 83 | 756(***) |
| Water use per year (in litres) | 284,700 | 60,000 | 200,000 |

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

# 4 Analysis of Mexican, Peruvian and Dutch housing

In this chapter, the indicators defined in Chapter 2 are used to analyse the dwellings. The environmental assessment is presented in three sections: the building and construction phase, the use or consumption phase, and the demolition phase. A table listing all the indicators can be found in Appendix 1. The classification of materials according to the different indicators can be found in Appendix 2. The values of all indicators for all types of houses can be found in Appendix 3.

## 4.1 Building and construction phase

The indicators used for building assessment in this phase are those related to the embodied resources in the building, such as the origin of the resources including recovered materials (i.e. reused, recycled or downcycled).

**Materials**

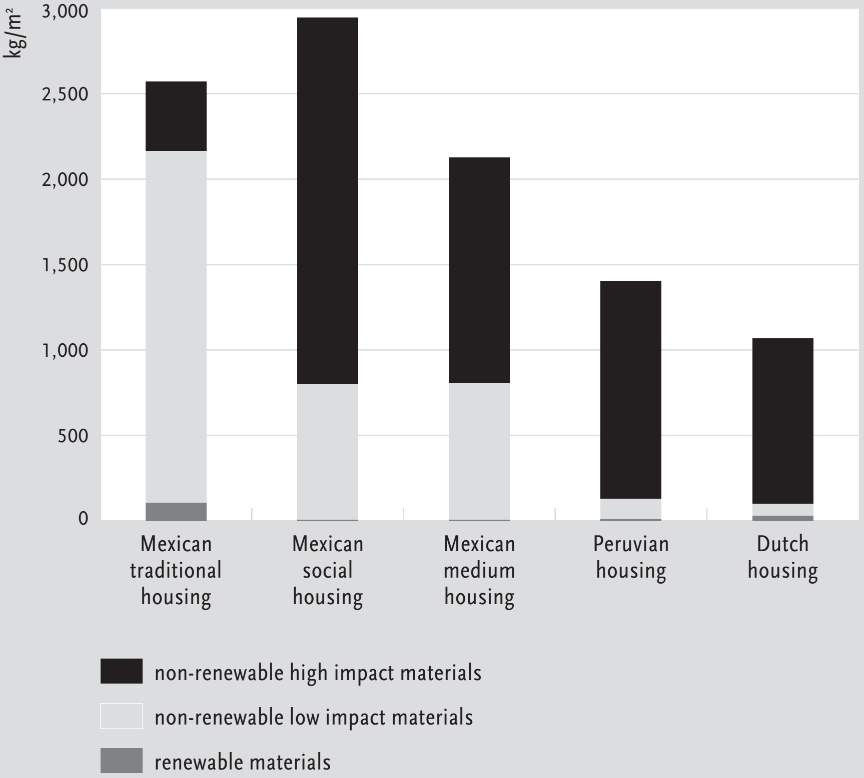
*Total material consumption (indicator D-B1)*

Material weight in the traditional Mexican dwelling is higher to the material weight in modern medium Mexican houses due to the fact that even though lighter materials are used, the thickness of the walls, at 0.5 m, increases the weight (Figure 4.1). The weight per useful living area of social housing in comparison to medium level housing is high; therefore the efficiency of material use is lower in social housing. The Mexican dwelling is more material consuming than Peruvian and Dutch dwellings. The quantity of material in the Peruvian house is lower than in Mexican houses because of the use of hollow bricks and lightweight concrete tiles. In Dutch houses, lighter walls and wooden roofs decrease material consumption in comparison to Mexican houses.

*Renewable, recovered and non-renewable materials (indicators D-B2, D-B3 and D-B4)*

The consumption of renewable material per square metre is minimal for all houses, while the use of non-renewable, low impact materials is twice as common in traditional houses as in the modern houses on account of the use of sun-dried adobe masonry units instead of fired clay units. In the traditional reference house the consumption of non-renewable high impact materials is minimal. For modern houses these materials are intensively used, due to concrete elements and ceramic bricks. The Mexican reference house performs better than Peruvian or Dutch houses in terms of the origin of material because of the higher percentage of low impact material from stone masonry footing, and clay finishes. All of the dwellings have a minimal percentage of renewable materials, which are mainly used in windows and doors. Recovered materials are not used in any of the reference houses (Figure 4.1).

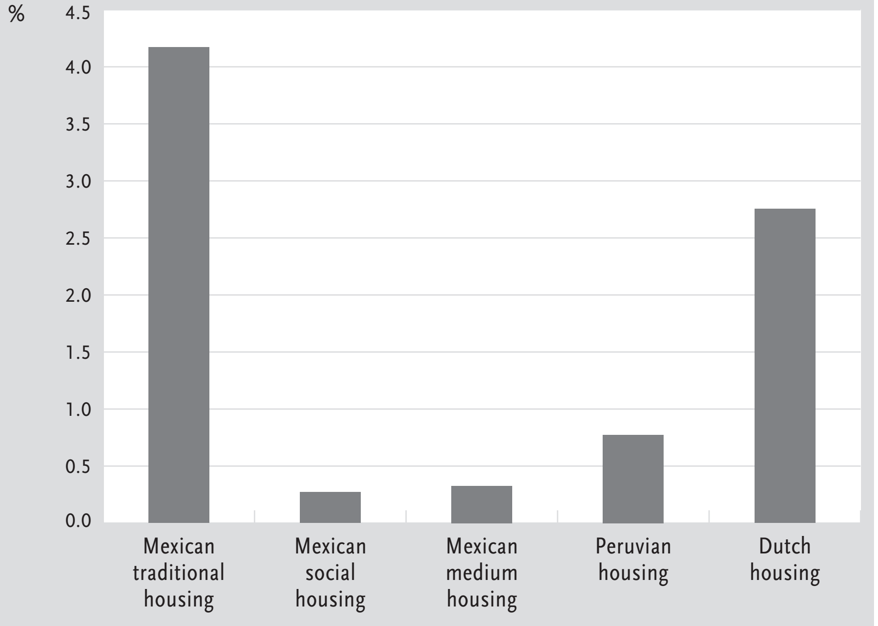
**Figure 4.1 Non-renewable high-impact and low-impact materials and renewable materials per useful living area in Mexican, Peruvian and Dutch housing**




*Material efficiency (indicator D-B5)*
Figure 4.2 shows the material efficiency of the dwellings on a scale from 0% to 5%. Material efficiency refers to the proportion of renewable and recovered materials in the total material quantity. Traditional Mexican houses perform better than modern Mexican houses in this respect because of the use of wooden beams and columns. In modern houses, only doors are made of wood. The Peruvian reference house uses 0.77% and the Dutch house 2.75% due to the use of wood in roofs. In all dwellings the material efficiency is low.

**Waste**
For the quantification of waste in Mexican reference houses, information was taken from books specialised in unitary prices of Mexican construction processes. Therefore, the information may be variable in reality and should only be considered as a rough indicator of the actual waste during construction. In general, the waste produced by this activity is considered to represent 5% of the material volume of the building. Of course, this may vary depending on the material or construction process used. For example, for the construction of brick walls in Mexico, waste is considered to be 15% for bricks and 30% for mortar (Plazona, 2001).

**Figure 4.2 Material efficiency in Mexican, Peruvian and Dutch housing**




*Estimated total waste materials from construction processes (indicator D-B6) and estimated recoverability of waste materials (indicators D-B7, D-B7.1, D-B7.2 and D-B7.3)*
Construction waste production per square metre in modern Mexican housing is higher than for traditional Mexican housing due to the extensive use of concrete and iron (Figure 4.3). During construction activities, it is estimated that almost 20% of the waste produced by building traditional houses can be reused; this figure being over 15% for modern houses. Reusable construction waste in the houses is similar because it consists of stone footing. Downcyclable construction waste in modern houses makes up the highest percentage due to the use of concrete and ceramics, while for traditional houses recyclable waste has the highest share due to the use of natural and homogeneous materials in masonry. Recyclable waste construction production of the traditional house equals the quantity of downcyclable construction waste in modern houses due to the influence of materials in walls and floor tiles made of concrete and ceramics in modern houses and made of adobe without mortar in traditional houses. The proportion of non-recoverable materials is over five times higher for modern houses than for traditional houses due to the use of PVC, mortar and plasters.

**Land**
*Total land use (indicator D-B8) and green area (indicator D-B9)*
This figure represents the useful living area per total land area. The efficiency of land use in the Peruvian house is 135% because the dwelling has 3 floors, incrementing the useful living area of the dwelling. Dutch and Mexican houses have an efficiency of 90%, meaning that the useful living area almost

Figure 4.3 Recoverability of waste in Mexican dwellings

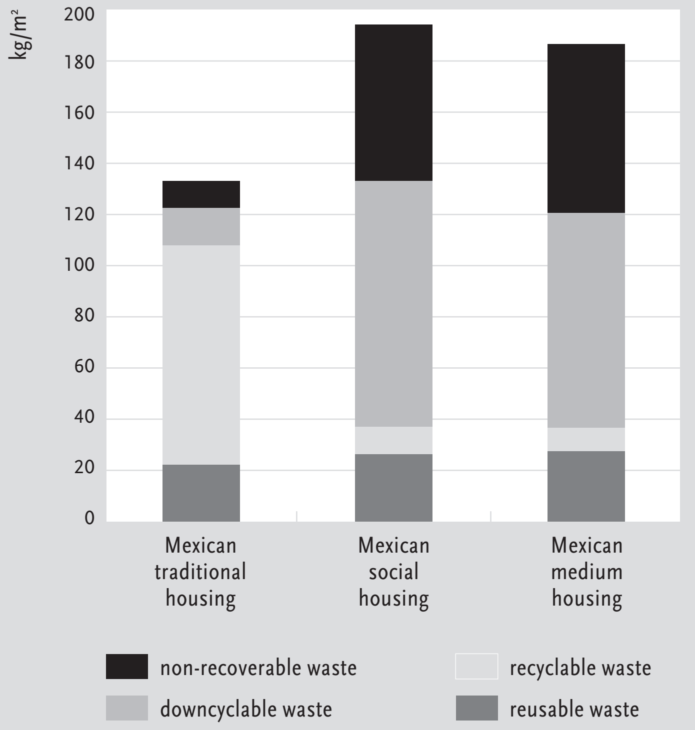



Figure 4.4 Land efficiency of Mexican, Peruvian and Dutch housing

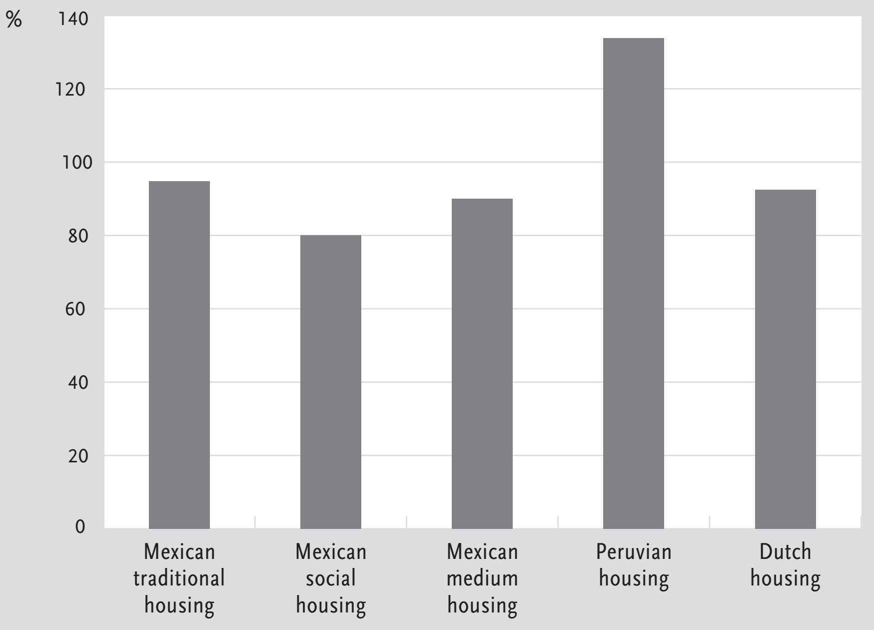
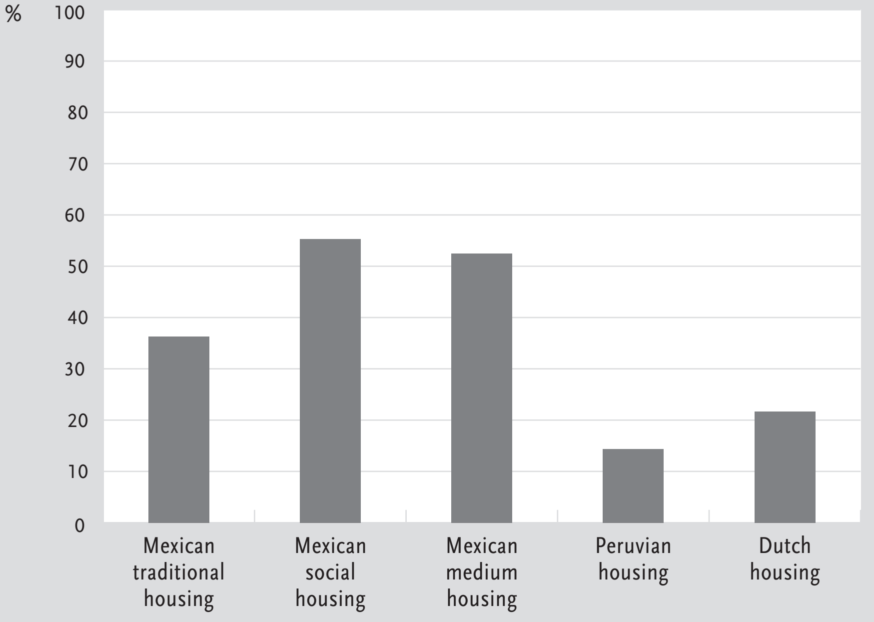


**Figure 4.5 Percentage of green area around Mexican, Peruvian and Dutch housing**




equals the area of the plot (Figure 4.4). The ratio is lower for social Mexican housing than for medium Mexican housing, which means that more area is left unconstructed. The green area in both modern Mexican houses is almost the same due to the fact that they do not differ so much in layout as in size. In traditional houses green area tends to be slightly less because there was no space reserved for cars. The percentage of green area in the Mexican dwelling accounts for more than 50% of the area of the plot. The green area is usually used to park cars, but it is left as a front garden, doubling the function of the parking area and green area and therefore increasing the land use efficiency. The percentage of green area in Dutch and Peruvian housing is significantly lower (Figure 4.5).

*Hazardous processes (indicators D-B10 and D-B11)*
The proportion of hazardous processes in all reference houses is less than 1% due to the use of natural non-toxic materials and simple handmade processes. This percentage refers to toxic emissions during paint application. It is important to consider that this indicator refers to the percentage of construction processes and does not refer to the harm caused to construction workers. An analysis focusing on the harm caused by such materials to construction workers would be preferable in the future.

*Cost of dwelling per useful living area (indicator D-B12)*
In this figure the dwelling cost per useful living area is shown. In order to take into account economic differences between countries, the cost of the house was divided by the annual minimum salary to obtain the number of annual minimum salaries that the house costs. The cost per square metre is slightly

**Figure 4.6 Cost of dwelling per useful living area in Mexico, Peru and the Netherlands**

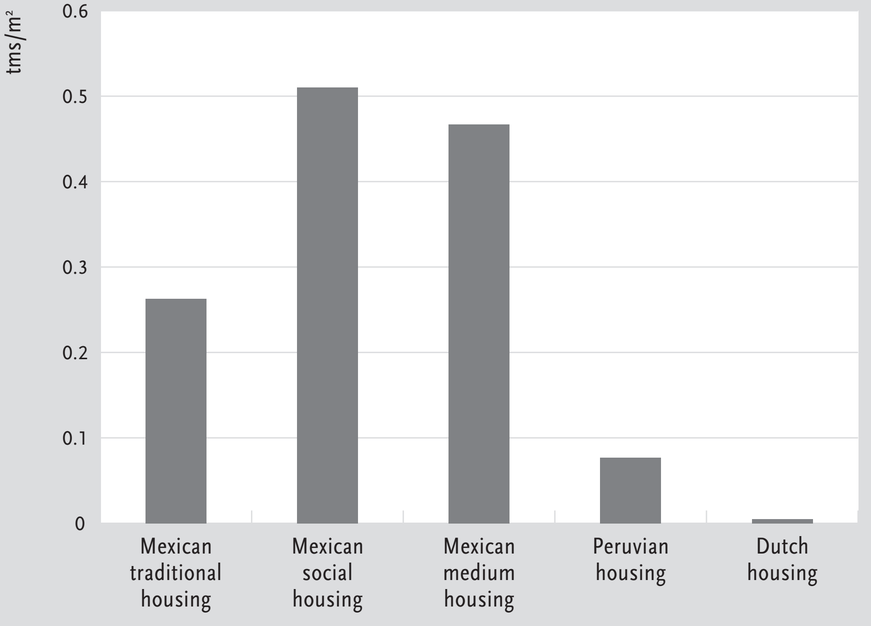



**Figure 4.7 Durability of materials in Mexican, Peruvian and Dutch housing**

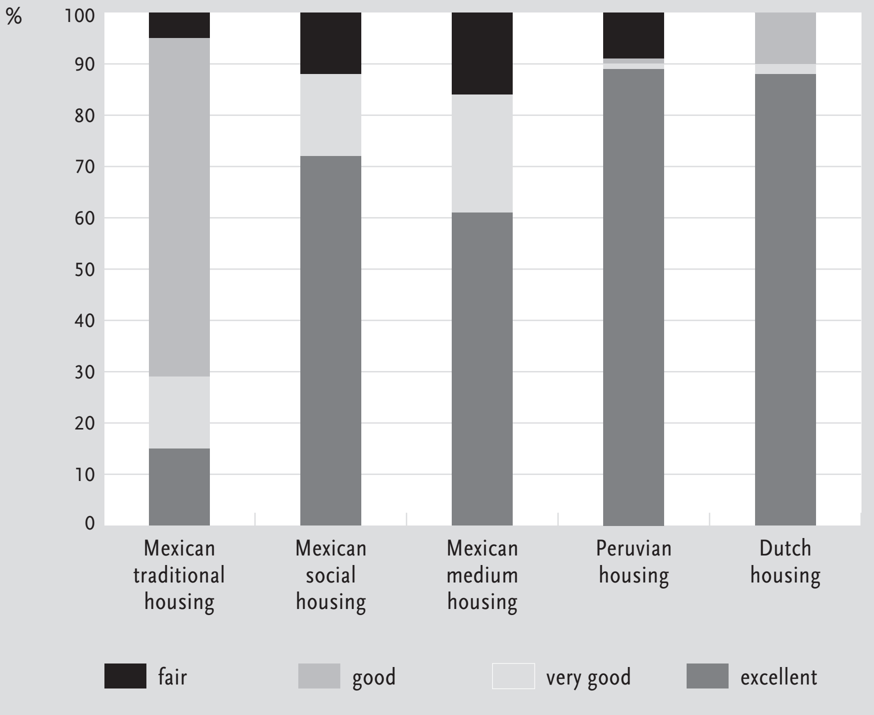
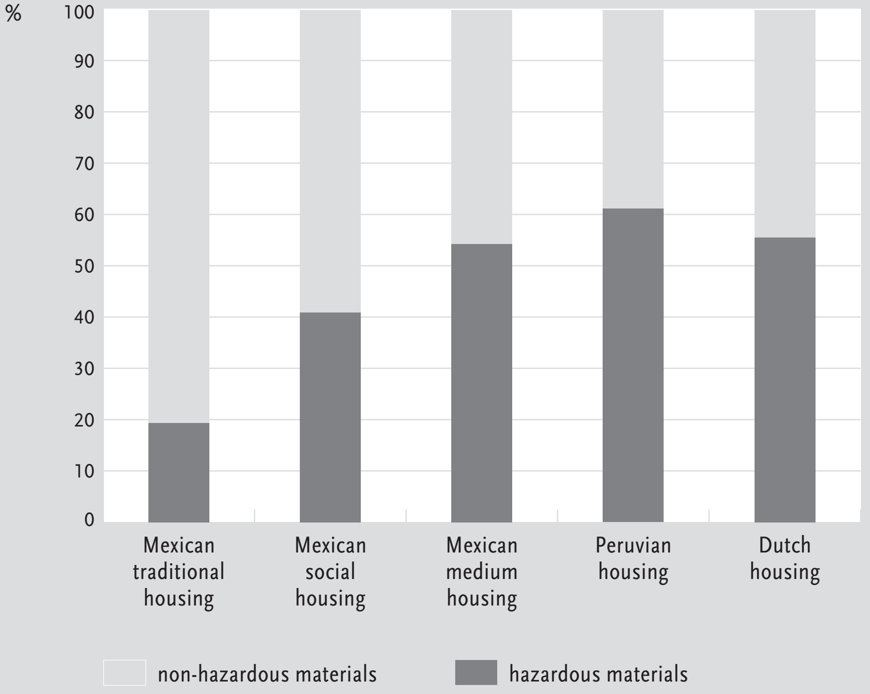


**Figure 4.8 Hazardous and non-hazardous materials in Mexican, Peruvian and Dutch housing**




higher for social Mexican housing than for medium Mexican housing (Figure 4.6). Peruvian housing is less affordable than Dutch housing, but Mexican housing is by far the most difficult to afford for the occupants.

## 4.2 Use phase

**Materials**

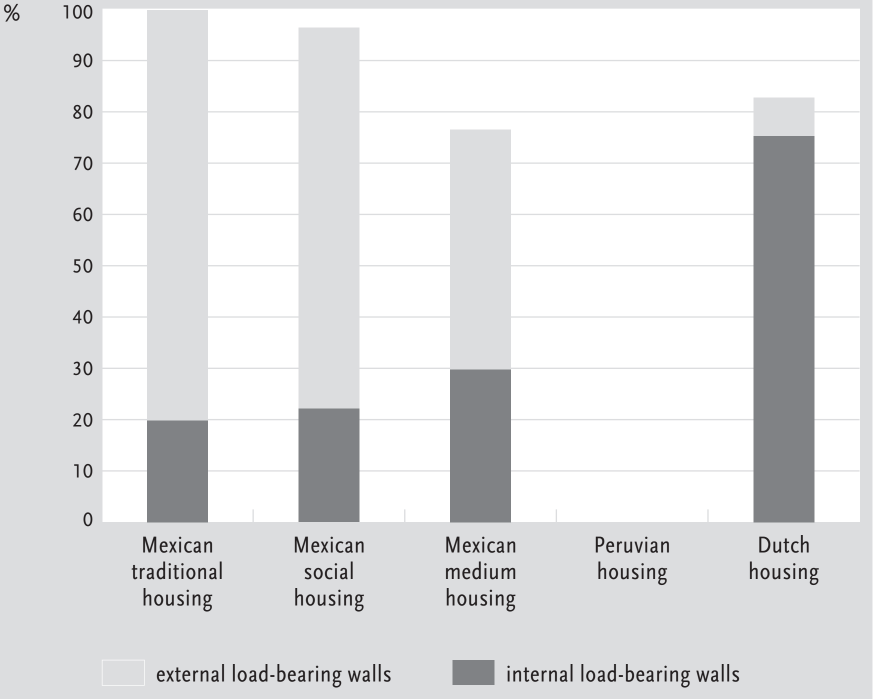
*Durability of materials (indicators D-U1 to D-U3)*

Modern Mexican housing has a higher percentage of materials with excellent durability, such as concrete, while traditional housing is mainly composed of materials with good durability. All of the Mexican dwellings have a low percentage of fairly durable materials, mainly in their finishes (Figure 4.7). Most of the materials in Dutch and Peruvian dwellings are very durable; Dutch houses perform the best of all the houses.

*Hazardous materials (indicators D-U4, D-U5)*

Around 50% of the materials used in modern Mexican housing are considered to be hazardous because of the use of concrete and other radon-emitting materials such as stone. Traditional Mexican housing has a lower share of hazardous materials because of the use of earth (Figure 4.8). More than 50% of all the materials in Peruvian and Dutch dwellings are also considered to be hazardous. The share of hazardous materials is similar in the modern dwellings

Figure 4.9 Percentage of structural walls in Mexican, Peruvian and Dutch housing




because of the extensive use of concrete and stone.

**Layout**

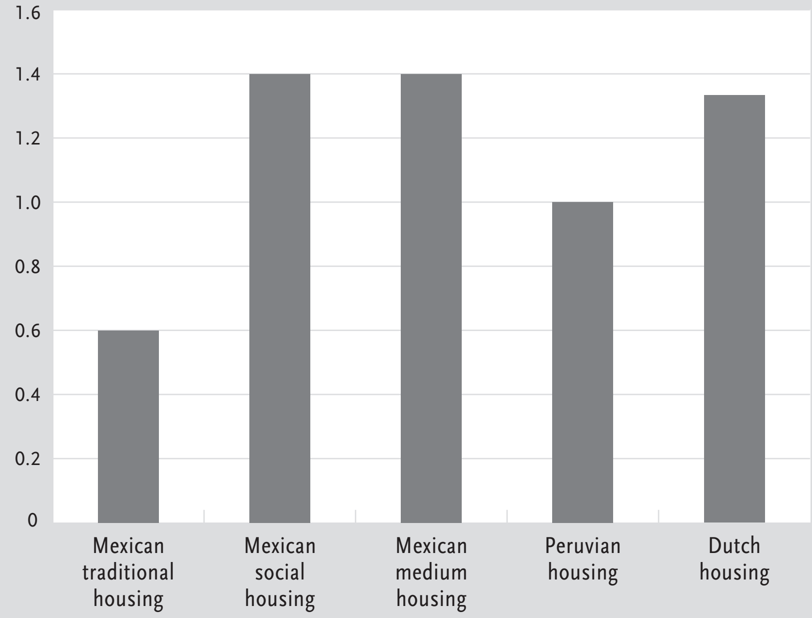
*Flexibility: Interior and exterior structural walls (indicators D-U6 and D-U7)*

In the traditional Mexican house, over 80% of the structural walls are external. In modern Mexican houses, the percentage of external structural walls is also large. Though all the walls in traditional housing are structural, and should be considered less flexible, the fact that most of the walls are exterior walls increases the flexibility of the dwelling (Figure 4.9). Medium reference house has 17% of external non-bearing walls which correspond to the fences. Modern Mexican houses have also a large percentage of internal load-bearing walls, which diminishes flexibility. Peruvian dwellings have 0% structural walls: instead, columns are used for structural processes and therefore these homes are the most flexible. The Dutch house has mostly internal structural walls given the layout of the dwelling (row house).

*Privacy: Persons per bedroom (indicator D-U8).*

The average number of bedrooms for both modern Mexican houses is three, due to the fact that nowadays families are considered to comprise four members. The difference between the houses is mainly their size (Figure 4.10). Traditional dwellings have more bedrooms than modern houses. Mexican households in the past needed more space in their dwellings to cater for storage and the larger size of their families. Peruvian houses tend to be bigger than Mexican and Dutch houses, therefore the persons per bedroom rate is lower

**Figure 4.10 Average persons per bedroom in Mexican, Peruvian and Dutch housing**




in Peruvian houses. Indicator D-U9 showed not to be relevant for this analysis and was therefore not included.

### Energy

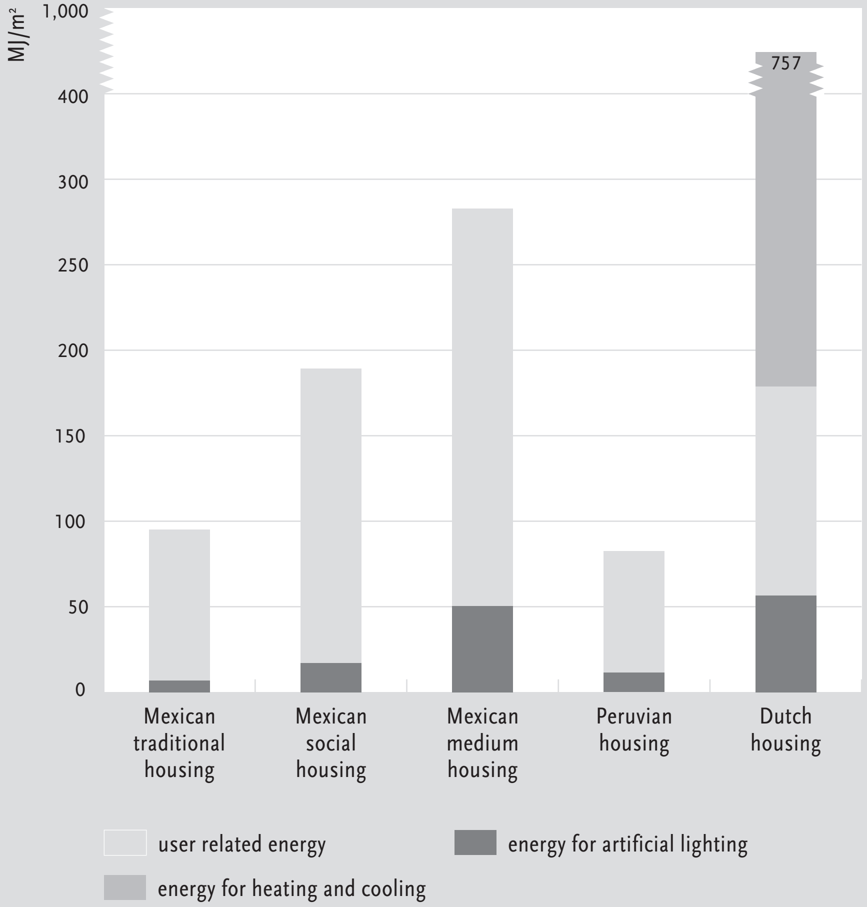
*Total energy consumption (indicator D-U10) and renewable and recycled energy (indicators D-U11, D-U12 and D-U13)*

Energy consumption in social Mexican housing is lower than in medium level but higher than in traditional housing (Figure 4.11). Energy consumption in Peruvian and Mexican houses is visibly lower than for Dutch houses. In the region of study in Mexico, houses use LPG and electricity produced in the local thermoelectric plant, therefore renewable energy is not used. None of the reference houses use renewable or recovered energy.

*Artificial lighting, climate related energy consumption and energy used for appliances, cooking and heating water (indicators D-U14, D-U15, D-U16)*

Energy consumption for artificial lighting and energy used for appliances, cooking and heating water in social Mexican housing is lower than in medium level housing and traditional housing, which reflects the large differences in income of Mexican households. Low-income households use around 30% less energy than middle-income households. The percentage of energy consumption on artificial lighting and energy used for appliances, cooking and heating water is similar in both dwellings, being 60% and 40% respectively. In the traditional house, these percentages change to 60% for energy for cooking, heating water and appliances, and 40% for artificial lighting, as a result of the layout of the dwelling (Figure 4.11). Climate related energy consumption is high for Dutch housing; this quantity is about five times higher than artificial

**Figure 4.11 Artificial lighting, user related energy and energy for heating and cooling in Mexican, Peruvian and Dutch housing**




lighting consumption. Energy consumption for appliances, cooking and heating water in modern Mexican reference dwellings is higher than in Dutch and Peruvian reference houses. Energy used for these activities 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 towards high consumption of energy for such activities. The Dutch dwelling shows a high trend of energy consumption for heating. On the one hand, the weather in Lima is mild and, therefore, it is reasonable that energy is not used for heating or cooling. On the other hand, Toluca is a city of cold nights, especially in winter, due to its altitude. This means that socioeconomic factors may have a significant effect on energy consumption. This may also result from the fact that heating is needed at night in Mexico, contrasting with the situation in the Netherlands where heating is needed all day.

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

**Table 4.1 Energy consumption in the Netherlands according to heating degree days in different countries**

| | Netherlands | Peru | Mexico |
|---|---|---|---|
| Number of heating degree days | 5,328 | 566 | 3,236 |
| Hypothetical energy use in relation to the heating degree days if the house was located in the Netherlands (MJ) | 80.11 | 5.32 | 48.65 |
| Real energy use (MJ) | 80.11 | 0 | 0 |

4.1). Heating degree days is a quantitative index designed to reflect the demand for energy needed to heat a home. These indices are derived from daily temperature observations, and the heating requirements. These figures show that in relation to the energy consumed in the Netherlands, energy in Peru is consumed according to its climate (real consumption is 0 while hypothetical consumption is 5.32 MJ a relatively small amount), 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) according to degree-days normalisation.

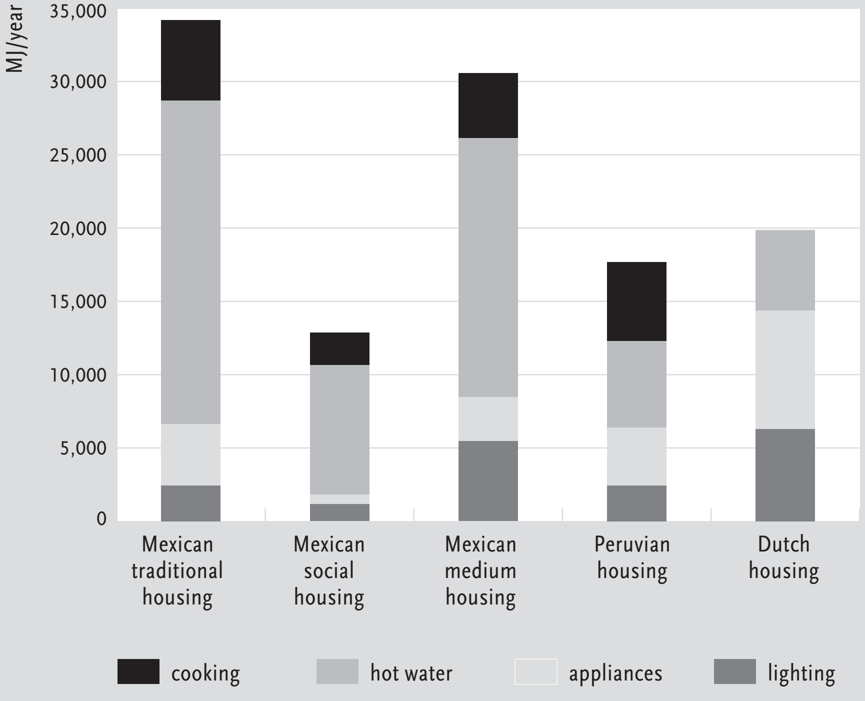
Energy consumption for appliances, cooking and water heating in Mexican housing is higher than in Peruvian and Dutch housing because of the large use of energy for heating water. Figure 4.12 shows the use of energy per activity (appliances, cooking and water heating). It is noticeable that while artificial lighting and energy for cooking and appliances is relatively similar in the three countries, the energy use for heating water in medium reference Mexican housing is higher. 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. The difference within social Mexican housing and Peruvian and Dutch housing is minor, probably due to the efforts to decrease energy costs in low-income households.

*Energy efficiency (indicator D-U17)*
The energy efficiency of all houses is zero because recovered and renewable energy is not used in the reference houses.

### Water

*Water consumption per person (indicator D-U18)*
Studies have shown that water consumption is 100 litres per person per day in social housing and 195 litres per person per day in medium level housing in Mexico. In social dwellings, the consumption per capita is lower than in medium and residential level housing (Figure 4.13). The consumption of water in Mexican houses is higher than in Peruvian or Dutch houses. Peruvian consumption of water is the lowest of all reference houses. It is clear that water consumption is not related to climate (the warmest climate is Lima, Peru), but to other factors such as the availability of the resource.

**Figure 4.12 Final use of energy per user related activity in Mexico, Peru and the Netherlands**

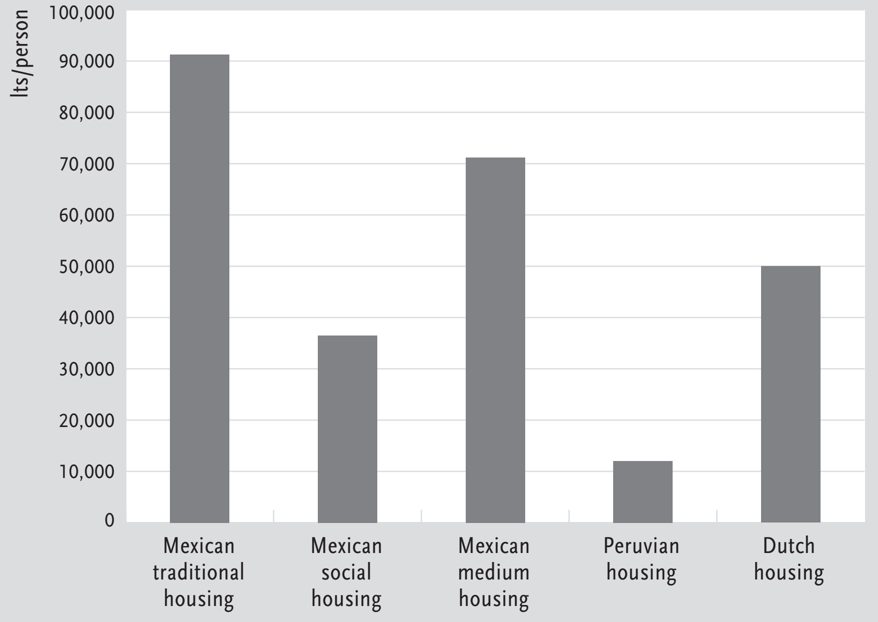



*Renewable and recovered water (indicators D-U19, D-U20 and D-U21) and water efficiency (indicator D-U22)*
The water systems in Mexico and Peru consist of treatment for clean but non-drinkable quality water. The treatment of water for all dwellings is realised off-site, therefore there is no proportion of renewable or recycled water. Rain-water is mixed with blackwater in the systems. Water efficiency is zero in all reference houses because water is neither recovered nor renewable.

## 4.3 Demolition phase

**Materials**
*Dismantleability of materials (indicators D-D1, D-D1.1 and D-D1.2) and recoverability of materials (indicators D-D2, D-D2.1, D-D2.2 and D-D2.3)*
There is a low percentage of dismantleable materials in all reference houses, mainly represented by loose elements and installations such as piping, windows and doors. There is a higher percentage of semi-dismantleable materials used in masonry. The proportion of non-dismantleable materials is highest in all dwellings due to the use of concrete and iron. The proportion of dismantleable materials in the modern Mexican houses is higher than in the traditional house because of the possibility of removing ceramic elements, although this share is mainly represented by semi-dismantleable materials. Most of the materials in traditional houses are not dismantleable, but due to their homo-

Figure 4.13 Water consumption per person per year in Mexico, Peru and the Netherlands



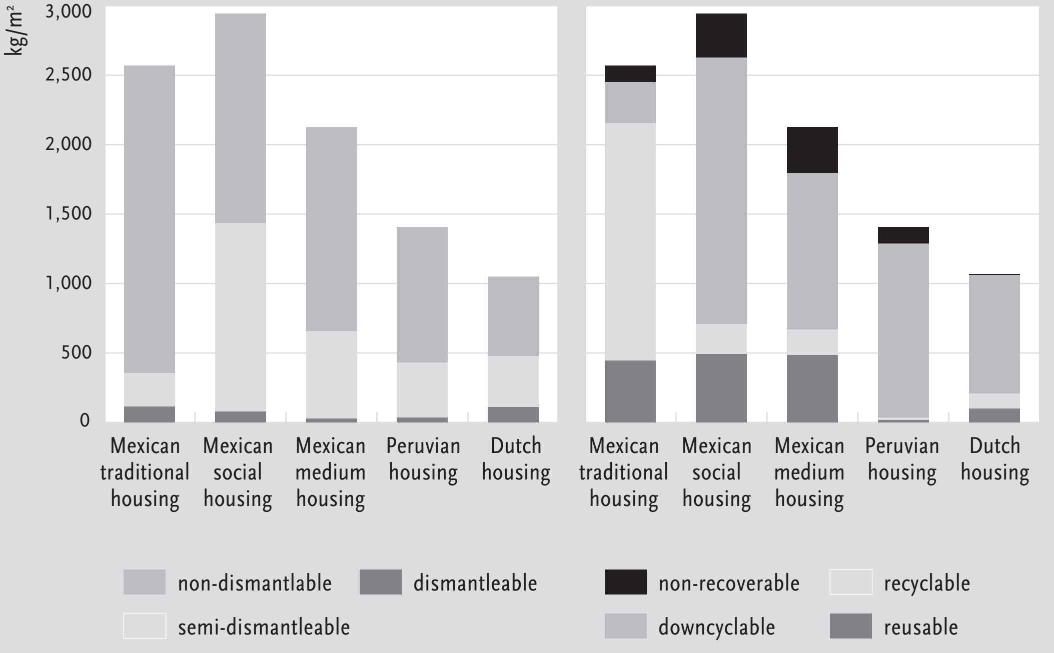

geneity, they have higher potential to be recycled (Figure 4.14). The proportion of reusable materials is low for all reference houses. The highest share is for Mexican housing, with 20% represented by stone masonry. The percentage of recyclable materials in traditional houses is over 90%. For modern Mexican houses the share of recyclable materials is lower due to the use of materials such as concrete, which have to be downcycled. The highest share for all modern houses is downcyclable material due to the extensive use of brickwork, concrete and ceramic for all houses. For Mexican and Peruvian houses the percentage of non-recoverable materials is low, and for the Dutch dwelling this is almost zero.

## 4.4 Conclusions

**Materials**

In traditional Mexican houses, the majority of materials are non-renewable with low environmental impact. Due to the extensive use of sun-dried adobe bricks and earth in floor and roof tiles, the manufacture of bricks and tiles does not have a significant impact on the environment. Traditional houses contain renewable materials in their structure; nevertheless, the share of renewable materials in comparison with low impact non-renewable materials is low. The use of stone foundations, adobe walls, earth in tiles and wooden beams seems to increase the possibilities for recovering materials as recyclable and reusable products. The dismantleability of the materials in the traditional dwelling seems quite low for most structural elements such as foundations and walls; nevertheless, the recoverability of these materials appears

**Figure 4.14 Dismantlability and reusability of materials in Mexican, Peruvian and Dutch housing**




to be high due to their homogeneity. The remainder of the materials in the house, such as wooden columns and beams, and roof tiles, could be easily dismantled and reused.

In modern Mexican housing, traditional processes remain, such as masonry in foundations and walls. The main changes in Mexican housing are related to the type of materials used and the construction process for floor and roof tiles. The switch in the type of materials from wood and adobe to concrete and ceramic was part of a drive towards modernisation in construction and due to structural safety requirements because of earthquakes in the region. Non-renewable materials with high environmental impact seem to be intensively used due to the concrete elements and ceramic bricks. Nevertheless, the houses still contain a high percentage of low impact materials because of their stone masonry foundation. The dismantleability of materials in modern housing appears to be low due to the use of reinforced concrete. Recoverability of the materials in modern housing seems high because of the possibilities for recycling concrete. Nevertheless, the higher percentage of low impact materials in traditional housing may be more environmentally friendly than the use of high impact materials in modern housing.

The weights of the traditional reference house and both modern reference houses seem comparable in relation to Peruvian and Dutch reference dwellings, which are visibly lower; however, the rate of use of renewable and non-renewable low impact material seems to have decreased over time. Usage of renewable materials has dropped to nearly zero. Concrete elements used in modern houses tend to be heavier than wooden elements used in traditional dwellings, causing the weight per useful living area to be higher than in the reference medium level dwelling.

Mexican and Peruvian houses tend to be larger in area and space than Dutch houses. There is an intensive consumption of material per square metre in Mexico due to the use of continuous stone masonry footing along all the walls (even those that are not structural) and due to the undifferentiated use of solid units in walls. In addition, floor and roof tiles are made of concrete and iron. 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. Nevertheless, the largest percentage of materials in the Mexican dwelling have a low environmental impact, and due to their homogeneity a large percentage can be reused, while Peruvian and Dutch dwellings mainly use high impact materials that are predominately downcyclable. Due to the tendency to use concrete and iron in all reference houses, the greatest proportion of the materials are non-renewable and have a high environmental impact.

**Estimated construction waste**

In traditional housing, the majority of the waste is non-renewable and low impact due to the use of sun-dried abode bricks for walls. Modern houses produce ten times more waste than traditional houses due to waste produced for concrete elements. Switching from concrete structural elements to wooden elements would not only increase the use of renewable materials but it would also decrease the quantity of waste generated during construction processes because auxiliary material (casting) would not be necessary.

**Energy**

In modern Mexican housing in the region of Toluca there is no consumption of energy for cooling or heating in spite of the weather conditions in the region. The activities that affect energy consumption are those related to lighting, cooking, heating water and appliances; therefore energy consumption is very much determined by the household, number of inhabitants per house (for cooking and heating water), income, and lifestyle (number and type of appliances). Nevertheless, the high consumption of energy for heating water could be mainly attributed to the use of low efficiency boilers.

The tendency in Latin-American dwellings is towards low consumption of energy for climate related energy. The energy consumption for artificial lighting is comparable for the Dutch the medium Mexican reference dwellings. The artificial lighting energy is comparable for Peruvian, social and traditional Mexican reference dwelling. Renewable energy is not used in any reference house, but in Dutch housing there is the possibility to choose sustainable sources.

**Table 4.2 Opportunities of Mexican housing**

| | Opportunities |
|---|---|
| Materials | • Traditional materials such as adobe and clay tiles and finishes are more environmentally friendly and offer better opportunities for recycling. Returning to some of these materials could increase the environmental performance of Mexican housing. A further opportunity is given by brick masonry in walls, which could be easily replaced with adobe without interfering with construction processes.<br>• There is no need to increase the quantity of materials in order to improve comfort in the perspective of Mexican society. |
| Energy | • No need to increase comfort by technological means.<br>• Trend of not using heating systems seems independent of household income or level of housing. |
| Water | • Water performance could be easily improved by changing the fixed tariff per household to a tariff per litre. |
| Land | • Land use in modern Mexican houses is already efficient in comparison to other reference dwellings; more efficient use of space could be achieved by means of better use of spaces within dwellings. |

### Water

The quality of delivered water in the Mexican and Peruvian dwellings is clean but non-drinkable, which decreases energy consumption in the treatment of water. Water consumption in the Mexican dwellings seems not to be dependent on the number of inhabitants per household, due to the fact that there is a fixed tariff per household and consumption is not metered in the region. Nevertheless, there is a trend towards more consumption in higher socioeconomic levels. The water system in Mexican housing still faces many problems, mainly related to policies, system efficiency and infrastructure.

The tendency in all reference houses is to not recover water, even though in Toluca (Mexico) and the Netherlands this could mean considerable water savings in the rainy season. In none of the reference houses is there separation of grey water, black water and rainwater water systems, although the possibility exists in the Netherlands.

### Land

In the past there was a high use of land in Toluca due to the need for a large house to cater for larger families and more storage space. Nowadays land is more expensive and scarce, therefore the layout and dimensions of traditional housing are not practical. The dual function of the garden and parking area allows more intensive use of land and other resources related to the construction of garages. Land use is more efficient in Peruvian housing because of the use of the third floor as a living area.

### Layout

Traditional housing has a higher percentage of external walls due to its layout and a higher percentage of walls facing onto the street, which offers more possibilities for building reuse for different purposes. The layout of modern houses includes concrete fences around the perimeter of the house to divide front gardens and back yards. Modern Mexican houses are less flexible than

**Table 4.3 Shortcomings of Mexican housing**

| | Shortcomings |
|---|---|
| Materials | • Lack of technology, knowledge and market can delay the use of sustainable materials.<br>• Preference for cheap and low quality materials for social and popular housing.<br>• Use of low impact materials could increase the frequency of maintenance. |
| Energy | • No production of green electricity in the region.<br>• No plans for switching to sustainable energy production.<br>• Use of low efficiency water boilers. |
| Water | • No awareness of water saving within households.<br>• Tariff per consumption could affect health of large families on low incomes. |
| Land | • A considerable part of the population does not have legal access to land and therefore sets up their homes in dangerous or protected areas. |

Peruvian and the traditional Mexican reference houses because of the use of interior structural walls, reducing the possibilities for reuse of the building for a purpose other than housing.

**Costs**

The accessibility of Mexican housing to the population is lower in comparison with Peruvian and in particular Dutch housing. Even though the minimum yearly salary in Peru (PEN 5,400 = EUR 1288.81) is as low as that of Mexico (MXN 15,858 = EUR 1055.66), the cost of housing in Lima is still not as high as in Toluca. The higher accessibility to Dutch housing is due to the fact that the minimum salary is more than ten times higher (EUR 16,392) than in the Mexican or Peruvian regions analysed.

**Opportunities and shortcomings of Mexican housing**

Table 4.2 and Table 4.3 present the opportunities and shortcomings of Mexican housing in terms of environmentally sustainable building.

# 5 Improving Mexican housing

## 5.1 Introduction

In previous chapters, three Mexican houses were analysed next to reference dwellings in Peru and the Netherlands. The conclusions from the analysis provide the basis on which to improve the environmental performance of Mexican housing. From the last chapter we can conclude that:
From the Mexican analysis:

1. Traditional houses used more renewable and non-renewable low impact materials than modern houses.
2. Traditional construction processes such as masonry foundation and walls are still in use nowadays.
3. The quantity of material used per square metre is higher in traditional than in modern medium level dwellings.
4. Energy consumption is determined by the occupants (use of appliances, cooking), the efficiency of the water boiler (heating water) and the natural lighting of the building (use of electricity for artificial lighting).
5. Modern houses have a low flexibility because of the use of internal structural walls.

From the international analysis:

1. The total weight of the materials per square metre in Mexican housing is considerably higher than in Peruvian or Dutch housing.
2. Energy demand for heating of Mexican housing related to consumption is low in comparison with Dutch housing, while the consumption of energy for heating water is very high; therefore energy performance can be improved by using more efficient water boilers and developing renewable sources of energy, because energy consumption is expected to increase with well-being.

Over-consumption of materials still seems to be an issue in Mexican housing. Therefore, in the first part of this chapter, possibilities for reducing material consumption in Mexican housing are studied.

The first part of the chapter consists of an analysis of materials in Mexican housing in order to identify the problem. After discerning areas in which there is a possible overweight, two scenarios will be studied in order to ascertain how the problem of material consumption in Mexican housing can be solved. The scenarios are: dematerialisation and material substitution. The scenarios are made according to solutions that are viable for Mexican housing based on the modern reference house at the medium socioeconomic level and in the region of study. Such scenarios will be defined and analysed in the second part of this chapter. The third part of this chapter consists of the conclusions of the scenario analysis. Shortcomings and opportunities will be presented as well.

## 5.2 Strategies for decreasing material consumption in medium level Mexican housing

Mexican construction differs from Peruvian and Dutch processes in several aspects. Each of the construction elements is analysed in order to ascertain which characteristics of the construction influence material consumption. The construction elements to be analysed are categorised as follows:

1. Foundation
2. Vertical structural elements
3. Horizontal structural elements
4. Vertical non-structural elements.

**Footing**

In Peruvian and Dutch dwellings, footing is made of concrete with iron reinforcement. Dutch foundations can also consist of concrete poles depending on the soil type. Footing in Mexican dwellings consists of continuous stone masonry along all walls, including non-structural walls, which increases the weight of the foundation, as shown in Figure 5.1. Footing in Mexican housing per useful living area is twice the weight of footing in Peruvian dwellings and more than triple that of Dutch houses.

**Structural vertical elements**

Peruvian dwellings have concrete columns with iron reinforcement; Mexican vertical structural elements consist of confined masonry walls with horizontal and vertical reinforcement elements made from reinforced concrete. This is why the weight of vertical structural elements differs so much between Mexican and international housing.

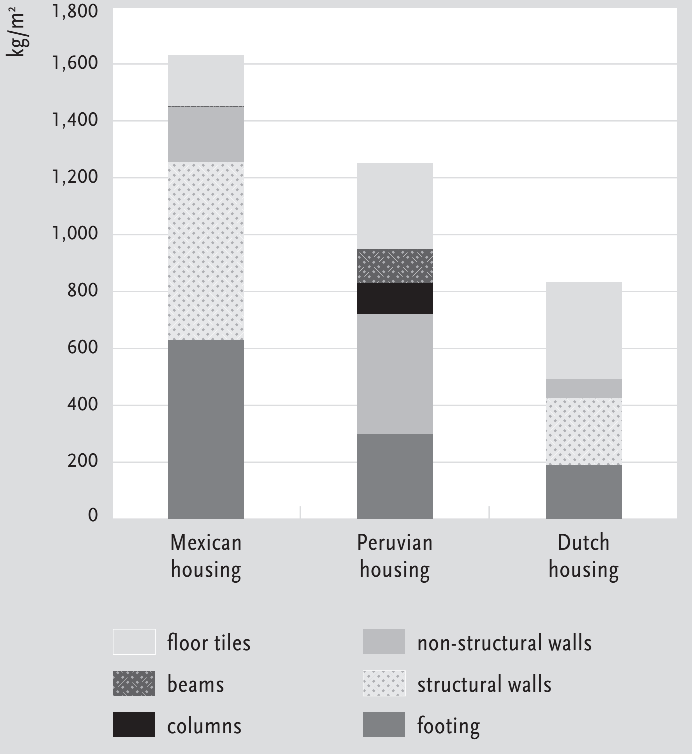
A high percentage of walls in Mexican housing are structural walls. Structural walls in Mexican dwellings double the amount of materials used in Dutch dwellings. The structural vertical elements in Peruvian housing (columns) consume half the quantity of material used in vertical structural elements of Dutch housing (walls).

**Non-structural vertical elements**

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 the 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 vertical elements (structural and non-structural) in Mexican

Figure 5.1 Weight of building elements in Mexican, Peruvian and Dutch housing




housing is more than double that of Dutch housing and around 30% greater than 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 efficient.

**Horizontal structural elements**

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

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, as shown in Figure 4.1, Mexican houses consume fewer high impact non-renewable materials than Dutch and Peruvian housing. This fact is attributable to the stone foundation which, even though it is a non-renewable material, it does not require processing for its use in construction. Therefore, weighing up the impact and benefits of different solutions is important. For this reason, different solutions are studied in order to analyse the environmental performance of the medium dwelling when improved with different strategies.

## 5.3 Strategies to improve sustainable housing

Different strategies can be used in order to improve sustainable housing. The two strategies considered here are dematerialisation and material substitution. The dematerialisation strategy is based on the conclusions from the international analysis, which showed that Mexican housing consumes more material per square metre than Peruvian and Dutch housing. The material substitution strategy is based on the conclusions from the analysis of Mexican dwellings, which showed that traditional houses have less environmentally damaging materials. Only the strategies that are considered to be feasible to follow in the country will be analysed; therefore only construction processes based on current construction methods in Mexico are considered.

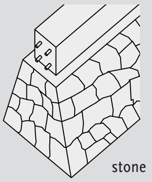
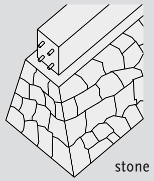
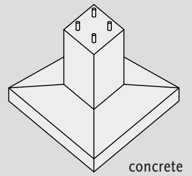
For the dematerialisation strategy, the medium case study is redesigned. The redesign consists of a more efficient use of the materials and surface. Nevertheless, the main characteristics of the design will remain. To decrease the amount of materials, the use of lighter materials and processes is the best option. The areas and sizes of the house design are considered to be fixed due to the fact that for cultural reasons families tend to look for a three-bedroom house. The kitchen wall will be removed from the design to provide an open plan. The second bathroom will be removed. In order to improve bathroom efficiency, separate shower and toilet rooms will be considered so that two people can use the bathroom at the same time. The concrete fences around the house are removed, as well as the wall in the roof that hides the water tank (see Figure 5.2). Wood will be considered for floors instead of ceramic finishes due to the fact that it is lighter and provides better insulation. Floor tiles are made of hollow tiles in order to decrease weight. Floors are made of pre-worked concrete beams and hollow tiles. For the walls, hollow clay units are considered, which are already on the market. Therefore concrete columns instead of confining concrete elements are proposed.

The material substitution strategy involves the use of less harmful materials for the environment and for the occupants of the dwelling. There are several ways of reaching this goal. For this scenario, the goal is to increase the amount of renewable and low impact materials in the design. For this approach, only the use of traditional processes and materials in the region of study will be considered. Therefore, only improvements based on the traditional and social reference house will be used. For this case, the design layout of the medium house will not be changed. The structure of the house will be built on a masonry foundation of basalt stone. The walls will be made of masonry recycled brick or sun-dried adobe with a thickness of 12 cm. Since reinforced-concrete confining elements would be used as it is common in the current practice, the section of the bricks can be diminished. For floor and roof tiles, concrete will be used also in according to current practice. Doors and window frames will be made of wood, like the other finishes. For the interior walls, plaster and natural

**Figure 5.2 Dematerialisation proposal for a medium level Mexican dwelling**


paint are proposed as finishes, and for the external walls, the adobe bricks will be exposed. Clay tiles for the kitchen and bathrooms are also proposed.

**Table 5.1 Technical strategies for Mexican houses**

| | | Scenarios | |
|---|---|---|---|
| | **Reference house** | **Material substitution** | **Dematerialisation** |
| Footing | • Continuous stone masonry footing   | • Continuous stone masonry footing   | • Concrete non-continuous footing with steel reinforcement   |
| Vertical structural elements | • Structural walls of confined masonry of fired clay units<br>• Confining elements of reinforced concrete | • Reinforced concrete columns and masonry walls of sun-dried adobe units | • Reinforced concrete columns and masonry walls of hollow fired clay units |
| Tiles | • Reinforced concrete floor tiles with steel reinforcement | • Roof and floor tiles made of earth and clay (*terrado*) | • Reinforced concrete beams and hollow concrete floor tiles |
| Finishes | • Ceramic tiles on ground floor<br>• Carpet on upper floor<br>• Gypsum plasters | • Wooden floors through the entire house except for clay tiles in bathroom and kitchen | • Ceramic tiles on ground floor<br>• Carpet on upper floor<br>• Gypsum plasters<br>• No finishing in outdoor floors |
| Layout | • Separate kitchen<br>• Living room/dining room<br>• 2 ½ bathrooms<br>• Concrete fences around the house | • Separate kitchen<br>• Living room/dining room<br>• 2 ½ bathrooms<br>• Adobe brick fences around the house | • Open plan kitchen<br>• 1 bathroom upstairs<br>• No fences around the house (or bushes instead of fences) |

## 5.4 Improvement scenarios

In this section, the indicators for each phase of the building life cycle are analysed. In Table 5.1 the main technical characteristics of the medium level reference house and the scenarios based on the different approaches are summarised.

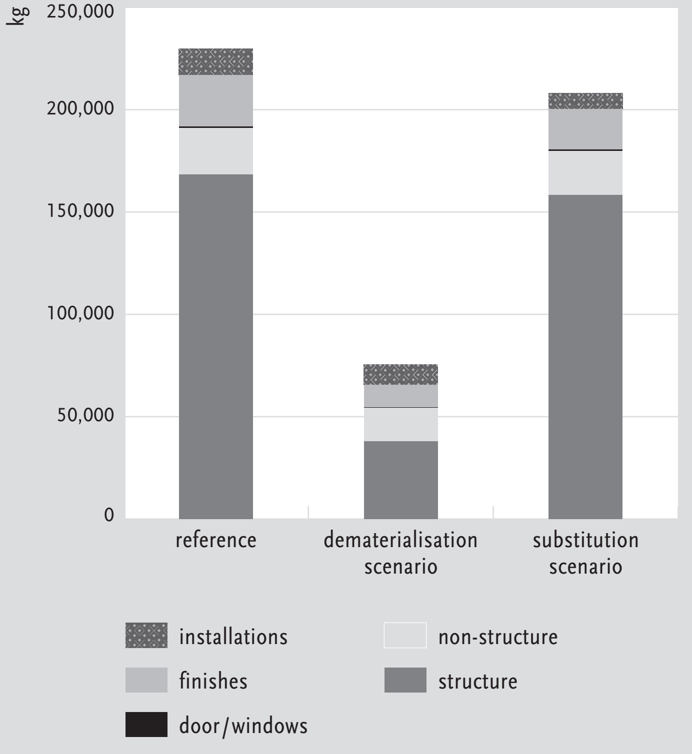
### 5.4.1 Building and construction phase

**Materials**

*Total material consumption (indicator D-B1) and material used per construction element*

The substitution of materials approach presents almost the same material consumption as the reference house due to the use of the same kind of construction process, including masonry and solid bricks with concrete confining elements. The decrease in material consumption in the dematerialisation approach in comparison with the reference house is one third; this is mainly due to the use of hollow bricks, hollow floor tiles and concrete non-continuous footing. Figure 5.3 shows the material consumption per element. In the

**Figure 5.3 Total material per construction element in two scenarios for Mexican housing**

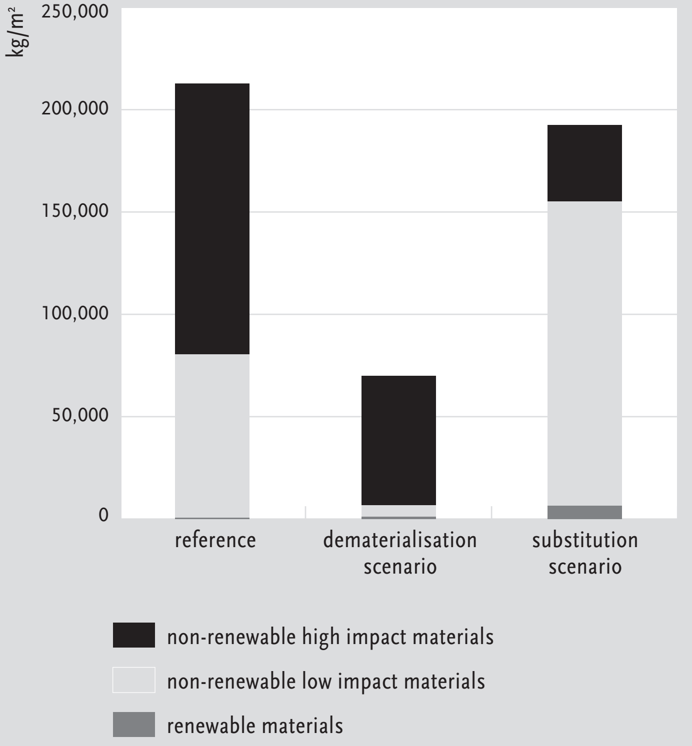



medium level dwelling, around 80% of materials are represented by structural elements due to the use of structural walls. This is reduced to one third in the dematerialisation approach by decreasing the quantity of structural walls and using concrete non-continuous footing. The quantity of non-structural elements and installations remains constant. Finishes are also reduced to half the weight of the case study by using wood instead of ceramics.

*Renewable, recovered and non-renewable materials (indicators D-B2, D-B3 and D-B4)*
In the dematerialisation approach, the share of non-renewable materials increased, and low impact materials decreased in comparison with the medium level house due to the use of concrete footing instead of masonry. Nevertheless, due to the use of traditional methods (adobe masonry) the greatest proportion is taken up by low impact materials. In addition, the percentage of non-renewable materials with high environmental impact is less than 20% (Figure 5.4).

*Materials efficiency (indicator D-B5)*
Material efficiency refers to the percentage of renewable and reused materials. In this figure a significant improvement is shown for the dematerialisation approach and the material substitution approach. Nevertheless, the greatest efficiency is still under 3.5% due to the low use of renewable materials (Figure 5.5).

**Figure 5.4 Impact of two scenarios for Mexican housing on the quantity of materials**




### 5.4.2 Use phase

**Materials**

*Hazardous materials (indicators D-U8 and D-U9)*

Hazardous materials increase in the dematerialisation approach due to the radiation emitted from stone used extensively in brick and stone foundation. For the material substitution approach this decreases due to the use of adobe brick in walls (Figure 5.6).

### 5.4.3 Demolition phase

**Materials**

*Dismantleable, semi-dismantleable and non-dismantleable materials (indicators D-D1.1, D-D1.2 and D-D1.3)*

For the dematerialisation approach, the highest proportion of materials is non-dismantleable due to the intensive use of concrete; in addition, the proportion of semi-dismantleable materials is high on account of the use of masonry.

For the material substitution approach, the proportion of dismantleable materials decreases due to the use of adobe masonry. Almost all materials are non-dismantleable due to the use of concrete and adobe masonry (Figure 5.7).

**Figure 5.5 Material efficiency for two scenarios for Mexican housing**

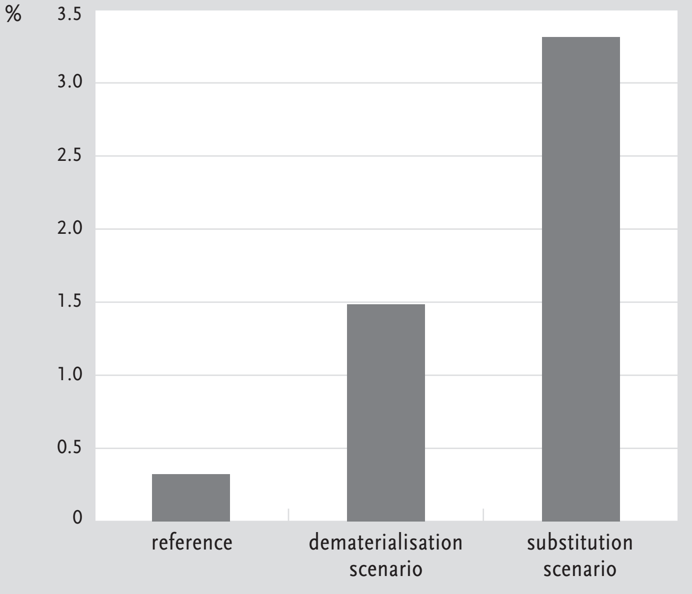



**Figure 5.6 Percentage of hazardous materials in two scenarios for Mexican housing**

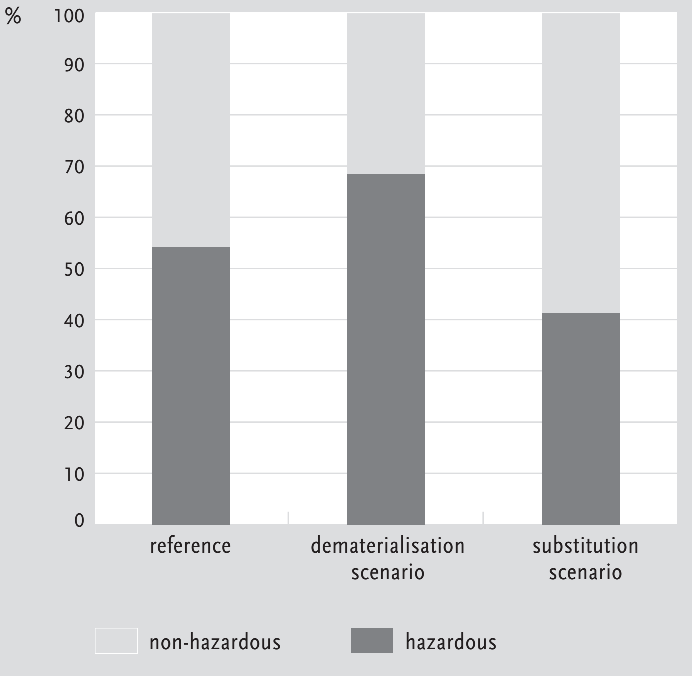
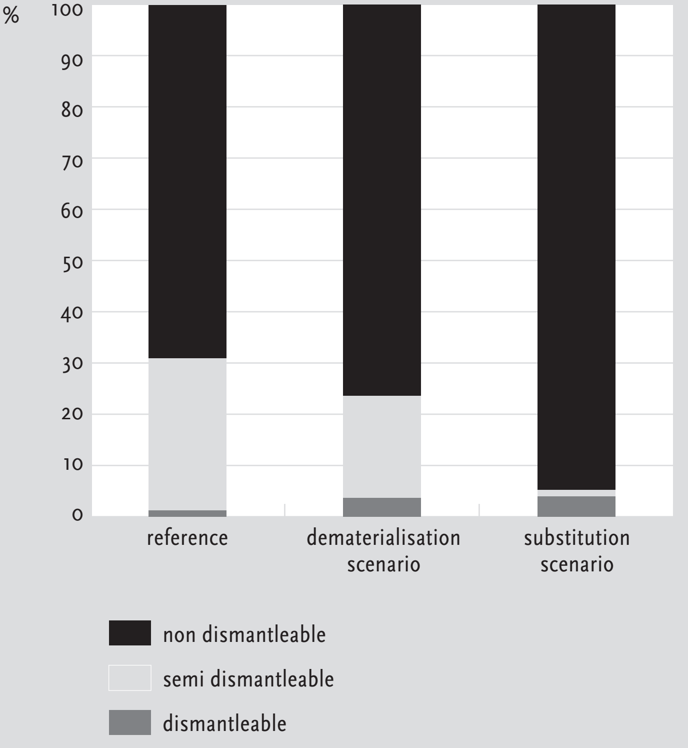


Figure 5.7 Dismatleability of materials for two scenarios for Mexican Housing




## 5.5 Conclusions

There seems to be a significant reduction of material in the dematerialisation approach because of the elimination of unnecessary elements and spaces such as the second bathroom and toilet on the ground floor. In contrast, the reduction of materials appears not to be significant in the material substitution approach because the difference in weight between adobe bricks and fired bricks is not significant. The increase of renewable material in the material substitution approach seems to be due to the use of wooden elements. In addition, the increase in recoverability in the material substitution approach seems high because of the possibility of recycling adobe bricks without high impact processes. The quantity of non-renewable materials with high impact appears to be still considerable in both approaches because the structure of the dwellings is made of concrete. The percentage of renewable material seems very low, therefore only the introduction of wood in structural elements instead of concrete could improve the performance of the dwelling in relation to the origin of the materials. Nevertheless, if reused concrete or concrete aggregates are used for new housing, the environmental performance of the house could also improve. The dematerialisation approach is the more efficient when the goal is to reduce the quantity of materials.

**Table 5.2 Opportunities and shortcomings of approaches**

| | Opportunities | Shortcomings |
|---|---|---|
| Dematerialisation approach | • Reduction in material consumption<br>• No changes in knowledge about construction processes | • Increase in the use of non-renewable, recoverable or dismantleable materials due to the use of concrete<br>• Reduction in the number of bathrooms may be difficult for people to accept |
| Material substitution approach | • Use of renewable and low impact materials<br>• Higher recovery and dismantleability due to the use of adobe brick<br>• Good acceptance due to tradition | • Still high consumption of material |

From a social perspective, the dematerialisation approach could be easier to achieve because the type of materials are the same as those in current use. Due to the difference in house design, the switch would be a matter for architects and developers. Nevertheless, some changes in the design, such as decreasing the number of bathrooms, and to a lesser degree, the kitchen without partition walls, could create barriers. The material substitution approach would imply bigger changes in the construction industry due to the use of recycled or adobe brick instead of ceramic or concrete brick. However, this approach would mark a return to traditional materials and processes, which could help in its acceptance by society. In Table 5.2 the opportunities and shortcomings of the strategies are summarised.

### Energy
A switch to solar energy for hot water and electricity production would be a real improvement. Energy consumption in Mexico is less determined by building characteristics because heating and cooling systems are not used. The use of solar energy would imply a big change in energy production; therefore this factor relates to policy at a national level.

### Water
Water use could decrease in the dematerialisation approach because of the decrease in the number of bathrooms, although more research is needed to confirm this. Greater efficiency could be achieved by changing the payment system from a fixed tariff to a price per litre. Some subsidies may be necessary for low-income families, which tend to be bigger in size. Closing water cycles in the material substitution approach would imply use of different technology systems and more system maintenance.

# 6 Recommendations for new housing in Mexico

In this chapter, design recommendations for new housing will be presented, based on the conclusions from the previous chapter, and on general ideas about sustainable construction. The following guidelines are presented according to the sector or stakeholders to which they are targeted. The stakeholders considered in this project are: designers and developers, users, the construction materials market, government, and housing institutions.

**Recommendations directed at designers and developers**
The guidelines directed at designers and developers are related to the type of materials used, the layout of the dwelling, construction processes, and the use of passive solar design.

**Recommendations directed at users**
Users are considered to be the stakeholders that affect mainly water and energy consumption during the use of the dwelling; therefore, guidelines directed at them are aimed at the efficient consumption of water and energy.

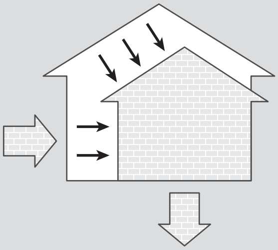
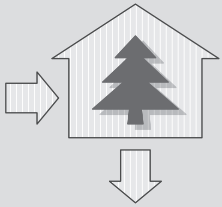
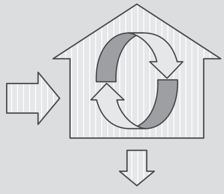
**Recommendations directed at the construction materials industry**
These guidelines are directed at the creation of an industry for sustainable and recycled materials.

**Recommendations directed at government**
The guidelines for the government are related to the creation of a sustainable building policy, although there are already plans and programmes in the country aimed at a more efficient use of energy. Reuse of materials is difficult for some groups of society to accept, and some materials (especially traditional materials) are sometimes considered a sign of underdevelopment or lack of quality in a dwelling. Government and housing institutions must support the creation of a market.

**Recommendations directed at housing institutions**
These associations, such as INFONAVIT, take charge of the development of new housing. In order to get them involved in sustainable building, specific policies and incentives are necessary.

**Materials**
In the case studies, the opportunities for a sustainable building strategy are mainly based on the design of the dwelling. Following the Three Step Strategy, the guidelines for sustainable use of materials are presented in Table 6.1.

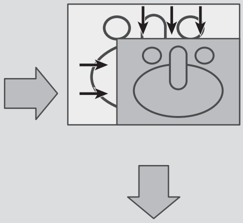
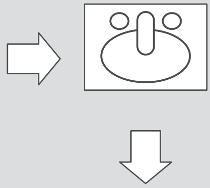
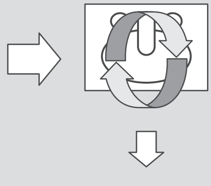
**Table 6.1 Guidelines for materials**

| | Decreasing material consumption | Use of renewable material | Efficiency in the remaining need |
|---|---|---|---|
| Three Step Strategy |  |  |  |
| Design | • Non-continuous reinforced concrete foundation<br>• Concrete structure or wooden elements (from sustainable sources) instead of confined masonry structure<br>• Masonry walls of hollow units should be preferred<br>• Reduced number of bathrooms by making them more flexible (e.g. separate toilet from shower)<br>• No pavement in front yard or back yard to allow the penetration of water into the ground<br>• No service room<br>• Open kitchen | • If possible, roof and floor tiles should be made of sustainable wood following traditional construction processes<br>• Wooden floors and traditional clay tiles as finishes<br>• Traditional insulation process in roofs<br>• Use of wooden fences or bushes for division of houses instead of common concrete fences | • Intervals to coincide with the standard lengths of construction elements<br>• Flexible structure of the building<br>• Less interior structural walls<br>• Use of easily dismantleable elements and materials<br>• Use of durable materials, especially in structural elements<br>• Use of reusable and recyclable materials and elements |
| Government | • Higher taxes for infrastructure in new areas, so companies would have to look for land inside urban areas<br>• Promotion of dematerialisation concept among people | • Promotion of awareness about reusable and renewable materials | • Use of legislation and subsidies in order to promote renovation of housing through construction companies<br>• Creation of government body dedicated to building stock<br>• Prevention of landfill: bans, taxing and environmental regulation for building materials |
| Materials industry | • Development of lighter materials | • Creation of renewable resources market | • Encouragment of supply of recycled material and creation of demand<br>• Development of materials with less impact on the environment |
| Housing institutions | • Improvement of skills of construction workers for new methods<br>• Inclusion of material requirements in legislation | | |

## Water system

The improvements to be made in Mexican housing concerning water consumption are mainly related to improvements in the design of the water system by reuse of water. Table 6.2 shows the guidelines for sustainable use of water.

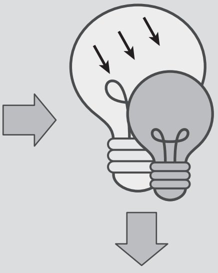
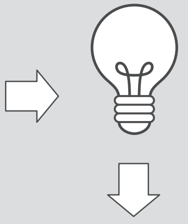
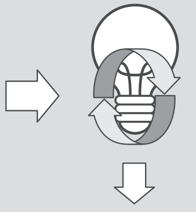
**Table 6.2 Guidelines for sustainable use of water**

| | Decreasing water consumption | Use of renewable sources | Efficiency in the remaining need |
|---|---|---|---|
| Three Step Strategy |  |  |  |
| Design | • Increase awareness of use of water<br>• Decrease number of bathrooms<br>• Incorporate water-saving devices in dwelling (e.g. in showers, toilets) | • Use of rainwater for flushing toilets and for outside taps (for gardening) | • Separate grey water from black water, and reuse grey water within the same dwelling or condominium<br>• Small treatment plant in the case of large condominiums |
| Government | • Water pricing in relation to consumption | • Encourage use of rainwater in new housing developments | • Encourage separation of grey water in new housing developments |
| Materials industry | • Less water consumption during the production of materials | | |
| Housing institutions | • Include separation and treatment of water in legislation<br>• Provide more facilities to purchase houses with efficient water systems | | |

**Energy**

The improvements aimed at reducing energy consumption are mainly related to the use of more renewable sources. Table 6.3 shows the guidelines for energy use.

**Table 6.3 Guidelines for energy use**

| | Decreasing energy consumption | Use of renewable sources | Efficiency in remaining need |
|---|---|---|---|
| Three Step Strategy |  |  |  |
| Design | • Double glazing in windows with attention to not increasing the need for cooling<br>• Use of passive solar design (e.g. orientation) | • Use of solar energy for electricity and heating water | • Use of high efficiency boilers for heating water |
| Government | • Increase awareness of energy use | • Subsidies for using solar energy or subsidies for housing companies if a design uses solar power systems | • Encourage use of energy-saving appliances<br>• Encourage use of boilers with higher efficiency |
| Materials industry | • Develop materials with less embodied energy<br>• Develop more efficient water boilers | | |
| Housing institutions | • Include parameters for thermal comfort in legislation<br>• Provide facilities to purchase houses with green energy systems | | |

# 7 Conclusions and discussion

## 7.1 Conclusions

This research focuses on the development of environmental indicators for the Three Step Strategy and on the improvement of Mexican housing design from the perspective of environmentally sustainable building. The research questions formulated for this study were as follows:

1. How can the environmental performance of housing design be assessed?
   - 1a. What are the factors that affect the environmental performance of a dwelling from a design perspective? (Indicators)
   - 1b. What indicators can be used to evaluate the environmental performance of the design of a dwelling? (Indicators)
2. How can the environmental performance of Mexican housing be improved?
   - 2a. What is the environmental performance of Mexican housing? (Analysis of dwellings)
   - 2b. How can the performance of Mexican housing be improved with sustainable building strategies? (Improving Mexican housing)
3. What are the aspects of design that can be improved in Mexican housing? (Guidelines)

To answer the first main question, the principal strategies used for assessing the environmental performance of buildings were identified in the first chapter of this book and indicators were developed according to the Three Step Strategy and the Atlas project (Rovers 2005). The case studies were used to test the usefulness of the indicators. The second research question was addressed in Chapters 2 and 3. The case studies of Mexican houses were introduced in Chapter 2, followed by the analysis of several types of dwellings, which provided the answer to research question 2.1. The strategies for improving the design of Mexican housing were studied in Chapter 3, answering question 2.2. The guidelines introduced in Chapter 3 answer question 2.3 regarding aspects of Mexican design that could be improved. The conclusions are summarised hereafter.

**1a. Factors that affect the environmental performance of the design of a dwelling**

The design of a building affects its environmental performance throughout its life cycle. From urban design to the choice of materials, the decisions taken during the design phase have consequences that affect not only the environmental impact of the building, but also the quality of life of the occupants.

The design factors that affect the building and construction phase are mainly the choice of materials and construction processes. These choices determine the impact of the materials, such as embodied energy, emissions, energy and material use during manufacturing and transport, and waste produced during the construction process.

The performance of the dwelling during the use phase is in part determined by design, such as the flexibility of the building and the durability of the materials, which determines maintenance needs. In countries with extreme weather conditions, energy consumption very much depends on the type of materials used, like insulation. User related energy and water consumption are determined by occupant behaviour, though factors such as natural lighting and number of bathrooms (or taps) can also influence the use of these resources.

The choice of materials used also has a significant influence in the demolition phase of the building. Characteristics such as recoverability and dismantleability affect the possibility of performing demolition in a sustainable way.

**1b. Indicators to evaluate environmental performance**

Importance is given in this research to materials in comparison to water and energy because they not only have a direct impact on the environment but they also affect the consumption of energy (during manufacturing of materials and use of the building) and water (during manufacturing). The choice of materials may have a large effect on energy consumption because this determines in part the climate related energy use (e.g. insulation) and the energy use related to lighting.

The indicators defined in this study measure the quantity of materials and their characteristics. They give an overview of the impact of the use of resources, and they mainly help to identify problems in a design. The indicators evaluate the main characteristics of the design in relation to the approaches taken in this research: the Three Step Strategy and dematerialisation. These main characteristics are:

a. Resource efficiency (for materials, energy, water and land) by using fewer resources and by increasing the intensity of use.
b. Use of renewables and low impact resources.
c. Efficiency in the remaining need by means of: closing the loop, extending the life cycle of the product, reusing elements and materials.

Occupant related indicators were also developed and showed that behaviour has a great impact on energy and water consumption, which is useful in analysing the extent of the impact of cultural and social factors on the environmental impact of the dwelling. Indicators to identify hazards for construction workers and building occupants were developed. Although these can give some indication of hazardousness, they do not show the real risk of potential harm posed by the material or activity. Therefore, methods based on risk assessment are a better option for health assessment.

**2a. Environmental performance of Mexican housing**

Environmental performance in Mexican housing of climate related energy use is good in comparison to other countries in relation to climate systems, because energy for air conditioning is not required. The consumption of energy for appliances and for cooking is relatively low. This situation should be maintained even if the economic situation of households were to change in the future. Mexican houses in Toluca tend to use more energy for heating water than Peruvian and Dutch housing because of the low efficiency of their boilers.

Performance in terms of materials is not as good as other countries from a dematerialisation perspective. Nevertheless, the use of low impact materials makes the performance of the dwelling appear better in comparison to other countries. The performance of Mexican dwellings could be easily improved by certain changes to the design that do not affect the construction industry.

**2b. Improvement of Mexican housing with sustainable building strategies**

To test the improvement of the case study design, two strategies were evaluated:

a. Dematerialisation strategy, where the goal was to reduce the quantity of material used.
b. Material substitution strategy, where the goal was to increase the use of renewable and low impact materials.

The improvements shown in the dematerialisation strategy concern a considerable reduction in the quantity of materials used in the dwelling; although the quantity of low impact material decreased due to the use of concrete instead of stone, the quantity of high impact material was reduced by 50%. In the material substitution approach, the improvement is seen in the percentage of low impact materials, which increased from 38% to 82%. The percentage of renewable material also increased, though to a lesser extent. Nevertheless, the total quantity of material is only slightly reduced in comparison to the case study; the quantity of high impact material is reduced and the quantity of low impact material is still considerable. Both strategies show improvements in the case study, proving the many possibilities for sustainable building through a well-adapted design.

**3. Aspects of design improved**

The most common type of construction process in Mexican dwellings is continuous stone masonry, and confined fired-clay masonry walls. The replacement of this type of structure by a reinforced concrete structure (footing, columns and beams) can significantly improve the performance of dwellings, because even the percentage of high impact materials can be reduced. Through slight changes to the layout of the dwelling, a greater reduction in material consumption could be accomplished. Unnecessary and resource-consuming elements such as concrete fences, service rooms and service bathrooms could be eliminated in exchange for more sustainable options. A reduction in the number of bathrooms and an open-plan kitchen could also contribute to the sustainability of the dwelling.

Energy consumption in Mexican housing can be decreased through better awareness and efficient appliances, lighting and water boilers, while water consumption can be decreased by means of a better tariff policy. Using passive solar design (orientation, colours, etc.) and double glazing could improve the indoor temperature of the building, thus ensuring that heating systems will not be used in better economic situations. The use of solar energy systems for heating water could reduce energy use. Solar energy systems could work well in the region because of the good solar insulation throughout the year. And, when finances allow it, solar energy for electricity could also be encouraged. Performance of water systems could be improved by using rainwater and reusing greywater within the dwelling.

## 7.2 Discussion

Sustainable building is acquiring more importance worldwide. Nevertheless, in developing countries there are many other problems that are the immediate priority. 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 a high quantity of resources. The main problem that these countries face is maintaining the current level of quality of life while minimising environmental interventions.

For developing countries, the main housing-related problem is the lack of access to good housing for a large part of the population. Developing countries have been focusing on improving housing quality, usually by using high environmental impact materials, which are seen as a sign of development or progress. The example of developed countries in sustainable building efforts and problems can help developing countries to choose a different path towards development in order to achieve better solutions.

The type of housing policy in Mexico could help to include sustainable building practices. Through housing institutions such as INFONAVIT, government organisations can set sustainability requirements with which private developers would have to comply. However, this type of incentive could only work for social housing; for middle- and high-income housing a different method would have to be used.

The quality of Mexican housing is an important factor to take into account. The use of hazardous materials (such as asbestos) is still allowed in Mexico, and these are used in particular by low-income families. Overcrowding is also a problem which, combined with lack of ventilation, results in a low indoor environmental quality. In addition, a percentage of the population lives in informal settlements which are generally of low quality and present dangers to the occupants. Therefore, the Mexican housing situation is in many cases more complex than a mere environmental impact, and solving social problems should still be the priority when looking for more environmentally sustainable solutions.

Some of the housing problems in developed countries, such as high climate-related energy consumption or materials with high environmental impact, are still not present in developing countries due to economic or cultural aspects. Supporting the current situation through policies and media is probably a way to achieve sustainable building. In order to truly reduce the environmental burden caused by construction and housing, it is sometimes necessary to change the mentality and values of people. In this respect, the dematerialisation approach has great importance and supporting this approach is probably a key towards sustainable building.

### Method

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 using literature and estimates. However, to determine quantitatively how far a material is recovered (D-B3), reused (D-B3.1) or recycled (D-B3.2), or to determine if a material has a low or high environmental impact (D-B4.1, D-B4.2), it would be better to use the LCA method, or at least parts of it, because it is the only widely accepted quantitative method for determining these characteristics.

### Material

The fact that Mexican and Peruvian houses tend to be larger in area and spaces than Dutch houses may be due to cultural preferences for more bedrooms and bathrooms, and available land. Large houses, more rooms and more bathrooms are in greater demand in Latin America than in the Netherlands. In addition, the use of a service room and service bathroom for domestic services is common in Latin America. Improvements in this area may be accomplished only if users are willing to accept changes in their lifestyle.

Changes in material type in Mexican housing are an important way of improving the environmental performance of dwellings, but such changes could affect the performance of a different aspect of sustainability. For example, more energy may be required to maintain a good indoor environment. Therefore, materials and construction processes should be chosen carefully.

### Energy

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 (and the indoor temperature) in the indoor environment is more subjective than it seems. Nevertheless, the low consumption of energy for heating could be a consequence of the high density of the materials used in Mexican housing and the fact that solar radiation heats the dwellings during the day. In the region of study, there is no apparent need to improve the comfort of the indoor environment, but thermal comfort could still be improved by using insulation and double glazing instead of heating systems, and paying attention to not increasing the need for cooling.

**Water**
Having no drinkable water system in Latin America is a common situation. Due to the fact that the treatment of water is not as resource-intensive as in places where the delivered water is drinkable, there is less consumption of resources in water for household use that does not require such a high quality. On the other side, not having drinkable water could cause health problems.

## 7.3 What further research is needed?

In this research, substitution of materials for others that have less environmental impact is proposed. This was based on the assumption that the thermal properties of the substituted materials are similar and that the use of different materials would not affect the use of energy for heating or cooling. Further research is needed to optimise both materials and energy use.

Maintenance is not considered in this method. More research should be carried out into maintenance indicators for design due to the fact that maintenance of buildings may contribute largely to the environmental burden of construction, and can also extend its service life.

Further research is also recommended regarding construction processes and construction waste. Indicators that take into account health and other social issues should also be studied.

The assessment method developed in this book is based on aggregated characteristics of the materials taken from different literature sources. A link between this method and the LCA of materials could make their selection more precise. An analysis of the compatibility of these two methods could improve the usability of the method.

There are also uncertainties related to occupant behaviour that may influence strongly the results. There are little statistical data known about occupant behaviour. For instance, the relation between the number of bathrooms or taps and water consumption should be further studied. It could be that fewer bathrooms and taps per person could lead to less consumption of water because the bathroom has to be shared. The fact that heating systems are not used in Toluca, a cold city, should be further studied as well to determine the relative effect of perceived comfort and weather conditions in the consumption of energy for heating.

The method used in this book proved to be useful in making analysis between different countries, and for giving design guidelines. In the context of the ATLAS project, more studies of housing on a worldwide level should be undertaken in order to share best practices.

# Appendix 1 Indicators

**Table A1.1 Indicators for the building and construction phase**

| Key | Name | Definition |
|---|---|---|
| D-B1 | Total material | Totality of embodied materials per useful living area |
| D-B2 | Renewable materials | Renewable materials per useful living area |
| D-B3 | Recovered materials | Recovered materials per useful living area |
| D-B3.1 | Reused materials | Reused materials per useful living area |
| D-B3.2 | Recycled materials | Recycled materials per useful living area |
| D-B3.3 | Downcycled materials | Downcycled materials per useful living area |
| D-B4 | Non-renewable materials | Non-renewable materials with low environmental impact plus non-renewable materials with high environmental impact, per useful living area |
| D-B4.1 | Low impact non-renewable materials | Non-renewable materials with low environmental impact per useful living area |
| D-B4.2 | High impact non-renewable materials | Non-renewable materials with high environmental impact per useful living area |
| D-B5 | Material efficiency | Renewable plus recovered materials in relation to raw materials |
| D-B6 | Total waste | Total waste weight per useful living area |
| D-B7 | Recoverability of waste | Recoverable construction waste per useful living area |
| D-B7.1 | Reusability of waste | Reusable construction waste per useful living area |
| D-B7.2 | Recyclability of waste | Recyclable construction waste per useful living area |
| D-B7.3 | Downcyclability of waste | Downcyclable construction waste per useful living area |
| D-B8 | Total land use | Ratio between the useful area of the house and the total land area |
| D-B9 | Green area | Percentage of land that is left free |
| D-B10 | Hazardous processes | Hazardous processes during construction activities per useful living area |
| D-B11 | Non-hazardous processes | Non-hazardous processes during construction activities per useful living area |
| D-B12 | Cost of housing per square metre | The cost of housing per square metre |

**A1.2 Indicators for the use phase**

| Key | Name | Definition |
|---|---|---|
| D-U1 | Excellent durability of materials | Materials with high durability |
| D-U2 | Good durability of materials | Materials with medium durability |
| D-U3 | Fair durability of materials | Materials with low durability |
| D-U4 | Hazardous materials | Hazardous materials per useful living area |
| D-U5 | Non-hazardous materials | Non-hazardous materials per useful living area |
| D-U6 | Interior structural walls | Percentage of internal structural walls out of the total |
| D-U7 | Exterior structural walls | Percentage of external structural walls out of the total |
| D-U8 | Persons per bedroom | Number of inhabitants divided by the number of bedrooms in the dwelling |
| D-U9 | Useful living area per person | Useful living area divided by the number of inhabitants in the dwelling |
| D-U10 | Total energy | Sum of renewable, recovered and non-renewable energy or climate related, artificial lighting, and energy used for cooking, water heating and appliances |
| D-U11 | Renewable energy | Renewable energy per useful living area |
| D-U12 | Recovered energy | Recovered energy per useful living area |
| D-U13 | Non-renewable energy | Non-renewable energy per useful living area |
| D-U14 | Climate related energy | Energy used for heating and cooling of the dwelling per useful living area |
| D-U15 | Artificial lighting energy consumption | Energy used for artificial lighting per useful living area |
| D-U16 | Energy use for cooking, water heating and appliances | Auxiliary energy needed to run a house per useful living area (cooking, heating water, appliances) |
| D-U17 | Energy efficiency | Renewable and recycled energy to climate related energy |
| D-U18 | Water consumption per person | Water consumption per number of inhabitants |
| D-U19 | Renewable water | Renewable water per useful living area |
| D-U20 | Recovered water | Recovered water per useful living area |
| D-U21 | Recycled water | Recycled water per useful living area |
| D-U22 | Water efficiency | Renewable, recovered and recycled water in relation to water consumption |

**A1.3 Design indicators for the demolition phase**

| Key | Name | Definition |
|---|---|---|
| D-D1.1 | Dismantleable materials | Dismantleable materials per useful living area |
| D-D1.2 | Semi-dismantleable materials | Semi-dismantleable materials per useful living area |
| D-D2.1 | Reusable materials | Reusable materials per useful living area |
| D-D2.2 | Recyclable materials | Recyclable materials per useful living area |
| D-D2.3 | Downcyclable materials | Downcyclable materials per useful living area |
| D-D3 | Hazardous demolition processes | Hazardous processes during demolition activities per useful living area |
| D-D4 | Non-hazardous demolition processes | Non-hazardous processes during demolition activities per useful living area |

# Appendix 2 Categories of building materials

**Table A2.1 Categories of building materials**

| | Mexican social/medium housing | Mexican traditional housing | Peruvian housing | Dutch housing |
|---|---|---|---|---|
| Renewable materials | Wood | Wood | Wood | Wood |
| Recovered materials | None | None | None | None |
| Non-renewable low impact materials | Stone, earth, sand | Adobe, stone, earth, sand | Mortar | Sand |
| Non-renewable high impact materials | Ceramic, paint, glass, concrete, steel, gypsum, aluminium, zinc, PVC, copper, iron, plastics | Ceramic, paint, glass, zinc, copper, iron | Ceramic, glass, concrete, steel, PVC, copper | Ceramic, glass, concrete, steel, gypsum, foam, PVC |
| Reusable materials | Stone, wood, earth, sand, textile | Stone, wood, earth, sand | Wood | Wood, sand |
| Recyclable materials | Glass, steel, gypsum, zinc, aluminium, copper, iron, plastic | Adobe, glass, zinc, copper, iron | Glass, steel, copper | Glass, steel, gypsum |
| Downcyclable materials | Concrete, ceramic | Concrete, ceramic | Concrete, ceramic | Concrete, ceramic |
| Dismantleable materials | Wood, steel, earth, glass, textile, aluminium, zinc, PVC, copper, iron | Wood, earth, sand, copper, glass, zinc, iron | Wood, steel, copper, glass, PVC | Wood, steel, sand, glass, PVC |
| Semi-dismantleable materials | Ceramic | Ceramic | Ceramic | Ceramic |
| Hazardous materials | Stone, paint, PVC, concrete, copper, zinc, plastic, aluminium | Stone, paint | PVC, concrete, copper | Paint, PVC, concrete, gypsum, foam |
| Excellent durability | Clay, fired bricks, concrete, glass, aluminium | | | |
| Very good durability | Plastics, bitumen, foam, PVC, stone, steel | | | |
| Good durability | Hardboard, adobe, earth, sand | | | |

# Appendix 3 Values of all indicators

A3.1 Values of all indicators for Mexican, Peruvian and Dutch houses

| | Unit | Mexican housing: Social housing | Mexican housing: Medium housing | Mexican housing: Traditional housing | Peruvian housing | Dutch housing |
|---|---|---|---|---|---|---|
| Useful living area | m² | 68 | 108 | 360 | 214 | 111 |
| Household size | Person | 4.2 | 4.2 | 4.2 | 5 | 4 |
| **Material** | | | | | | |
| Total material weight | kg | 200,160.75 | 229,707.38 | 925,372.19 | 300,728.41 | 118,645.18 |
| Renewable materials | kg | 543.51 | 745.64 | 38,595.91 | 2,328.21 | 3,268.20 |
| Recovered materials | kg | 0 | 0 | 0 | 0 | 0 |
| Non-renewable low impact materials | kg | 53,817.05 | 86,141.73 | 740,779.98 | 25,228.52 | 7,750 |
| Non-renewable high impact materials | kg | 145,800.19 | 142,820.01 | 145,996.30 | 273,171.68 | 107,626.98 |
| Reusable materials | kg | 33,319.11 | 52,330.34 | 159,953.71 | 3,660.30 | 11,018.20 |
| Recyclable materials | kg | 14,775.17 | 19,728.13 | 616,357.59 | 3,765.78 | 12,060.98 |
| Downcyclable materials | kg | 130,550.77 | 121,801.17 | 105,725.06 | 267,969.80 | 94,512 |
| Dismantleable materials | kg | 5,250.99 | 2,728.81 | 41,259.11 | 7,530.08 | 12,047.18 |
| Semi-dismantleable materials | kg | 92,331.84 | 68,362.85 | 85,872.41 | 84,507.08 | 40,962 |
| Hazardous materials | kg | 81,753.71 | 124,438.09 | 178,630.85 | 183,593.60 | 65,740 |
| Non-hazardous materials | kg | 118,407.04 | 105,269.29 | 746,741.34 | 117,134.81 | 52,905.18 |
| **Layout** | | | | | | |
| Internal structural walls | m³ | 6.17 | 15.01 | 69.66 | 0.00 | 14.00 |
| External structural walls | m³ | 20.72 | 23.55 | 282.00 | 0.00 | 1.40 |
| Internal non-structural walls | m³ | 0.00 | 3.09 | 0.00 | 40.16 | 3.20 |
| External non-structural walls | m³ | 1.00 | 8.75 | 0.00 | 0.00 | 0.00 |
| Total walls | m³ | 27.89 | 50.40 | 351.66 | 40.16 | 18.60 |

▶

| | Unit | Mexican housing | | | Peruvian housing | Dutch housing |
|---|---|---|---|---|---|---|
| | | Social housing | Medium housing | Traditional housing | | |
| **Energy** | | | | | | |
| Total energy | MJ/m² | 99.1 | 78.8 | 56.51 | 186.72 | 578.43 |
| Renewable energy | MJ/m² | 99.1 | 78.8 | 56.51 | 0.00 | 0.00 |
| Recycled energy | MJ/m² | 99.1 | 78.8 | 56.51 | 0.00 | 0.00 |
| Energy for air conditioning | MJ/m² | 0.0 | 0.0 | 2.00 | 0.00 | 357.39 |
| Energy for artificial lighting | MJ/m² | 62.44 | 50.52 | 20.19 | 30.74 | 56.61 |
| Energy for cooking, water heating and appliances | MJ/m² | 36.66 | 28.28 | 34.32 | 155.98 | 164.42 |
| **Water** | | | | | | |
| Water consumed per household | Litres | 153,300 | 153,300 | 153,300 | 60,000 | 200,000 |
| Renewable water | Litres | 0 | 0 | 0 | 0 | 0 |
| Recycled water | Litres | 0 | 0 | 0 | 0 | 0 |
| **Land** | | | | | | |
| Total area land | m² | 85 | 120 | 380 | 160 | 120 |
| Free land area | m² | 47 | 63 | 138 | 23 | 26 |
| **Other** | | | | | | |
| Cost of house per TMS | Times minimum salary | 34.68 | 50.45 | 94.59 | 27.69 | 1.77 |
| Minimum salary per year | Local currency | 15,858 | 15,858 | 15,858 | 5,400 | 16,392 |
| Cost of dwelling | Local currency | 550,000 | 800,000 | 1,500,000 | 149,500 | 84,000 |

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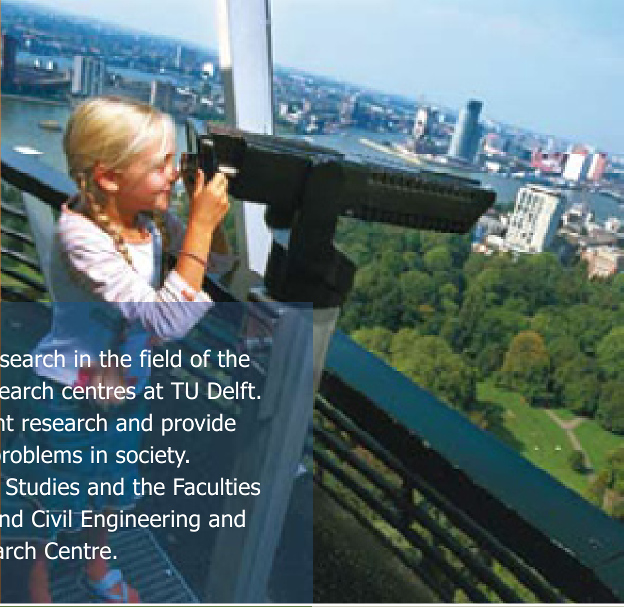

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Design determines the environmental performance of a building. The building envelope, heating and ventilation systems, and layout should determine energy efficiency and a healthy environment; meanwhile the materials used determine the impact of construction activities on the environment. The author developed a series of indicators based on a Three Step Strategy to assess the design of dwellings in relation to their potential for a sustainable life cycle. This book aims to provide designers with indicators needed to assess housing design with an eye on improvements. The indicators are applied to a case study in the central region of Mexico in order to provide possible improvements to the environmental performance of Mexican dwellings.

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