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UNIVERSITAT ROVIRA I VIRGILI
SUSTAINABILITY ASSESSMENT WITHIN THE RESIDENTIAL BUILDING SECTOR: A PRACTICAL LIFE CYCLE METHOD
APPLIED IN A DEVELOPED AND A DEVELOPING COUNTRY.
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Sustainability assessment within the residential building sector: A practical life cycle method applied in a developed and a developing country

A dissertation submitted to the Universitat Rovira i Virgili to fulfill the requirements for obtaining the degree of *Ph.D.* with the mention of *Doctor Europeus*

Presented by:
Oscar Orlando Ortiz Rodríguez

Universitat Rovira i Virgili

Tarragona, Spain
2009

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UNIVERSITAT ROVIRA I VIRGILI

Departament d'Enginyeria Química
Escola Tècnica Superior d'Enginyeria Química
Universitat Rovira i Virgili
Av. Països Catalans 26
43007 Tarragona, Espanya

Tel. 977 55 9644
Fax 977 55 9621

Els sota signants Dr. Francesc Castells i Dr. Guido Sonnemann

FAN CONSTAR:

Que el present treball que porta per títol:

Sustainability assessment within the residential building sector: A practical life cycle method applied in a developed and a developing country.

i que presenta el Sr. Oscar Orlando Ortiz Rodriguez per a optar al grau de Doctor per la Universitat Rovira i Virgili, ha estat realitzat sota la seva direcció i que tots els resultats presentats i la seva anàlisi són fruit de la investigació realitzada per l'esmentat doctorant.

I perquè se'n prengui coneixement i tingui els efectes corresponents, signen aquest certificat-

Dr. Francesc Castells Pique **Dr. Guido W. Sonnemann**

Tarragona, 26/10/2009

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Universität Stuttgart
Lehrstuhl für Bauphysik (LBP)
Ganzheitliche Bilanzierung (GaBi)

Univ.-Prof. Dr.-Ing. Dipl.-Phys. Klaus Sedlbauer
Universität Stuttgart, LBP, Abt. GaBi • Hauptstr. 113 • 70771 Echterdingen

Dipl.-Ing. Matthias Fischer
Telefon
+49 (0)711 / 489999-21
Telefax
+49 (0)711 / 489999-11
e-mail
matthias.fischer@lbp.uni-stuttgart.de
Aktenzeichen/Kürzel
Fi

08. May 2009

Doctoral Program in Chemical, Environmental and Process Engineering

University of Rovira i Virgili

Tarragona
Spain

Internship

To whom it may concern

Herewith I certify that Oscar Orlando Ortiz Rodriguez with Colombian passport number 88217201 who is a PhD student in Chemical, Environmental and Process Engineering at the University of Rovira i Virgili in Tarragona, Spain stayed at the Abteilung Ganzheitliche Bilanzierung, LBP (Universität Stuttgart) doing an internship starting from 01st of October to 31st of December 2008.

During this time, Mr Ortiz performed research work under my supervision where the main objective of the internship was to evaluate environmental impacts through the whole building life cycle for a standard Mediterranean Spanish home. To accomplish this goal, our research group provided him the necessary equipment, infrastructure as well as technical and scientific support such as the GaBi software system and utilizes data from the GaBi database for this period.

Please feel free to contact me to request any additional information.

Sincerely,

M. Fischer

Matthias Fischer
Head of Department

Lehrstuhl für Bauphysik (LBP)
http://www.lbp.uni-stuttgart.de/
Tel.: +49(0)711/685-66577
Fax: +49(0)711/685-66583
Pfaffenwaldring 7
70569 Stuttgart (Vaihingen)

Abteilung Ganzheitliche Bilanzierung (GaBi)
http://www.lbpgabi.uni-stuttgart.de/
Tel.: +49(0)711/489999-0
Fax: +49(0)711/489999-11
Hauptstrasse 113
70771 Echterdingen

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Examination board members

Dra. Marta Schuhmacher
Grup d'Anàlisi i Gestió Ambiental (AGA)
Departament d'Enginyeria Química
Universitat Rovira i Virgili
Av. dels Països Catalans 26, 43007, Tarragona, España
E-mail address: marta.schuhmacher@urv.cat

Dra. Sonia Valdivia
Associate Programme Officer
Sustainable Consumption and Production Branch,
United Nations Environment Programme, Division of Technology, Industry and Economics,
15, rue de Milan, 75009 Paris, Francia
E-mail address: Sonia.Valdivia@unep.fr

Dr. Alberto Cuchi Burgos
Escola Tècnica Superior d'Arquitectura del Vallés (ETSAV)
Universitat Politècnica de Catalunya
C. Pere Serra, 1-15, 08190 Sant Cugat del Valles, Barcelona, España
E-mail address: alberto.cuchi@upc.edu

Dr. Alejandro Josa
Departament d'Enginyeria del Terreny
Universitat Politècnica de Catalunya
C/ Jordi Girona Salgado, 1-3, 08034, Barcelona, España
E-mail address: alejandro.josa@upc.edu

Dr. Joan Carles Bruno
Grup d'Enginyeria Tèrmica Aplicada (CREVER)
Departament d'Enginyeria Mecànica
Universitat Rovira i Virgili (URV).
Av. dels Països Catalans 26, 43007, Tarragona, España
E-mail address: juancarlos.bruno@urv.cat

External reviewers

Dra. Ing Marzia Traverso
Institute for Environmental Engineering (Institut für Technischen Umweltschutz)
Technische Universitaet Berlin
Str. des 17. Juni 135, D-10623 Berlin
E-mail address: marzia.traverso@tu-berlin.de

Dr. Stefan Petrus Salhofer
Institute of Waste Management
Universität für Bodenkultur Wien
University of Natural Resources and Applied Life Sciences, Vienna
Gregor Mendel Straße 33, A-1180 Wien, Österreich
E-mail address: stefan.salhofer@kerp.at

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To Rachi, Ozy and future generations.

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Abbreviations

AC:	Air chamber (IM)
AP:	Acidification potential
BMCC:	Building materials and components
BRE:	Building Research Establishment
C:	Construction phase
COP:	Coefficient of performance
CSD:	Commission on Sustainable Development
CTE:	Spanish Building Technical Code
DANE:	Colombian Administrative Department of National Statistics
DHW:	Domestic hot water
E:	Energy
ECLAC:	Economic Commission for Latin America and the Caribbean
EIPRO:	Environmental Impact of Products
EL:	External layers
EP:	Eutrophication potential
EPD:	Environmental Product Declarations
EWC:	European Waste Catalogue
GDP:	Gross Domestic Product
GHG:	Global Greenhouse Gas emissions
GWP:	Global warming potential
GTZ:	German Technical Cooperation Agency
HT:	Human toxicity
HVAC:	Heating, ventilation and air conditioning
IEA:	International Energy Agency
IM:	Insulation materials
IL:	Internal layers
ISO:	International Standardisation Organisation
IPP:	Integrated Product Policy
Ktoe:	Kilo tones oil equivalent
FU:	Functional unit
LCA:	Life Cycle Assessment
LCI:	Life Cycle Inventory
LCIA:	Life Cycle Impact Assessment
LCT:	Life Cycle Thinking
LCSA:	Life Cycle Sustainability Analysis
M:	Maintenance phase
MDG:	Millennium Development Goals
MEA:	Material and Energy Analysis

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MSW:	Municipal Solid Waste
NRE:	Non renewable energy
OLADE:	Latin American Energy Organization
PP:	Payback period
RC:	Resources consumption
RE:	Renewable energy
SOD:	Stratospheric ozone depletion
SW:	Solid waste
TE:	Total energy
U:	Use phase
UNCED:	United Nations Conference on Environment and Development
USGBC:	United States by the Green Building Council
VEE:	Vertical external enclosures
VIE:	Vertical Interior Enclosures
W:	Watt
WC:	Water consumption
WCED:	World Commission on Environment and Development
WPC:	Whole process of constructions

Academic productivity resulting from the thesis

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2. Ortiz O, Bonnet C, Bruno JC, Castells F. (2009): Sustainability based on LCM of residential dwellings: A case study in Catalonia, Spain. Building and Environment. Volume 44, Issue 3, March 2009, pages 584 – 594.

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Summary

More than ever, the residential building sector is concerned with improving the social, economic and environmental indicators of sustainability. In order to overcome the increasing concern of today's resource depletion, environmental considerations and to address sustainability indicators, a practical life cycle method has been proposed to decision making integrating environmental and socio-economical aspects to analyse the impact of sustainability within the residential building sector using two practical life cycle methods. One method is the Material and Energy Analysis (MEA) which is suggested as an appropriate tool to provide a systematic picture of the direct and physical flows of the use of natural resources and the other is the environmental management tool of Life Cycle Assessment (LCA) as a complement to evaluate environmental impacts throughout the life cycle of the system.

Furthermore, the method provides sustainability information that facility an adequate decision making towards sustainable development at macro and micro levels. Sustainability assessment at macro level is determined by exogenous variables that can influence the development of a country. Meanwhile sustainable at the micro level is made within the limits of the whole building life cycle, starting from the construction, use (operation and maintenance) and finishing with the end-of-life phase. To illustrate it, a case study has been carried out based on the application to two buildings, one located in Barcelona, Spain and one situated in Pamplona, Colombia. Then, the main objective of this thesis is to propose a practical life cycle method including environmental and socio-economical aspects to evaluate indicators that explicitly measure the residential building sector's impacts. This thesis has also provided initiatives for residential dwellings to reduce environmental impacts and assist stakeholders in improving customer patterns during the dwelling life cycle.

The findings of this thesis state that the appropriate combination of building materials, improvement in behaviours and patterns of cultural consumption, and the application of government codes would enhance decision-making in the residential building sector towards sustainability. The difference in consumption in Colombia and Spanish dwellings is not only due to the variation in results for bio-climatic differences but also because of the consumption habits in each country. The importance of consumption habits of citizens and the need to decouple socio-economic development from energy consumption are sought for achieving sustainability from a life cycle perspective. There is a crucial necessity to provide satisfaction to basic needs and comfort requirements of population with reasonable and sustainable energy consumption.

Therefore, there is no doubt that applying environmental managements tools as Life Cycle Assessment (LCA) and Material and Energy Analysis (MEA) to the full building life cycle can be very important for reducing environmental loads and thereby improving sustainability indicators. Then, any improvement in building sustainability is oriented generally to building materials, energy use and waste management in all phases of the building life cycle, having always in mind that building has to be

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accessible from an economical and social part of view. The type of standard dwelling varies substantially depending on the geographic location where it is built. Climate, technological, cultural, socio-economical differences clearly define the standard of a building in any context and in any region. This leads to important differences in the LCA results and it means that any extrapolation of existing European LCA data to the case of a developing country would imply important errors. However, the function is always the same, to provide protection and housing for its habitants.

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Resumen

Hoy en día, el sector residencial busca mejorar los indicadores de sostenibilidad en los aspectos sociales, económicos y ambientales. Con el fin de considerar la creciente preocupación del agotamiento de los recursos naturales y buscar reducir las emisiones adversa al medio ambiente, un método practico basado en el ciclo de vida se ha propuesto para la evaluación socio-económica y evaluación del impacto ambiental en sector residencial utilizando dos métodos. El primero es el Análisis de Materiales y de Energía (AME) que proporciona una visión sistemática de los flujos directos e indirectos de la utilización de los recursos naturales y el segundo método es el Análisis del Ciclo de Vida (ACV) como complemento para evaluar los impactos ambientales en todo el ciclo de vida del sistema.

Adicionalmente, el método proporciona información de sostenibilidad permitiendo la adecuada toma de decisiones hacia el desarrollo sostenible en los niveles macro y micro. Evaluación de la Sostenibilidad en el nivel macro está determinado por variables exógenas que influyen en el desarrollo de un país. Mientras tanto, sostenibilidad en el nivel micro hace referencia dentro de los límites de todo el ciclo de vida de una vivienda, comenzando por la fase de construcción, uso (operación y mantenimiento) y terminando con la fase final. Para ilustrarlo, un caso de estudio ha sido llevado a cabo en la aplicación de dos edificios, uno situado en Barcelona, España y otro situado en Pamplona, Colombia. Por consiguiente, el objetivo principal de esta tesis es proponer un método que tenga en cuenta los aspectos medio-ambientales y socio-económicos que tiendan a mejorar la sostenibilidad y que explícitamente midan los impactos del sector de residencial. Esta tesis también propone iniciativas de mejora en las viviendas residenciales que conlleven a reducir los impactos ambientales y asistir a los agentes involucrados del sector.

Las conclusiones de esta tesis soportan que la combinación adecuada de materiales de construcción, el buen comportamiento en los patrones de consumo, y la aplicación de códigos y leyes mejoraran los aspectos sostenibles en el sector de la construcción. La diferencia en el consumo en las viviendas de Colombia y en las Españolas no sólo se debe a la variación de las diferencias bio-climáticas, sino también por los hábitos de consumo en cada país. Se puede observar la importancia de los hábitos de consumo de los ciudadanos y la necesidad de disociar el desarrollo socio-económico del consumo de energía. Existe una necesidad fundamental de dar satisfacción a las necesidades básicas y requerimientos de confort de la población con un consumo energético razonable y sostenible.

Por lo tanto, no hay duda de que la aplicación de herramientas medioambientales como el análisis del ciclo de vida (ACV) y análisis de materiales y energía (AME) es muy importante para minimizar el impacto ambiental y buscar mejorar los indicadores de sostenibilidad. Queda implícito entonces que cualquier mejora en la sostenibilidad está orientado generalmente a la selección apropiada de materiales de construcción, el uso eficiente de energía y la correcta gestión de residuos

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en todas las fases del ciclo de vida del edificio, teniendo siempre en cuenta que el edificio tiene que ser accesible desde una parte económica y social. El tipo de vivienda estándar varía sustancialmente dependiendo de la ubicación geográfica donde se construya. Aspectos como el clima, la tecnología, la cultura y las diferencias socio-económicas definen claramente el nivel de un edificio en cualquier contexto y en cualquier región. Esto da lugar a importantes diferencias en los resultados del ACV y significa que cualquier extrapolación de datos europeos existentes del ACV para el caso de un país en desarrollo implicaría errores importantes. Sin embargo, la función es siempre la misma, proporcionar protección y vivienda para sus habitantes.

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PART A: INTRODUCTION

Chapter 1: Introductory notes

- Fundamentals
- Research aims and objectives
  - General objective
  - Specific objectives
- Outline of the thesis

Chapter 2: Principles of sustainability

- Background of sustainability
- Sustainability indicators within the construction industry
- Environmental management concepts

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CHAPTER 1

1. INTRODUCTORY NOTES

This chapter describes the fundamentals of this dissertation research and the research objectives. Furthermore, the relevance of the research is described as well as an overview of how the dissertation is structured.

1.1 FUNDAMENTALS

Economical and socially, in 2001 the construction sector represented 10% of global Gross Domestic Product (GDP) with an annual output of USD 3.000 billion, of which 30% was in Europe, 23% in developing countries, 22% in the United States, 21% in Japan, and 4% in the rest of the developed word [European Commission, 2006]. Furthermore, the European Commission (2006) stated that 11.8 million operatives are directly employed in the sector in Europe and that is Europe's largest industrial employer, accounting for 7% of total employment and 28% of industrial employment in the EU-15. About 910 billion euros were invested in construction in 2003, representing 10% of the GDP [UNEP, Industry and Environment 2003]. Environmentally, taking into account its entire lifespan, the built environment is responsible in each country for 25 to 40% of total energy use, 30 to 40% of solid waste generation and 30 to 40% of Global Greenhouse Gas (GHG) emissions [CICA, 2002].

Some initiatives for tackling adverse environmental impacts have been taken. For instance, the European Commission analysed within its Integrated Product Policy (IPP) in how far housing was relevant with regard to environmental impacts and how these impacts could be reduced systematically. The Environmental Impact of Products (EIPRO) study concluded that housing, food and drink, and private transport sectors were responsible for 70-80% of environmental impacts [Tukker et al., 2006]. This policy looks to identify products within the construction residential sector with the greatest potential environmental impacts by focusing on the whole product life cycle. Additionally, the Environmental improvement potentials of residential buildings (IMPRO-Building) report presented a systematic overview of how to reduce the environmental life cycle impacts of residential buildings in EU-25 [European Commission, 2008].

After nearby two decades of the Agenda 21, more recently the Millennium Development Goals (MDG) have been set and should be met by the year 2015; governments, researchers, engineers, environmental scientists and other stakeholders involved in the industry are then motivated for improving environmental and socio-economic indicators of sustainability.

To accomplish it, diverse technical and conceptual approaches must be applied. In particular, our interest has been on research on analytical tools based on Life Cycle Thinking. Then, this thesis is concerned from a quantitative life cycle perspective to measure sustainability within the residential building sector based on the application of two tools. One tool is the Material and Energy Analysis (MEA) which is suggested as an appropriate tool to provide a systematic picture of the direct and physical flows of the use of natural resources. The second tool is Life Cycle Assessment (LCA) as a complement tool to evaluate environmental impacts throughout the life cycle. Use of materials is characterized by MEA and its environmental performance is determined by LCA. The usefulness of MEA and LCA tools has been applied within the residential building sector in two countries: one in a developed country (Spain) and one in a developing country (not emerging Colombia). To our knowledge, this thesis is one of the first applying the mentioned tools to the sector in Colombia and the first that demonstrates the errors that would come up of just extrapolating European database for buildings (case study in Spain to Latin America, case study in Colombia). This is one of the main contributions of the present thesis.

Finally, considering that there is a need to deploy environmental management concepts from a life cycle perspective in developed and developing countries, this thesis articulates sustainability principles to be used within the residential building sector. Hence, the need to propose methods linking environmental and socio-economical indicators are promising given the complexity and number of sustainability indicators involved. Moreover, it is a problem that needs to be faced in a multidisciplinary way. According to the statement above, the hypothesis underlying this thesis is that "the practical life cycle method proposed ensures sustainability and would determine its prominence and competitiveness within the residential building sector".

1.2 RESEARCH AIMS AND OBJECTIVES

1.2.1 General Objective

The main objective of this thesis is to propose a practical life cycle method including environmental and socio-economical aspects to evaluate indicators that explicitly measure the residential building sector's impacts. The study aims at assessing sustainability assessments in two countries: one in a developed (Spain) and one in a developing country (not emerging Colombia).

1.2.2 Specific Objectives

In this research the following specific objectives are:

1. Promote Life Cycle Thinking (LCT) in a developed (Spain) and a developing country (Colombia), analysing its capability and feasibility to assist the decision making and improve sustainability within the residential building sector.

2. Apply Material and Energy Analysis (MEA) and Life Cycle Assessment (LCA) in order to assess environmental and socio-economic aspects at macro and micro level.

3. Give initiatives when trying to improve sustainability indicators for residential dwellings.

4. Perform a sensitivity analysis in order to see how environmental results can vary using different European database for the life cycle inventory analysis.

1.3 OUTLINE OF THE THESIS

To accomplish the proposed objectives, all information obtained in this research has been compiled in four parts, which are a short introduction, the evaluation of methods from a life cycle perspective, the method application and finally conclusions and discussions corresponding to ten chapters as follows.

Part A starts with the introduction. This part A is divided up in three chapters. Chapter 1: “Introductory notes” presents the reader to the fundamentals and the research aims and objectives described as well as an overview of how the dissertation is structured. Chapter 2: “Principles of sustainability” describes the important issues around sustainable development, details concepts and focuses on the promotion of the principles of sustainable indicators within the construction industry. This chapter also shows the environmental management concepts of commonly used methods to provide a basis for achieving sustainability from a life cycle thinking perspective.

Part B entitled “A practical life cycle method” provides the framework of the method. This part explains the theory of importance for this research. It is the theoretical basis for the method research conducted in this thesis. This chapter starts with Chapter 3: “Towards sustainability assessment within the residential building sector” which describes the practical life cycle method and more briefly states the driving variables (exogenous and endogenous) behind the method. Furthermore, the application of the method in two levels: macro and micro are illustrated as well as an overview of how the sustainability indicators are calculated.

The proposed method is based on the application of two tools. At first, Chapter 4: “Material and Energy Analysis” (MEA) is described, followed by Chapter 5: “Life Cycle Assessment (LCA)”. In both chapters familiarise the reader to the fundamentals, the current state of the art and the different steps applied in both tools. Its application in a macro and micro level is explained in detail.

Chapter 4 outlines the sustainability analysis at a macro level which is determined by exogenous variables that can influence the development of a country. Exogenous variables are classified in the socio-economic sphere (i.e. GDP, population, employment rate, etc.), materials (production, export and import of a product) and energy (i.e. primary energy consumption and final energy consumption). The output in this level is a composite indicator, calculated through a limited number of variables on the social, economic and environmental conditions in the residential building sector.

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Meanwhile for the sustainability analysis at micro level is determined by endogenous variables that can influence a dwelling during their life cycle, starting from the construction, use and finishing with the end-of-life phase. The end product for the sustainability assessment at micro level is a detailed input-output analysis for a specific dwelling showing all materials, energy, emissions and waste that enter and leave the house during their life cycle. Economical assessment has been evaluated according to the common used method of the Payback period (PP). Social aspects are also assessed considering labour in a micro level and other variables such as employment rate and demographic are considered at the macro level.

Chapter 5 provides the sustainability indicators that are derived from the LCA tool and covers the environmental impacts such as global warming potential, acidification potential and others typical life cycle indicators. Eco-efficiency indicators such as resource consumption, renewable energy and non-renewable energy have been also proposed.

Part C familiarizes the research work carried out. This parts starts with Chapter 6 “Presentation of the case studies: Application to two buildings, one in each a developed (Spain) and a developing (Colombia) country”. Here, the fundamentals data needed to apply the practical life cycle method for sustainability assessment is shown.

This part shows the main findings of the thesis. Results are shown in two case studies: one in each, Spain and Colombia. First, Chapter 7: “Detailed results at macro level” gives a general idea of how exogenous variables are correlated in order to see the evolution of the construction building sector in both countries during the last two decades. The assessment covers two main categories: social and economical variables including population, GDP, number of units for residential use (starting - finishing), demographic, number of persons who works within the sector, etc. The energy demand management considerations in both countries are evaluated. Finally, this chapter presents the results of the environmental impacts for the mixed energy sources.

Second, Chapter 8: “Detailed results at micro level” reports the findings of the research based in two buildings, one located in Barcelona, Spain (Case Study I) and one situated in Pamplona Colombia (Case study II). In both case studies the construction, use and end-of-life phases have been evaluated. In each case study some initiatives to minimize CO_2 emissions have been proposed.

Part D closes the thesis with chapter 9 “Sensitivity analysis and comparison of the results at the micro level” and Chapter 10 “General discussion and concluding remarks and perspectives”.

Chapter 9 concerns the question of whether there is an environmental advantage to using one source X instead of Y by modelling the input data and see the variation of the output in small but realistic system. A special focus is given on the operational energy for activities during the operation phase such as Heating, ventilation and air conditioning (HVAC), domestic hot water, electrical

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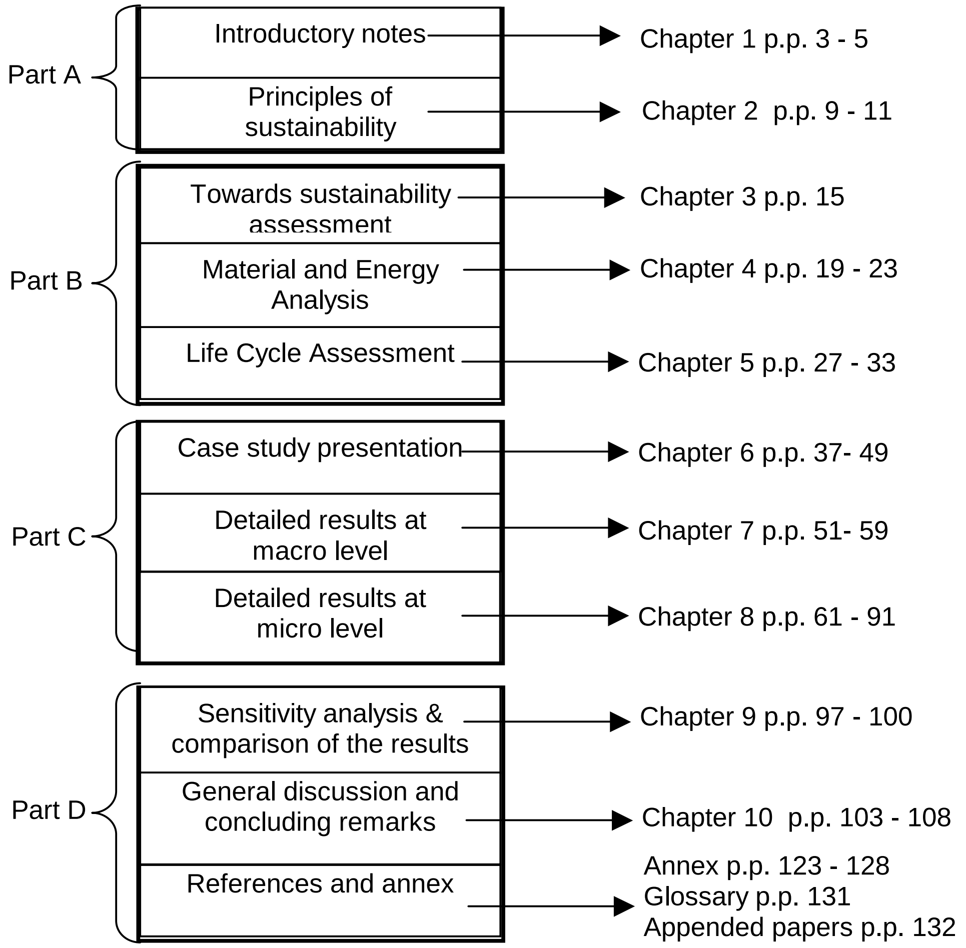
appliances, cooking and illumination. The results are compared in two real scenarios: Situation 1, where 100% of the dwelling's energy is supplied with electricity only and Situation 2, where dwellings can be operated with natural gas plus electricity. After that, the results are modelled with different life cycle inventory databases and LCIA methods.

Finally, Chapter 10 closes the dissertation containing the general conclusions, discussion, challenges perceived and recommendations for future research as well as the references and annex. The dissertation structure is shown in figure 1 below.

Figure 1: Dissertation structure of the thesis.



CHAPTER 2:

2. PRINCIPLES OF SUSTAINABILITY

2.1 BACKGROUND OF SUSTAINABILITY

There have been plenty of definitions of sustainability and sustainable development, but most agree that both terms can be described as enhancing quality of life and thus allowing people to live in a healthy environment and improve social, economic and environmental conditions for present and future generations [Brundtland report, 1987]. Since the World Commission on Environment and Development (WCED), entitled Our Common Future in 1987, sustainable development has gained much attention in all nations and a report was published which called for a strategy that united development and the environment and which also made a declaration describing “Sustainable Development as meeting the needs of the present without compromising the ability of future generations to meet their own needs” [Ibid “Brundtland report, 1987]. The United Nations Commission on Sustainable Development (CSD) was created in 1989 to promote an action plan on the progress of the Agenda 21. The Agenda 21 is a strategic document adopted by the United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro in 1992 of which indicators for monitoring progress towards sustainable development are needed in order to assist decision-makers and policy-makers at all levels and to increase focus on sustainable development [De Plessis, 2004].

Sachs believed that the great challenge of the 21st century would be sustainable development [Sachs and Warner, 1995]. Vollenbroek stated that sustainable development is a balance between the available technologies, strategies of innovation and the policies of governments [Vollenbroek, 2002]. Other definition stated that sustainable development is the challenge of meeting growing human needs for natural resources, industrial products, energy, food, transportation, shelter, and effective waste management while conserving and protecting environmental quality and the natural resource base essential for future life and development. This concept recognizes that meeting long-term human needs will be impossible unless we also conserve the earth’s natural physical, chemical, and biological systems [US Green Building Council, 1996].

Sustainable development encompasses three aspects, commonly called three pillars of sustainability [Sonnemann et al., 2003], [Ellen, 2007]:

- ***Economic***: we need economic growth to assure our material welfare. The economy is essential to long-term community subsistence. In the world of sustainability, many people associate this category with environmental business practices, energy efficiency, and sustainable businesses.

- ***Environmental***: we need to minimize environmental damage, pollution, and exhaustion of resources. Environmental issues are the heart of the sustainability movement and are intricately involved with both the economy and society components of the planner's triangle. A community's relationship with the environment is complex, involving resource extraction and consumption that affects both local and global eco-regions.

- ***Social***: the world's resources should be shared more equitably between the rich and the poor. Social equity in terms of sustainability is often considered as inter-generational in that our actions today will dramatically affect the communities of the future. However, existing social patterns play a significant role in future community sustainability. One notable example is the income, race, and class divide between many inner cities and their suburbs.

2.2 SUSTAINABILITY INDICATORS WITHIN THE CONSTRUCTION INDUSTRY.

The construction industry is a worldwide key sector and a highly active one in both developed and developing countries, which is particularly relevant in these days of economic renewal activities by the governments. This sector is gaining attention through the practice of environmental building performance assessment, of which sustainable development has emerged as one of the key issues due to the significant effects of building on the environment [Ortiz et al, 2009a], in particular due to its energy intensity with corresponding Greenhouse Gas (GHG) emissions and its land use. Therefore, improving social, economic and environmental indicators of sustainable development are then drawing attention to the construction industry [Zimmermann at al, 2005], [UNEP, Industry and Environment, 2006].

During the last decade research studies explicitly dedicated to sustainability indicators have been done, linking sustainability issues and exploring their usefulness as a concept and the different types of indicator that might be used for different things [Bell and Morse, 1999], [Campbell, 1996], [Jepson, 2004].

Within the construction industry there are considerable research done on indicators of sustainability. A relevant research to measure the sustainability indicators of buildings is the work performed in the United States by the Green Building Council (USGBC) Leadership in Energy and Environmental Design [USGBC, 2006], [Mitra, 2003]. In Europe, the Building Research Establishment (BRE) provides a Sustainability Checklist for Developments, whilst Comprehensive Project Appraisal provides an interesting attempt at a generic form of appraisal for sustainability within development or regeneration schemes [Centre for Sustainable Construction, 2000], [Sarah, 2003]. In Latin American the framework of the Energy and Sustainable Development Project being conducted jointly by the Latin American Energy Organization (OLADE), the Economic Commission for Latin America and the Caribbean (ECLAC), and the German Technical Cooperation Agency (GTZ), a series of case studies focusing on a wide range of countries in the region were conducted essentially to examine how energy policies contribute to enhancing sustainable development [ECLAC, 2006].

The development of indicators for the (comprehensive) wealth of a nation (or a region) is a useful way towards securing sustainable development at the national or regional scale [Knut and Mads, 2006]. An indicator in essence is simply a sign or signals that relay a complex message, from potentially numerous sources, in a simple and useful manner [Kurtz et al, 2001]. An indicator should both help communities identify how current practices are performing through policy relevant and scientifically valid measurements [Levett, 1998].

Furthermore, an indicator can perform many functions. This can lead to better decisions and more effective actions by simplifying, clarifying and making aggregated information available to policy makers. They can help incorporate physical and social science knowledge into decision-making, and they can help measure and calibrate progress toward sustainable development goals. They can provide an early warning to prevent economic, social and environmental setbacks. They are also useful tools to communicate ideas, thoughts and values [United Nations, 2007].

Hence, data availability plays an important role to measure sustainability performances of a country/region, as it enables to describe a nation/region through quantitative tools [Caratti et al, 2007]. Data availability should not be a constraint in selecting relevant indicators. If it is, then the result could be maintenance of the status quo with people using what is available rather than taking a more imaginative stance [Ibid "USGBC]. Resource and researcher time availability dictate the number of indicators which may be included in a study: if too few are employed, important information is excluded, but if too many are included, adequate time is often not available for data collection and analyses [Moles at al, 2007] and communities should ask, "What sort of things do we need to measure to form a sensible picture of sustainable development?" [Ibid "Levett, 1998].

2.3 ENVIRONMENTAL MANAGEMENT CONCEPTS

In order to overcome the increasing concern of today's resource depletion, environmental considerations and to address socio-economic sustainability indicators, environmental management tools are sought for decision making and to integrate environmental and socio-economical assessment within the residential building sector.

Therefore, there have been increasing interests in environmental research during the last decades. Some concepts for assessment of environmental performance have been developed to reduce the environmental effects of a variety of products and services [Sonnemann, 2002]. For example, includes concepts such as cleaner production, industrial ecology, and life cycle thinking.

Cleaner production is the continuos use of an integrated and preventive environmental strategy. It is applied to processes, products and services to increase the eco-efficiency and reduce risks to the population and the environment [Ibid "Sonnemann, 2002].

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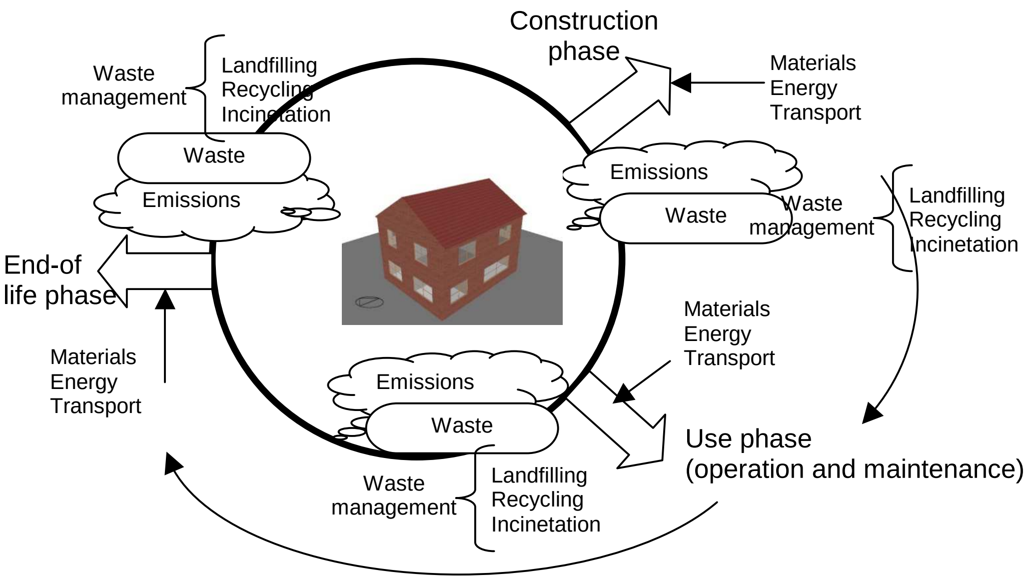
Industrial ecology means an approximation of the industrial systems to natural systems. It is about analysing systematically the material and energy flows of the industrial systems with the objective to minimize the generation of waste and environmental impacts [Ibid “Sonnemann, 2002].

Finally, Life Cycle Thinking implies that everyone in the whole chain of a product's life cycle, from cradle to grave, has a responsibility and a role to play, taking into account all the relevant external effects, see figure 2 below. The impacts of all life cycle stages need to be considered comprehensively when taking informed decisions on production and consumption patterns, policies and management strategies [Toepfer, 2001]. Life Cycle Thinking (LCT) is a way of addressing environmental issues and opportunities from a system or holistic perspective. In this way of thinking, a product or service system is evaluated with the goal of reducing potential environmental impacts over its entire life cycle [Udo de Haes, 2002].

Figure 2. Life cycle of a product system



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PART B: A PRACTICAL LIFE CYCLE METHOD

Chapter 3: Towards sustainability assessment within the residential building sector

- Practical life cycle method

Chapter 4: Material and Energy Analysis

- Fundamentals
- Defining the system boundary
    - Macro or national level
    - Micro or local level

Chapter 5: Life Cycle Assessment (LCA)

- Fundamentals
- LCA state of the art within the construction industry
    - Comparison WPC versus BMCC
- LCA methodology
    - Goal and scope definition
    - Life cycle inventory
    - Life cycle impact assessment
    - Interpretation
- LCA software and database
- Sensitivity analysis

Article:

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UNIVERSITAT ROVIRA I VIRGILI
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APPLIED IN A DEVELOPED AND A DEVELOPING COUNTRY.
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CHAPTER 3:

3. TOWARDS SUSTAINABILITY ASSESSMENT WITHIN THE RESIDENTIAL BUILDING SECTOR

In this chapter, the research method will be described and more briefly states the driving variables (exogenous and endogenous) behind the method. Furthermore, the levels of the method are explained as well as an overview of how the socio-economic and environmental aspects are evaluated.

3.1 PRACTICAL LIFE CYCLE METHOD

The practical life cycle method for this dissertation is illustrated in Figure 3. It can be seen that the method is based on the application of two tools: life cycle assessment and material and energy analysis evaluating the macro and micro level. Then, the idea of the proposed method is to provide consistent sustainability information that facility an adequate decision making towards sustainable development.

Sustainability assessment at macro level is determined by exogenous variables that can influence the development of a country. Exogenous variables are classified in socio-economic sphere (i.e. GDP, natural growth, employment rate, etc.), and environmental sphere. The outcome of this level is a composite indicator calculated through a limited number of factors considering the social, economic and environmental conditions in the residential building sector.

Sustainability assessment at the micro level is made within the limits of the whole building life cycle, starting from the construction, use (operation and maintenance) and finishing with the end-of-life phase. The final sustainability analysis is done of the inputs (materials, energy and labour), and outputs (emissions and wastes) of the dwelling.

For the macro and micro levels were viewed from an analytical life cycle perspective. In both levels the environmental, social and economical aspects have taken into account. Environmental assessment (EA) is a systematic process that examines the environmental consequences that may result from a proposed or impending intervention. As identified by Environmental Protection Agency (EPA) the overall purpose for undertaking an EA is to seek ways to avoid or minimize adverse effects of a proposed project to the extent practicable, and the maintenance, restoration or enhancement of environmental quality as much as possible [Chowdhury and Amin, 2006].

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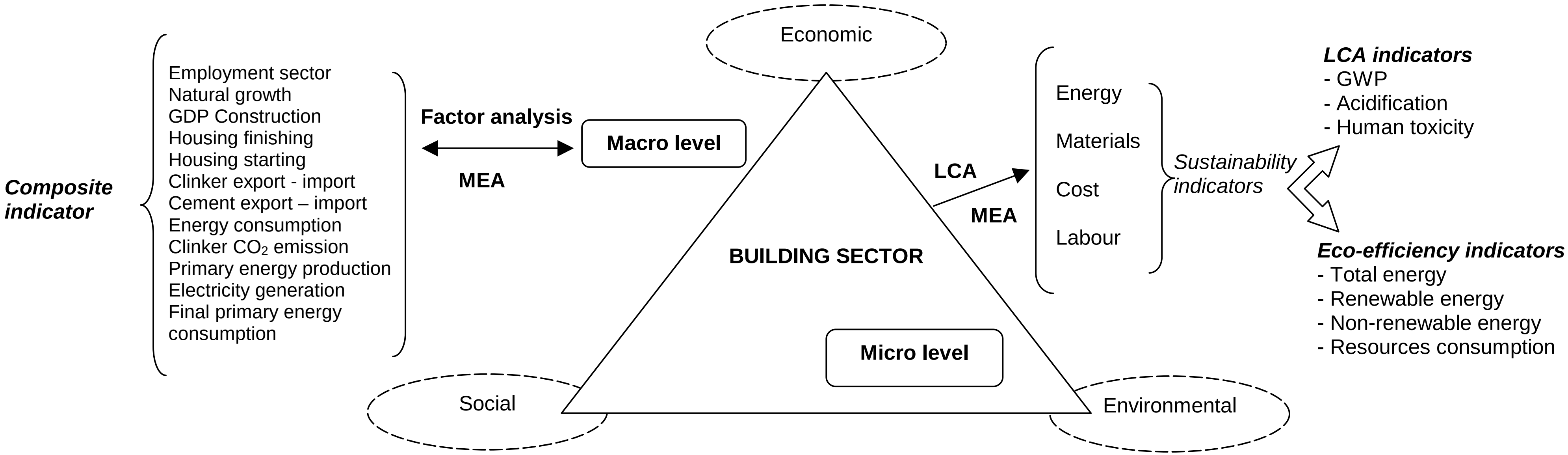
Figure 3: Links between social, economic and environmental aspects with the building sector



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Second, social assessment includes variables such as population, economic, social and health characteristics [Rietbergen and Narayan, 1998]. Here, social assessment in the macro level is based on the variable of employment rate and related with the micro level labour is the variable to evaluate.

Third, the economic assessment at macro level considers exogenous variables that are classified in socio-economic sphere, materials and energy.

For micro level, an indicator derived from the economical assessment is used according to the common applied used method of the payback period (PP). The purpose of calculating PP is to determine the period of time required to recover the capital invested (I_0) in a project by annual returns (R_i). The PP is an indicator that shows the level of profitability of an investment (I_i) in relation to time (T) [Shim et al, 1999]. PP of a project of T periods can be calculated as follow Eq. (1):

$$PP = \frac{I_0}{\left(\sum_{i=1}^{T}(R_i - I_i)\right)/T} \qquad (1)$$

Finally, this method articulates sustainability principles to be used within the residential building sector from a quantitative life cycle perspective based on the application of the tools mentioned before. One tool is the Material and Energy Analysis (MEA) which is suggested as an appropriate tool to provide a systematic picture of the direct and physical flows of the use of natural resources. The second tool is Life Cycle Assessment (LCA) as a complement tool to evaluate environmental impacts throughout the life cycle of the system.

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CHAPTER 4:

4. MATERIAL AND ENERGY ANALYSIS

4.1 FUNDAMENTALS

Material and Energy Analysis (MEA) has been emerged as a significant approach for tracking the flows of materials and energy and for comparing the industrial system in a study of industrial metabolism [Yildiz and Güngör, 2009], [Chung W.S. et al, 2009], [Thormak, 2006], [Ayres and Simonis, 1994], [Erkman, 1997]. A number of MEAs have been focused mainly in two dimensions: territorial dimension and product-chain or life cycle product dimension. Some studies explicitly dedicated to the territorial level have been applied to national or regional level, for instance in developed countries [Ayres and Ayres, 1999], [IHOBE, 2002], [Adriaanse et al, 1997], [Bringezu and Schütz, 2001a], [Matthews et al, 2000], [Bringezu and Schütz, 2001b], [Cañellas et al, 2005]; in emerging economies [Hammer and Hubacek, 2003], [Xu and Zhang, 2007], [Mündl et al, 1999], [Scasny et al, 2003], [Newcombe et al, 1978]; and in developing countries [Amann et al, 2002], [Giljum, 2004]. There has been a fair amount of descriptive work on construction materials, but limited research has been published thus far a complete product-chain, although the first attempts started appearing during the last decade [Low M-S, 2005], [Hashimoto et al, 2007], [McEvoy et al, 2006], [Mutha et al, 2006]. Previous studies show that there is an urgent need for global physical accounts as they “provide an integrated framework for analysing flows of materials from the natural environment into the human economic system” [Ibid “Matthews et al]. Eventually, it is thought that standardized input/output balances sheets will be considered as important as typical economic indicators to describe the state of an economy [Quinn, 2008].

Material and energy flow analysis provides a comprehensive description of material flows between the environment and economy as well as within the economy (production and consumption), distinguishing not only categories of materials but also branches of production [Suh, 2005]. Material flow analysis is a well recognized tool to characterize the industrial metabolism [Ayres and Ayres, 2002] of material flows through the economic system, and a useful precursor to understanding the complex interaction between economic activity and the environment [Fischer-Kowalski, 1998], [Boustead and Hancock, 1979]. Energy analysis has long been used to account for the energy resource implications of technological processes and consumption patterns [Fischer-Kowalski and Hüttler, 1999]. Then, the analysis of material and energy flows is widely recognized as one important and necessary step for reducing the impact of human activities on the environment [Binder, 2007].

Material and Energy Analysis (MEA) is applied to calculate the physical inputs into an economy, material accumulation in the economy and outputs to other economies or back to nature [EUROSTAT, 2002]. Analysis of material and energy use can provide an overview of the measure of renewable resources (e.g. timber), non-renewable resources (e.g. minerals, metals, and plastics), fossil fuels (e.g. oil, coal, and gas) and renewable energies (e.g. wind power, solar etc) that any country supply, demand and the inhabitants consume.

The fundamental basis of Material and Energy Flow Analysis lays on the first law of thermodynamics (the law of the conservation of mass) which states that energy cannot be created or destroyed, but only changed in form [Kleijn, 2002]. MEA uses input/output analysis where, the principle concept is a simple model of the interrelation between the economy and the environment, in which the economy is an embedded subsystem of the environment and – similar to living beings – dependent on a constant throughput of materials and energy [Ibid "Kleijn, 2002]. The nomenclature from MEA lays on the following terms [Brunner and Rechberger, 2004]:

- Processes are linked by flows,
- Flows across boundaries are called input – output,
- A system boundary is defined within the space and time,
- A process is defined as transport or transformation of materials,
- A system comprises of a set of material flows, and processes within a defined system boundary.

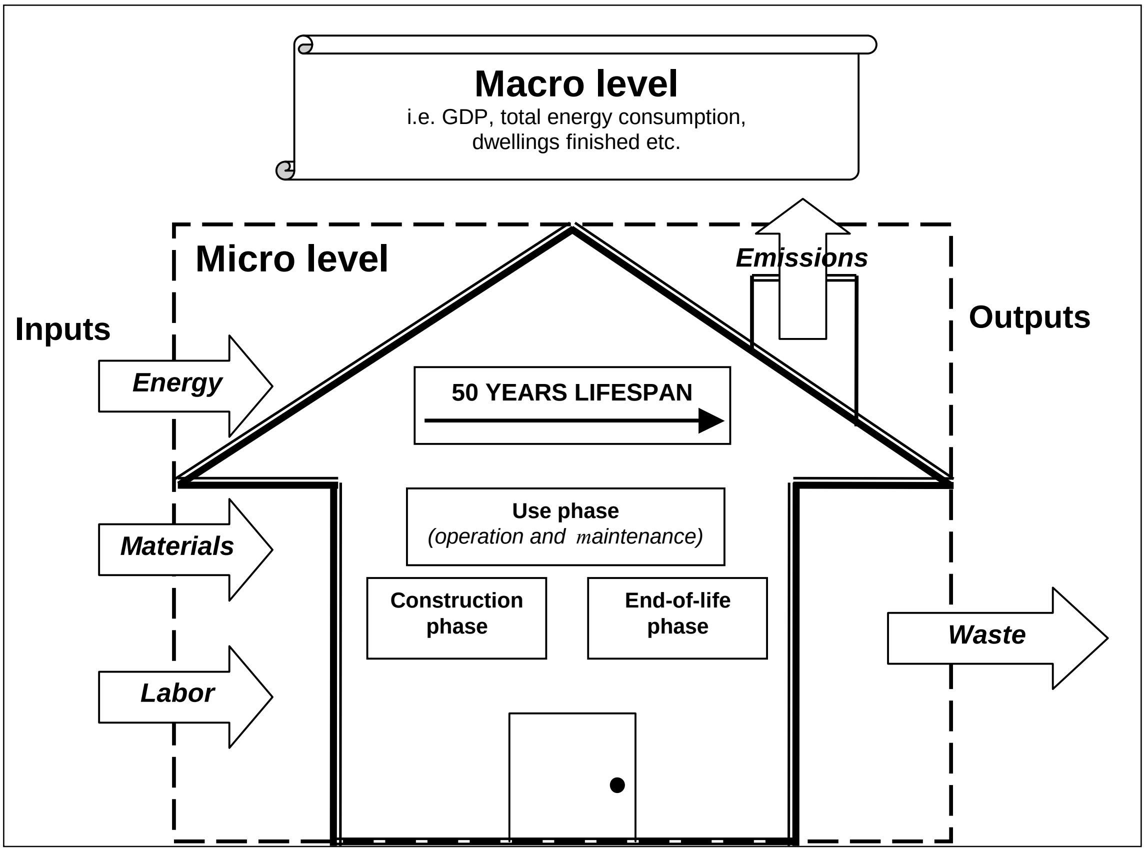
4.2 DEFINING THE SYSTEM BOUNDARY

The system boundary presents the scheme of the life cycle of a system, detailing the dimensions considered under study. These dimensions indicate whether flows are directly observed or calculations of up-stream material requirements [Hinterberger et al, 2003]. The inputs and outputs to be taken into account must be established. According to Lindfors et al, 1995, these can be the overall input to production as well as input to a single process; the same is true for output. Even for a quite subjective operation, the definition of system boundaries can be carried out according to the following criteria: life-cycle boundaries, geographical boundaries, and environmental load boundaries [Sonnemann, 2003].

In this thesis, inputs and outputs are considered in two main boundaries: macro or national level and micro or local level. Calculating what the effects of macro and micro levels are within the residential building sector gives a general overview that enable to measure improvements of sustainability indicators and provide improvement of how sustainability indicators can be used in order to obtain practical guidelines for improvements from a life cycle perspective. Therefore, sustainability improvement is oriented to enhancing environmental and socio-economical conditions having always in mind, that buildings have to be accessible from an economical and social point of view. Although, climate, geographic, technological, cultural, economic and social differences clearly define the standard of a building in any context and in any region or area; the function is always the same, to provide protection and housing for its habitants.

Figure 4 shows a systematic picture of the macro and micro levels in order to provide a basis for achieving more sustainable solutions by assessing sustainability indicators that explicitly measures the impacts of the residential building sector.

Figure 4: Scheme of macro and micro levels applied within the residential building sector.



4.2.1 Macro or national level

The idea in the macro level is to give an overview of how exogenous variables are correlated and see the evolution of the construction building sector in a specific country and compare it with others. The sustainability analysis at macro level is determined by exogenous variables that can influence the development of a country (in our particular case: Spain and Colombia). Examples of exogenous variables are: economic growth measured in GDP, population, employment rate, total energy consumption and number of houses built etc.

Inputs are classified into three groups: socio-economic sphere, materials and energy. The energy analysis includes the amount of fossil and non-fossil fuels required to provide the energy used and the

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goods and services consumed by the inhabitants of a country. This includes the primary energy, internal energy transformations and energy use. The output is a composite indicator.

4.2.1.1 Composite indicator

The number of composite indicators in existence around the world is growing year after year to provide simple comparisons of countries that can be used to illustrate complex and sometimes elusive issues in wide ranging fields, e.g., environment, economy, society or technological development [Bandura, 2006]. The composite indicator has been calculated using the Handbook on constructing composite indicators: methodology and user guide using the following steps [OECD, 2008]:

1. Theoretical framework which provides the basis for the selection and combination of variables into a meaningful composite indicator.

2. Data selection which is based on the analytical soundness, measurability, country coverage and relevance of the indicators to the phenomenon being measured and relationship to each other.

3. Multivariable analysis is used to study the overall structure of the dataset, assess its suitability, and guide subsequent methodological choices. Factor analysis (FA) is used as a multivariable analysis technique in order to reduce and reveal how different variables change in relation to each other and how they are associated. The main objective of FA is the orderly simplification of a large number of intercorrelated measures to a few representative constructs or factors and there are three basic factor analysis steps [Ho, 2006]:
    a. Computation of the correlation matrix
    b. Extraction of initial factors
    c. Rotation of the extracted factors to a terminal solution

Computation of the correlation matrix

As factor analysis is based on correlations between measured variables, a correlation matrix containing the intercorrelation coefficients for the variables must be computed [Ibid "Ho, 2006].

Extraction of initial factors

At this phase, the number of common factors needed to adequately describe the data is determined. To do this, the researcher must decide on (1) the method of extraction, and (2) the number of factors selected to represent the underlying structure of the data. If the purpose is no more than to "reduce data" to obtain the minimum number of factors needed to represent the original set of data, then Principal Component Analysis is appropriate. For determining the number of initial unrotated factors to be extracted. These are the Eigenvalues criterion. Only factors with eigenvalues of 1 or greater are considered to be significant; all factors with eigenvalues less than 1 are disregarded. An eigenvalue is a ratio between the common (shared) variance and the specific (unique) variance explained by a specific factor extracted. The rationale for using the eigenvalue criterion is that the amount of common variance explained by an extracted factor should be at least equal to the variance explained by a single variable (unique variance) if that factor is to be retained for interpretation. An eigenvalue greater than 1 indicates that more common variance than unique variance is explained by that factor. [Ibid "Ho, 2006].

Rotation of the extracted factors to a terminal solution

Orthogonal rotation has been used because the goal of the composite indicator is no more than to "reduce the data" to more manageable proportions, regardless of how meaningful the resulting factors may be, and if there is reason to assume that the factors are uncorrelated [Ibid "Ho, 2006].

4. Visualization is the last step to calculate the composite indicator, therefore the results should receive proper attention, given that the visualization can influence (or help to enhance) interpretability.

4.2.2 Micro or local level

Figure 5 depicts the system boundaries considered in this study. This figure presents the scheme of the life cycle of a building. The analysis is divided into the following life cycle phases:

C1. Construction evaluates the fabrication of building materials and the energy used by the building machinery. This phase also includes the (T1), which is the transport of the raw materials from the factory to the building site and also the internal waste management with the transport of the wastes generated at the building site to their final destination (T2).

U1. Use includes the operation and maintenance activities.

O1. Operation covers the full service life for HVAC: Heating, Ventilation and Air Conditioning, and other activities such as illumination, domestic hot water (DHW), electrical appliances and cooking.

M1. Maintenance and refurbishment has been calculated including activities such as repainting, PVC siding, kitchen and bathroom cabinet replacement, re-roofing and changing windows. This phase includes also the transport (T1 and T2).

E1. End-of-life evaluates the energy consumed by the machinery used during the demolition; and also considers the amount of wastes generated during the dismantling of the original construction materials, including their transport (T2) to the final treatment waste.

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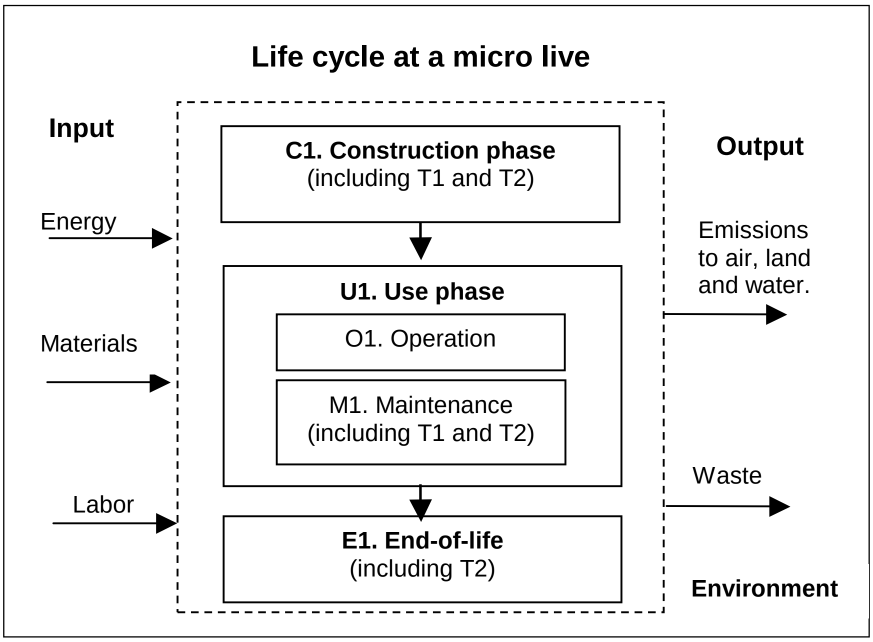
Figure 5: Building system life cycle and phases considered within this study



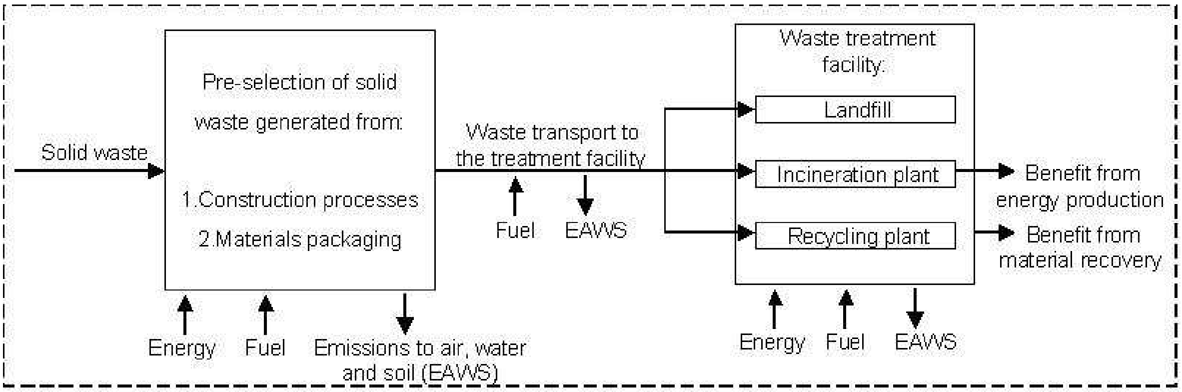
Finally, through the full building life cycle of a dwelling, there are wastes generated from the building materials, therefore in order to assess the waste management in each building phase; figure 6 presents the scheme for assessing the final disposition of this waste. Then, three scenarios: landfilling, recycling and incineration, representing the possible options of waste management have been considered.

L1. Landfilling includes the dump infrastructure, the use of land and the effect of the landfilled waste (leachate). Construction wastes that are to be landfilled are special wastes disposed of in underground deposits or controlled landfills, inert wastes are disposed of in inert material landfills and non-special wastes are disposed of in landfills or sanitary landfills.

R1. Recycling takes into account the plant infrastructure, recycling process, products obtained and wastes generated. This scenario considers the sorting and recycling processes and their transport and, the material saved as a result of recycling. In this scenario all recyclable wastes are sent to a recycling plant, non-recyclable wastes are sent to an incineration plant and non-recyclable or non-incinerable wastes are sent to landfill. This scenario gives positive and negative values. Positive values mean emissions to the environment whereas negative values represent a benefit corresponding to the fact that these recovered materials would actually displace virgin materials.

I1. Incineration covers the plant infrastructure, the incineration process, the electricity generated and the disposal of ashes. Electrical energy recovery (calculated from calorific value data) and the amount of residual ashes (which are disposed by landfill) are also considered. Besides, this scenario includes the additional process of transporting the slag and residues of the incineration process to landfill. Incineration generates significant power and thermal energy because of the high calorific value of the construction materials wastes, thus placing the incineration process in credit in terms of its environmental impact. Here negative values represent a credit obtained from the power and thermal energy recovery generated by burning the highly calorific construction material wastes. In this scenario, incinerable wastes are disposed of at an incineration plant and non-incinerable wastes are disposed of in landfill.

Figure 6: System boundaries for the wastes from construction.



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SUSTAINABILITY ASSESSMENT WITHIN THE RESIDENTIAL BUILDING SECTOR: A PRACTICAL LIFE CYCLE METHOD APPLIED IN A DEVELOPED AND A DEVELOPING COUNTRY.
Oscar Orlando Ortiz Rodríguez
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CHAPTER 5:

5. LIFE CYCLE ASSESSMENT (LCA)

5.1 FUNDAMENTALS

During the last decades, there have been plenty methodologies to promote sustainable building [Boonstra and Pettersen, 2003; Cole, 2005; CRISP, 2004; Ding, 2008; Haapio, 2008; Peuportier and Putzeys, 2005]. Currently, Life Cycle Assessment (LCA) is a well known environmental methodology to evaluate environmental impacts throughout a system. Life Cycle Assessment (LCA) is a methodology for evaluating the environmental load of processes and products (goods and services) during their life cycle from cradle to grave [Fava, 2004], [Hauschild, 2005]. LCA was standardised by the International Standardisation Organisation (ISO) in the 14040 series ISO 14040:2006 and ISO 14044:2006 [ISO, 2006].

LCA has been used in the building sector since 1990 and is an important tool for assessing buildings to improve environmental sustainability throughout all stages of the building's life cycle, from its origins (extraction of raw materials) to its end of life (waste disposal) [Fava, 2006]. Sartori and Hestnes, 2007 stated that increased interest and better methodologies such as LCA provide a better understanding and better estimates of the energy (and other environmental) aspects in the life cycle of all kinds of product [Sartori and Hestnes, 2007].

Most recently, CALCAS is the EU 6th Framework **C**o-ordination **A**ction for innovation in **L**ife-**C**ycle **A**nalysis for **S**ustainability aimed at identifying research lines on how to increase the efficacy of sustainability decision making, going beyond the shortcomings and limitations of current Life Cycle Assessment (LCA). Its general objective is to further develop the ISO-LCA into a broader scientific framework, named Life Cycle Sustainability Analysis (LCSA) with the following features [CALCA, 2009]:

- Improved reliability and usability of ISO-LCA;
- "Deepening" of the present model (i.e. adding more mechanisms and/or more sophistications) to improve its applicability in different contexts while increasing its reliability and usability;
- "Broadening" the LCA scope by better incorporating sustainability aspects and linking to neighbouring models, to improve their significance;
- "Leaping forward" by a revision/enrichment of foundations, through the crossing with other disciplines for sustainability evaluation.

5.2 LCA STATE OF THE ART WITHIN THE CONSTRUCTION INDUSTRY

For a more comprehensive history of LCA see [Hunt et al., 1992; Hunt and Franklin, 1996]. However, a review of the existing literature shows various studies on complete LCAs [Ibid "Ortiz et al, 2009a]. It deals with topics such as the differences between LCAs of building materials and components (BMCC) for instance a construction material i.e. cement, steel etc versus LCAs of the whole process of constructions (WPC) for example a dwelling. Hence, thirty–three case studies have been analyzed, 58% of those applying LCA to BMCC and 42% applying LCA to WPC. These case studies have been taken from the last 9 years from 2000 to 2009. The following table 1 summarizes the characteristics of some published LCA case studies for both BMCC and WPC with their respective environmental loads considered LCA methodology in the determination of the functional unit (FU).

Table 1: Characteristics of published LCA applied within the building sector for both BMCC and WPC.

Reference	BMCC	WPC	Content, country and year.	Environmental Loads Analysed								
				GWP	AP	OD	HT	EL	WC	DA	W	RS
Adalberth K. et al, 2001		X	Life cycle of four dwellings located in Sweden (2001).	X	X	X	X	X				
Alanne and Sari, 2008	X		Estimating the environmental burdens of residential energy supply systems through material input and emissions factors	X	X			X				X
Ardente F. et al, 2005	X		LCA of a solar thermal collector, Italy (2005).						X		X	X
Ardente F et al, 2008	X		Building performance: A LCA case study of kenaf-fibres insulation board	X	X	X				X		X
Arena and Rosa, 2003		X	LCA of energy of the implementation of conservation technologies in school buildings in Mendoza, Argentina (2003).	X	X			X				X
Asif M. et al, 2005	X		LCA for eight different building materials for a dwelling located in Scotland (2005).	X								
Blengini G.A, 2009		X	Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy	X	X	X						
Chen T.Y. et al, 2001		X	Analysis of embodied energy use in the residential building of Hong Kong					X				
Citherlet S. et al, 2000	X		LCA of a window and advanced glazing systems in Europe (2000).	X	X	X						X
Dimoudi and Tompa, 2008		X	Energy and environmental indicators related to construction of office buildings	X	X			X				
Gustavsson and Sathre, 2006	X		LCA Sweden case study: wood and concrete in building materials (2006).									X
Huberman and Pearlmutter, 2008	X		A life cycle energy analysis of building materials in the Negev desert					X				X
Jian G. et al, 2003		X	LCA of urban project located in Hyogo, Japan (2003).	X				X	X		X	
Junnila S, 2004		X	LCA for a construction of an office: a Finland case study (2004).	X	X			X				X

Reference	BMCC	WPC	Content, country and year.	Environmental Loads Analysed								
				GWP	AP	OD	HT	EL	WC	DA	W	RS
Koroneos and Dompros, 2006	X		LCA of brick production in Greek (2006).	X	X						X	X
Mroueh UM et al, 2001]		X	A Finnish LCA case study of road construction (2001).									X
Nebel B et al, 2006	X		LCA for floor covering, Germany (2006).	X	X	X						X
Nicoletti GM et al, 2002	X		LCA of flooring materials (ceramic vs. marble tiles), Italy (2002).	X	X	X	X			X		X
Nyman and Simonson, 2005	X		LCA of residential ventilation units over a 50 year life cycle in Finland (2005).	X	X	X				X		X
Ortiz et al, 2009b		X	Sustainability based on Life Cycle Management of residential dwellings: A case study in Catalonia, Spain (2008).	X	X	X	X					X
Peuportier, 2001		X	Comparison of three types of houses with different specifications located in France (2001).	X	X	X	X	X	X	X	X	X
Petersen and Solberg, 2005	X		LCA by comparing wood and alternative materials in Norway and Sweden (2005).		X	X	X					
Prek, 2004	X		LCA of heating and air conditioning systems. A Case study for a single family dwelling in a residential building in Slovenia (2004).	X		X						
Ross and Evans, 2003	X		An Australian LCA case study for a plastic-based packaging based on two strategies: re-use vs. recycle (2003).								X	X
Saiz S et al, 2006	X		LCA for green roofs located in downtown Madrid, Spain (2006).	X	X	X	X		X		X	X
Scheuer C. et al, 2003		X	LCA to a new University building campus with a total area of 7300 m^2 in USA (2003).	X	X	X		X			X	X
Schleisner L, 2000		X	LCA Case Study to produce different energy production technologies in Denmark (2000).					X				X
Seo and Hwang, 2001		X	Estimation of CO2 emissions in Life Cycle of residential buildings	X				X				
Sépala J. et al, 2002	X		LCA for Finnish metal products (2002).		X		X	X	X		X	X
Van der Lugt . et al, 2006	X		LCA for using bamboo as building material vs. steel, concrete and timber in Western Europe (2006).									X
Xu X. et al, 2008	X		Life cycle assessment of wood fibre reinforced polypropylene composites	X	X							X
Wu X et al, 2005	X		LCA: a Chinese case study for different building materials (2005).	X	X	X		X	X			X

<u>Abbreviations:</u>
GWP: global warming potential AP: acidification potential
HT: human toxicity EL: energy consumption OD: photochemical ozone creation
WC: water consumption W: waste creation RS: resources consumption
DA: depletion abiotic resource
BMCC: building and materials components combinations WPC: whole process construction

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5.2.1 Comparison whole process construction (WPC) versus building material and component combinations (BMCC)

First, when applied to the whole process construction, LCA is divided up in three common scenarios: dwellings, commercial buildings and civil engineering constructions. From the reviewed scientific literature it was found that LCA of the full building life cycle as a process is not static; it varies from building to building since each has its own function and different characteristics of engineering [Lutzkendorf and Lorenz, 2006], [Pushkar et al, 2005]. For example, construction techniques, architectural style and different conditions such as household size, climate and cultural consumption behavior vary from country to country. Furthermore, a variation in each design can affect the environment during all life cycle stages of a building.

LCA for BMCC studies presented are not fully comparable; there are differences in the final product and also most studies neglect cost except those works which show the application of shadow prices [Seppala et al, 2002], [van der Lugt, 2006]. However, the most recent methodologies which incorporate information regarding environmental impacts and embodied energy in building materials are necessary for more sustainable materials. To achieve this, the European Commission in 2003 officially released the Integrated Policy Product (IPP) voluntary approach [European Commission, 2003]. This policy looks to identify products within the construction sector with the greatest potential environmental impact by focusing on the whole product life cycle and consists basically of three stages: EIPRO (environmental impact products), IMPRO (environmental improvement products) and Policy Implications. A strategy used in the implementation of the IPP is the Environmental Product Declarations (EPD). EPD is a strategy adopted for external communication and is committed to reducing the environmental impact of a product [EPD, 2006]. EPDs such as those made on concrete, wood and metals such as aluminium are based on LCA and contain information associated with the acquisition of raw materials, energy use, content of materials and chemical substances, emissions into the air, land and water and waste generation [Askham, 2006], [Skaar and Magerholm, 2006], [Leroy and Gilmont, 2006].

Second, the notation that has been chosen for these LCAs studies was based on the functional unit. The functional unit for the building material and component combinations was focused on a final product e.g. kg of product, while for whole building the functional unit (FU) was analysed, taking into account a dwelling, building or m^2 usable floor area.

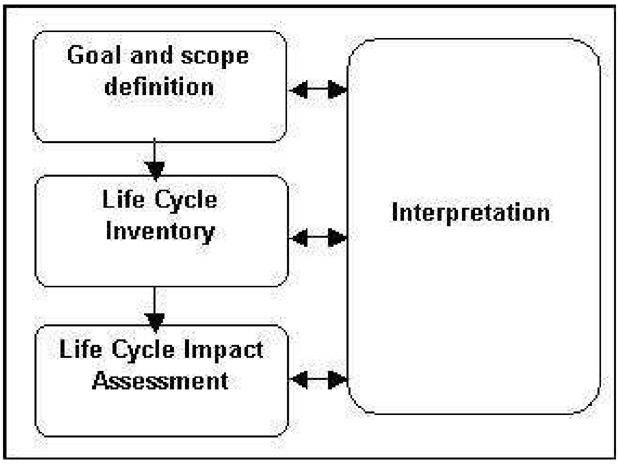
Third, LCA for both scenarios is very industry specific. For instance, construction and building projects have complex processes and many assumptions have to be made, while in building materials and products, processes are based on a single product. Paulsen and Borg, 2003 stated that characteristic of buildings and building products is their significantly longer life compared to most other building materials and industrial products, and the involvement of many different factors during their life cycle. Furthermore, Gregory and Yost, 2002 concluded that the direct application of LCA in the construction sector is not a simple or straightforward process. It is expensive and cannot be applied without assumptions or additional modifications.

Fourth, most LCA of WPC data have been taken from architects, engineers, drawings, engineering specifications, suppliers and interviews, while the LCA for BMCC are based in industrial processes.

5.3 LCA METHODOLOGY

Klöpffer stated that LCA has become a widely used methodology because of its integrated way of treating topics like framework, impact assessment and data quality [Klopffer, 2006]. The description of the LCA methodology is based on the International standards of series ISO 14040 and ISO 14044 and consists of four distinct analytical steps: defining the goal and scope, creating the inventory, assessing the impact and finally interpreting the results [Ibid "ISO 2006], see figure 7.

Figure 7: Framework of the LCA methodology according to ISO 14040 (2006)



5.3.1 Goal and scope definition

Firstly, the goal and scope definition is designed to obtain the required specifications for the LCA study. The scope describes the system and marks which information is necessary, in what categories, and the level of detail and quality [Curran, 1996]. Defining goal and scope covers the functional unit. The functional unit is used as a basis for calculation and usually also as a basis for comparison between different systems fulfilling the same function [Guinée et al, 2002]. It means that all data collected are quantitatively related to one quantitative output of the product. In this research, the functional unit is defined as: one square meter of living area of a dwelling with a projected 50 years lifespan.

5.3.2 Life Cycle Inventory (LCI)

Secondly, LCI involves collecting data for each unit process regarding all relevant inputs and outputs of material flow and energy, as well as data on emissions to air, water and land. Source of information and data collection will be further given in detail in the following chapter 6.

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5.3.3 Life Cycle Impact Assessment (LCIA)

The third step in a LCA methodology is the Life Cycle Impact Assessment (LCIA). LCIA phase evaluates potential environmental impacts and estimates the resources used in the modelled system. LCIA aims to improve the understanding of the inventory result. It is determined which extractions and emissions contribute to which impact categories. An impact category can be defined as “a class representing environmental issues of concern to which life cycle inventory analysis results may be assigned” [Ibid “ISO, 2006]. Consequently, in this step the LCA developer has to select and define impact categories, classify, characterize and includes weighting in the optional elements [Ibid “Hauschild, 2005].

In a Life Cycle Impact Assessment (LCIA), there are essentially two methods: problem-oriented methods (mid-points) and damage-oriented methods (end points) [Procter and Gamble, 2005]. The mid-points approach involves the environmental impacts associated with Global Warming Potential, acidification potential, eutrophication, potential photochemical ozone creation and human toxicity and the impacts can be evaluated using the CML 2 method (2001), EDIP 97& EDIP 2003, TRACI and IMPACT 2002+. The end points approach classifies flows into various environmental themes, modeling the damage each theme causes to human beings, natural environment and resources. Ecoindicator 99 and IMPACT 2002+ are methods used in the damage-oriented method.

In this thesis, the impact assessment is based upon the CML 2 method (2001) developed by Leiden University’s Centre for Environmental Science [CML, 2001]. This method is a midpoint approach, which covers all emissions, and resource related impacts (e.g. carbon dioxide, methane, N_2O and other greenhouse gas emissions were aggregated into CO_2 equivalent emissions in accordance with the respective global warming potentials). We have chosen Global Warming Potential (GWP) (kgCO_2-Eq) as the main environmental impact because of its effect on the whole planet and because it is the greatest environmental challenge facing the built environment [United Nations, Department of Economic and Social Affairs, 2005], [Houghton et al, 2001]. Nevertheless, we categorized also the acidification potential in (kgSO_2-eq) and others typical life cycle indicators, see table 2. Annex 1 shows the definitions of the impacts used by CML 2 method.

Table 2: Environmental impacts derived from LCA.

Indicator	Unit	Description
Acidification (AP)	kg SO_2 Eq	See Annex 1
Global warming potential (GWP)	kg CO_2 Eq	
Human Toxicity (HT)	Kg 1.4-DCB Eq	
Stratospheric ozone depletion (SOD)	kg CFC-11-Eq	

Furthermore, Eco-efficiency indicators such as total energy, resource consumption, renewable energy and non-renewable energy have been assessed. These indicators have been considered for general and also for specific audiences working in the building sector, reflecting the results in a clear and easy way for non-environmental expert users, see table 3.

Table 3: Description and categorization of the eco-indicators studied.

Indicator	Unit	Description
Total energy (TE)	MJ	Energy consumption throughout the whole life cycle. Sum of the renewable and non-renewable energy MJ
Renewable energy (RE)	MJ	MJ from solar, wind, hydraulic and biomass energy, consumed throughout the whole life cycle
Non renewable energy (NRE)	MJ	MJ from geothermic, nuclear, petroleum, coal and natural gas energy, consumed throughout the whole life cycle
Resources consumption (RC)	kg	Use of resources, except for water, fuels and other energy sources, throughout the whole life cycle.
Water consumption (WC)	m^3	Water consumption from different sources (freshwater, superficial, subterranean, refrigeration, etc) throughout the whole life cycle

5.3.4 Interpretation

The last stage of ISO 14040 is the interpretation. This stage identifies significant issues, evaluates findings to reach conclusions and formulate recommendations. The final report is the last element to complete the phases of LCA according to ISO 14040.

5.4 LCA-SOFTWARE AND DATABASES

During the last decade various LCA software tools have been developed and made available for use in environmental assessment of products in particular buildings. These tools can be classified according to 3 levels. Level 3 is called "Whole building assessment framework or systems" and consists of methodologies such as BREEAM (UK), LEED (USA); level 2 is titled "Whole building design decision or decision support tools" Ecoquantum (NL), Envest (UK), ATHENA (Canada); finally level 1 is for product comparison tools and includes Gabi (GER), SimaPro (NL), TEAM (Fra). Some databases used for environmental evaluation are: DEAM TM, Ecoinvent Data, GaBi, [RMIT, 2001], [Erlandsson and Borg, 2003], [Forsberg and von Malmborg, 2004], [Larsson, 2006]. In this thesis, the Ecoinvent V2.01 (2007) database and GaBi software system were used to obtain the inventory data of the processes involved in the study. In addition, the LCA Manager® has been used to validate, create and modify the scenarios under study and also to make the material balances and the inventory.

5.5 SENSITIVITY ANALYSIS

Sensitivity analysis plays a fundamental role in decision-making because it determines the effects of a change in a decision parameter on system performance [Andriantiatsaholiniaina et al, 2004]. Sensitivity analysis is the study of how the variation in the output of a model can be apportioned, qualitatively or quantitatively, to different sources of variation, and how the given model depends upon the information fed into it [Saltelli et al, 2000]. The parameter can be, among others, an assumption in the study (e.g. the choice to include or exclude infrastructure data) or a data source (e.g. different databases [Rypdal and Flugsrud, 2001]. Hence, this part determines the effects of a change in a decision parameter on system performance in order to see and predict how varying projections of variables affect environmental impacts.

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PART C: METHOD APPLICATION

Chapter 6: Presentation of the case studies: Application to two buildings, one in each a developed (Spain) and a developing (Colombia) country

Chapter 7: Detailed results at macro level

Chapter 8: Detailed results at micro level

Articles:
Ortiz O, Bonnet C, Bruno J.C., Castells F (2009): Sustainability based on LCM of residential dwellings: A case study in Catalonia, Spain. Building and Environment. Volume 44, Issue 3, March, pages 584 – 594.
Cited numbers: 2
Journal Impact Factor: 1.192 (Construction and Building Technology 6 of 38)

Ortiz O, Castells F, Sonnemann G (2010): Operational energy in the life cycle of residential dwellings: the experience of Spain and Colombia. Applied Energy. Volume 87, Issue 2, February, Pages 673-680
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CHAPTER 6:

6. PRESENTATION OF THE CASE STUDIES: APPLICATION TO TWO BUILDINGS, ONE IN EACH A DEVELOPED (SPAIN) AND A DEVELOPING (COLOMBIA) COUNTRY

6.1 INTRODUCTION

This chapter describes the data availability for the cases studies. The application of the conceptual life cycle approach within the residential building sector has been examined considering two countries: one in each a developed (Spain) and a developing country (not emerging Colombia). The process of obtaining data in Colombia was a laborious one due to the lack and widely dispersed of the data, therefore it was necessary to draw up estimates, while the development of data collection in a developed country (Spain) was straight forward process because of the national database available. Then, data were broken into two categories; macro and micro level.

6.2 SOURCE OF INFORMATION AT MACRO LEVEL

Historical data was taken from a time series period between 1990 and 2008. This time series was then used as the basis for evaluating the composite indicator within the residential building sector in both countries. The main sources of information have been taken from national database statistics; in Spain from the Spanish National Statistics [INE, 2006] and the Official Statistics website of Catalonia, 2009, and in Colombia data were taken from the Administrative Department of National Statistics, 2006 and the Mining and Energy Planning Unit which is an administrative special unit assigned to the Ministry of Mines and Energy, 2009. Other international database such as International Energy Agency (IEA), 2006 has been used. Then, table 4 and table 5 shows the data used for those variables in both countries: Spain and Colombia.

Table 4: Historical data from the Spanish scenario between 1990 and 2008

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1990	3.88E+04	1.28E+03	2.40E+02	2.81E+02	3.60E+00	9.80E+00	6.81E+02	1.29E+04	1.92E+10	5.70E+05	3.26E+04	1.14E+03	2.81E+04	2.29E+03	2.77E+03	2.86E+04	2.34E+10	1.29E+05
1991	3.89E+04	1.34E+03	2.04E+02	2.73E+02	2.40E+00	3.00E+00	6.27E+02	1.29E+04	1.92E+10	4.26E+05	1.28E+05	1.15E+03	2.76E+04	2.15E+03	3.28E+03	2.88E+04	2.30E+10	1.38E+05
1992	3.92E+04	1.25E+03	2.11E+02	2.22E+02	9.00E-01	-4.00E+00	5.62E+02	1.28E+04	1.90E+10	4.39E+05	1.81E+05	1.08E+03	2.46E+04	1.74E+03	3.25E+03	2.61E+04	2.05E+10	1.39E+05
1993	3.93E+04	1.14E+03	1.97E+02	2.22E+02	-1.10E+00	-6.20E+00	5.99E+02	1.30E+04	1.93E+10	1.09E+06	0.00E+00	1.09E+03	2.28E+04	2.65E+03	2.56E+03	2.27E+04	1.90E+10	1.39E+05
1994	3.93E+04	1.10E+03	2.35E+02	2.31E+02	2.40E+00	2.30E+00	6.66E+02	1.35E+04	2.00E+10	1.53E+06	0.00E+00	1.17E+03	2.51E+04	3.44E+03	2.25E+03	2.40E+04	2.09E+10	1.45E+05
1995	3.94E+04	1.19E+03	3.03E+02	2.21E+02	2.70E+00	6.20E+00	7.24E+02	1.37E+04	2.04E+10	2.07E+06	2.34E+05	1.20E+03	2.64E+04	3.48E+03	2.80E+03	2.55E+04	2.20E+10	1.50E+05
1996	3.95E+04	1.23E+03	2.87E+02	2.74E+02	2.40E+00	-1.40E+00	6.68E+02	1.22E+04	1.81E+10	2.38E+06	4.77E+05	1.22E+03	2.54E+04	3.88E+03	3.17E+03	2.47E+04	2.11E+10	1.55E+05
1997	3.96E+04	1.31E+03	3.23E+02	2.99E+02	3.90E+00	2.20E+00	6.85E+02	1.37E+04	2.04E+10	1.76E+06	4.85E+05	1.22E+03	2.79E+04	3.81E+03	2.56E+03	2.68E+04	2.32E+10	1.62E+05
1998	3.97E+04	1.39E+03	4.07E+02	2.98E+02	4.50E+00	7.20E+00	7.15E+02	1.48E+04	2.20E+10	6.32E+05	1.21E+06	1.24E+03	3.24E+04	3.47E+03	1.89E+03	3.10E+04	2.70E+10	1.74E+05
1999	3.99E+04	1.57E+03	5.10E+02	3.56E+02	4.70E+00	8.50E+00	6.62E+02	1.49E+04	2.20E+10	4.81E+04	2.35E+06	1.26E+03	3.58E+04	3.06E+03	1.99E+03	3.46E+04	2.98E+10	1.86E+05
2000	4.03E+04	1.72E+03	5.34E+02	4.16E+02	5.00E+00	6.10E+00	7.05E+02	1.60E+04	2.38E+10	3.88E+04	2.74E+06	1.25E+03	3.81E+04	2.12E+03	2.45E+03	3.84E+04	3.17E+10	1.96E+05
2001	4.07E+04	1.88E+03	5.24E+02	5.05E+02	3.60E+00	8.60E+00	7.13E+02	1.65E+04	2.45E+10	8.49E+03	3.93E+06	1.29E+03	4.05E+04	1.44E+03	3.16E+03	4.22E+04	3.37E+10	2.24E+05
2002	4.13E+04	1.98E+03	5.43E+02	5.20E+02	2.70E+00	6.30E+00	7.04E+02	1.64E+04	2.44E+10	3.40E+04	4.66E+06	1.34E+03	4.24E+04	1.42E+03	3.19E+03	4.41E+04	3.53E+10	2.33E+05
2003	4.20E+04	2.10E+03	6.22E+02	5.06E+02	3.10E+00	4.40E+00	7.23E+02	1.64E+04	2.44E+10	1.09E+04	5.89E+06	1.34E+03	4.47E+04	1.24E+03	2.26E+03	4.62E+04	3.72E+10	2.39E+05
2004	4.27E+04	2.25E+03	6.87E+02	5.64E+02	3.30E+00	5.10E+00	9.20E+02	1.77E+04	2.63E+10	6.91E+03	6.27E+06	1.37E+03	4.66E+04	1.52E+03	1.93E+03	4.80E+04	3.88E+10	2.50E+05
2005	4.34E+04	2.36E+03	7.16E+02	5.91E+02	3.60E+00	5.20E+00	9.79E+02	1.79E+04	2.66E+10	0.00E+00	7.83E+06	1.43E+03	5.03E+04	1.45E+03	2.89E+03	5.15E+04	4.19E+10	2.61E+05
2006	4.41E+04	2.54E+03	7.60E+02	6.58E+02	3.90E+00	5.00E+00	1.05E+03	1.84E+04	2.73E+10	0.00E+00	9.59E+06	1.56E+03	5.40E+04	1.13E+03	3.16E+03	5.59E+04	4.50E+10	2.69E+05
2007	4.49E+04	2.70E+03	6.16E+02	6.47E+02	3.70E+00	3.50E+00	1.12E+03	1.90E+04	2.82E+10	0.00E+00	1.07E+07	1.68E+03	5.47E+04	1.09E+03	2.85E+03	5.60E+04	4.54E+10	2.79E+05
2008	4.55E+04	2.45E+03	3.60E+02	6.33E+02	1.20E+00	-3.30E+00	1.22E+03	1.86E+04	2.77E+10	9.46E+05	5.95E+06	1.72E+03	4.21E+04	1.45E+03	1.78E+03	4.28E+04	3.50E+10	2.82E+05

Observations:
1: Year
2: Natural growth (% GDP)
3: Employment sector (# people)
4: Housing starting (# units)
5: Housing finishing (# units)
6: GDP (% total)
7: GDP construction (% of the sector)
8: Index price clinker (price base 100)
9: Clinker production (Mton)
10: Clinker CO_2 emissions
11: Clinker export (Mton)
12: Clinker import (Mton)
13: Index price cement ((price base 100)
14: Cement production (Mton)
15: Cement export (Mton)
16: Cement import (Mton)
17: Cement consumption (Mton)
18: Cement CO_2 emissions
19: Energy consumption (ktoe)

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Table 5: Historical data from the Colombian scenario between 1990 and 2007

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1990	3.40E+07	6.10E+06	2.00E+00	4.20E+00	6.80E+03	5.10E+03	5.60E+05	5.70E+06	6.30E+06	8.40E+05	2.20E+03	1.60E+02	7.50E+03	4.90E+05	8.30E+04	3.30E+04
1991	3.50E+07	8.40E+06	2.00E+00	4.30E+00	7.20E+03	4.60E+03	8.10E+05	5.90E+06	6.40E+06	7.80E+05	2.40E+03	1.60E+02	7.80E+03	4.70E+05	8.30E+04	3.70E+04
1992	3.60E+07	1.20E+07	1.80E+00	4.40E+00	7.10E+03	6.10E+03	7.60E+05	6.10E+06	6.80E+06	5.60E+05	1.10E+03	1.70E+02	4.30E+03	4.90E+05	7.70E+04	3.70E+04
1993	3.60E+07	1.10E+07	1.90E+00	4.90E+00	7.10E+03	9.10E+03	6.90E+05	6.80E+06	7.80E+06	5.70E+05	1.10E+05	2.00E+02	2.50E+03	5.00E+05	7.30E+04	3.90E+04
1994	3.70E+07	1.20E+07	1.90E+00	5.30E+00	8.50E+03	1.10E+04	3.00E+05	7.30E+06	9.20E+06	9.20E+05	1.20E+05	2.20E+02	2.80E+03	5.10E+05	7.70E+04	3.90E+04
1995	3.70E+07	1.00E+07	1.80E+00	5.20E+00	1.00E+04	1.30E+04	3.20E+05	7.40E+06	9.30E+06	9.40E+05	5.00E+04	2.20E+02	4.00E+03	5.90E+05	7.70E+04	4.20E+04
1996	3.80E+07	7.60E+06	3.20E+00	6.20E+00	1.10E+04	1.30E+04	5.40E+05	7.00E+06	8.30E+06	1.00E+06	6.30E+04	2.00E+02	4.10E+03	6.50E+05	7.30E+04	4.20E+04
1997	3.90E+07	9.00E+06	3.10E+00	6.10E+00	1.20E+04	1.40E+04	3.60E+05	7.20E+06	8.80E+06	1.20E+06	1.30E+05	2.00E+02	4.20E+03	6.80E+05	7.50E+04	4.40E+04
1998	3.90E+07	8.00E+06	3.20E+00	5.60E+00	1.10E+04	1.40E+04	3.70E+05	7.10E+06	8.60E+06	1.30E+06	9.20E+04	1.80E+02	4.20E+03	7.40E+05	7.40E+04	4.40E+04
1999	4.00E+07	5.50E+06	3.20E+00	4.30E+00	1.20E+04	1.00E+04	3.60E+05	5.40E+06	6.50E+06	1.50E+06	2.00E+04	1.30E+02	3.90E+03	7.70E+05	7.20E+04	4.20E+04
2000	4.00E+07	5.80E+06	3.10E+00	4.00E+00	1.30E+04	1.10E+04	5.20E+05	6.10E+06	7.10E+06	1.60E+06	2.90E+04	1.40E+02	3.90E+03	7.40E+05	7.20E+04	4.20E+04
2001	4.10E+07	6.40E+06	3.10E+00	4.50E+00	1.20E+04	1.20E+04	5.50E+05	5.80E+06	6.80E+06	1.70E+06	2.60E+04	1.20E+02	3.80E+03	7.40E+05	7.20E+04	4.30E+04
2002	4.10E+07	8.50E+06	3.10E+00	4.50E+00	1.20E+04	1.20E+04	6.70E+05	5.80E+06	6.60E+06	1.60E+06	4.70E+03	1.20E+02	3.50E+03	7.00E+05	7.40E+04	4.50E+04
2003	4.20E+07	9.20E+06	3.10E+00	4.90E+00	1.30E+04	1.30E+04	5.50E+05	6.30E+06	7.30E+06	1.90E+06	1.40E+04	1.30E+02	3.20E+03	7.50E+05	7.60E+04	4.70E+04
2004	4.20E+07	1.00E+07	3.00E+00	5.30E+00	1.70E+04	1.60E+04	3.90E+05	6.40E+06	7.80E+06	1.90E+06	1.60E+03	1.40E+02	3.90E+03	7.70E+05	7.70E+04	4.90E+04
2005	4.30E+07	9.90E+06	8.10E+00	1.30E+01	2.10E+04	2.00E+04	6.20E+04	7.70E+06	9.90E+06	2.20E+06	3.90E+02	1.80E+02	3.90E+03	8.10E+05	7.70E+04	5.00E+04
2006	4.30E+07	1.10E+07	7.80E+00	1.30E+01	2.40E+04	2.50E+04	7.70E+04	7.70E+06	1.00E+07	1.80E+06	9.00E+02	1.80E+02	4.50E+03	8.10E+05	8.10E+04	5.20E+04
2007	4.40E+07	1.40E+07	8.10E+00	1.50E+01	3.00E+04	3.10E+04	1.60E+05	8.50E+06	1.10E+07	1.80E+06	4.20E+03	2.10E+02	4.90E+03	8.20E+05	8.10E+04	5.40E+04

Observations:

1: Year
2: Natural growth (% GDP)
3: Initial m^2
4: GDP services (%)
5: GDP construction (%)
6: Total exportation (ton)
7: Total importation ($)
8: Clinker export (ton)
9: Clinker import (ton)
10: Cement production (ton)
11: Cement export (ton)
12: Cement import (ton)
13: Cement consumption (ton)
14: Cement consumption within the sector (ton)
15: Primary energy production (Tcal)
16: Final primary energy consumption (Tcal)
17: Electricity generation (Kwh)

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6.3 SOURCE OF INFORMATION AT MICRO LEVEL

We analyze one type of urban dwelling located in Barcelona, Spain and one situated in Pamplona, Colombia. In both scenarios, we assess the construction, use and end-of-life phases.

6.3.1 Case study I: Mediterranean home

6.3.1.1 Construction phase

The Spanish reference house (known hereafter as base case), is located in Barcelona on the Mediterranean coast at 41º23N, 2º11E, an elevation of 12m and the annual average temperatures are in winter 9º, spring 15º, summer 24º and autumn 20ºC. The detached home has an area of 160m² with four bedrooms, an attic, a living, a dinning room, a kitchen and two bathrooms. It is two-storeys high and is mainly of brick. Table 6 shows the main building materials used for the Spanish home based on the description of the system elements. The mode of transporting building materials is 100% truck and the distance from manufacture to the building site is assumed to be 80 km. The waste of construction is further described in table 12.

Table 6: Materials required during the construction phase for the Spanish home.

Building Elements	Main building materials used for the dwelling	Thickness (m)	Density (kg m^{-3})	Area (m^2)	Mass (kg)
External walls	Brick Expanded polystyrene (EPS) Plaster	0.140 0.040 0.015	900 30 825	193.5 193.5 114.5	24384 232.2 2394.8
Windows	Glass (Clear 3MM): 2 units Wooden frame (0.04m) Dividers (0.02m)	0.003 0.020 0.020	2500 700 700	36.2 30.1 7.53	543.5 421.7 105.4
Pitched roof	Clay tile MW stone wool Bitumen	0.025 0.092 0.005	2000 30 960	83.5 83.5 83.5	4178.6 230.6 401.1
Internal walls	Gypsum plastering: 2 units Brickwork (inner leaf) Pine (20 % Moisture) (doors)	0.013 0.115 0.030	1000 1700 419	107.9 107.9 140.0	1403.1 21101.4 1760.9
Ground floor	XPS expanded Cast concrete	0.060 0.200	38 2000	72.3 72.3	162.8 28950.4
Internal floor	Cast concrete Reinforced concrete	0.050 0.250	2000 1110	144.7 144.7	14474.5 40169.2
Floors	Ceramic tiles Wooden flooring	0.050 0.010	2500 650	72.3 72.3	904.7 470.4
Painting and other architectural finishing	Emulsion paints and varnish Mortar Timber	- - -	- 2200 650	140.0 - -	35.0 250.0 850.0

Figure 8 and figure 9 show the architectural style.

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Figure 8: General overview of the Spanish home studied.

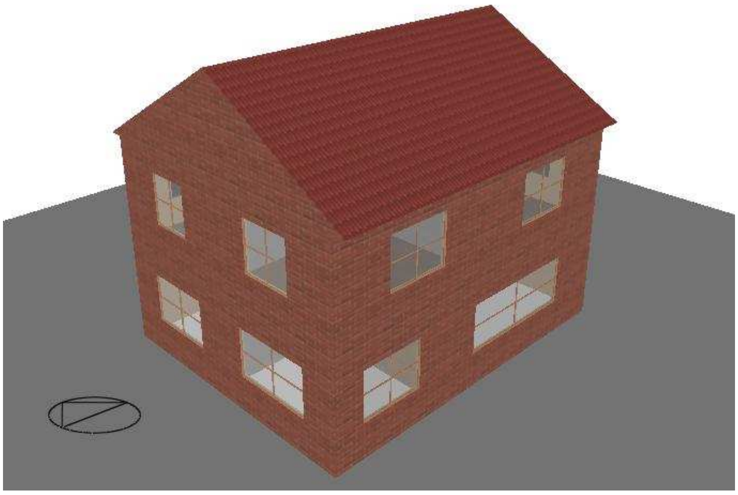

Figure 9: Architectural style for the Mediterranean home (base case).

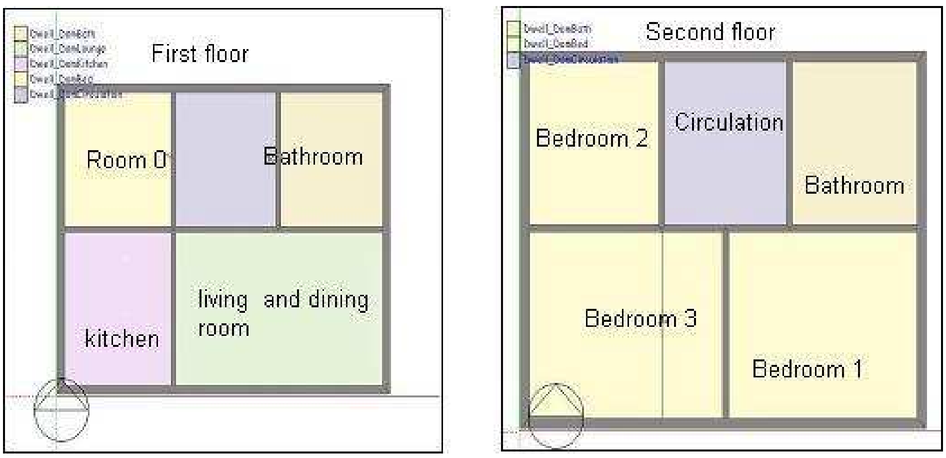

Table 7 summarizes the areas built for the dwelling studied

Table 7: Areas of the Mediterranean dwelling.

Area (in storeys)	Mediterranean home (m^2)
Area built ground floor	72.3
Area built first floor	72.3
Usable floor area	144.6
Total area	160
First floor	**Area for windows (m^2)**
Bathroom	1.4
Dining room	8.0
Kitchen	6.5
Bedroom	3.1
Total area	19.0
Second floor	
Bathroom	1.4
Bedroom	5.2
Bedroom	4.0
Corridor	0.9
Bedroom	5.3
Total area	16.8

6.3.1.2 Use phase

The use phase is divided up in two elements: operation and maintenance:

Operation phase

In this study, the dwelling has been evaluated using the building energy simulation software DesignBuilder which is a user interface for the EnergyPlus thermal simulation engine and taking into the considerations of the Spanish Building Technical Code (CTE). The dwelling was modeled in collaboration with the Group of Applied Thermal Engineering (CREVER) in the Department of Mechanical Engineering at the URV.

In order to evaluate the building's energy consumption during the operation phase, the following parameters have been considered:

- Daily DHW consumption has been estimated at 3.00E+01 l $pers^{-1}$ y^{-1} at a temperature of 60ºC. DHW is produced by an electrical heater with an estimated 95% efficiency.

- Annual energy consumption for cooking is estimated at 2.50E+02 kWh $pers^{-1}$ y^{-1} using an electrical cooker.

- Heating and cooling setpoints in the different rooms are presented in table 8. The dwelling has a split system with a coefficient of performance (COP) of 2.35 for heating and 1.85 for cooling.

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Table 8: Main characteristics of the heating and cooling setpoints

Environmental control					
	Dinning room	Kitchen	Bath	Bedrooms	Corridor + stair
Temperature for heating ºC	21	18	22	18	18
Temperature for ventilation ºC	25	27	24	25	25

- Annual energy consumption for other electrical appliances is estimated at 1.20E+01 kWh m^{-2}. The electrical equipment consists of the following conventional equipment: T.V., D.V.D player, stereo, PC, washing machine, microwave and other small appliances.

- The annual energy consumption for lighting are shown in table 9. This shows the required lighting level in the different rooms and the lighting power which has been installed. This is estimated at about 1.60E+01 kWh m^{-2} y^{-1}.

Table 9: Level of illumination required for the dwelling

Level of illumination required	**lux**
Kitchen	300
Dinning – Living room	150
Bath 1	150
Corridor + stairs	100
Bedrooms	100
Potential illumination installed	3.4 W m^{-2}.100 lux

Table 10 briefly shows the current electricity consumption per final user in the Mediterranean house where all the energy is supplied by electricity only.

Table 10: Electricity input for the household energy consumption (100% electrical only)

Scenario / **100% Electrical**	**Mediterranean home** kWh y^{-1}
Heating	8.87E+02
Domestic hot water	2.57E+03
Electrical appliances	1.91E+03
Cooking	1.07E+03
Illumination	2.57E+03
Cooling	3.24E+03
Total	**1.22E+04**

Maintenance phase

This phase includes the transport of the building materials from the factory to the building site and also the internal waste management with the transport to the final destination. In this phase, maintenance and refurbishment have been calculated including activities such as repainting, PVC siding, kitchen and bathroom cabinet replacement, re-roofing and changing windows. Table 11 shows the maintenance and refurbishment activities which have been done according to the following schedule based on a home life of 50 years.

Table 11: Maintenance schedule based on a 50 years life span.

Maintenance activities	Years occurring after the construction
Painting (interior and exterior) and door repair	10 - 20 - 30 - 40
PVC Siding	20 – 40
New kitchen and cabinets (bathroom)	15 – 30
New re-roofing and walls repair	15 – 30
Window replacement	15– 30

6.3.1.3 End-of-life phase

Wastes are classified into two main groups: one corresponding to the waste generated from the construction process itself as a result of surplus materials, such as concrete, mortar, ceramic tile etc.; and the other to the waste originated from the packaging arriving on site, wood paper, plastics, etc. We have classified the first waste into five groups: stone, metals, timber, plastic, and others construction waste. The packaging materials have been classified into three groups: timber, plastic, and paper and cardboard. This classification has been done in accordance with the Life Programme Environment Directive of the European Commission and taking into account the recommendations of the European Waste Catalogue (EWC) and the information from the Catalan waste catalogue. Then, as our first reference, all the waste generated during the life cycle is transported to landfill treatment and is considered the waste originated from construction process. Table 12 describes others scenarios to carry out: landfilling, recycling and incineration that will be further studied in chapter 8 section 8.1.3.3

Table 12: Overview of the waste management and difference scenarios.

<table>
<tr><th rowspan="2">Type of construction waste</th><th rowspan="2">Collection rate</th><th colspan="3">Scenario, Catalan plant and distance from the origin of waste to the plant in km</th></tr>
<tr><th>Landfilling</th><th>Recycling</th><th>Incineration</th></tr>
<tr><td>Stone</td><td>70-80%</td><td>Construction wastes controlled landfill (5.6km)</td><td>Gelabert SA - Services and Maintenance (7.9km)</td><td rowspan="2">Non-incinerable</td></tr>
<tr><td>Metals</td><td>90%</td><td rowspan="5">Cespa SA - Waste Management (28.1km)</td><td rowspan="3">Femarec SCCL (6.2km)</td></tr>
<tr><td>Plastic</td><td>80%</td><td rowspan="4">Uniland SA Cement Plant (38.2km)</td></tr>
<tr><td>Paper and Cardboard</td><td>80%</td></tr>
<tr><td>Wood</td><td>80%</td><td rowspan="2">Cespa SA - Waste Management (28.1km)</td></tr>
<tr><td>Others (unspecific)</td><td>Variable</td></tr>
</table>

6.3.2 Case study II: Colombian home

6.3.2.1 Construction phase

The Colombian dwelling we studied is located in the Province of Pamplona. The semidetached dwelling is part of an existing house divided into two storeys, with approximately 110m² of usable-floor area distributed over three bedrooms, a living and dining room, a kitchen and two bathrooms. The main construction materials are brick, concrete and steel, and the upper ceiling is covered in roof tiles. Table 13 summarizes the general construction materials used for the dwelling. The mode of transporting building materials is 100% truck and the distance from manufacture to the building site is assumed to be 30km.

Table 13: Principal inputs materials required for the Colombian dwelling

Flow	Quantity	Units	Category
Concrete	40	m^3	Concrete
Mortar	3500	kg	Masonry
Brick	12500	kg	Masonry
Steel	3500	kg	Metals
Ceramic tiles	1800	kg	Covering
PVC	100	kg	Pipes, wiring
Timber	5	m^3	Covering / Roofing / Internal and External use
Roof tile	3500	kg	Covering / Roofing
Glass	150	kg	Covering
Aluminum	55	kg	Covering
Alkyd paint	19.25	kg	Painting

Figure 10 and figure 11 shows the layout of the Colombian home studied. The dwelling was built according to local regulations such as the Earthquake Resistant Buildings Code (Decree 1400 of 1984). Valuable assistance in data collection was given by C.E. Bruno Brito and Mr. Edisson Villamizar, and architectural drawing was provided by Mr. Marlon Barrera V.

Figure 10: General overview of the Colombian home studied.

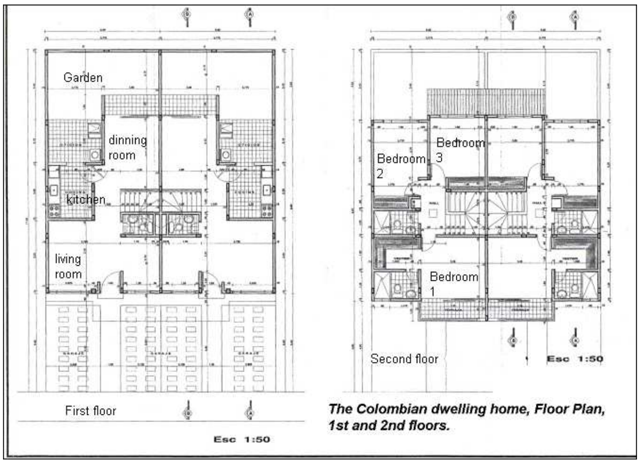

Figure 11: Sketch of the Colombian studied home.

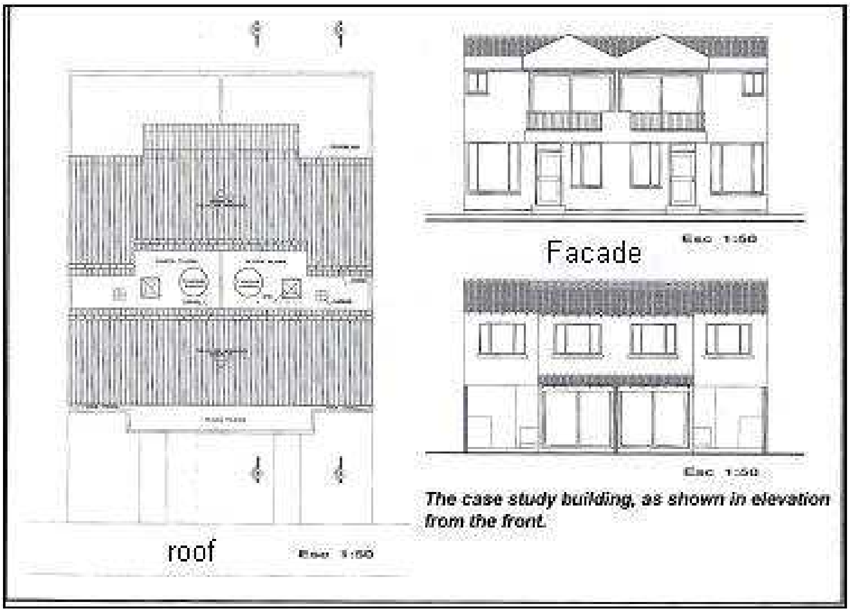

Table 14 summarizes the areas built for the dwelling studied.

Table 14: Areas of the Colombian dwelling

Area (in storeys)	**home (m^2)**
Area built ground floor	52.24
Area built first floor	56.31
Usable floor area	104.10
Total area	107.55
First floor	**Area for windows (m^2)**
Dining room	6.8
Kitchen	5.6
Total area	12.4
Second floor	
Bathroom	1.7
Bedroom	6.6
Bedroom	5.6
Bedroom	4.6
Total area	18.5

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6.3.2.2 Use phase

Operation phase

It can be very important to consider the climate conditions when analyzing the energy consumption in residences of a region. Then, Colombia is located between the Caribbean Sea and Pacific Ocean between the latitudes of 15º north and 5º south. Also, it is important to stress that due to its geographic location, Colombia does not have conventional seasons such as autumn, winter, summer or spring, but rather has two main periods: one of heavy rains (called the humid season) and another consisting of isolated rainfall or drought (called the hot season). Pamplona city has a latitude and longitude of 07º23'N and 72º39'W and an elevation of 2342m, the annual average temperatures are between 17 and 20ºC. The average sunshine per year in Pamplona is 1300 – 1700 h. Consequently, normal behaviour involves using DHW without heating and air conditioning loads.

It was difficult to find the information on residential energy consumption of the providence of Pamplona because all the statistics were based on the main cities populated such as Bogotá, Medellin, Cali and Barranquilla. Therefore, to study the operation phase, we assess the actual scenario of electricity consumption for the bio-climatic condition of Pamplona city. Due to the lack of data during this phase to assist electricity system planning and end-uses, 223 samples for dwellings have been taken considering aspects such as: household size, inhabitants, energy uses and types of electrical appliance used in the houses. Data was categorized and classified according to four main aspects: domestic hot water (DHW), electrical appliances, cooking and illumination. The monthly energy consumption during the operation phase has been calculated using the Eq. (2).

$$E_t = n * Q * d, \qquad (2)$$

where E_t is the total monthly electricity end-use of the dwelling during the operation phase (kWh); n is the number of electrical appliances operated in the house; Q is the consumption of the appliance (W) and d is the total h day^{-1} period used [*1].

The electricity end-use of the final consumer has then been classified into three situations: optimum use, normal use and excessive use. This research considered only the normal use as the average time that the electrical appliances should be used by final owner, see table 15. Finally, samples which did not have their data indicated were discarded; then the total number of samples included in the analysis was 175 dwellings and after the survey studied, the annual electricity consumption for the dwelling was calculated at 6.21E+03 kWh y^{-1}.

[*1] The simulator software provided by CENS (Colombian Electrical Company) was used to provide data for the energy consumption (www.cens.com.co/simulador.htm).

Table 15: Household energy consumption (100% electrical only).

Household activity	***Consumption (W)***	***Optimums behavior (h day^{-1})***	***Normal Use (h day^{-1})***	***Inappropriate Behavior (h day^{-1})***	***Annual energy consumption (kWh)***
Domestic hot water					
Electrical shower	3.97E+03	<0.5	0.5	>0.5	7.25E+02
				Subtotal domestic hot water	7.25E+02
Illumination					
Light bulb (5 units)	1.00E+02	<5	5	>5	9.13E+02
Light bulb (6 units)	6.00E+01	<4	4	>4	5.26E+02
				Subtotal illumination	1.44E+03
Cooking					
Electrical cooker	8.58E+02	<2	2	>2	6.26E+02
				Subtotal cooking	6.26E+02
Electrical appliances					
• **Room**					
T.V.	6.60E+01	<4	4	>4	9.64E+01
D.V.D.	5.50E+01	<0.3	0.3	>0.3	6.02E+00
Music stereo	5.50E+01	<1	1	>1	2.01E+01
• **Bathroom**					
Hairdryer	5.17E+02	<0.25	0.25	>0.25	4.72E+01
• **Bedroom**					
Radio	6.60E+01	<1	1	>1	2.41E+01
Computer	1.65E+02	<4	4	>4	2.41E+02
• **Patio**					
Washing machine	5.61E+02	<0.3	0.3	>0.3	6.14E+01
Iron	9.90E+02	<0.3	0.3	>0.3	1.08E+02
• **Kitchen**					
Refrigerator	2.75E+02	<24	24	>24	2.41E+03
Extractor	1.54E+02	<0.5	0.5	>0.5	2.81E+01
Microwave	2.09E+03	<0.25	0.25	>0.25	1.91E+02
Pressure cooker	6.38E+02	<0.25	0.25	>0.25	5.82E+01
Sandwich toaster	1.35E+03	<0.25	0.25	>0.25	1.23E+02
Blender	9.90E+01	<0.25	0.25	>0.25	9.03E+00
				Subtotal electrical appliances	3.42E+03
Total household energy consumption kWh per year					**6.21E+03**

Maintenance phase

Table 16 shows the maintenance and refurbishment activities which have been done according to the following schedule based on a home life of 50 years.

Table 16: Maintenance schedule based on a 50 years life span.

Maintenance activities	**Years occurring after the construction**
Painting (interior and exterior) and door repair	15 - 30
PVC Siding	30
New kitchen and cabinets (bathroom)	10 – 20 - 30
New re-roofing and walls repair	15 – 30
Window replacement	20 - 40

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6.3.2.3 End-of-life

There are currently two final treatment scenarios that can be modelled: landfilling and recycling. In the first scenario, all the wastes are disposed of in landfill. The mode of transporting the waste is 100% truck and the distance from the building site to the treatment plant is assumed to be 20 km.

6.4 GENERAL ASSUMPTIONS

The following assumptions have been considered:

- Both dwellings are assumed to be located in the center of each city.

- For typical heat values of various fossil fuels, data were collected from the international literature of the Centre for Building Performance Research, the World Nuclear Association and alternative energy sources.

- All building materials and processes considered are well known; therefore we focus on the environmental impacts from a life cycle perspective. For instance, we have chosen from the Ecoinvent database the Ref. #537 for cement mortar. This material includes "the whole manufacturing process to produce cement mortar (raw material provision, raw material mixing, packing, and storage), transports to plant, and infrastructure." In those cases where the environmental information about a product or process was not found, we have selected a proxy taking into account that it should be a product or process with similar characteristics considering the experience and expertise of the LCA developers.

- Minor maintenance activities such as replacing household electrical appliances and changing light bulbs will not be considered in the present study, and neither will other environmental impacts such as those resulting from water consumption and wastewater.

- Data for construction waste to calculate the benefit from the electrical energy produced (calculated using the calorific value data) and the amount of residual ashes was taken also from the Ecoinvent data base. For instance, according to the aforementioned database, the incineration of 1kg of timber provides 3.61E-01kWh of electrical energy and produces 5.82E-03 kg of slag and residues, which are then landfilled.

- The transport for the waste management considers the distance (in km) to the waste management plants closest to the building site.

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CHAPTER 7:

7. DETAILED RESULTS AT MACRO LEVEL

7.1 INTRODUCTION

The relevance of the residential building sector becomes evident when looking at macro indexes that show the strong growth in the building sector in Spain and Colombia during the last two decades. The sustainability analysis in a macro level is evaluated by exogenous variables that can influence socio-economic conditions and the development of a country. Then, this chapter shows and evaluates the Spanish and the Colombian composite indicator using factor analysis by using the statistical software package of SPSS [Ho, 2006]. Factor analysis (with principal components extraction) was employed to calculate the composite indicator, consequently evaluate the evolution of the residential building sector in both countries in two main aspects: socio and economics conditions.

7.2 COMPOSITE INDICATOR AND INTERPRETATION

Factor analysis as an appropriate technique for multivariable analysis was chosen because this technique is based on correlations between measured variables, so a correlation matrix containing the intercorrelations coefficients for the variable must be computed.

Examination of the correlation matrix shown in annex 2, illustrates high correlations between the nineteen Spanish variables and the seventeen Colombian variables. For example, in Spain the intercorrelations between the variables of natural_growth, GDP_construction and housing_finishing are greater than 0.90. Similarly, the intercorrelations between cement_production, energy_consumption and housing_finishing are also greater than 0.90. In Colombia the intercorrelations between the variables of natural_growth, total_exportation and primary_energy are greater than 0.85. Similarly, the intercorrelations between electricity_generation, GDP_construction and GDP_services are also greater than 0.85.

We analyze the communalities in order to present the proportion of variance in each variable accounted for by the common factors. As can be seen in table 17, for the Spanish case, the variable cement_import is the worse meaning that the model is only capable of produce 65.1% of the original variability. Meanwhile, for the Colombian case was the initial_m^2 built with 61.4%.

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Table 17: Communalities for the Spanish and Colombian case studies.

	Spain		Colombia	
	Initial	Extraction	Initial	Extraction
Year	1.000	0.951	1.000	0.981
Natural_growth	1.000	0.991	1.000	0.982
Employment_sector	1.000	0.995	1.000	
Housing_Starting	1.000	0.888	1.000	
Housing_Finishing	1.000	0.978	1.000	
GDP	1.000	0.899	1.000	0.903
GDP_Construction	1.000	0.894	1.000	0.940
Index_price_clinker	1.000	0.892	1.000	
Clinker_production	1.000	0.979	1.000	
CO2_Clinker	1.000	0.978	1.000	
Clinker_Export	1.000	0.740	1.000	0.735
Clinker_Import	1.000	0.965	1.000	0.973
Index_price_cement	1.000	0.928	1.000	
Cement_production	1.000	0.991	1.000	0.980
Cement_export	1.000	0.893	1.000	0.937
Cement_import	1.000	0.651	1.000	0.833
Cement_Consumption	1.000	0.994	1.000	
Emissiones_CO2	1.000	0.991	1.000	
Energy_consumption	1.000	0.980	1.000	0.948
Initial_m2			1.000	0.614
Total_Expor_FOE			1.000	0.969
Total_Impor_FOE			1.000	0.966
Consumption			1.000	0.964
Consump_Construc			1.000	0.849
Primary_energy			1.000	0.949
Final_PE_consumption			1.000	0.918

Extraction Method: principal component analysis

The total variance explained as shown in the SPSS output in annex 2, it can be seen the number of common factors computed. Then, using the criterion of retaining only factors with eigenvalues of 1 or greater, the first three factors will be retained for rotation. For the Spanish case, there are three factors with eigenvalues greater than 1, meaning that for 92.52% of the total variance is attributable to these three factors. The remaining sixteen factors together account for only approximately 7.48% of the variance. In Colombia, the first three factors will accounted for 90.83% (56%; 21.34% and 13.47% respectively). Thus, a model with three factors can be adequate to represent the composite indicator.

So, the rotation component matrix presents the three factors after varimax (orthogonal) rotation which main purpose is to achieve a simpler, theoretically more meaningful factor pattern. It has been applied varimax because is the most widespread use as it seems to give the clearest separation of factors. It does this by producing the maximum possible simplification of the columns (factors) within the factor matrix as shown in table 18 and table 19.

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Comparing the component matrix which represents the unrotated component analysis factor matrix, and presents the correlations that relate the variables to the three factors, it can be seen that in Spain, the first factor is highly made up for variables such as: employment_sector, housing finishing and cement production. The second factor is composed of both GDP index which represents the economic aspect within the building sector. Lastly, the last factor shows that the variables are not related to the factor 3. In Colombia, the variable total_Expor_FOE has loaded highly on factor 1; the variable consumption has loaded highly on factor 2 and the variable final_PE_consumption has loaded highly on factor 2 and 3. Then, examination of the factor loadings shows in Spain that thirteen of the nineteen variables loaded highly on the first factor. Meanwhile, in Colombia fourth of the eighteen variables loaded on the second factor.

Table 18: Rotated component matrix [(a)] for the Spanish scenario.

	Component		
	1	2	3
Natural_growth	0.993		
Energy_consumption	0.980	0.137	
Employment_sector	0.977	0.142	0.146
CO2_Clinker	0.966	0.210	
Clinker_production	0.966	0.213	
Housing_Finishing	0.963	0.179	0.138
AÑO	0.957	0.153	-0.107
Clinker_Import	0.952	0.167	0.175
Index_price_cement	0.952		-0.146
Index_price_clinker	0.922		-0.193
Cement_production	0.919	0.338	0.182
Emissiones_CO2	0.918	0.339	0.182
Cement_Consumption	0.914	0.311	0.249
Housing_Starting	0.772	0.520	0.151
Cement_export	-0.723		-0.608
GDP_Construction		0.944	
GDP	0.150	0.923	-0.157
Cement_import	-0.184	-0.120	0.776
Clinker_Export	-0.502	-0.453	-0.532

Extraction method: principal component analysis
Rotation method: Varimax with Kaiser normalization
a Rotation converged in 5 iterations

Table 19: Rotated component matrix [(a)] for the Colombian scenario.

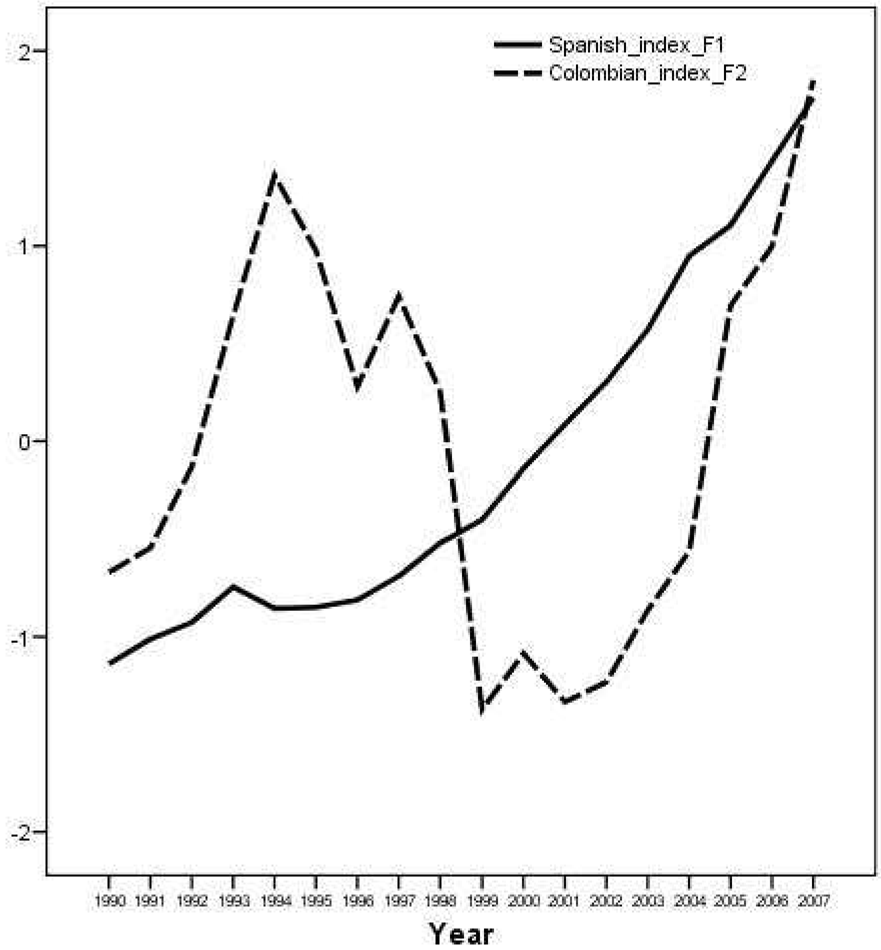
	Componente		
	1	2	3
Year	0.985		
Natural_growth	0.980		-0.132
Cement_Expor	0.959	-0.130	
Primary_energy	0.957		-0.177
Electricity_generation	0.918	0.319	
Total_Expor_FOE	0.875	0.403	0.201
GDP_Services	0.815	0.419	0.253
Total_Impor_FOE	0.800	0.569	
GDP_Construction	0.656	0.653	0.290
Clinker_Expor	-0.635	-0.574	
Clinker_Import	0.320	0.932	
Consumption	-0.306	0.930	
Cement_Prod	0.421	0.894	
Initial_m2		0.774	
Final_PE_consumption		0.350	0.889
Consump_Construc	-0.245	-0.124	0.879
Cement_Impor	-0.450	0.404	-0.684

Extraction method: principal component analysis
Rotation method: Varimax with Kaiser normalization
a Rotation converged in 5 iterations

Figure 12 shows the composite leading indicator within the Spanish and Colombian building sector from the first and second factor respectively. In Spain, as a result of the multivariable analysis, from nineteen indicators including socio-economic index, the percentage of variance of the first factor was 73.03%. All of the explanatory variables are correlated with housing_finished except for cement_import. The Spanish indicator showed the crisis occurred during the 1993 and 1996 years and the ascending from the 1997. Results shows that there is a strongly correlation between the housing finished and the other variables studied except for exportation of cement. It can be concluded that as Spanish economy becomes more active, with people increasing and building new buildings the electricity consumption will increase. As the correlation between electricity consumption and cement exportation is weaker, there is an indication that such end-uses are more depend on GDP than price. Then, the more electricity is consumed by its inhabitants, the higher GDP production.

In Colombia for the composite indicator from a total of seventeen indicators, it can be clearly seen the trend to increase the evolution within the construction industry during the last ten years. It is possible to observe about two main periods with different growth rates (1991 – 1994 and 2001 – 2007). The low growth rate over 1998 and 2002 periods was due to economic problems that put the country into a recession. It is surprising that the variable of initial_m^2 is not strongly correlated with other except for the consumption of cement with 0.602.

Figure 12: Composite indicator for Spain and Colombia.



Finally, as a result of the scores analysis, the following table 20 shows the coefficient matrix which contain the weighting coefficient of each variable in the calculation factor. Combining each explanatory variables were chosen to estimate the factorial scores for Spanish and Colombian index:

From nineteen Spanish variables and seventeen Colombian variables, the regression equation attains the adjusted coefficient of determinations. The prediction equation is:

$$Y' = A + B1X1 + B2X2 + ... BnXn$$

where Y' = the predicted dependent variable, A = constant, B = unstandardized regression coefficient, and X=value of the predictor variable.

Therefore, looking at the component coefficient matrix in table 20, it can be built the two lineal equation based in the calculation of the factor score.

$Y_{(Spanish\ composite\ index)}$: -1,13900 (1) - 1,01182 (2) - ,92724 (3) - ,74408 (4) - ,85500 (5) - ,84893 (6) -,81131 (7) - ,68992 (8) - ,51988 (9) - ,39987 (10) - ,13997 (11) + ,08528 (12) + ,30367 (13) + ,57124 (14) + ,94905 (15) + 1,10554 (16) + 1,43451 (17) + 1,76108 (18) + 1,87666 (19).

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$Y_{(\text{Colombian composite index})}$: -,66989 (1) - ,54482 (2) - ,13236 (3) + ,64147 (4) + 1,36130 (5) + ,97627 (6) + ,28045 (7) + ,74207 (8) + ,25255 (9) - 1,37236 (10) - 1,08515 (11) - 1,33429 (12) - 1,23256 (13) - ,86379 (14) - ,56218 (15) + ,69500 (16) + ,99754 (17) + 1,85076 (18).

Table 20: Resume for the lineal equation of the factor score [(a)]

	Spanish	Colombian
	REGR factor score 1 for analysis 1	REGR factor score 2 for analysis 1
1	-1,13900	-0,66989
2	-1,01182	-0,54482
3	-0,92724	-0,13236
4	-0,74408	0,64147
5	-0,85500	1,36130
6	-0,84893	0,97627
7	-0,81131	0,28045
8	-0,68992	0,74207
9	-0,51988	0,25255
10	-0,39987	-1,37236
11	-0,13997	-1,08515
12	0,08528	-1,33429
13	0,30367	-1,23256
14	0,57124	-0,86379
15	0,94905	-0,56218
16	1,10554	0,69500
17	1,43451	0,99754
18	1,76108	1,85076
19	1,87666	

a Limited to the first 100 cases.

In summary, it can be concluded that factor analysis has identified three factor from the list of nineteen variables of the Spanish case and seventeen variables of the Colombian case. In the main, the first factor for the Spanish and the second factor for the Colombian was represented by the specific statements written to reflect the evolution of the residential building sector in both countries. Energy and cement can be used as suitable proxies to capture the global development of the building sector and because are significant inputs for any construction especially for housing to get a real vision about the operation of the building sector.

7.2.1 Comparison results in energy and materials consumption

Regarding building materials, in Spain a direct measure of the evolution can be seen in the number of houses built, which increased from 187165 units in 2000 to 209752 units in 2005. Furthermore, in 2005 the construction industry took a lead growth rate of 6%, which accounted for 17.8% of Gross Domestic Product (GDP), and contributed almost 11% to the Gross Value Added (GVA). Indirect measures within the industry can be seen in the trends of steel and cement

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consumption. In Spain about 1200 kg of cement and 400 kg of steel were consumed per capita due to the growth in investment in the construction of housing and roads during the last five years. In Colombia, the DANE (Administrative Department of National Statistics) confirmed that in 2006 the construction sector represented 6.2% of the total GDP and also that about 85000 dwellings had been built. Furthermore, in 2007 Colombia had lower per capita consumption of cement (approx 208 kg) and steel (41.6 kg). Table 21 shows some socio-economic and materials index during the last five years.

Table 21: Macro-index and trends in the use of cement and steel during the last five years

SPAIN	**2007**	**Variation % 2007 - 2006**	**Variation % 2006 - 2005**	**Variation % 2005 - 2004**	**Variation % 2004 - 2003**
Total area (km²)	504030				
Population	45200737	1.1%	1.3%	2.1%	1.1%
GDP per capita (US$)	27400	4.5%	16.5%	5.6%	-1.8%
Cement (Mton)	56.1	7.7%	6.8%	3.7%	4.5%
Steel (Mton)	18.9	2.2%	1.7%	8.0%	5.0%
Number of units for residential use (approved)	135659	-55%	-8%	5%	3%
COLOMBIA					
Total area (km²)	1141748				
Population	43222037	1.9%	1.9%	1.9%	1.9%
GDP per capita (US$)	397	5.5%	5.3%	8.2%	7.4%
Cement (Mton)	9.0	3.8%	26.0%	5.3%	5.6%
Steel (Mton)	1.8	20.0%	8.3%	36.4%	3.0%
Number of units for residential use (approved)	94617	9%	19%	7%	8%

According to energy demand management and supply index, the challenge for the global energy sector is twofold: first, to dramatically increase access to affordable, modern energy services in countries that lack them, especially for poor communities; and secondly, to find the mix of energy sources, technologies, policies, and behavioural changes that will reduce the adverse environmental impacts of providing necessary energy services [Spalding-Fecher et al., 2005], meaning that first we must find out what makes up the electricity supply is in each country.

Hence, table 22 shows the electricity mix generation taking into account the data originated from the Spanish Electricity System (REE) and the data published in Colombia from the Ministry of Mines and Energy.

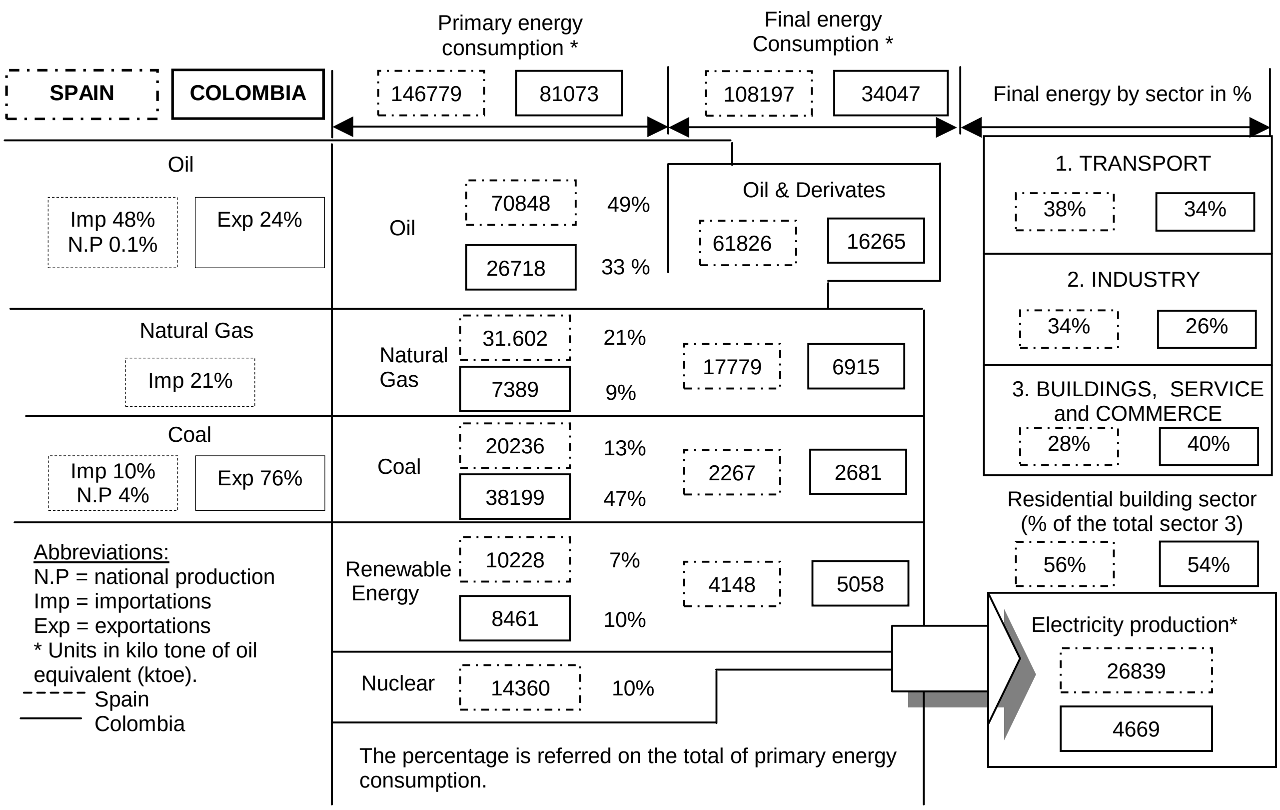
Table 22: Electricity mix generation in Spain in 2008 and Colombia in 2007

Production from:	Spanish Electricity Mix		Colombian Electricity Mix	
	(GWh)	%	(GWh)	%
Coal	49647	16.36	4084	7.60
Oil	10691	3.52	118	0.21
Gas	95529	31.48	6710	12.50
Nuclear	58973	19.44	0	0
Hydro	25845	8.51	42742	79.69
Wind	31777	10.47	0	0
Other no-renewable	23314	7.68	0	0
Other renewable	7645	2.21	0	0
Total Production	**303421**	**100**	**53618**	**100**

Observation: 1GWh = 8.60E-02 ktoe

The energy analysis included the amount of fossil and non-fossil fuels required to provide the energy used to provide the goods and services consumed by the inhabitants of a country. This included the primary energy, energy input, internal energy transformations and energy use. Therefore, the energy demand management considerations in both countries are summarized in figure 13. It illustrates the Sankey diagram which shows the graphic representation of the energy flow considering the methodology of the International Energy Agency (IEA).

Figure 13: Sankey diagram (the energy demand management considerations in both countries).



It can be seen in figure 13 that in 2007 in Spain had the primary energy consumption of 146779 kilo tonnes oil equivalent (ktoe) of which was based on renewable energy with 7% and non-renewable accounted for 93% (mainly oil accounted for 49%, natural gas represented 21%, coal 13% and nuclear 10%). The annual energy consumption was 108197 ktoe of which the final consumption of petroleum products was 61826 ktoe, natural gas 17779 and coal 2267. In 2006 in Colombia, the primary energy consumption was 81073ktoe, of which approximately 10% was renewable energy and 90% non-renewable fossil fuels. Furthermore, in Colombia there is an annual final energy consumption of 34047 ktoe which is about 3 times lower than Spanish consumption. In 2006 the Colombian foreign trade represented a total of 45879 ktoe, of which the exportation of coal accounted for 76% and oil was 24%. Meanwhile, in Spain there is energy dependence on fossil fuel from overseas, specifically oil (48%), natural gas (21%) and coal (10%), making Spain very vulnerable to potential supply crises. Therefore, it can be stated that Colombia is self-sufficient and less vulnerable that than Spain in a potential supply crisis. But in fact, there is uncertainty regarding energy supply in coming years due to high levels of industrial and economic investment, oil prices worldwide and energy consumption [Williams and Alhajji, 2003].

In Spain, the final energy consumption within the transport sector represented 38%, behind industry sector with 34% and buildings, service and commerce sector with 28% of which 56% accounted for the residential building sector. In Colombia the higher highest final energy consumption was for the building, service and commerce sector with 40% and the net electricity production was about 4669 ktoe. For its part the second most important was the transport sector with 34% followed by the industry sector with an average of 26%. Finally, in Spain the consumption of electricity for end-uses was equivalent to 26839 ktoe while in Colombia this total was 4669 ktoe.

7.2.2 Comparison on environmental impacts for the electricity mix

Table 23 shows the total environmental impacts for the electricity mix in both countries. Regarding the significant environmental challenge of GWP, the major reason why the Colombian technologies emit less CO_2 equivalent is because of the current electricity mix. For instance, in Spain there was a total emission of 5.22E-01 kg CO_2-Eq of which the energy source it is more mixed, gas represented 31%, nuclear 19%, coal 16%, and wind 10%. In terms of the Colombian dwelling's technologies, 79% accounts for hydroelectric plants and 12% accounts for gas, 7% for coal from a total of 2.43-01 kg CO_2-Eq.

Table 23: Total environmental impacts for the electricity mix for both countries.

Scenarios / Environmental Impacts	Final Colombian ecoprofile per 1kWh	Final Spanish ecoprofile per 1kWh
AP (kg SO_2-Eq)	3.64E-03	4.25E-03
GWP (kg CO_2-Eq)	2.43E-01	5.22E-01
HT (kg 1.4-DCB-Eq)	9.09E-02	1.29E-01
SOD (kg CFC-11-Eq)	1.12E-08	2.55E-08

UNIVERSITAT ROVIRA I VIRGILI
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Oscar Orlando Ortiz Rodríguez
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CHAPTER 8:

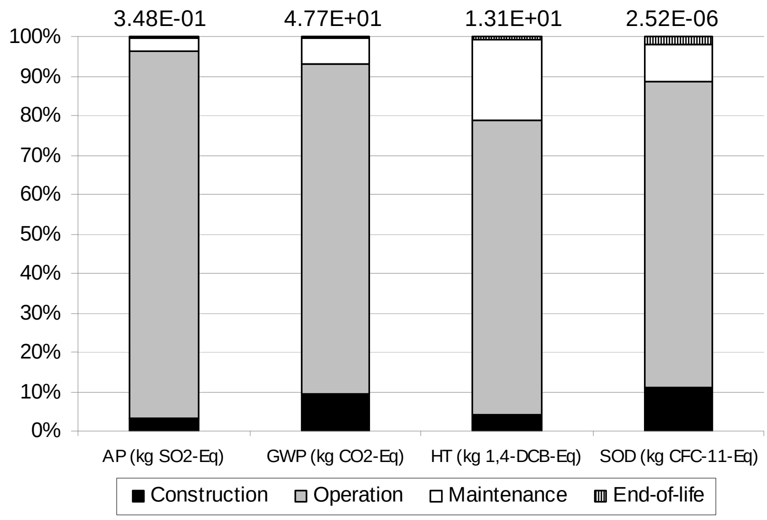
8. DETAILED RESULTS AT MICRO LEVEL

8.1 CASE STUDY I: SUSTAINABILITY ASSESSMENT RESULTS FOR THE APPLICATION OF THE MEDITERRANEAN RESIDENTIAL DWELLING HOME

8.1.1 General results

Figure 14 shows how the life cycle environmental impact is distributed over four categories: acidification potential (AP), global warming potential (GWP), human toxicity (HT) and stratospheric ozone depletion (SOD). As can be seen in the figure 14, the time phase with the highest environmental impact is the operation phase; approximately 77-93% of the life cycle's total, except for the human toxicity impact, of which the operation accounts for approximately 75% and the maintenance and refurbishing activities contributed up to 20%. Regarding the environmental issue of SOD, there was a total emission of 2.52E-06 kg CFC-11-Eq m^{-2} y^{-1} during the 50 years occupation, of which about 11% was during the construction phase (external and internal walls represented 54%) and the use phase accounts for 87% and 2% was during the end-of-life due to the construction waste of stone with 97% (concrete 61%, brick 32%, and roof tile and ceramic tiles 7%) of the total stone waste.

Figure 14: Total environmental impacts distribution during the Mediterranean full building life cycle.



8.1.2 Life cycle impact results according to the dwelling life cycle

One of the first analyses during the last five years on the environmental impact of the construction phase was performed by Asif et al, 2005. The main aim of this study was evaluated eight construction materials for a dwelling in Scotland. These materials were: timber, concrete, glass, aluminum, slate, ceramics tiles, plasterboard, damp course and mortar. The study concluded that the material used in

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the house with the highest level of embodied energy was concrete, at 61%. Additionally, Dimoudi and Tompa, 2008 performed a study to evaluate energy and environmental indicators related to construction of office buildings in Greece. The results showed that slabs have the higher contribution at the embodied energy of the studied buildings and from the envelope elements; the external wall is contributing the maximum in the overall embodied energy of the building.

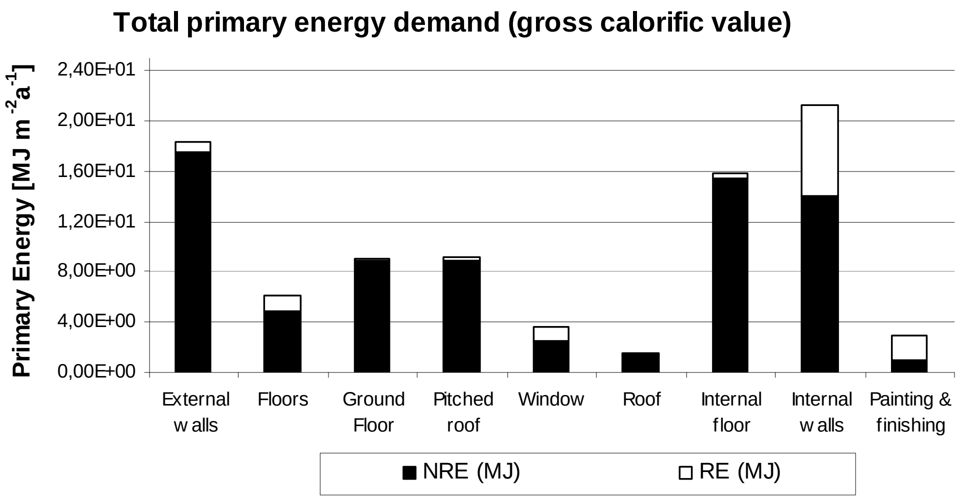
In a brief analysis on the evaluation of environmental impact in a life cycle perspective for selecting sustainable materials for buildings in Sri Lanka, Yasantha et al, 2008 compared two cases along with existing buildings in a matrix of environmental, economic and social scores. Five building elements, viz., foundations, roofs, ceilings, doors and windows, and floors were analyzed based on materials used for these elements. Result shows that the buildings with tile roof, rubble foundation, etc. (buildings of category 1) perform better than the buildings with asbestos roof, brick foundation, etc. (buildings of category 2). Those studies presented are not fully comparable; there are differences in the type of building construction, geographical location, bioclimatic conditions, energy management, and the methodology applied. Previous studies mentioned also do not show in detail environmental impacts during the construction phase and there is a lack of research for the final disposal of construction process. Therefore, next we focus on the construction phase in detail for the reference home.

8.1.2.1 Results of the construction phase

Environmental loads of the construction phase have been evaluated starting from fabrication of building materials, transport of building materials to the building site, the energy consumed by the machinery, and the disposal of material wastes. The fabrication of building materials represented 97% of the total environmental impacts, transport to the job site 2% and waste management 1%. During the construction phase the total primary energy demand was 8.78E+01 MJ m^{-2} y^{-1} (gross calorific value) of which non renewable primary energy demand represents 85% and renewable energy demand 15%.

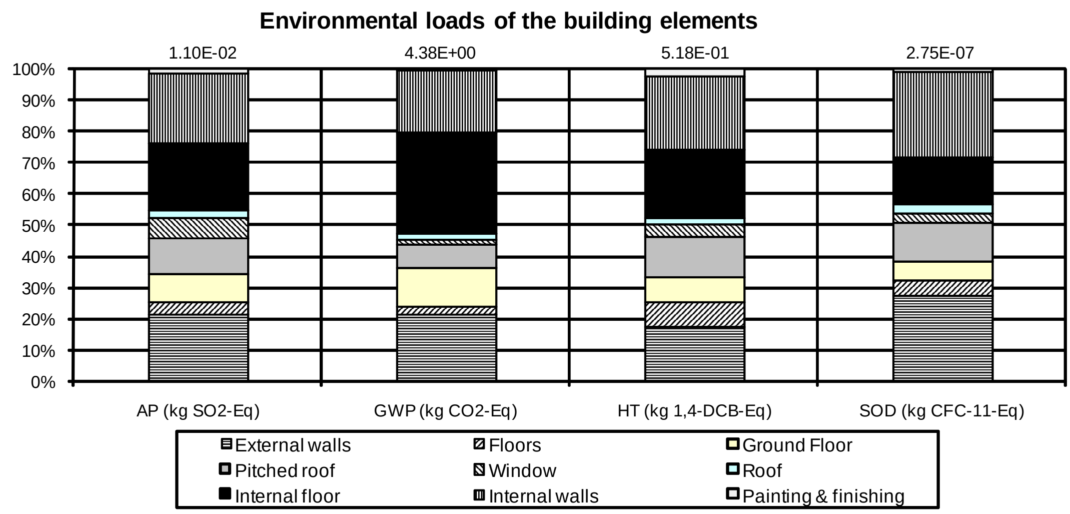
The contributions to the total primary energy demand (non-renewable and renewable) of the production materials are shown in figure 15. Internal walls had the highest value in non-renewable energy demand, accounting for about 2.13E+01 MJ m^{-2} y^{-1}. External walls with 1.84E+01 MJ m^{-2} y^{-1}, internal floors with 1.58E+01 MJ m^{-2} y^{-1} and pitched roofs 9.15E+00 MJ m^{-2} y^{-1} are also important in terms of the total energy demand. Results in floors, internal walls, and painting and other architectural finishing system, renewable energy are high with about 1.19E+00 MJ m^{-2} y^{-1}, 7.24E+00 MJ m^{-2} y^{-1} and 2.01E+00 MJ m^{-2} y^{-1} respectively, of which in all systems mentioned 27% is due to the use of timber. Therefore, sustainable managed wood can be not only positive for its carbon sequestration but also for avoiding the fossil energy consumption for concrete manufacturing. The total resource consumption accounted for 3.02E+01 kg m^{-2} y^{-1} and water consumption was 6.39E-02 m^{3} y^{-1}. Figure 15 shows the contribution of the construction system for the total energy source indicator.

Figure 15: Total primary energy demand of building elements (Mediterranean home).



The total impact of GWP was 4.38E+00 kg CO_2-Eq m^{-2} y^{-1}, of which internal floor accounted for 33%, external walls 21% and internal walls 20% due to the use of solid brick with 37%. The other two important materials were steel with about 18% and concrete mix with 11%. Figure 16 shows the final distribution of the environmental impacts by system of the construction phase.

Figure 16: Total environmental loads of the building elements (Mediterranean home).



8.1.2.2 Results of the use phase

<u>Results of the operation phase</u>

Table 24 shows the total environmental impacts results for the different household activities using 100% electrical only. As a result, of all the Mediterranean home environmental impacts resulting from household energy consumption, almost 33% of the electricity was used for HVAC needs (cooling 26% and heating 7%), 21% for DHW, 21% for illumination, 16% for electrical appliances and 9% for

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cooking. The life cycle impacts of all household activities for the environmental impact category of global warming potential shows that cooling accounted for a total of 1.06E+01 $kgCO_2$-Eq m^{-2} y^{-1}, followed illumination 8.39E+00, DHW 8.39E+00, electrical appliances 6.23E+00, heating 2.89E+00, and cooking 3.49E+00.

Table 24: Operation phase with 100% electrical only (emissions m^{-2} y^{-1}) for the Mediterranean home.

Environmental impact / Household activity	AP	GWP	HT	SOD	€ y^{-1}
Heating	2.35E-02	2.89E+00	7.14E-01	1.41E-07	9.98E+01
Cooling	8.60E-02	1.06E+01	2.61E+00	5.16E-07	2.89E+02
Electrical appliances	5.07E-02	6.23E+00	1.54E+00	3.04E-07	2.15E+02
Illumination	6.82E-02	8.39E+00	2.07E+00	4.10E-07	1.20E+02
Cooking	2.84E-02	3.49E+00	8.61E-01	1.71E-07	2.89E+02
DHW	6.82E-02	8.39E+00	2.07E+00	4.10E-07	3.65E+02
Total	**3.25E-01**	**4.00E+01**	**9.85E+00**	**1.95E-06**	**1.38E+03**

Results of the maintenance phase

Environmental impact of GWP due to maintenance activities contributed less than 6% of the total life cycle accounting for 3.03E+00 $kgCO_2$-Eq m^{-2} y^{-1}. Regarding the HT impact represented 20% of the total life cycle, of which 79% is due to the process of aluminum for windows replacement during the occupation of the home.

8.1.2.3 Results of the end-of-life phase

The total environmental impacts of this phase represented less than 1% of the total life cycle. GWP accounted for 2.84E-01 $kgCO_2$-Eq m^{-2} y^{-1}. Table 25 summarizes the environmental impacts occurs during this phase.

Table 25: Results for the Mediterranean home during the end-of-life phase

Scenario / From	Landfilling
AP (kg SO_2 eq)	1.82E-03
GWP (kg CO_2 eq)	2.80E-01
HT (kg 1.4-DCB eq)	1.02E-01
SOD	5.37E-08
RC (kg)	2.07E+00
RE (MJ)	5.18E-02
NRE (MJ)	6.67E+00
WC (m^3)	1.82E-03

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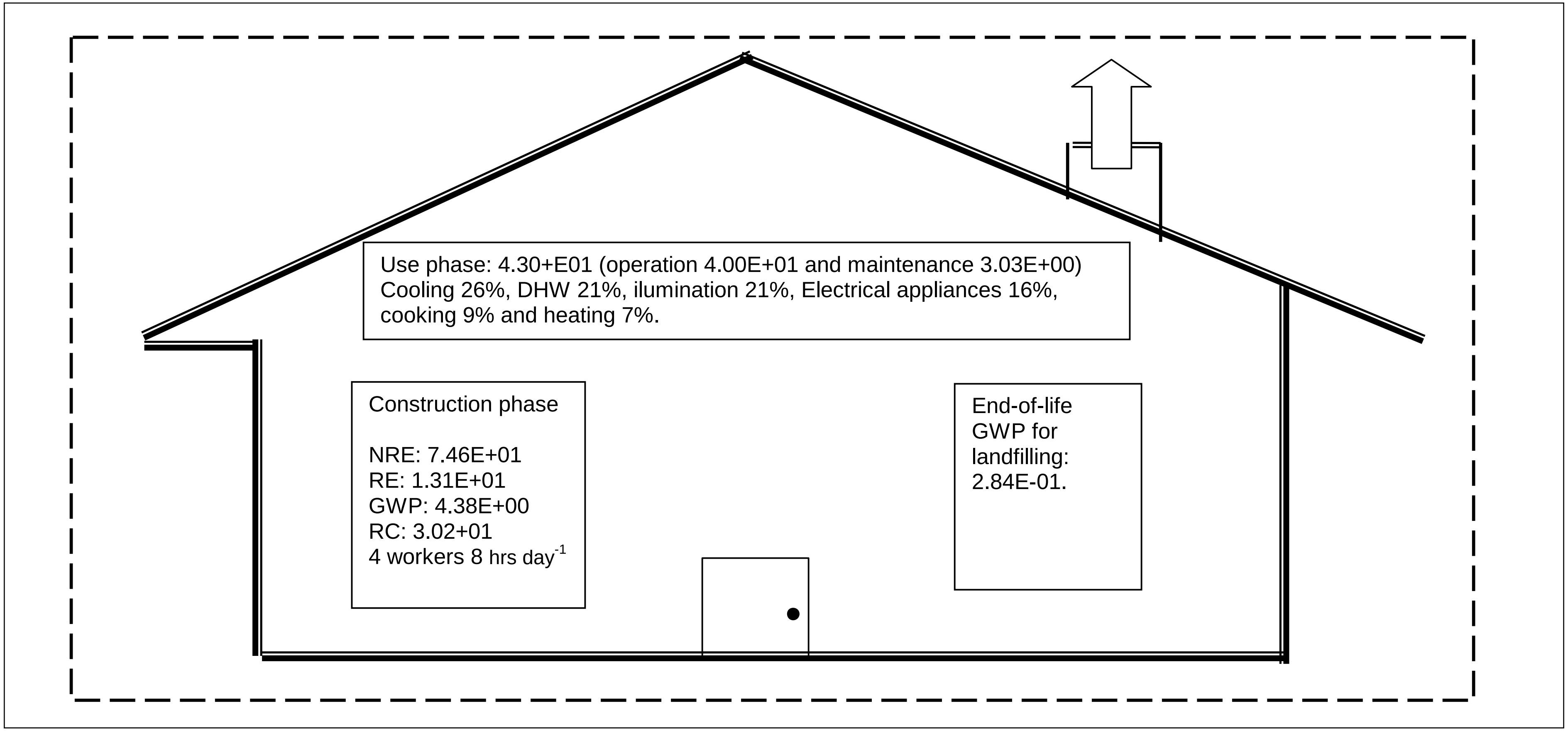
Figure 17 depicts the final sustainability indicators results for the Mediterranean home using 100% electrical during the full building life cycle. As can be seen in the figure, the total impact of global warming potential (GWP) was 4.66E+01 kg CO_2-Eq m^{-2} y^{-1} of which the use phase accounted for 92% (operation 86% and maintenance 6%), construction phase represented 7% and end-of-life phase contributed less than 1%.

Figure 17: Resume of environmental impact results for the Mediterranean dwelling life cycle.



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8.1.3 Initiatives to improve sustainability indicators for the Mediterranean home

Life cycle thinking can be applied to the whole building process, thus making it possible to improve sustainability indicators. For example, a proper design and choice of building materials during the construction phase can improve the energy efficiency during the operation phase and the final distribution of buildings' consumption for heating and cooling. Also applying strategies during the operation phase, such as making changes in consumption patterns, would improve consumption for illumination and household equipment in terms of energy and environmental considerations. Therefore, building materials and patterns of consumption have been specifically dealt. This has meant government policies have been applied to reduce the final energy demand and environmental impacts without compromising quality and the healthy indoor environment for users. The activities that are involved during the operation phase may include direct and indirect patterns. For instance, direct patterns may relate to energy consumption resulting from leaving blinds open or replacement an equipment. Indirect patterns may include the whole process of producing, transmitting, transforming and distributing the electricity needed to meet the energy consumption of every Spanish household.

The present section has particularly dealt with GWP because of its importance within the construction industry both globally and locally and because it is an environmental impact that affects the whole planet. For instance, Spain's second National Allocation Plan (NAP) for 2008 - 2012 (approved by Royal Decree 1370/2006 of 24 of November) has assigned emission rights for the first commitment period, limiting to +37% greenhouse gas (GHG) emissions compared to the base year. Given that Spain is allowed to increase its emissions by only 15% above 1990 levels in order to comply with Spain's Kyoto Protocol (KP) commitment, the remaining reductions in GHG emissions will be obtained via carbon sinks (2%) and emission trading (20%) [Lazaro-Touza, 2008]. Locally, the Catalan office for Climate Change created by Decree 573/2006 on 19 December is to provide technical support for the Interdepartmental Climate Change Committee in seeking to reduce environmental impacts and implement climate change policies to mitigate its effects and find the most appropriate formulas for adaptation [Framework Plan for Mitigation of Climate Change in Catalonia, 2009]. Then, Catalunya's emissions reduction objectives are calculated on basis of Spain's KP target (+15% under EU burden sharing), as well as the commitments under the EU Emission Trading Scheme (ETS) for sectors concerned [The climate group of Catalonia, 2009].

Therefore, this part gives initiatives in the distribution of building's consumption and also some of the matters that should be taken into account when trying to improve sustainability indicators for Mediterranean residential dwellings mainly in three scenarios:

Scenario 1: building materials and consumption patterns,

Scenario 2: New envelope components to composite wall, and

Scenario 3: Waste management.

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8.1.3.1 Scenario 1: Building materials and consumer patterns

This part addresses the question of whether there is an environmental advantage in using Material A instead of Material B and compares the reference house with three different cases. Regarding the heat transfer coefficient (U-values) of the base case, the limit values given by the aforementioned CTE code have been taken into account. Table 26 presents the U-values used in this study and table 27 summarizes the description of each case.

Table 26: Reference house (base case) and cases versus requirements in the CTE

System		Base case U-values $W(m^{-2}.K)$	Case 1 U-values $W(m^{-2}.K)$	Case 2 U-values $W(m^{-2}.K)$	Case 3 U-values $W(m^{-2}.K)$	U- values limit CTE $W(m^{-2}.K)$
Wall		0.38	0.60	0.38	0.38	0.73
Roof		0.40	0.40	0.40	0.40	0.41
Floor		0.48	0.48	0.48	0.48	0.50
Windows	North	3.22	3.22	3.22	2.06	3.40
	W/E	3.22	3.22	3.22	2.06	3.90
	South	3.22	3.22	3.22	2.06	4.40

Table 27: Description of the base case versus each case

Parameter	Base case	Case 1	Case 2	Case 3
Insulation	External walls using 4 cm thick expanded polystyrene.	External walls using 8 cm thick expanded polystyrene.	X	X
Blinds	Aluminium window blinds with medium reflectivity slats located on the outside of the windows.	X	Blinds are closed during the night if there is a heating demand and open during the day if there is a cooling demand.	X
Windows	Clear glass on the internal side of the window.	X	X	Windows with low-emissivity glass.

Materials of the base case were described in table 6 in chapter 6 section 6.3.1.1. The first case (case 1) was to vary the insulation of the external walls using 8 cm thick expanded polystyrene (4.64E+02 kg) instead of 4 cm (2.32E+02 kg). Results showed a 2.02% increase in the overall greenhouse gas emissions during construction phase due to increased quantities of materials but there is a reduction of 3.66E-01 kg CO_2-Eq m^{-2} y^{-1} because the energy demand for heating decreases by 20.7%; result that is in the same order of magnitude with the study performed by Cuchi and Wadel, 2007.

In the second case (case 2), window blinds are evaluated. In this case, user behavior regarding the blinds is also taken into account. These are aluminum blinds with medium reflectivity slats located on the outside of the windows. Here, we study two different alternatives. Alternative 2a represents a passive user where blinds are always closed. This means that they reduce the solar heat gains in summer but also in winter, leading to a significant reduction in the cooling demand but also a major increase in the heating demand in winter. In alternative 2b user behavior is optimal. Blinds are inside and are closed during the night if there is a heating demand and open during the day if there is a cooling demand. This reduces the cooling demand in summer by reducing solar gains and reduces heat losses through the windows at the night during the winter. Values of energy demand in alternatives 2a and 2b are presented in table 28.

Table 28: Effect of using window blinds

	Base case	Alternative 2.a	Alternative 2.b
Energy demand for heating (kWh m^{-2} y^{-1})	2.09E03	2.04E03	2.19E03
Energy demand for cooling (kWh m^{-2} y^{-1})	5.97E03	4.00E03	5.73E03
Energy savings - heating (%)	-	2.0%	-5.0%
Energy savings - cooling (%)	-	33.1%	4.0%
Energy savings - heating + cooling (%)	-	25.1%	1.7%

In this case, GWP emissions had an increase of 2% of the total phase (especially significant emissions of PFCs with about 90%) due to the production of aluminium for the blinds (4.80E+01 kg). Nevertheless, even if this alternative presents a fairly high value of CO_2-Eq when compared to the base case, it is demonstrated that it can be a good alternative because of its high energy savings during the operation phase.

The application of alternatives 2a could reduce this impact to about 9% CO_2-Eq m^{-2} per year. These results demonstrate the importance of using appropriate building design practices for energy saving during the operation phase. Nevertheless, it is obvious that this type of action must be accompanied by changes in behaviours patterns on the part of the user to reduce the remaining part of the household energy and not depend on the building design. Then, consumption patterns play an important role in savings and sustainability indicators in the operation phase for every aspect of energy consumption. For example, good patterns of use by consumers and users are indispensable for reducing environmental impacts. The advantage of changing users' behaviour is that there is no additional cost for this strategy. Energy saving strategies are, for example, not leaving windows open and using blinds correctly and could lead to energy consumption being reduced by up to 25.1% and 1.7% respectively, and save an average of 1.06E+02 kg CO_2-Eq m^{-2} during the occupation in environmental loads which represents a savings of 5% in relation to the impact of the house analysed.

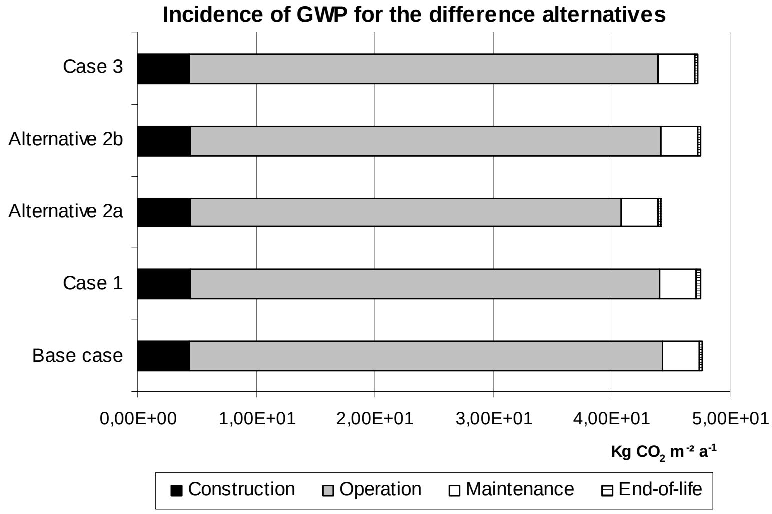
In the third case (case 3) windows with low-emissivity glass were used instead of clear 3mm glass (base case) on the internal side of the window, as shown in table 29.

Table 29: Variations in the windows' characteristics

	Base case	Alternative 3
Outside pane	Clear 3 mm	Clear 4 mm glass
Air gap	Air gap	Air gap 12 mm
Inside pane	Clear 3 mm	Low-Emissivity 4 mm glass

As a result, windows with low-emissivity glass have a lower heat transfer coefficient (U-value) than the conventional windows of the base case, reducing the energy demand of the building for heating and cooling by 2.2 % and 3.1 % respectively; and leading to a reduction in the corresponding CO_2-Eq emissions of 4.10E-02 kg of CO_2-Eq m^{-2} y^{-1}. Figure 18 shows the effect of the full dwelling life cycle on GWP. Therefore, it can be observed that in all the options the most significant impact comes from the operation phase and the best alternative to reduce CO_2 emissions is the application of alternative 2a.

Figure 18: Incidence of GWP for the difference alternatives (Mediterranean home).



Therefore, the energy demand can be optimized and emissions can be reduced of a building during its operational phase by design parameters and good behaviours patterns. However, whether the same U-value (design parameter) is achieved using one material or another (as for example expanded polystyrene rather than mineral wool or "greener" materials like natural fibers) makes no difference in the annual energy demand. Achieving a low energy design is not a matter of choice of material but the best way to reduce the energy use in Spain would be reducing the cooling load by means of passive measures such as better control of shading devices, natural ventilation and material use for thermal mass.

On the other hand, illumination is strictly dependent on consumption behaviour, so the reduction and initiatives taken could only be in the area of energy efficiency. Some of the following are proposals to achieve this.

a. Lighting: use sunlight as much as possible and turn off lights whenever not strictly needed. Together these alternatives will be lead to an overall reduction of 15% of the final annual energy consumption.

b. Lighting equipment: install sensors at indoor and outdoor sites and use suitable lighting throughout the dwelling; lighting energy needs for bedrooms is estimated at 10W m^{-2} and living rooms and at 20 W m^{-2} for kitchens, using incandescent lamps. If fluorescent lamps are used then the energy

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requirements are 4 to 5 W m^{-2} in bedrooms and 7 to 10 W m^{-2} in kitchens. It is estimated that installing suitable lighting throughout the dwelling will cost approximately 100€. However, the resulting savings are estimated at 10% of the annual lighting energy consumption.

c. For cooling and heating, combining building products and components for insulation can reduce environmental loads by almost 1.83E+01 $kgCO_2$-Eq m^{-2} y^{-1}. However, in order to achieve this, the owner faces an additional investment cost of about 4.800€. Regarding energy savings, heating would have a positive balance while cooling would be negative. Other aspects that have been taken into consideration are the use of windows with low emissivity glass. Here, heating and cooling accounted for a total energy saving of 2.9%. Table 30 shows some good initiatives of residential dwellings within the Spanish building sector.

Finally, in this research, we did comparative LCA analyses of single buildings to assess the environmental impact during the full building life cycle. For instance, Blanchard and Reppe, 1998 analysed the total life cycle energy consumption and the global warming potential (GWP) of a standard home of 227.8 m^2. The life cycle GWP was 8.88E+01 $kgCO_2$ m^{-2} y^{-1}. Adalberth et al, 2001, evaluated the life cycle of four dwellings located in Sweden with different construction characteristics. The results concluded that global warming potential was approximately 3.00E+01 $kgCO_2$ m^{-2} y^{-1} for all buildings. Peuportier, 2001 compared three types of house with different specifications located in France and results showed that the amount of $KgCO_2$-Eq m^{-2} y^{-1} emitted during their 50 year life cycle was approximately 4.20E+01. In our studied home the significant environmental issue of GWP, there was a total emission of 4.75E+01 $kgCO_2$-Eq m^{-2} y^{-1} during the full building life cycle. Then, our dwelling home studied has GWP emissions in the same order of magnitude of previous homes with similar energy consumption.

Previous results shows that the phase with the highest environmental impact is the use phase with approximately 90% (operation with 84% and maintenance with 6%) of the life cycle's total, while the construction phase accounted for a total of 9% and the end-of-life phase represented about less than 1%. Nevertheless, even if the contribution of the construction phase is low compared with values of the whole life cycle, this phase cannot be neglect because of the negative environmental impacts on the environment due to the excessive consumption of building materials, water consumption and the improper waste management. Then, the following scenario give some design initiatives to composite walls to improve sustainability for future construction possibilities that allows decisions to be made at the draft stage on the choice of materials and constructive solutions.

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Table 30: Initiatives of residential dwellings within the Spanish building sector.
Functional unit (one square meter of living area of a dwelling with a projected 50 years lifespan)

Phase	Aspect		Normal behaviour Reference house	Proposed behaviour	Annual energy savings			Annual economic savings		Environmental savings	Social cost aspect
					k Wh / FU		Total energy savings demand (%)	II (€)	PP (years)	$kgCO_2$ Eq m^{-2} y^{-1}	Labor (per 1 worker)
C	IS	D	External walls using 4 cm thick expanded polystyrene.	External walls using 8 cm thick expanded polystyrene.	20.7 [b] SHD	-2.3 [b] SCD.	3.6	4800	>50	3.66E-01	12€ m^{-2}
C	IS	D	Clear glass on the internal side of the window.	Windows with low-emissivity glass.	2.2 [b] SHD	3.1 [b] SCD.	2.9	10141	>50	4.10E-01	12€ m^{-2}
U	UB	D	Leaving windows open carelessly.	Taking care to close windows.	2.0 [b] SHD	33.1 [b] SCD.	25.1	0	-	3.96E+00	0
U	USH	D	Aluminium window blinds with medium reflectivity slats located on the outside of the windows.	Blinds are closed during the night if there is a heating demand and open during the day if there is a cooling demand.	-5.0 [b] SHD	4.0 [b] SCD.	1.7	0	-	2.92E-01	0
U	E	IN	Electrical cooker.	Gas cooker.	450 [a]		42.2	700	8	1.15E+02	14€ h^{-1}
U	DHW	IN	Electrical heater.	Boiler of natural gas.	-220 [a]		-8.5	1200	-	6.14E+02	14€ h^{-1}
M	R	D	Cooker: dirty or clogged orifice.	Clean burner orifice.	100 [a]		9.4	0	-	1.90E+01	0
M	IL	D	Illumination not adequate.	Proper illumination.	80 [a]		3.1	100	11	4.60E+01	0

Abbreviations
C: Construction U: Use M: Maintenance IS: Insulation SCD: Saving cooling demand
E: Equipment IN: Indirect patterns D: Direct patterns R: Repairs SHD: Saving heating demand
USH: Use of solar heating UB: User behaviour a: Measured in k Wh electric IL: IlluminationII: Initial investment
DHW: Domestic hot water FU: Functional unit b: Measured in k Wh thermic PP: Payback period

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8.1.3.2 Scenario 2: New envelope components to composite walls

This part was carried out in collaboration with the Construction Technological Centre (iMat). Barcelona, Spain[*2]. This scenario 2 compares the different combinations of real construction techniques for external and internal walls whilst taking into account the environmental and economic aspects. The scenarios under study have been divided into two main groups: eight external walls (Vertical external enclosures (VEE), such as facades) and seven internal walls (Vertical Interior Enclosures (VIE), such as partition walls). Each VEE is the result of the combination of external layers (EL), insulation materials with (IM+AC) or without air chamber (IM) and internal layers (IL). Each VIE is a combination of internal layers (IL) and insulation materials without air chamber (IM). The Ref VEE scenario represents the material combination in the reference building, while the rest of VEE scenarios are alternative combinations containing different insulation materials, types of bricks and structural blocks. The VIE alternatives represent different combinations for rooms separation walls (1-A1 and 2-A2), humid areas separation walls (3-B1 and 4-B2), and building common areas separation walls (5-C1, 6-C2 and 7-C3). The alternatives present in the reference building correspond to the first option of each type (1-A1, 3-B1 and 5-C1 scenarios), while the rest of the scenarios are alternative combinations. Final combinations for VEE and VIE are summarized in table 31 and table 32 respectively.

Table 31: External wall (VEE) details regarding material combination.

Item	Combination		
	External Layer (EL)	**Internal Layer (IL)**	**Insulation materials without chamber (IM)**
Ref	**02** (Drilled brick, 14 cm think). **11** (Mortar single layer).	**01** (Simple hollow brick, 4cm thick). **03** (Double hollow, 14cm thick).	**01** (Polyurethane, 4cm thick).
3A-1	**02** (Drilled brick, 14 cm think). **11**(Mortar single layer).	**01** (Simple hollow brick, 4cm thick). **03** (Double hollow, 14cm thick).	**02** (Extruded polystyrene, 4.5cm thick).
3A-2	**04** (Hollow brick, 14 cm thick). **11** (Mortar single layer).	**01** (Simple hollow brick, 4cm thick). **03** (Double hollow, 14cm thick).	**02** (Extruded polystyrene, 4.5cm thick).
3B-1	**10** (Light clay block, 24 cm thick). **11** (Mortar single layer). **18** (Steam barrier).	**06** (Plaster board partition).	**05** (Rock wool, 6cm thick)
3B-2	**07** (Expanded clay block, 25 cm thick). **11** (Mortar single layer). **18** (Steam barrier).	**06** (Plaster board partition).	**05** (Rock wool, 6cm thick)
3C-1	**02** (Drilled brick, 14 cm think). **12** (Mortar coating layer, 10 – 15 cm thick).	**01** (Simple hollow brick, 4cm thick). **03** (Double hollow, 14cm thick).	**02** (Extruded polystyrene, 4.5cm thick).
3C-2	**02** (Drilled brick, 14 cm think). **12** (Mortar coating layer, 10 – 15 cm thick).	**06** (Plaster board partition).	**02** (Extruded polystyrene, 4.5cm thick).
3D-1	**08** (Expanded clay block, at sight, 25 cm thick). **12** (Mortar coating layer, 10 – 15 cm thick). **18** (Steam barrier).	**06** (Plaster board partition).	**05** (Rock wool, 6cm thick)

[*2] iMAT. Construction Technology Centre. Wellington 23. 08018. Barcelona. Spain

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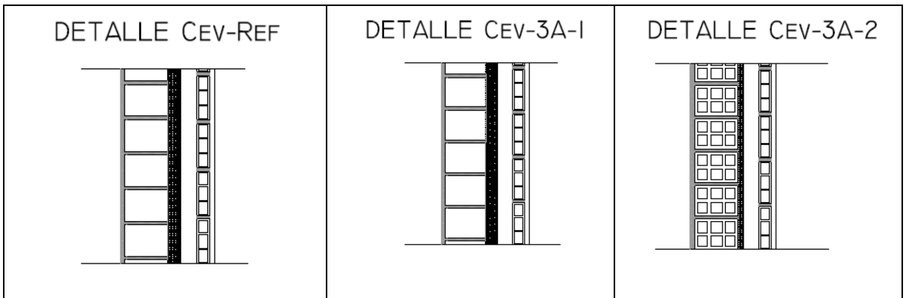
Table 32: Internal wall (VIE) details on material combination.

Item	Combination	
	Internal Layer (IL)	**Insulation materials without chamber (IM)**
1- A1	**01** (Simple hollow brick, 4cm thick). **05** (Rendering).	-
2- A2	**11** (Rolled plaster board, over steel structure, 1.5 cm thick): 2 units **12** (Galvanised steel structure).	**01** (Glass wool, 5cm thick)
3- B1	**02** (Double hollow brick, 10 cm thick). **05** (Rendering). **06** (Mortar coating layer) **07** (Tiled with mortar, 26 – 45 units/m^2	-
4- B2	**08** (Tiled with glue, 26 – 45 units/m^2 **11** (Rolled plaster board, over steel structure, 1.5 cm thick): 2 units **12** (Galvanised steel structure).	**01** (Glass wool, 5cm thick)
5- C1	**05** (Rendering). 2 units. **04** (Drilled brick, 14 cm thick).	-
6- C2	**11** (Rolled plaster board, over steel structure, 1.5 cm thick): 5 units **12** (Galvanised steel structure): 2 units.	**01** (Glass wool, 5cm thick): 2 units.
7- C3	**11** (Rolled plaster board, over steel structure, 1.5 cm thick): 4 units **12** (Galvanised steel structure): 2 units. **13** (Corrugated steel sheet).	**01** (Glass wool, 5cm thick): 2 units.

Figure 19 shows the typical section drawings of external wall (VEE) and figure 20 illustrates the internal wall (VIE) studied. The descriptions of the scenarios are based on real construction techniques taking into consideration the Spanish technical construction code. Annex 3 illustrates the architectonic drawing of the VEE studied and the engineering specifications.

Figure 19: Typical section drawings of external wall (VEE)



External wall (VEE) reference.	External wall (VEE) 3A-1.	External wall (VEE) 3A-2.

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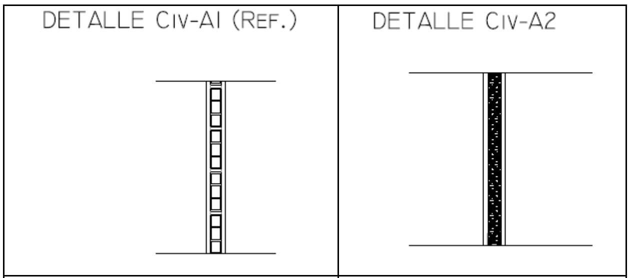
Figure 20: Typical section drawings of internal wall (VIE) studied



Internal wall (VIE). 1- A1	Internal wall (VIE). 2- A2

Evaluation of the composite walls

The complete environmental profiles for the eight VEE combinations and the seven VIE combinations are detailed in table 33 and table 34 respectively.

Table 33: Sustainability profiles for VEE scenarios (m^{-2} y^{-1})

System analysed	Ref	3A1	3A2	3B1	3B2	3C1	3C2	3D1
AP (kg SO_2-Eq)	3.60E-03	3.20E-03	2.40E-03	4.40E-03	1.40E-02	3.20E-03	4.80E-03	1.42E-02
GWP (kg CO_2-Eq)	1.36E+00	1.42E+00	1.06E+00	1.36E+00	2.34E+00	1.40E+00	1.48E+00	2.34E+00
RC (kg)	7.50E+00	7.44E+00	6.12E+00	7.50E+00	6.80E+00	7.40E+00	6.04E+00	6.82E+00
TE (MJ)	1.58E+01	1.48E+01	1.12E+01	3.48E+01	2.94E+01	1.47E+01	1.78E+01	2.96E+01
RE (MJ)	1.22E+00	1.14E+00	9.00E-01	1.37E+01	1.16E+00	1.14E+00	1.20E+00	1.16E+00
NRE (MJ)	1.45E+01	1.36E+01	1.03E+01	2.10E+01	2.82E+01	1.35E+01	1.66E+01	2.84E+01
WC (m^3)	1.24E-01	1.16E-01	1.20E-02	1.60E-02	2.40E-02	1.16E-01	1.24E-01	2.40E-02
Total cost of the scenario (€ m^{-2})	7.55E+01	7.37E+01	7.06E+01	7.74E+01	7.36E+01	6.77E+01	7.23E+01	6.93E+01
Labor cost (€ h^{-1})	1.40E+01	1.40E+01	1.40E+01	1.40E+01	1.40E+01	1.40E+01	1.40E+01	1.40E+01

Table 34: Sustainability profiles for VIE scenarios (m^{-2} y^{-1})

System analysed	1-A1	2-A2	3-B1	4-B2	5-C1	6-C2	7-C3
AP (kg SO_2-Eq)	8.00E-04	2.80E-03	2.60E-03	4.40E-03	2.00E-03	5.80E-03	5.40E-03
GWP (kg CO_2-Eq)	3.00E-01	4.60E-01	8.60E-01	9.00E-01	8.00E-01	1.02E+00	9.40E-01
RC (kg)	2.20E+00	8.40E-01	4.76E+00	1.62E+00	5.28E+00	1.98E+00	1.68E+00
TE (MJ)	3.66E+00	8.88E+00	1.14E+01	1.69E+01	8.98E+00	1.95E+01	1.79E+01
RE (MJ)	3.60E-01	5.20E-01	8.00E-01	8.80E-01	8.40E-01	1.14E+00	1.04E+00
NRE (MJ)	3.32E+00	8.36E+00	1.06E+01	1.60E+01	8.16E+00	1.83E+01	1.69E+01
WC (m^3)	3.20E-03	1.16E-02	1.22E-02	2.22E-02	7.00E-03	2.48E-02	2.34E-02
Total cost of the scenario (€ m^{-2})	2.23E+01	4.08E+01	5.86E+01	5.94E+01	3.58E+01	9.49E+01	9.86E+01
Labor cost (€ h^{-1})	1.40E+01	1.40E+01	1.40E+01	1.40E+01	1.40E+01	1.40E+01	1.40E+01

The impacts for the acidification generated by the different combinations are similar. However, combinations containing steel (especially galvanised steel) among their materials have a higher impact due to high emissions made during the steelmaking process and galvanization. Considering global warming potential indicator, we observe that the alternatives that contain steel have the highest emissions followed by those that contain large amounts of that have a high weight of prefabricated blocks, mortar, expanded clay and glazed pottery.

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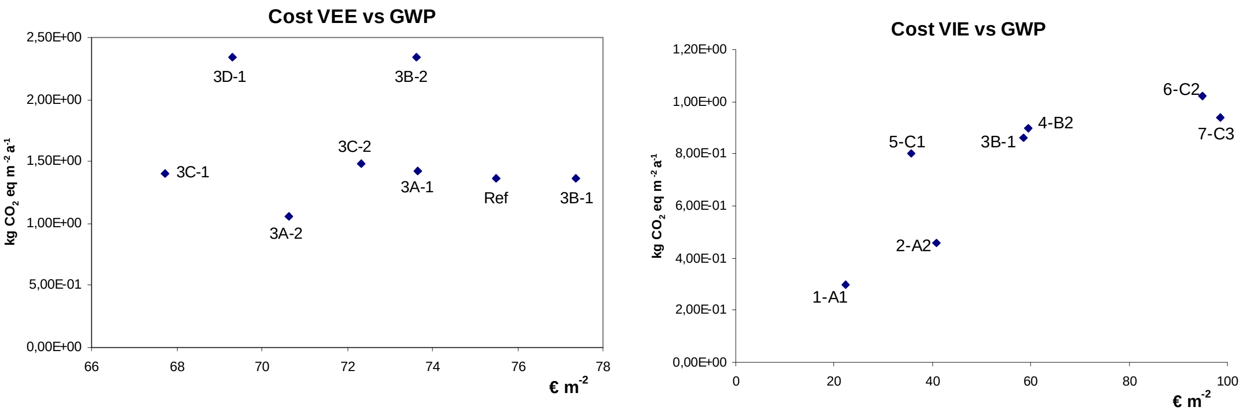
Comparing the resources consumption and the materials consumption at the building site, it can be seen that the efficiency is similar for all alternatives and that the use of resources is proportional to the materials consumed at the building site. On the other hand, analysing the use of energy, it can be observed that all the alternatives use more non-renewable than renewable energy while the scenarios that contain steel have the highest total energy consumption. The water consumption is higher for those alternatives that contain lime as a material followed by those containing galvanized steel.

Comparing the cost of different alternatives with their impact on GWP, it appears that the VIE designs have an almost linear tendency which leads to the conclusion that the more economic alternatives are those that have less impact while in the VEE designs there is no clear trend due to the similarity in cost between alternatives, see figure 21.

Figure 21: Cost versus GWP impact for the different composite walls.



Finally, giving special relevance to the impact on GWP and resource consumption these particular results have been plotted in figure 22 and figure 23.

Figure 22: Total environmental profiles of 8 VEE combinations.

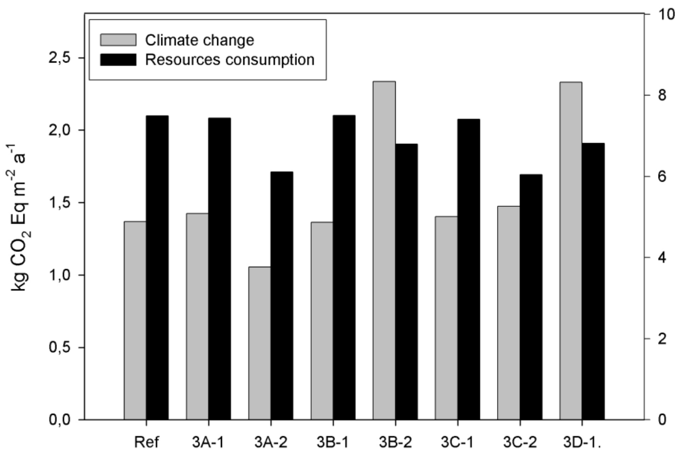
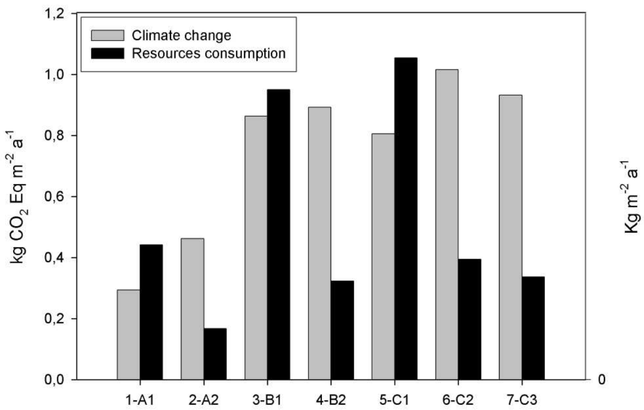


Figure 23: Total environmental profiles of 7 VIE combinations.



__**Evaluation of the construction waste management of this scenario**__

Here, we also study the contribution of the waste management resulting from the disposal of material and packaging wastes and comparing with different treatment scenarios such as land filling, incineration and recycling.

Results in impacts on global warming potential and resources consumption are showed in figure 24, figure 25, figure 26 and figure 27 respectively. The global warming potential indicator shows that the disposal in landfill is the worst treatment of waste management for most of the scenarios while incineration and recycling show environmental benefits due to the energy production and material saving respectively. It is also observed that for those scenarios that contain glass wool as insulating material (2-A2, 4-B2, 6-C2, 7-C3) and plastic packaging waste, the best option is recycling. When analyzing resources consumption, it can be concluded that recycling is the best environmental option for all the building scenarios due to the material recovered, while incineration and landfill present similar results.

Comparing the different waste management scenarios shows that incineration is the best environmental option for most impact categories except for resource consumption where the best option is recycling. When comparing combinations of VEE and VIE, it appears that those that contain hazardous waste have a high credit of energy in the incineration process due to the high heat capacity of these wastes. In combinations containing plastic waste, recycling is the best environmental option. Nevertheless, the amount of energy recovered could be minor significance in comparing with the global environmental load.

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Figure 24: GWP impact for the waste management within VIE scenarios.

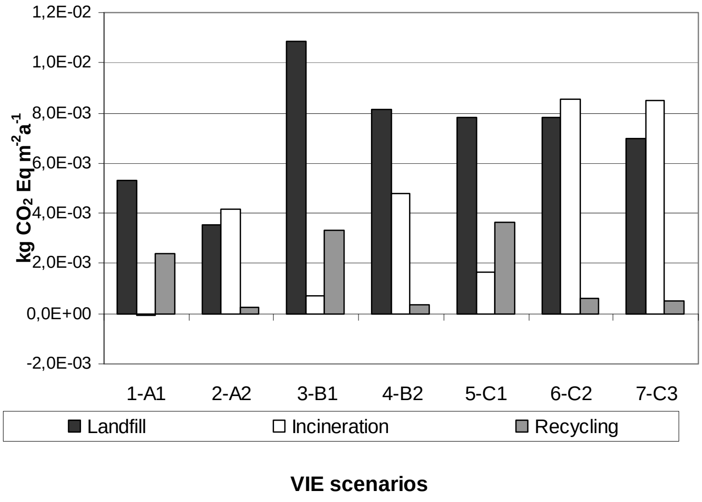

Figure 25: GWP impact for the waste management within VEE scenarios.

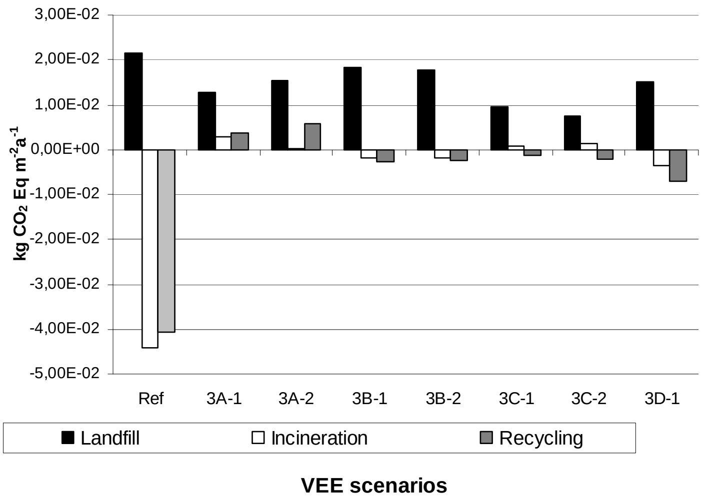

Figure 26: Resources consumption VIE scenario.

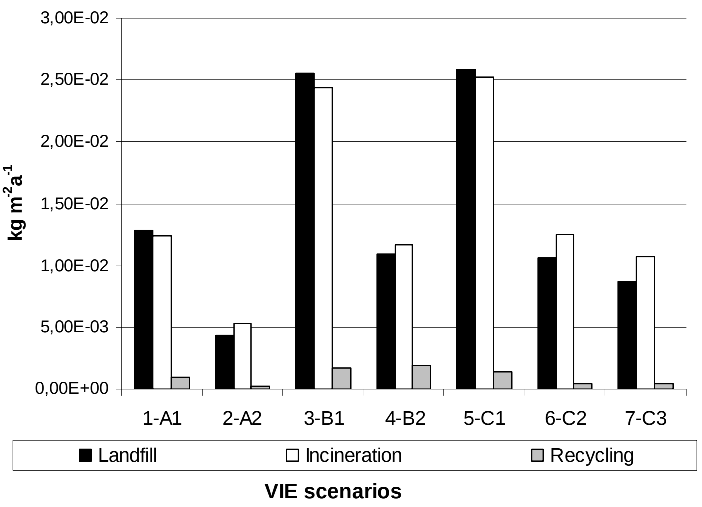

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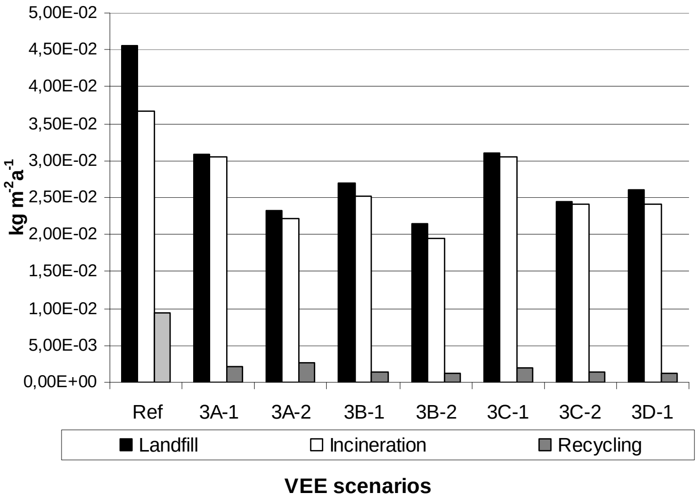
Figure 27: Resources consumption VEE scenario.

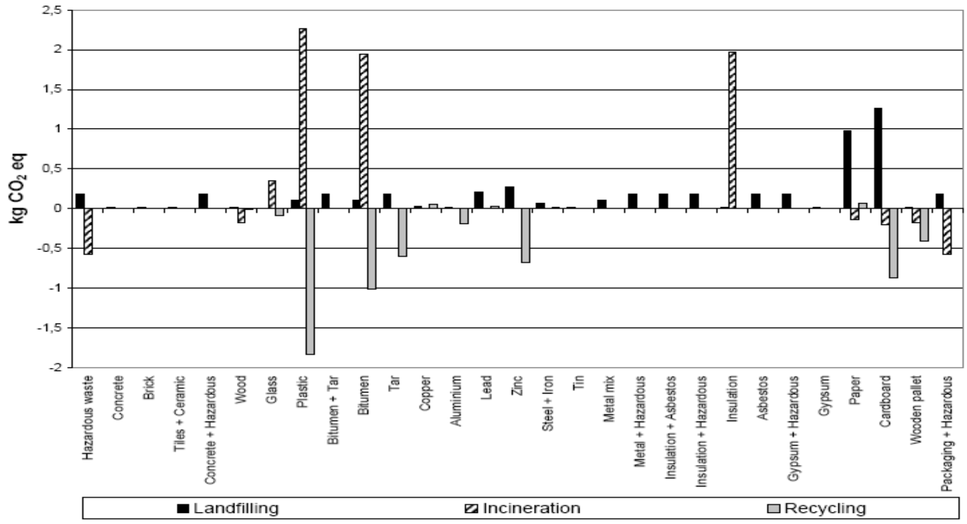


By concluding in this scenario 2, we observed that CO_2 emissions are higher for the pre-fabricated elements than for when similar components are used at the building site. Besides, the combination of materials analysis and waste management reflects the importance of recycling materials that generate a high environmental impact during their fabrication. According to the materials selection, the highest environmental impact results from the use of steel (2-A2, 4-B2, 6-C2, 7-C3) especially galvanised steel (6-C2). This is true for most of the environmental categories studied but especially for acidification and energy consumption.

The use of lime increases the overall water consumption. Energy consumption is higher in the scenarios that use galvanised steel, however the relation between renewable and non-renewable energy use is similar in all the scenarios. In summary, the selection of material combinations during the project phase on the basis of the LCA results helps to select those combinations that have the lowest environmental impact, or which use the lowest amount of material at the building site, thus generating lower amounts of waste and reducing the environmental impact of transporting the materials.

Finally, it can be stated that the incineration and recycling scenarios reduce the environmental impacts because of the savings in energy production and raw-materials. Incineration is recommended due to the high energy content of the waste, while recycling is recommended for inert and non-special wastes, especially for plastic packaging. Figure 28 summarizes the GWP of 1kg of different construction and demolition wastes when they are disposed of in landfill, incineration (those which are incinerable) and recycling (those which are recyclable).

Figure 28: GWP indicator for the management of 1kg of each type of waste.



When similar amounts of each type of waste are compared, we can observe that landfilling paper and cardboard is the major contributor to GHG emissions due to the gases emitted during decomposition of these wastes. The incineration of plastics, bitumen and insulation materials emit more GHG gases than the avoided emissions due to the energy produced. Incineration of hazardous construction wastes, wood, paper and cardboard presents credit due to the energy recovery. We can also observe that the recycling of most of all construction wastes that are recyclable is beneficial for the environment as many of them have negative GWP results while others have impacts lower than that of the landfilling or incineration scenarios. Therefore, classifying construction wastes in situ and promoting the recycling of building materials are very important options for waste management and reduction. This is especially important for waste materials such as plastic, wood, metal, paper and glass because these materials can be easily recycled.

Influence of the transport

The influence of transport has been also evaluated. Then, having the data for the distance from the origin of waste to the plant in table 12 “overview of the waste management and difference scenarios”, they are used for comparing influence of transport. For instance, landfills are usually close to building sites whereas recycling and incineration plants can often be further from them. Thus, we have determined how the distance from the building site to the treatment plants influences the treatment of the different type of wastes. The waste was considered to be transported entirely by trucks with a capacity of 16 tons. Considering an emission of 3.30E-04 $kgCO_2$ per kg of waste transported in 1km, we have calculated the additional km that are needed for the incineration and recycling plants in order to reach the GHG emissions of the landfill process. This calculation has been done for those wastes that present lower GHG emissions for the incineration or recycling process in comparison to the landfilling. We have also considered that wastes will not probably be transported for long distances (for example, higher than 300 km), as there are several incineration and recycling

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plants located in Spain and particularly in Catalonia, and because transport costs may not allow such long distance transport for wastes.

Table 35 summarizes the maximum distances recommended from the landfill facility to the incineration and recycling plants based on the GWP indicator. According to the results, incineration of hazardous construction wastes, wood, paper and cardboard is always recommended instead of landfilling given the long distances to which incineration is better than landfilling in terms of GHG emissions. Recycling of timber and stone waste is recommended when the recycling plant is not far from the building site. However, we should mention that the most environmentally friendly option for stone waste should be the recycling “in situ” if they can be used as gravel replacement at the building site. In this case, transport of such amounts of wastes should be avoided. For the rest of the recyclable wastes evaluated, recycling is always the recommended option as the maximum distances calculated are high enough to be considered as long distances.

Table 35: Influence of waste management plants locations and transport, according to the GWP indicator (cut-off criteria >300km).

Maximum distance from landfill to treatment plant		
Building material waste	**Incineration Plant (km)**	**Recycling Plant (km)**
Concrete	-	42
Brick	-	42
Tiles + Ceramic	-	42
Timber	577	53
Glass	-	265
Steel + Iron	-	164
Sealing	-	30
Gypsum	-	42

8.1.3.3 Scenario 3: Waste management

Within the European Union, more than 450 million tons per year of construction and demolition waste is generated, this being the largest waste stream in quantitative terms, apart from mining and farm wastes [European Commission, 2000]. For instance, in many countries, the large volumes of construction and demolition waste have put a strain on landfill capacities and have led to environmental concerns [Esin and Cosgun, 2007]. However, construction waste has a very high recovery potential as 80% of this waste can be recycled, although only a small proportion is actually recovered in the European Union as a whole. Currently, 75% of waste is being landfilled, although 80% recycling rates have been achieved in countries such as Denmark, the Netherlands and Belgium [Erlandsson and Levin, 2005]. In Spain, about 40 million tonnes of waste are produced every year, representing 32% of the total volume of waste generated. Because of the magnitude of this ratio, the Spanish government would like to recycle or reuse 40% of the total waste generated, although <5% is a more realistic recycling rate achieved. In Catalonia in 2003, 6.3 million tonnes (approximately 1.000 kg/inhabitant) of construction waste was recovered at approved recovery plants, transfer plants and warehouses [Waste management of Catalonia, 2006]. Most of these wastes are currently disposed of by landfill, thus occupying a volume which clearly exceeds that occupied by domestic wastes. However, better alternatives have already been adopted such as reusing, recycling and reducing waste generation by controlling aspects such as design quality, applied technology and habitual construction methods [Rodriguez et al, 2007].

Other waste management methods, such as incineration with energy recovery whenever possible, seem to be appropriate options, whereas landfills are only considered as a last alternative. Nevertheless, incineration involves processes such as sintering which continue to generate ash, residuals, non-combustibles and other elements which must be safely landfilled due to their toxic potential [A policy statement on the incineration of municipal waste, 1996].

Directives and legislation have been drawn up globally and locally to reduce and manage wastes. In this respect, the European Union has also published directives and legislations for waste management. For example, the Directive 2006/12/EC was created by the European Union to push for improvements relating to the production and management of waste. This policy encouraged the use of strategies such as recycling, recovery or any other action to obtain secondary raw materials, as well as promoting the use of waste as an energy source. Locally, in Catalonia the management of waste follows European Union guidelines which prioritize waste reduction and evaluation. For instance, the project LIFE98 ENV/E/351 is aimed at increasing environmental awareness in the construction industry, particularly in terms of controlling and reducing the heterogeneous composition of the waste generated, both in manufacturing (construction and rehabilitation of buildings) and demolition.

With the possible exception of prevention, there are potential environmental impacts regarding previous directive for waste management. Then, Life Cycle Assessment (LCA) methodology is one of the current well established methods to provide solid waste planners and decision makers with an excellent framework to evaluate Municipal Solid Waste (MSW) management strategies [Obersteiner et al, 2007]. According to Birgisdottir, 2004, the broad perspective of LCA makes it possible to take into account the significant environmental benefits that can be obtained through different waste management processes:

- Waste incineration with energy recovery reduces the need for other energy sources,
- Material from recycling processes replaces production of virgin material,
- Residues from waste incineration may replace gravel at road constructions.

There has been a fair amount of research into the generation and management of construction waste [Al-Mutairi and Haque, 2003], [Poon et al, 2002], [Begun et al, 2007]; in Spain, Solís-Guzmán, 2009 analyzed with the Alcores model the waste volume that is expected to be generated on the building site in both new construction and demolition dwelling projects. So far only limited research

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has been published from the point of view of environmental impacts, although some of the first attempts using life cycle waste management perspective have started to appear during the last five years [Berkhout and Howes, 1997] [Wittmaier et al, 2009], [Banar et al, 2009], [Manfredi and Christense, 2009].

Therefore, this scenario focuses on the environmental impacts from a waste management perspective evaluating the environmental loads in the base case of construction waste. Then, three alternatives: landfilling, recycling and incineration, representing the possible options of waste management in Barcelona have been considered taking into account the data supplied in table 12.

Overall results

We have modeled the waste considering the data from the table 12. Table 36 shows the environmental profile for the end-of-life phase for the Mediterranean home comparing three different alternatives of waste management.

Table 36: Environmental profile of the waste management scenarios (m^{-2} y^{-1}) scenarios compared (based on 1m² y^{-1} of constructed area) for the Mediterranean home.

Impact \ Alternative	Incineration_2	Incineration_1	Recycling_1	Recycling_2	Landfilling
AP (kg SO_2 eq)	7.17E-04	1.54E-03	7.83E-05	9.49E-04	1.82E-03
GWP (kg CO_2 eq)	2.39E-01	3.94E-01	-3.12E-02	1.30E-01	2.84E-01
HT (kg 1.4-DCB eq)	5.60E-02	9.93E-02	-3.91E-02	2.76E-02	1.02E-01
SOD	1.38E-08	5.12E-08	-8.45E-10	2.90E-08	5.43E-08
RC (kg)	-5.57E+00	2.06E+00	-1.55E+01	-6.45E+00	2.07E+00
RE (MJ)	-1.67E-01	-5.42E-02	-6.50E+00	-2.63E+00	5.31E-02
NRE (MJ)	-7.39E-01	4.87E+00	-5.49E+00	6.54E-01	6.76E+00
WC (m^3)	-9.72E-03	2.01E-03	-2.27E-02	-8.94E-03	5.07E-03

Due to the avoided loads of the recovered materials, the recycling treatment presents negative values in almost all the impact categories calculated except for AP. We shall remember that negative values mean environmental benefits, as the avoided impact (material recovered) is higher than the generated impact (recycling process and transport to the plant). Waste from construction process present a final beneficial impact meaning that the recycling is the most environmentally friendly from the three compared.

When comparing the landfilling and incineration treatments we observe that except for the GWP indicator, the incineration presents lower environmental impacts than the landfilling. For RE, the incineration presents negative values, and thus, credits to the system. This means that in these cases, the avoided impact (energy generated) is higher than the generated impact (transport to the incineration plant, incineration process and landfilling of ashes). Final recommendations should be to recycle as much wastes as possible, incinerate the rest and landfill when there is no other option.

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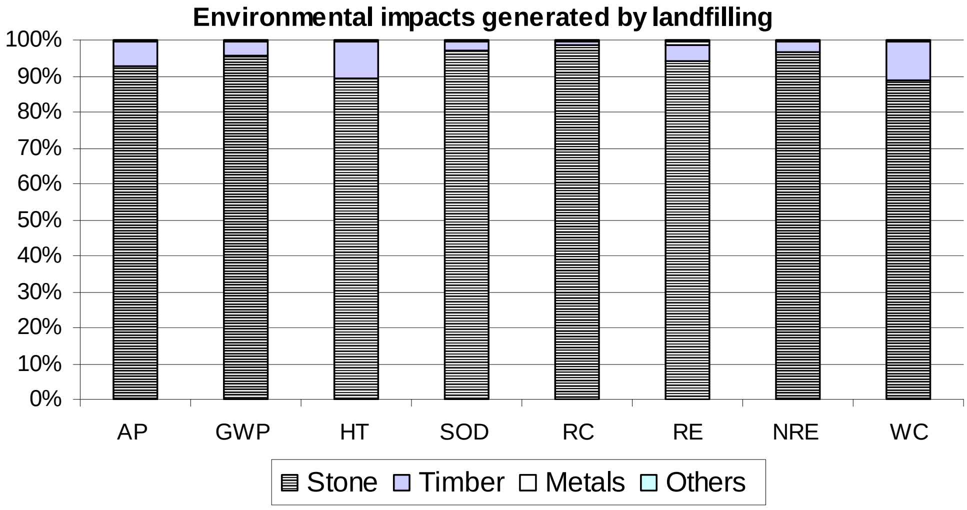
Landfill results

Figure 29 shows the environmental impacts analyzed for the landfilling. The results include the environmental impacts of both the landfill process and transport of the waste to the landfill site. For most of the environmental categories calculated, stone waste is the mayor contributor to the impact of the construction process wastes landfilling, followed by timber, others waste (insulation materials), and finally metals. This is due to the high amount of this type of waste that is generated.

Figure 29: Total environmental profile for the landfilling of construction process waste (Mediterranean home).



Recycling results

Figure 30 shows the environmental impacts analyzed for the recycling treatment. The results include the environmental impacts of the recycling process, the transport of the waste to the recycling site and the avoided loads of the materials generated. Recyclable wastes were inert wastes (such as concrete, bricks, tiles and ceramic materials, and gypsum) and non-special wastes (such as wood and metals). Non recyclable wastes were disposed of to incineration or landfilling.

The findings of this alternative showed that wastes from construction process all the total environmental impacts were negative because of the recovery of recycled materials except for AP. For most of the environmental categories calculated, insulation materials waste (classified as "other" in figure 30) causes the mayor environmental benefits due to the high avoided loads of the recovered materials. We should also mention that the recycling of timber waste is beneficial for RC and RE environmental categories. Stone recycling results in environmental negative effect for most of the environmental categories, RC and WC, where the recycling process has an impact higher than that of the material obtained. Metals recycling results in environmental benefits for GWP, HT and NRE, where the recycling process has an impact higher than that of the virgin metals avoided.

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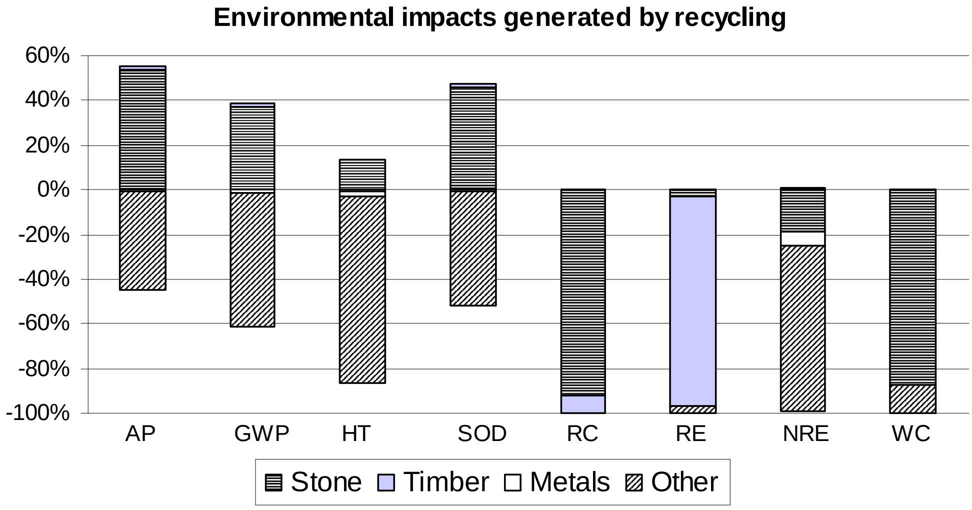
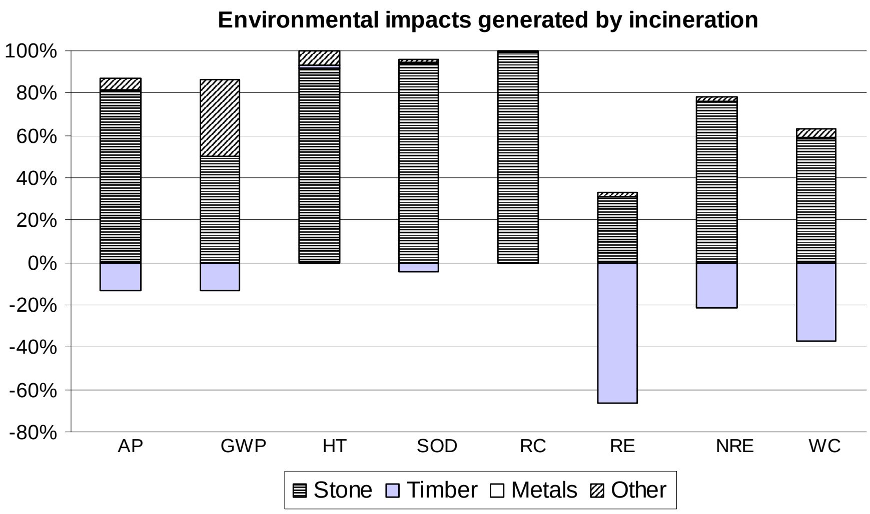
Figure 30: Total environmental profile for the recycling of construction process waste.



Incineration results

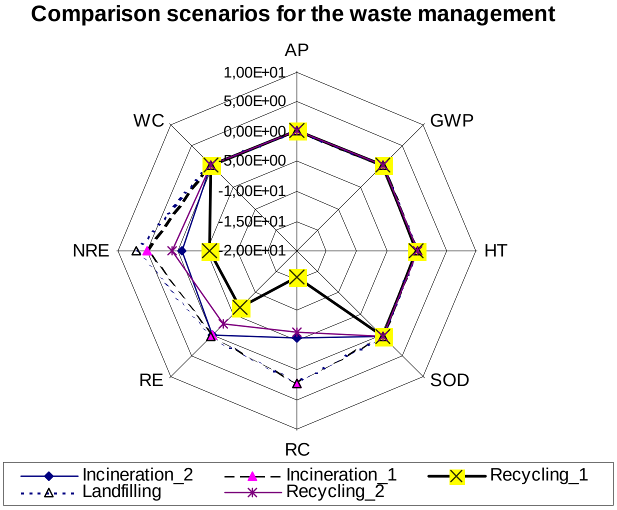
Incinerable wastes were non-special wastes waste containing wood. Non-incinerable wastes such as stone materials and metals were considered to be disposed of in landfills, thus producing no environmental benefits. The avoided loads calculated for the incinerable wastes correspond to the energy production which depends on the calorific value of the material. Thus, the avoided energy generation produces environmental benefits for the incineration of timber and insulation materials; see figure 31. However, for those indicators where the incineration process causes more impact than the avoided one, the results are lower than the disposal of these wastes to a landfill.

Figure 31: Total environmental profile for the incineration of construction process wastes.



Finally, we varied the final deposition process from incineration and recycling. This meant two new alternatives called Incineration_2 (incineration plus recycling) and recycling_2 (recycling plus landfilling) have been evaluated. The first alternative consists where incinerable wastes are disposed of in an incineration plant and non-incinerable wastes are disposed by recycling. The new recycling_2 treatment considers the optimistic rate of 40% of waste recycled or reused. By comparing the waste management of the five alternatives in terms of GWP (kgCO_2 m^{-2} y^{-1}), the most environmentally friendly alternative is the recycling_1 where is a high recovery potential of 80%, followed recycling with 40% of recovery, landfilling and lastly both incineration alternatives, see figure 32.

Figure 32: Comparison for different waste management alternatives.



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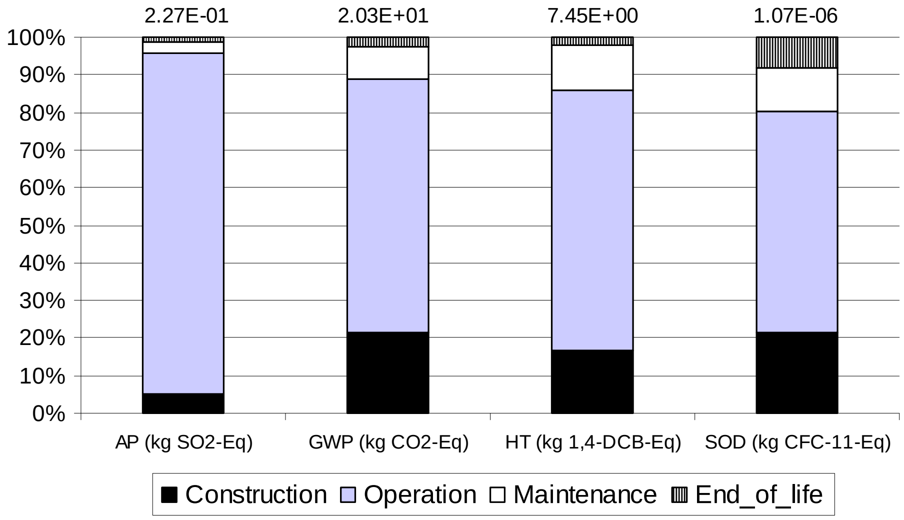
8.2 CASE STUDY II: SUSTAINABILITY ASSESSMENT RESULTS FOR THE APPLICATION OF A COLOMBIAN DWELLING HOME.

8.2.1 General results

The highest environmental impacts during the Colombian dwelling's life cycle took place during the use, while construction was about 9-31%, transportation and maintenance combined only account for less than 10% of the life cycle impacts. Figure 33 shows the environmental impact results presented for the dwelling life cycle studied.

Figure 33: Total environmental impact results during the full building life cycle (Colombian home).

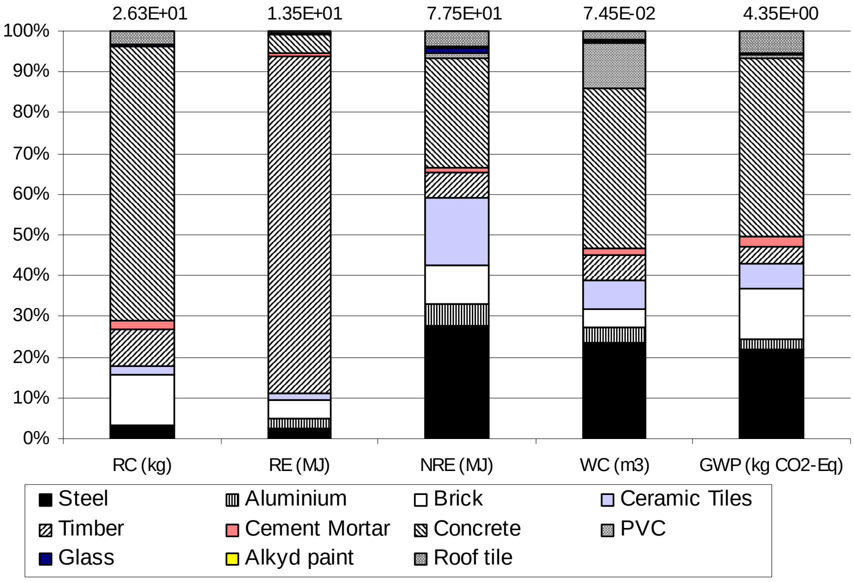


8.2.2 Results according to the dwelling life cycle

8.2.2.1 Results of the construction phase

The fabrication of building materials represented 99% of the total environmental impacts, transport to the job site and waste management represented less than 1%. The total life cycle mass of the main construction and building materials during the construction phase was 1.56E+05 kg (the total number of materials was limited to the top-ten materials with the largest life cycle mass contributions). Total resource consumption was 2.63E+01 kg m^{-2} y^{-1}, of which concrete makes 67% of the total. The total energy used where the main building materials are brick, concrete and steel was 9.10E+01 MJ m^{-2} y^{-1}, of which renewable energy represents 15% (83% for timber) and non-renewable energy 85% (28 for steel and 27% for concrete). The total water consumption was approximately 7.45E-02 m^3 m^{-2}. The total GWP impact for the building materials was 4.35E+00 kg CO_2-Eq m^{-2} y^{-1}, of which concrete alone stands for 42% and brick and steel make up 38%. Figure 34 summarizes the five eco-indicators proposed and GWP impact of the main building materials for the Colombian dwelling.

Figure 34: Eco-indicators and GWP impact of the main building materials during the fabrication.



In the present Colombian case study, roof tile has been used as a ceiling covering material instead of the asbestos that is a popular covering material in most dwellings built in this zone. Nevertheless since the 1990s, the use of roof tiles as a covering material for current and new dwellings in this area has depended on the social-economic status of the inhabitants of Pamplona. Using roof tiles instead of asbestos reduces the impact on human health but increases the total impact in GWP to 92% in kgCO_2-Eq per square meter. Table 37, shows the total embody energy of main construction building materials and environmental loads.

Table 37: Embody energy of main construction building materials and environmental loads for the Colombian home.

Flow	GWP (kg CO_2-Eq m^{-2} y^{-1})	RC (kg m^{-2} y^{-1})	Total energy (MJ m^{-2} y^{-1})
Steel	9.45E-01	8.28E-01	2.20E+01
Aluminum	1.15E-01	2.76E-02	4.20E+00
Brick	5.42E-01	3.28E+00	8.12E+00
Ceramic tiles	2.67E-01	5.59E-01	1.29E+01
Timber	1.88E-01	2.31E+00	1.62E+01
Cement mortar	9.69E-02	6.10E-01	1.05E+00
Concrete	1.91E+00	1.77E+01	2.12E+01
PVC	3.56E-02	1.29E-02	1.19E+00
Glass	1.81E-02	4.07E-02	8.21E-01
Roof tile	2.27E-01	9.00E-01	3.01E+00
Alkyd paint	9.77E-03	4.84E-03	3.51E-01
Total impact	**4.35E+00**	**2.63E+01**	**9.10E+01**

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8.2.2.2 Results of the use phase

During this phase the total GWP kg of CO_2-Eq m^{-2} y^{-1} was 1.55E+01 of which the operation phase accounts for 89% and maintenance 11% of the total phase. Regarding the GWP resulting from the operation phase, it is also important to stress that the use of electrical appliances is the most important household activity at 55%. Illumination presented 23%, followed by domestic hot water 12% and cooking 10% (see table 38).

Table 38: Environmental impacts for the Colombian household activities.

Environmental impact / Household activity	AP	GWP	HT	SOD	€ y^{-1}
Electrical appliances	1.13E-01	7.56E+00	2.83E+00	3.50E-07	6.47E+01
Illumination	4.77E-02	3.18E+00	1.19E+00	1.47E-07	1.24E+02
Cooking	2.07E-02	1.38E+00	5.17E-01	6.40E-08	5.38E+01
DHW	2.40E-02	1.60E+00	5.99E-01	7.41E-08	2.94E+02
Total	**2.06E-01**	**1.37E+01**	**5.13E+00**	**6.35E-07**	**5.36E+02**

Next the environmental impacts during the occupation phase have been also assessed in detail. Table 39 shows the environmental impacts that occur during the operation phase of the dwelling analysed.

Table 39: Environmental impacts that occur during the operation phase (cut-off criteria of 1%).

Environmental impact / ***Household activity***	***GWP*** **2.06E-01**	***AP*** **1.37E+01**	***HT*** **5.13E+00**	***SOD*** **6.35E-07**
Electrical appliances				
T.V.	3.19E-03	2.13E-01	7.96E-02	9.85E-09
Hairdryer	1.56E-03	1.04E-01	3.90E-02	4.82E-09
Computer	7.98E-03	5.33E-01	1.99E-01	2.46E-08
Washing machine	2.03E-03	1.36E-01	5.07E-02	6.28E-09
Iron	3.58E-03	2.39E-01	8.92E-02	1.10E-08
Refrigerator	7.98E-02	5.33E+00	1.99E+00	2.46E-07
Extractor	9.30E-04	6.21E-02	2.32E-02	2.87E-09
Microwave	6.32E-03	4.22E-01	1.58E-01	1.95E-08
Pressure cooker	1.93E-03	1.29E-01	4.81E-02	5.95E-09
Sandwich toaster	4.07E-03	2.72E-01	1.02E-01	1.26E-08
Subtotal electrical appliances	1.13E-01	7.57E+00	2.83E+00	3.50E-07
Cooking				
Electrical cooker	2.07E-02	1.38E+00	5.17E-01	6.40E-08
Illumination				
Illumination 100w	3.02E-02	2.02E+00	7.54E-01	9.33E-08
Illumination 60w	1.74E-02	1.16E+00	4.34E-01	5.38E-08
DHW				
Electrical shower	2.40E-02	1.60E+00	5.99E-01	7.41E-08

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8.2.2.3 Results of the end-of-life phase

The total contribution of this phase represented from 1 to 8% of the total. For instance there was a total emission of 5.04E-01 kgCO_2-Eq m^{-2} y^{-1} representing less than 1% of the total building life cycle.

Figure 35 shows the environmental impacts analyzed for the landfilling. It can be observed that stone waste is the mayor contributor to the impact, followed by metals, timber and plastics. The landfilling of metals and plastics greatly influences the human toxicity. Landfilling of plastic is significant in human toxicity, due to the contaminants generated in the process, while the landfilling stone is the mayor contributor to the GWP.

Figure 35: End of life environmental impacts analyzed for the Colombia landfilling

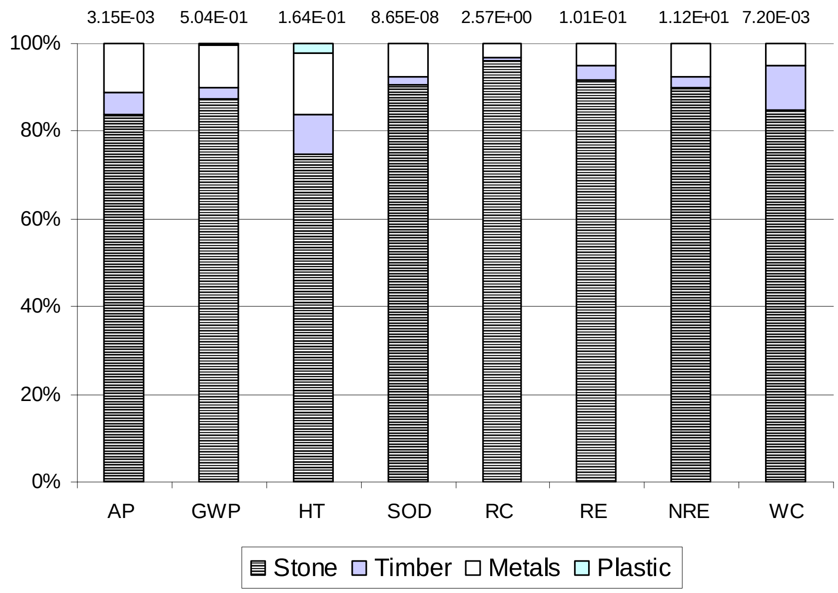

Figure 36 summarize the environmental impact results of the GWP. The house studied had emitted approximately 2.02+01 kgCO_2-Eq m^{-2} y^{-1} during the dwelling life cycle, of which the use phase (operation with 68% and maintenance with 9%) represented 77%, construction 21% and end-of-life 2%. Then, the contribution of the construction phase can be as important as the use phase.

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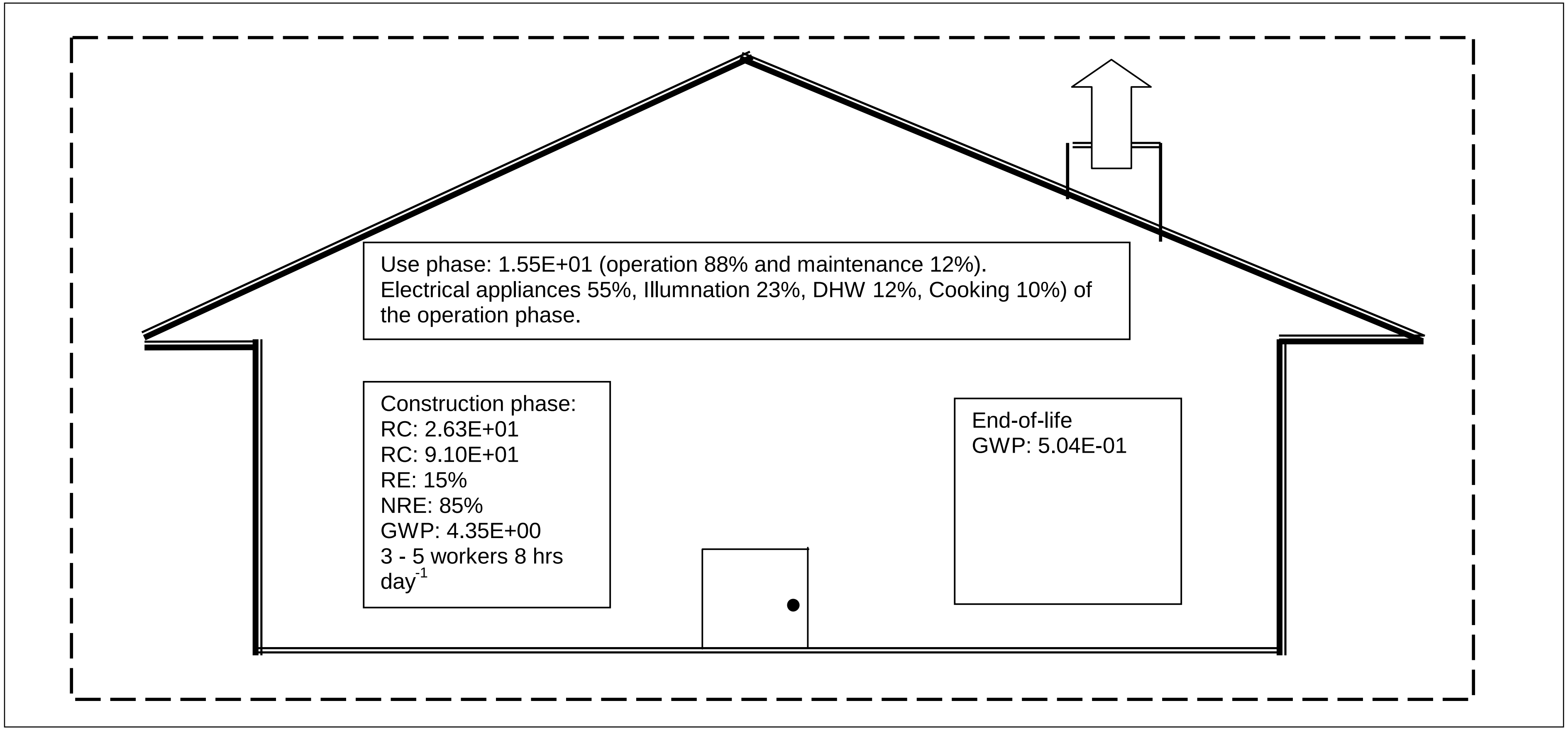
Figure 36: Resume of environmental impact results for the full building life cycle in the Colombian home



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8.2.3 Initiatives to encourage energy efficient for Colombian residential dwellings

The residential energy consumption is gaining attention through the practice of environmental building performance assessment in different countries as it usually accounts for a large percentage of the total energy consumption [Ghisi et al, 2007]. In order to promote energy conservation in the residential sector, and to estimate CO_2 emission, it is important to examine the residential energy consumption in different countries and to exchange information about residential energy consumption so that policy makers and energy experts in different countries can learn from each other in the policy-making of residential energy standards [Zhang, 2004]. Therefore, due to the fact that the Colombian government needs to apply strategies, policies and codes that lead to improved quality of life for its citizens, this section focuses by giving initiatives to encourage energy efficient residential dwellings and improve sustainability indicators.

The first parameters which varied were equipment for DHW, illumination and electrical appliances. This was due both to demographic variables resulting from a sharp increase in the population rates and changes in the average family size resulting from an increased quality of life. DHW was studied after the survey showed that approximately 10% of the dwellings were using water heating. The results showed energy savings of 4% on the total and 41% corresponding to the household activity. Electrical appliances were considered using the Energy Label. In the present research, a class A refrigerator was chosen instead of a class E one. The results showed that the adverse environmental impacts were reduced by 141% due to the kWh generated by the appliance during the 50 year operation phase. However, in order to achieve this, the owner faced an additional investment cost of about 421€.

According to the Colombian Ministry of Mines and Energy by 30 June 2010 all homes in the country should have made the changeover from conventional light bulbs to energy saving bulbs as was established by decree 2501. Therefore, 10 energy saving bulbs have been included in the model, saving 23% off the electricity bill. Furthermore, energy consumption patterns play an important role in savings and sustainability indicators during the use phase, and good patterns of use by consumers are indispensable for reducing environmental impacts. Examples of beneficial consumption patterns are unplugging appliances on standby or using the correct amount of water in the shower and thus the advantage of changing users' behaviour is that it has no additional cost, see table 40.

Other parameter was studied after Colombian forecasts for the following year's energy sources. This alternative is based on the energy source supplied to the dwelling. There is a clear significant reduction in the environmental impacts when natural gas is used instead of electricity for cooking. Using natural gas has been estimated to reduce environmental loads by approximately 8 - 10% per annum. Using this non-renewable resource is not sustainable in the long term if there is to be no dependence on fossil fuel from overseas, specifically oil, natural gas and coal. Nevertheless, the Colombian government is currently self-sufficient in energy and less vulnerable to a potential supply crisis. Then, applying strategies during the operation phase, such as changing consumption patterns,

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would reduce energy consumption for illumination and household equipment and thus benefit the environment. This has led to government policies being applied to reduce the final energy demand and environmental impact without compromising quality and the healthy indoor environment for users. Finally, applying policies and codes or changing cultural consumption behaviors are options for improving customer satisfaction and consequently the final embodied energy and environmental impacts during the dwelling life cycle.

Regarding the other option for waste management, it can be seen that recycling of stone is the mayor contributor to the environmental impacts categories except for renewable energy, due to the contaminants generated in the process, while the recycling of metal is the mayor benefits contributor to the GWP and AP. The recycling of plastics results in environmental benefits in most of the environmental categories, except for HT indicator, see figure 37.

Figure 37: Total environmental impacts analyzed for the Colombian dwelling for the recycling

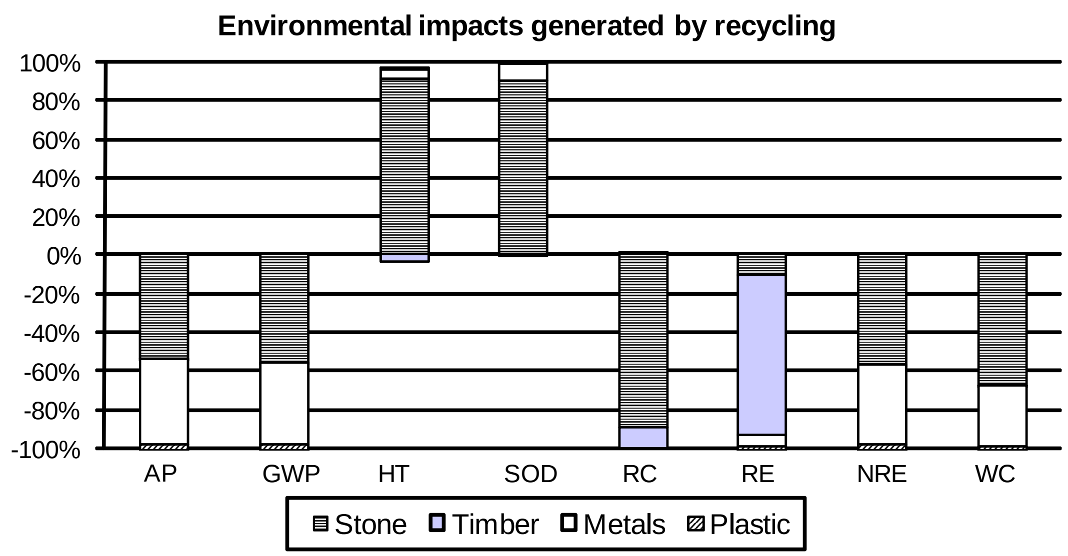

Table 40: Initiatives to minimize environmental loads and encourage energy efficiency in Colombian residential dwellings

		Energy savings			***Economic savings***		***Environmental savings***	**Social aspect**
Normal behavior	**Proposed behavior**	k Wh / FU (year)	% on the total	% on the household activity	II (€)*	PP (years)	GWP kg CO_2-Eq m^{-2} y^{-1}	Labor (per 1 worker)
Electrical shower	Water heating	2.08E+02	4	41	210	10	1.70E+01	2 - 4€ m^{-2} y^{-1}
Refrigerator Class E	Refrigerator Class A	9.85E+02	19	41	421	5	8.03E+01	-
10 Light bulbs	10 Savings bulbs	7.70E+02	23	119	21	1	6.28E+01	-
Computer and electronic appliances left on stand-by	Unplug appliances left on standby	2.62E+02	4	8	-	-	2.14E+01	-
Using 150 liters in the bath	Shower using 50 liters.	2.14E+02	4	43	-	-	1.74E+01	-
Electric cooker	Natural gas cooker	-	-		300	8	4.54E+02	2 - 4€ m^{-2} y^{-1}

Abbreviations

* 1€ (euro) = $2850 (Colombian peso)

PP: Payback period

II: Initial investment

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PART D: SENSITIVITY ANALYSIS, GENERAL DISCUSSION AND CONCLUDING REMARKS AND PERSPECTIVES

Chapter 9: Sensitivity analysis and comparison of the results at the micro level

- General results
  - Results using 100% electrical only: situation 1
  - Results using a mix of natural gas plus electricity: Situation 2
  - Results of the comparison during the operation phase

- Results changing energy source
  - Changing different life cycle inventory databases and LCIA methods

- Comparison results

Chapter 10: General discussion and concluding remarks and perspectives

- Generals discussions

- Overall conclusions

- Perspectives and challenges for future research

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CHAPTER 9:

9. SENSITIVITY ANALYSIS AND COMPARISON OF THE RESULTS AT MICRO LEVEL

Sensitivity analysis is recommended in order to discuss results qualitatively that are more affected by changes in the inputs. Therefore, sensitivity analysis plays a key role in decision-making because it determines the effects of a change in a decision parameter on system performance. This chapter concerns the question of whether there is an environmental advantage to using one source X instead of Y by modelling the input data and see the variation of the output in small but realistic system. A special focus is given on the operational energy for activities during the operation phase such as Heating, ventilation and air conditioning (HVAC), domestic hot water, electrical appliances, cooking and illumination. The results are compared in two real scenarios: Situation 1, where 100% of the dwelling's energy are supplied with electricity only and Situation 2, where dwellings can be operated with natural gas plus electricity. After that, the results are modelled with different life cycle inventory databases and LCIA methods.

9.1 GENERAL RESULTS

9.1.1 Results using 100% electrical only: Situation 1

Situation 1, where 100% of the dwelling's energy was supplied with electricity only has been already studied for both cases studies in Spain and Colombia in chapter 8 section 8.1.2.2 and 8.2.2.2 (see table 24 and table 39 respectively). Results have showed that in Colombia CO_2 emissions were about 73% lower than in the Mediterranean home. The difference between the two dwellings can be explained by the household energy consumption due to the thermal installations (HVAC and domestic hot water) and lighting installations and also because of residential equipment such as electrodomestic appliances and cooking and offimatic equipment.

Figure 38 shows the environmental impact resulting from the household activities in both countries using 100% electrical. As a result, of all the Spanish environmental impacts resulting from household energy consumption, almost 33% of the electricity was used for HVAC needs (cooling 26% and heating 7%), 21% for DHW, 21% for illumination, 16% for electrical appliances and 9% for cooking. For the environmental burdens in Colombia it is important to stress that electrical appliances are the most important household activity with 55%, illumination accounted for 23%, domestic hot water 12% and cooking 10%.

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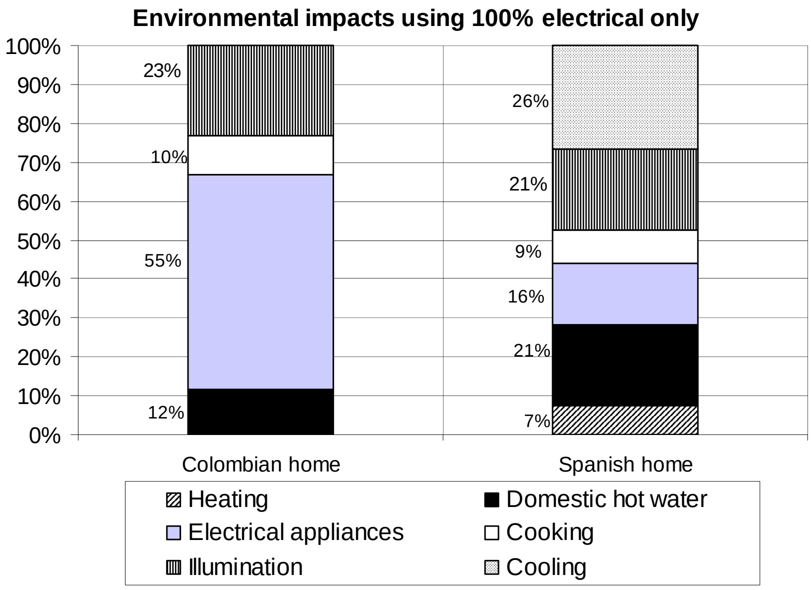
Figure 38: GWP environmental impact resulting from the household activities in both countries using 100% electrical only: Situation 1.



9.1.2 Results using a mix of natural gas plus electricity: Situation 2

To reflect a more realistic scenario, situation 2 has considered the respective Colombian and Spanish dwellings using natural gas plus electricity with the requirements and equipments presented in the following table 41.

Table 41: Equipment and energy source (natural gas).

Annual (2007) household energy demand by	COLOMBIA	SPAIN	Equipment
Heating	-	79 m^3 natural gas	Mixed gas boiler
Domestic hot water	725 kWh electrical	231 m^3 natural gas	Mixed gas boiler
Electrical appliances	3420 kWh electrical	1908 kWh electrical	-
Cooking	58 m^3 natural gas	96 m^3 natural gas	Gas hob oven
Illumination	1448 kWh electrical	2569 kWh electrical	-
Cooling	-	3240 kWh electrical	Split system COP 1.85

Figure 39 shows the total environmental impacts resulting from the household activities in both countries using a mix of natural gas plus electricity. After the aforementioned LCA manager software tool has been re-loaded with the new input data, the results for the environmental impacts using natural gas plus electricity show that of the Spanish environmental impacts cooling had the highest impact with approximately 27 - 42% due to the electricity used to power it. GWP of the remaining household activities such as illumination was 26%, electrical appliances 20%, DHW 12%, cooking 5% and heating 4%.

Colombian results showed that electrical appliances had the highest environmental impacts in the same order of magnitude with approximately 60%. The environmental impact of GWP for illumination accounted for 25% and domestic hot water for about 13%. Finally, cooking had the best reduction of emissions due to the use of natural gas, from 10% down to less than 2%.

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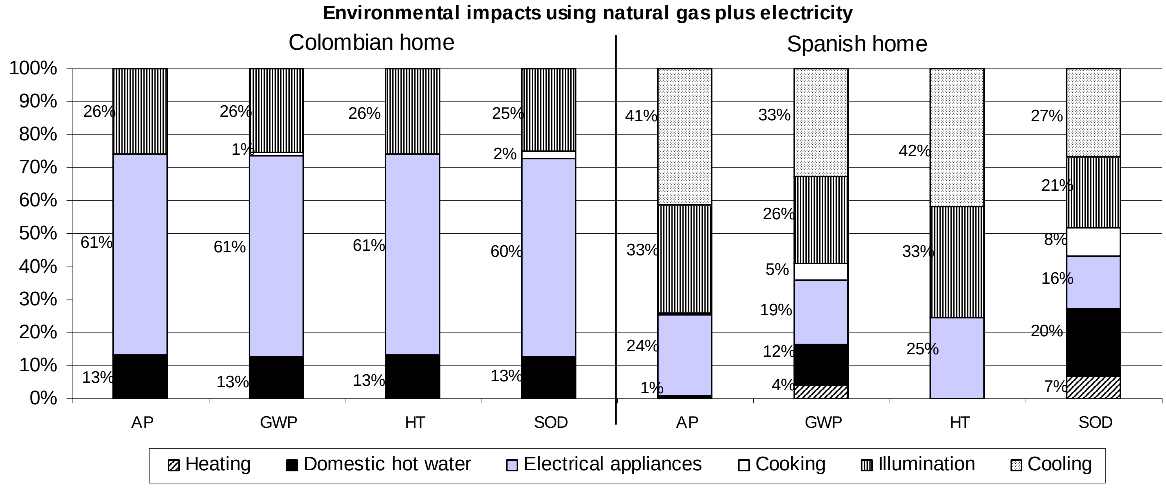
Figure 39: Total environmental impact resulting from the household activities in both countries using electricity plus natural gas: Situation 2.



9.2 RESULTS OF THE COMPARISON DURING THE OPERATION PHASE

The results of acidification potential, GWP and other impact assessment indicators comparing 100% electrical with the mix of natural gas plus electricity are shown in Table 42a and table 42b. These tables show that the alternatives had favorable and unfavorable values. Unfavorable values mean an increase of emissions to the environment while favorable values represent a reduction of emissions due to the energy use.

In the Spanish Mediterranean home operation of electricity is unfavourable for the GWP impact due to the additional energy consumption with 20%. In Colombia, Situation 2 is more favourable than Situation 1 where 9% of GWP impact from the household activities was incurred during user occupancy. Hence, it can be concluded that the use of natural gas clearly reduces the environmental impacts during the operation phase, however there is a widespread necessity to promote use of renewable energies such as, solar and wind. The relationship between environmental impacts that occur during the full building life cycle should also be analysed. It should be verified whether the improvement of one environmental impact does not cause an adverse effect in another environmental impact.

The difference in consumption in Colombia and Spanish dwellings is not only due to the variation in results for bio-climatic differences but also because of the consumption habits in each country. It can be seen that the importance of consumption habits of citizens and the need to decouple socio-economic development from energy consumption. There is a crucial necessity to provide satisfaction to basic needs and comfort requirements of population with a reasonable and sustainable energy consumption and provide energy with the appropriate energy source.

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Table 42a: Comparison of energy consumption for the Spanish dwelling.

Environmental burdens	Spanish home			
	Situation 1: 100% Electrical	Situation 2: Gas + Electricity	* %	Concept
AP (kg SO_2-Eq)	3.25E-01	2.08E-01	36	Favorable
GWP (kg CO_2-Eq)	4.00E+01	3.22E+01	20	Favorable
HT (kg 1.4-DCB-Eq)	9.85E+00	6.21E+00	37	Favorable
SOD (kg CFC-11-Eq)	1.95E-06	1.91E-06	2	Favorable
Benefit cost (€)	1.36E+03	1.08E+03	21	Favorable

Table 42b: Comparison of energy consumption for the Colombian dwelling.

Environmental burdens	Colombian home			
	Situation 1: 100% Electrical	Situation 2: Gas + Electricity	* %	Concept
AP (kg SO_2-Eq)	2.06E-01	1.85E-01	10	Favorable
GWP (kg CO_2-Eq)	1.37E+01	1.25E+01	9	Favorable
HT (kg 1.4-DCB-Eq)	5.13E+00	4.61E+00	10	Favorable
SOD (kg CFC-11-Eq)	6.35E-07	5.84E-07	8	Favorable
Benefit cost (€)	5.28E+02	4.56E+02	14	Favorable

*Difference in percentage = ((Situation 1 – Situation 2) / Situation 1) * 100

9.3 RESULTS CHANGING ENERGY SOURCE

The other parameter to vary was the energy source. This parameter was studied after Spanish and Colombian forecasts for the following year's energy sources on the promotion of renewable energies. Therefore, in Spain estimating wind power market penetration is expected to reach 15% by 2020. Results showed that there is a reduction of adverse GWP impact of –10% due to the use of clean energy sources generated by wind power. Meanwhile, in Colombia this analysis is based on the construction of two hydroelectric projects and the results show that there is a reduction of –11% of GWP.

Other second parameter which varied was energy database. For example we compare the local database used from table 22 in chapter 7 section 7.3, and compare it with data supply at the international database of the IEA. Results show that there is an insignificant change of the total results with represented less than that 3%.

9.3.1 Changing different Life cycle inventory databases and LCIA methods

The results of the Ecoinvent were compared with the data from the GaBi software. In this study several Life cycle inventory databases and LCIA methods were applied. The overall results are presented in table 43 below apart from the CML 2002, for EDIP 2003 and TRACI.

Table 43: Comparison of results for the difference database.

	GABI CML 2001	Ecoinvent CML 2001	GABI EDIP 2003	Ecoinvent EDIP 2003	GABI TRACI	Ecoinvent TRACI
Construction	8%	9%	8%	9%	9%	8%
Operation	89%	84%	89%	84%	84%	89%
Maintenance	2%	6%	2%	6%	6%	2%
End-of-life	1%	1%	1%	1%	1%	1%
	100%	100%	100%	100%	100%	100%

It can be observed that the selected methods can deliver results with the same order of magnitude, if using the same database. For example the total impacts during the full building life cycle using Ecoinvent for CML, EDIP and TRACI represented 4.77E+01 kgCO2 m^{-2} y^{-1}, 4.79E+01 and 4.77 kgCO2 m^{-2} y^{-1} respectively. Nevertheless, comparing both database there is a differences in 17% of the total result for the full building life cycle where construction and end-of-life deliver results with the same tendency, whereas the use phase indicate the contrary. Using CML 2001, such a result is found because of the selection of proxys.

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CHAPTER 10:

10. GENERAL DISCUSSION AND CONCLUDING REMARKS AND PERSPECTIVES

In this chapter, the results at macro and micro level are summarised with new conclusions and perspectives drawn from the theoretical foundation. The chapter starts with a discussion of the results addressing six aspects, followed by overall conclusions. Finally, suggestions for further research are presented.

10.1 GENERAL DISCUSSION

Discussions concerning six aspects have been evaluated:

10.1.1 Method proposed

The practical life cycle method proposed is a straightforward method that encompasses environment, economic, and social aspects. The method can be valid and can contribute towards sustainability within different sectors especially the building sector. Furthermore, the method have included typical sustainability indicators of LCA like GWP, AP, HT and SOD to compare our results with others presented in common LCA indicators. Furthermore, eco-efficiency indicators like TE, RE; NRE and WC have been added to enable understating to maximum audience.

The method was proved on two cases studies, one in a developed country (Spain) and one in a developing (not emerging Colombia) country. In both cases studies data collection and inventory performing for the environmental, social and economical points of view have been evaluated at macro and a micro level.

Nevertheless, in the method proposed there are some issues to be improved.

- The method needs to include a procedure for indicators selection, indicators calculation, normalization and weighting performing for the triple bottom line principles using more socio-economic sustainability indicators.

- For sustainability assessment the method should use a set of indicators to analyze the impacts, and the methodology must include a procedure for the selection of this indicators

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- The application of the method can be time consuming if data are not available. For instance, the process of obtaining data in Colombia was a laborious one due to the lack and widely dispersed of the data, therefore it was necessary to draw up estimates, while the development of data collection in a developed country (Spain) was straightforward process because of the national database available.

10.1.2 Macro level

Macro level has been evaluated calculating the composite indicators in both countries. It can be concluded that factor analysis has identified three factor from the list of nineteen variables of the Spanish case and seventeen variables of the Colombian case. In the main, the first factor for the Spanish and the second factor for the Colombian was represented by the specific statements written to reflect the evolution of the residential building sector in both countries. Energy and cement were used as suitable proxies to capture the global development of the building sector and because are significant inputs for any construction especially for housing to get a real vision about the operation of the building sector.

10.1.3 Micro level

In a micro level, we evaluated and analyzed adverse environmental impacts during the construction, use and end-of-life phases. The present research has studied in detail the environmental impact during the full building life cycle for two residential dwellings located in Spain and Colombia, on the one hand, the Mediterranean dwelling house located in the Province of Barcelona and, on the other hand, a Colombian home with the same constructive characteristics, but with different location and consumption patters during the operation phase.

Environmental impact results show that the use phase in the Mediterranean home has the highest environmental burden (approximately 89-98% of the impact during the dwelling's life cycle), whereas in Colombia the contribution of the construction phase can be as important as the use phase in some impacts. The highest environmental impact during the Colombian dwelling's life cycle took place during the use approximately 64-92%, while construction was about 7-28% and end-of-life accounted for approximately 1-9% of the life cycle impact. The Mediterranean house had emitted approximately 4.00E+01 kgCO_2-Eq m^{-2} y^{-1} during the dwelling life cycle of which the use phase (operation and maintenance) represented 90%, construction 9% and end-of-life 1%. For the Colombian dwelling, the total impact was 2.04+01 kgCO_2-Eq m^{-2} y^{-1} of which construction accounted for 21%, operation and maintenance made up 76% and end-of-life contributed 3%.

10.1.4 Building materials

The present thesis has shown that in Spain the combination of building materials can lead to reduced environmental impacts. There is a widespread desire to reduce CO_2 emissions, therefore decisions need to be made with rigorous and appropriate environmental goals set out by the government. The practical life cycle method has been used in decision-making when applying the environmental management principle of "choose it right first" without compromising the quality of a construction project. Hence, this allowed us to see and evaluate environmental burdens based on combinations of different building materials.

10.1.5 Energy

We analyzed both dwellings taking into consideration the type of energy used during the operation phase: electricity only versus natural gas plus electricity. Then, the adequate combination of energy supplies leads to reduced environmental impacts. The use of efficient energies such as natural gas clearly reduces the environmental impacts during the operation phase. Regarding electrical appliances, the most recent methodologies which incorporate information about environmental aspects, embodied energy and efficiency are necessary for minimizing environmental impacts. Decision-making regarding any environmental impact depends on global and local environmental quality goals and also on environmental threats identified in research and development by governments. Governments need to apply policies and construction codes that lead to improved quality of life for citizens because these same citizens want assurances that an investment in a dwelling will pay for itself over an acceptable time period. In other words, cost is an important issue for the market in facilitating the best economic and ecological value for society, customers and users.

The origin of the energy source used in each Country plays an important role to minimize adverse environmental impacts, as was demonstrated by the environmental impacts of its use in Colombia where 78% of the electricity came from hydroelectric plants whereas in Spain it is more mixed, 50% coming from fossil fuel combustion. Then, there is a widespread necessity to preserve the environment from the use of fossil fuels (oil and coal) and also to promote the use of renewable energies. Nevertheless, even electricity usage data was based on modelling, data was checked with electricity bills and results it can be concluded that it is not understand that in Colombia where electricity is generated from hydroelectric and there is a charge of € 0.086 per kilowatt-hour, when in Spain the cost is € 0.1125 per kilowatt-hour and in some Latin American regions such as Venezuela, Ecuador, Peru and Brazil the energy is cheaper than in Colombia and thus Colombia lose competitiveness of green markets.

10.1.6 Waste

In Spain, the waste management phase represented less than 1% of the environmental impact of the total full building life cycle. However, when building wastes are not recycled the amount of waste generated at the building site is higher than urban waste generated by other means. Therefore, architects, contractors, designers and engineers should be proactive and consider sustainability criteria that help decision making at the planning and design stage that allows decisions to be made at the draft stage on the choice of materials and constructive solutions according to techniques during the construction phase. In the incineration scenario attention should mainly focus on plastic and insulation materials because they emit toxic compounds. Paper and cardboard are materials that provide power and thermal energy recovery due to their high calorific value. Recycling plastic and cardboard is important because it reduces the amount of raw materials that have to be sourced. Meanwhile, in Colombia there is a urgent need to foster techniques such as recycling, reusing and recovering materials for optimum waste disposal.

Then, three different waste management scenarios have been evaluated: landfilling. recycling and incineration. The landfilling of metals and plastics should be avoided as much as possible due to their influence in the toxicity categories while the landfilling of stone should be avoided due to huge amount of these wastes generated and the huge volumes they occupy in landfills. It is important to notice, that even when the environmental impact corresponding to the recycling of specific wastes results in a positive value (meaning no net benefit for the environment), these impacts are always lower than that caused by the landfilling of these wastes and thus recycling shall always be the recommended option.

In the case of incineration of construction wastes, we should say that different indicators suggest different recommendations, as in the case of plastic wastes that get environmental benefits or detriments depending on the indicator chosen. Thus, final decisions on incineration should be taken considering several factors as the importance of the different impact categories, together with economic and social aspects.

10.2 OVERALL CONCLUSIONS

Keeping the reference of impact per m² of living area in a dwelling we have considered two residential buildings, one located in Pamplona (Colombia) and one situated in Barcelona (Spain) as representing two different geographical and climate conditions and technology settings with in particular very different electricity supply system. It has been considered that in both cities dwellings are built according to local regulations. For instance in Spain considering the Spanish Technical Building Code and in Colombia the Earthquake Resistant Buildings Code (Decree 1400 of 1984).

Construction as a process is not static; it varies from building to building since each has its own function and different engineering characteristics. The direct application of LCA in the construction sector is not a simple or straightforward process. It is expensive and cannot be applied without assumptions or additional modifications. Consequently, a variation in each design can affect positively or negatively the environment during all the life cycle stages of a building. One characteristic of buildings and building products is their significantly longer life compared to most other industrial products, and the involvement of many different factors during their life cycle. Therefore, this thesis evaluated and analysed adverse environmental impacts during the full building life cycle. LCA was used applying the environmental management principle of “choose it right first” without compromising the quality of the construction project. This allowed - before a dwelling was built – evaluating the environmental impact that would happen once the building was operating, by looking at how a combination of different building materials would reduce or increase a number of environmental impacts.

The present research demonstrates that there are important differences in the construction techniques, consumer pattern, energy sources and waste management in the countries chosen for the case studies: Spain and Colombia. Therefore, the following challenges were perceived that are particular for the present work:

First, architectural styles, technologies used and conditions such as household size, climate, geography and energy sources vary from country to country. That means any extrapolation of existing European LCA data (here from Spain) to the case of a developing country (here Colombia) would imply an important numbers of errors.

Second, in Colombia any intervention to reduce environmental impacts in building materials can be important as the building's use phase. In the Spanish Mediterranean house, there is first of all a need to reduce the contribution to GHG emissions per capita through housing, since the contribution of the building materials to the GWP is low compared with the values of the whole life cycle. That means that for the lesson learnt from LCA studies in Europe and the US that the use phase is most relevant in a building life cycle is not always true and cannot be easily transferred to the developing county context, without a previous detailed analysis for the exact geographic and technological conditions.

Third, the differences are motivated in Colombia by the need to use materials with high resistance to earth tremor, which is a legal requirement, and corresponding construction codes must be applied within the residential building sector. In Spain thermal performance is an important factor and thus materials with good insulation properties must be used.

Fourth, the most recent methodologies to incorporate information regarding environmental impacts and embodied energy in building materials are the Environmental Product Declarations (EPD). This strategy needs still to be developed for building materials produced in Colombia and most developing countries.

Fifth, in Colombia the building material of asbestos is still used as a ceiling covering material. As widely known, this material can have a huge impact on human health and therefore needs to be substituted as soon as possible.

Sixth, Life Cycle Thinking (LCT) is definitely a frame that helps decision making towards finding more sustainable solutions and this is a good concept for improving environmental sustainability performance within the construction industry, also in developing countries. Generally speaking, Life Cycle Thinking can be applied to the whole construction process, thus making it possible to improve the sustainability of buildings. For example, a proper design and choice of building materials during the construction phase can improve the energy efficiency during the use phase and the final distribution of buildings' consumption for heating and cooling. Also applying strategies during the

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operation phase, such as making changes in consumption patterns, would improve consumption for illumination and household equipment in terms of energy and environmental considerations.

Life Cycle Thinking (LCT), Life Cycle Assessment (LCA) and Material and Energy Analysis (MEA) can be the best practical tools to evaluate, analysis and check the construction life cycle to prevent environmental impacts and assist the field of engineering techniques of buildings. These tools are used more and more and these are not utopian tools to deploy in developing countries.

Seventh, LCA can help looking for ways to minimize environmental loads worldwide. There is a particular need to foster its use significantly in developing countries using a combination of promotion among natural science and engineering experts. For industrial activities within the building sector, organizations must understand how to apply LCA not only to meet consumer demands for environmentally friendly products but also to increase the productivity and competitiveness of the green construction markets.

Eighth, the possibility within this study of transferring LCT knowledge, experiences and technology to Colombia and comparing the results obtained with available data from a project in Spain shows that such a parallel continuous research process allows at the same time to promote the use of LCA within the Colombian industry and to underline the different assumptions used for a standard building model in Spain and Colombia. In addition, to the promotion of the LCA tool within the Colombian construction and energy industry, this is an important learning exercise to understand what the key factors are that influence the results of a LCA study for buildings in different countries.

Ninth, any environmental improvement in building sustainability is generally oriented to changing energy use and building materials in all phases of the building life cycle, having always in mind that buildings have to be accessible from an economical and social part of view. The description of what a standard dwelling is varies substantially depending on the geographic locations where it is built. Climate, geographic, technological, cultural, economic and social differences clearly define the standard of a building in any context and in any region or area. However the function is always the same, to provide protection and housing for its habitants.

10.3 PERSPECTIVES AND CHALLENGES FOR FUTURE RESEARCH

There is potential to update the state of research and improve the current method tool. Future research will analyze whether the practical guidelines used in the construction industry for single buildings in Spain, strong depending on climate conditions, can be applied in tropical areas. Social and economic indicators the two other parts of sustainability will be considered more in detail because of their major and particular role in developing countries. This is expect to use an optimization model (based on a friendly environment software) that considers variables like thickness of walls, type of window, type of insulation material etc, in order to optimize a model to the correct conditions determined by variables like temperature, direction and wind speed. Also the final cost plays an

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important issue for the market to facilitate the best economic and ecological value for society, customers and users. So, this model will include economic aspects as an objective function, having the option to define the years of amortization of the investment that can affect a reduction of energy consumption or environmental criteria like CO_2 emissions.

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UNIVERSITAT ROVIRA I VIRGILI
SUSTAINABILITY ASSESSMENT WITHIN THE RESIDENTIAL BUILDING SECTOR: A PRACTICAL LIFE CYCLE METHOD
APPLIED IN A DEVELOPED AND A DEVELOPING COUNTRY.
Oscar Orlando Ortiz Rodríguez
ISBN: 978-84-693-0723-6 / DL:T-428-2010

ANNEX 1

CML 2001 Method: Environmental Impacts Definitions

Impact Category	Definition
Acidification potential	Acid gases that are released into the air or resulting from the reaction of non-acid components of the emissions are taken up by atmospheric precipitations and the falling "acid rain" forms an acid input which is absorbed by plants, soil and surface waters leading to leaf damage and superacidity of the soil. which in turn affects the solubility and hence availability of plant nutrients and trace elements plants can take in. This may lead to an increased take up of heavy metals or reduced take up of some plant nutrients and hence negatively affect the growth of plants. Acidifying pollutants have a wide variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystem and material (buildings).
Global Warming Potential	Global warming potential is defined as the impact of human emissions on the radioactive forcing (i.e. heat radiation absorption) of the atmosphere. This may in turn have adverse impacts on ecosystem health, human health and material welfare. Most of these emissions enhance radioactive forcing, causing the temperature at the earth's surface to rise. This is popularly refereed to as the "greenhouse effect".
Human toxicity	This impact category covers the impacts on human health of toxic substances present in the environment.
Stratospheric ozone depletion	Stratospheric ozone depletion refers to the thinning of the stratospheric ozone layer as a result of anthropogenic emissions. This causes a greater fraction of solar UV-B radiation to reach the earth's surface, with potentially harmful impacts on human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and materials.

CML 2001 method was chosen in the present case study because it provides operational guidelines for conducting an LCA study step by step on the ISO standards according to Guinée. J.B.

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ANNEX 2

Spanish statistical data

Matrix correlations

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Year (1)	1,000	,932	,935	,842	,943	,305	,131	,840	,957	,957	-,462	,914	,912	,913	-,598	-,249	,895	,913	,982
Natural_growth (2)	,932	1,000	,958	,712	,938	,106	-,035	,950	,938	,938	-,434	,933	,967	,884	-,694	-,176	,878	,883	,956
Employment_sector (3)	,935	,958	1,000	,841	,988	,263	,158	,868	,970	,970	-,629	,980	,914	,972	-,799	-,079	,974	,971	,979
Housing_Starting (4)	,842	,712	,841	1,000	,851	,551	,456	,584	,850	,849	-,666	,872	,646	,932	-,608	-,084	,920	,932	,848
GDP (5)	,943	,938	,988	,851	1,000	,292	,202	,845	,969	,969	-,618	,959	,901	,966	-,782	-,073	,968	,966	,983
GDP_Construction (6)	,305	,106	,263	,551	,292	1,000	,838	,139	,319	,317	-,340	,283	,203	,423	,016	-,137	,385	,424	,260
Index_price_clinker (7)	,131	-,035	,158	,456	,202	,838	1,000	-,008	,226	,224	-,407	,173	,036	,334	-,073	-,037	,314	,335	,146
Clinker_production (8)	,840	,950	,868	,584	,845	,139	-,008	1,000	,862	,863	-,272	,838	,959	,782	-,540	-,219	,767	,781	,856
CO2_Clinker (9)	,957	,938	,970	,850	,969	,319	,226	,862	1,000	1,000	-,618	,944	,901	,956	-,734	-,211	,948	,956	,979
Clinker_Export (10)	,957	,938	,970	,849	,969	,317	,224	,863	1,000	1,000	-,617	,944	,901	,955	-,735	-,208	,948	,955	,979
Clinker_Import (11)	-,462	-,434	-,629	-,666	-,618	-,340	-,407	-,272	-,618	-,617	1,000	-,606	-,341	-,692	,804	,004	-,717	-,693	-,558
Index_price_cement (12)	,914	,933	,980	,872	,959	,283	,173	,838	,944	,944	-,606	1,000	,884	,979	-,759	-,015	,977	,978	,952
Cement_production (13)	,912	,967	,914	,646	,901	,203	,036	,959	,901	,901	-,341	,884	1,000	,839	-,577	-,187	,824	,839	,918
Cement_export (14)	,913	,884	,972	,932	,966	,423	,334	,782	,956	,955	-,692	,979	,839	1,000	-,760	-,053	,997	1,000	,951
Cement_import (15)	-,598	-,694	-,799	-,608	-,782	,016	-,073	-,540	-,734	-,735	,804	-,759	-,577	-,760	1,000	-,188	-,806	-,761	-,726
Cement_Consumption (16)	-,249	-,176	-,079	-,084	-,073	-,137	-,037	-,219	-,211	-,208	,004	-,015	-,187	-,053	-,188	1,000	-,004	-,053	-,162
Emissiones_CO2 (17)	,895	,878	,974	,920	,968	,385	,314	,767	,948	,948	-,717	,977	,824	,997	-,806	-,004	1,000	,997	,946
Energy_consumption (18)	,913	,883	,971	,932	,966	,424	,335	,781	,956	,955	-,693	,978	,839	1,000	-,761	-,053	,997	1,000	,951
Housing_Finishing (19)	,982	,956	,979	,848	,983	,260	,146	,856	,979	,979	-,558	,952	,918	,951	-,726	-,162	,946	,951	1,000

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Varianza total explicada

Componente	Autovalores iniciales			Sumas de las saturaciones al cuadrado de la extracción		
	Total	% de la varianza	% acumulado	Total	% de la varianza	% acumulado
1	14,039	73,888	73,888	14,039	73,888	73,888
2	2,126	11,189	85,077	2,126	11,189	85,077
3	1,415	7,447	92,525	1,415	7,447	92,525
4	,752	3,956	96,481			
5	,304	1,602	98,082			
6	,141	,741	98,823			
7	,098	,517	99,340			
8	,045	,234	99,574			
9	,042	,222	99,797			
10	,022	,116	99,912			
11	,009	,047	99,960			
12	,003	,018	99,978			
13	,002	,011	99,990			
14	,001	,006	99,995			
15	,001	,003	99,999			
16	,000	,001	100,000			
17	2,19E-005	,000	100,000			
18	4,32E-007	2,27E-006	100,000			
19	-5,99E-017	-3,15E-016	100,000			

Método de extracción: Análisis de Componentes principales.

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Colombian statistical data

Matrix correlations

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Year (1)	1,000	,994	,189	,785	,650	,875	,831	-,627	,384	,476	,939	-,364	-,245	-,350	,937	-,100	,953
Natural_growth (2)	,994	1,000	,183	,773	,635	,859	,817	-,621	,375	,468	,937	-,328	-,248	-,383	,944	-,149	,946
Initial_m2 (3)	,189	,183	1,000	,348	,558	,416	,509	-,297	,706	,663	-,051	,082	,602	-,230	-,066	,390	,384
GDP_Services (4)	,785	,773	,348	1,000	,954	,932	,886	-,752	,637	,693	,700	-,356	,130	-,018	,717	,259	,826
GDP_Construction (5)	,650	,635	,558	,954	1,000	,899	,901	-,763	,800	,829	,514	-,234	,389	,008	,542	,393	,765
Total_Expor_FOE (6)	,875	,859	,416	,932	,899	1,000	,961	-,746	,639	,704	,755	-,368	,095	-,082	,787	,239	,919
Total_Impor_FOE (7)	,831	,817	,509	,886	,901	,961	1,000	-,797	,785	,838	,664	-,150	,284	-,212	,745	,170	,924
Clinker_Expor (8)	-,627	-,621	-,297	-,752	-,763	-,746	-,797	1,000	-,723	-,825	-,587	-,028	-,379	,207	-,641	-,142	-,701
Clinker_Import (9)	,384	,375	,706	,637	,800	,639	,785	-,723	1,000	,984	,198	,271	,786	-,206	,289	,253	,600
Cement_Prod (10)	,476	,468	,663	,693	,829	,704	,838	-,825	,984	1,000	,305	,224	,725	-,245	,394	,222	,668
Cement_Expor (11)	,939	,937	-,051	,700	,514	,755	,664	-,587	,198	,305	1,000	-,431	-,414	-,233	,923	-,099	,834
Cement_Impor (12)	-,364	-,328	,082	-,356	-,234	-,368	-,150	-,028	,271	,224	-,431	1,000	,560	-,421	-,279	-,401	-,242
Consumption (13)	-,245	-,248	,602	,130	,389	,095	,284	-,379	,786	,725	-,414	,560	1,000	-,064	-,293	,255	,009
Consump_Construc (14)	-,350	-,383	-,230	-,018	,008	-,082	-,212	,207	-,206	-,245	-,233	-,421	-,064	1,000	-,311	,733	-,326
Primary_energy (15)	,937	,944	-,066	,717	,542	,787	,745	-,641	,289	,394	,923	-,279	-,293	-,311	1,000	-,254	,874
Final_PE_consumption (16)	-,100	-,149	,390	,259	,393	,239	,170	-,142	,253	,222	-,099	-,401	,255	,733	-,254	1,000	,011
Electricity_generation (17)	,953	,946	,384	,826	,765	,919	,924	-,701	,600	,668	,834	-,242	,009	-,326	,874	,011	1,000

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Varianza total explicada

Componente	Autovalores iniciales			Sumas de las saturaciones al cuadrado de la extracción		
	Total	% de la varianza	% acumulado	Total	% de la varianza	% acumulado
1	9,520	56,002	56,002	9,520	56,002	56,002
2	3,629	21,349	77,351	3,629	21,349	77,351
3	2,291	13,479	90,830	2,291	13,479	90,830
4	,768	4,520	95,350			
5	,266	1,566	96,916			
6	,236	1,386	98,301			
7	,127	,749	99,050			
8	,076	,449	99,499			
9	,032	,188	99,688			
10	,026	,151	99,839			
11	,012	,073	99,912			
12	,007	,040	99,951			
13	,004	,025	99,976			
14	,003	,020	99,996			
15	,001	,003	99,999			
16	9,32E-005	,001	100,000			
17	2,77E-006	1,63E-005	100,000			

Método de extracción: Análisis de Componentes principales.

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ANNEX 3

Item description on materials combination, wastes and cost for Internal walls (VIE)

Item	Description	Materials	Construction and demolition wastes	Packaging waste	Cost (€/m^2)
IL01	Simple hollow brick, 4 cm thick	Water, sand, cement, ceramic brick	Concrete, brick	Paper, plastic, wood	13.28
IL02	Double hollow brick, 10 cm thick	Water, sand, cement, ceramic brick	Concrete, brick	Paper, plastic, wood	17.57
IL03	Double hollow brick, 14 cm thick	Water, sand, cement, ceramic brick	Concrete, brick	Paper, plastic, wood	25.36
IL04	Drilled brick , 14 cm thick	Water, sand, cement, ceramic brick, additive	Concrete, brick	Paper, plastic, wood, packaging with special remains	26.72
IL05	Rendering	Water, plaster	Plaster	Paper, plastic, wood	4.52
IL06	Mortar coating layer	Water, sand, cement	Concrete	Paper, plastic, wood	12.79
IL07	Tiled with mortar, 26-45 ud/m^2	Water, sand, cement, ceramic tiles, additive	Concrete, tiles	Paper, cardboard, plastic, wood	23.73
IL08	Tiled with glue, 26-45 ud/m^2	Sand, cement, ceramic tiles, additive, polyester resin	Concrete, tiles, special remains	Paper, cardboard, plastic, wood, packaging with special remains	19.22
IL09	Ceramic vitreous tiles, 76-115 ud/m^2	Water, sand, cement, ceramic tiles, additive	Concrete, tiles	Paper, cardboard, plastic, wood	30.63
IL10	Rolled plaster board, over the surface, 1,5 cm thick	Acrylic filler, paper, plaster, plaster board	Plaster	Paper, cardboard, plastic, wood, packaging with special remains	12.12
IL11	Rolled plaster board, over steel structure, 1,5 cm thick	Steel, acrylic filler, paper, plaster, plaster board	Plaster	Paper, cardboard, plastic, wood, packaging with special remains	13.21
IL12	Galvanised steel structure	Galvanised steel, bitumen, glass wool, nylon, polyethylene	Bitumen, iron-steel	Cardboard, plastic	8.65
IL13	Corrugated steel sheet	Galvanised steel	-	Cardboard	16.93
IL14	Ceramic block + plaster, 6 cm thick	Ceramic block, plaster	Plaster, tiles	Paper, plastic, wood	13.45
IM01	Glass wool, 5 cm thick	Nylon, glass wool	Insulating material	Plastic, wood	5.77
IM02	Rock wool, 5 cm thick	Rock wool	Insulating material	Plastic, wood	9.48

Abbreviations:
VIE: Internal WallIL: internal layers IM: insulation materials without air chamber

Item description on materials combination, wastes and cost for External Wall (VEE)

Item	Description	Materials	Construction and demolition wastes	Packaging waste	Cost (€/m^2)
EL01	Solid brick , 14 cm thick	Water, sand, cement, ceramic brick	Concrete, brick	Paper, plastic, wood	57.17
EL02	Drilled brick , 14 cm thick	Water, sand, lime, cement, ceramic brick	Concrete, brick	Paper, plastic, wood	27.74
EL03	Drilled brick, at sight , 14 cm thick	Water, sand, cement, ceramic brick	Concrete, brick	Paper, plastic, wood	51.90
EL04	Hollow brick , 14 cm thick	Water, sand, cement, ceramic brick	Concrete, brick	Paper, plastic, wood	25.36
EL05	Mortar block, 13 cm thick	Water, sand, lime, cement, mortar block	Concrete, brick	Paper, plastic, wood	21.62
EL06	Mortar block, at sight, 13 cm thick	Water, sand, lime, cement, mortar block	Concrete, brick	Paper, plastic, wood	23.91
EL07	Expanded clay block, 25 cm thick	Water, sand, cement, expanded clay block	Concrete, brick	Paper, plastic, wood	23.70
EL08	Expanded clay block, at sight, 25 cm thick	Water, sand, cement, expanded clay block	Concrete, brick	Paper, plastic, wood	25.31
EL09	Light clay block, 14 cm thick	Water, sand, cement, light clay brick	Concrete, brick	Paper, plastic, wood	18.71
EL10	Light clay block, 24 cm thick	Water, sand, cement, light clay brick	Concrete, brick	Paper, plastic, wood	27.45
EL11	Mortar single layer	Additive, sand, cement	Concrete	Paper, plastic, wood	19.14

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EL12	Mortar coating layer, 10-15 cm thick	Additive, water, sand, cement	Concrete	Paper, plastic, wood, packaging with special remains	13.23
EL13	Airy ceramic façade	Galvanised steel, nylon, plaster	Iron-steel, plaster	Paper, cardboard, plastic, wood	48.08
EL14	Reinforced concrete sheet, 12 cm thick	Hot rolled steel, sheet rolled steel, concrete block, antirust paint, silicone filler	-	Plastic, wood, packaging with special remains	106.12
EL15	Artificial stone sheet	Galvanised steel, additive, water, sand, cement, cement plaster	Concrete	Paper, cardboard, plastic, wood	92.34
EL16	Expanded clay block, 15 cm thick	Water, sand, cement, expanded clay block	Concrete, brick	Paper, plastic, wood	18.50
EL17	Expanded clay block, at sight, 15 cm thick	Water, sand, cement, expanded clay block	Concrete, brick	Paper, plastic, wood	20.07
EL18	Steam barrier	Polyethylene	Plastic	Cardboard, plastic, wood	0.89
IM01	Polyurethane, 4 cm thick	Polyurethane foam	Special wastes	Packaging with special remains	10.82
IM02	Extruded polystyrene, 4,5 cm thick	Nylon, extruded polystyrene	Insulating material	Cardboard, plastic, wood	14.22
IM03	Expanded polystyrene, 5 cm thick	Nylon, expanded polystyrene	Insulating material	Cardboard, plastic, wood	7.68
IM04	Glass wool, 6 cm thick	Nylon, glass wool	Insulating material	Cardboard, plastic, wood	5.28
IM05	Rock wool, 6 cm thick	Nylon, rock wool	Insulating material	Cardboard, plastic, wood	11.94
IM06	Cork board, 8 cm thick	Nylon, cork board	Insulating material	Cardboard, wood	16.38
IM+AC01	Polyurethane, 4 cm thick	Polyurethane foam	Special remains	Packaging with special remains	10.82
IM+AC02	Extruded polystyrene, 3,5 cm thick	Nylon, extruded polystyrene	Insulating material	Cardboard, plastic, wood	11.59
IM+AC03	Expanded polystyrene, 4 cm thick	Nylon, expanded polystyrene	Insulating material	Cardboard, plastic, wood	5.83
IM+AC04	Glass wool, 4 cm thick	Nylon, glass wool	Insulating material	Cardboard, plastic, wood	7.53
IM+AC05	Rock wool, 4 cm thick	Nylon, rock wool	Insulating material	Cardboard, plastic, wood	9.32
IM+AC06	Cork board, 6 cm thick	Nylon, cork board	Insulating material	Cardboard, wood	12.48
IL01	Simple hollow brick, 4 cm thick	Water, sand, cement, ceramic brick	Concrete, brick	Paper, plastic, wood	13.28
IL02	Double hollow brick, 10 cm thick	Water, sand, cement, ceramic brick	Concrete, brick	Paper, plastic, wood	17.57
IL03	Rendering	Water, plaster	Plaster	Paper, plastic, wood	4.52
IL04	Ceramic block + plaster, 6 cm thick	Ceramic brick, plaster	Plaster, tiles	Paper, plastic, wood	13.45
IL05	Plaster board	Acrylic filling, paper, plaster, plaster board	Plaster	Paper, cardboard, plastic, wood, packaging with special remains	12.12
IL06	Plaster board partition	Acrylic filling, paper, nylon, plaster board, steel, galvanised steel	Plaster, iron-steel	Paper, cardboard, plastic, wood, packaging with special remains	22.39

Abbreviations:
VEE: external walls EL: external layers
IM+AC: insulation materials with air chamber IM: insulation materials without air chamber

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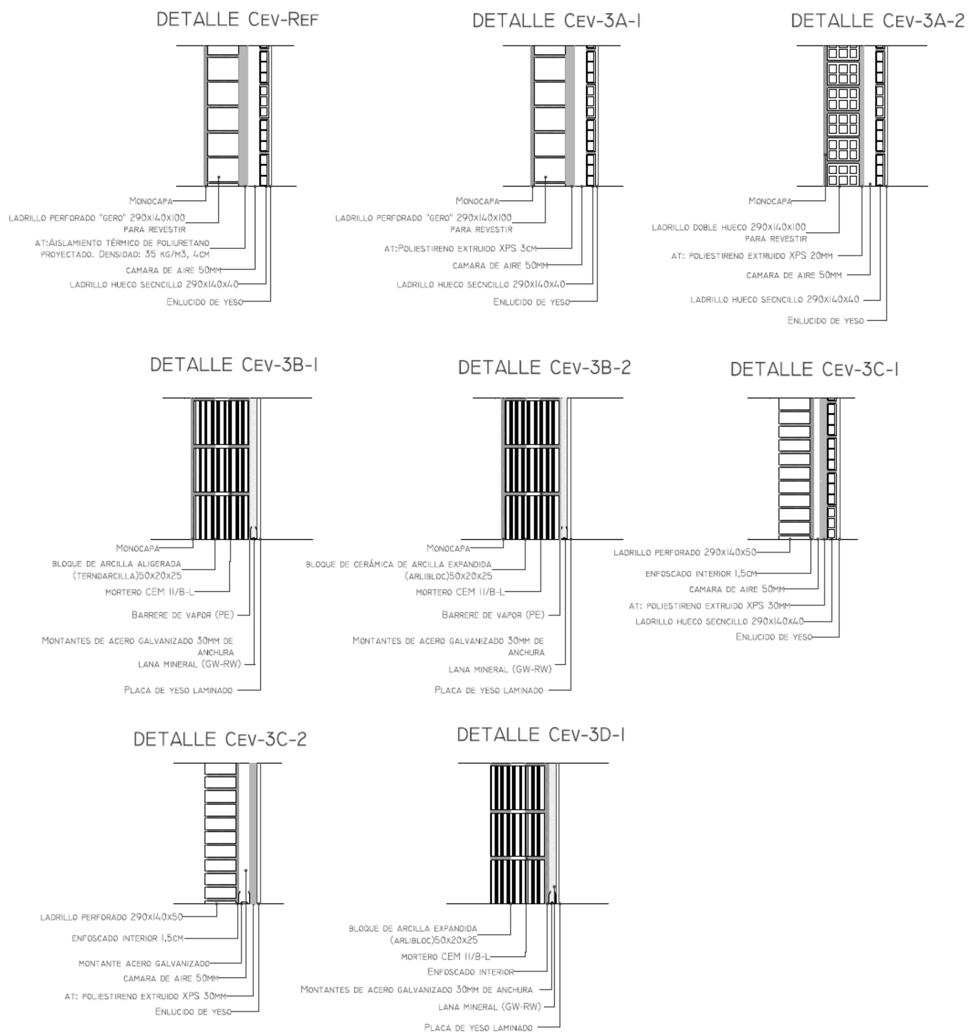

Abbreviations:

Cev –Ref Hoja exterior de ladrillo perforado con acabado monocapa y hoja interior cerámica (AT: poliuretano)

Cev – 3A1 Hoja exterior de ladrillo con acabado monocapa y hoja interior cerámica (AT: XPS)

Cev – 3A2 Hoja exterior de ladrillo hueco con acabado monocapa y hoja interior cerámica. (AT: XPS)

Cev – 3B1 Hoja exterior de bloque de arcilla aligerada (termoarcilla) con acabado monocapa y hoja interior de yeso laminado (AT: lana mineral)

Cev – 3B2 Hoja exterior de bloque de arcilla expandida (arlibloc) con acabado monocapa y hoja interior de yeso laminado (AT: lana mineral)

Cev – 3C1 Hoja exterior de ladrillo perforado visto y hoja interior cerámica (AT: XPS)

Cev – 3C2 Hoja exterior de ladrillo perforado visto y hoja interior de yeso laminado (AT: lana mineral)

Cev – 3D1 Hoja exterior de bloque de arcilla expandida (arlibloc) visto y hoja interior de yeso laminado (AT: lana mineral)

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GLOSSARY

Building Materials and Component Combinations (BMCC) focus on a final building materials or product, while for Construction and Edification (C/E) the functional unit (FU) will be a dwelling, building or m^2 usable floor area.

CML 2001: CML 2 baseline method (2001). The CML 2 baseline method elaborates the problem-oriented (midpoint) approach. The CML Guide provides a list of impact assessment categories grouped into: Obligatory impact categories (Category indicators used in most LCAs). Additional impact categories (operational indicators exist, but are not often included in LCA studies), other impact categories (no operational indicators available, therefore impossible to include quantitatively in LCA).

Ecopoints: is a measure of the overall environmental impact of a particular product or process. More Ecopoints indicate higher environmental impact. The environmental impacts considered were: acidification potential, global warming potential, human toxicity and stratospheric ozone depletion.

Environmental Product Declarations (EPD) is a strategy adopted for the external communication and commitment to reduce environmental impacts caused by a product.

Life Cycle Assessment (LCA) is a methodology to evaluate environmental loads of processes and products (goods and services) during the life cycle, starting from extraction of raw materials, manufacturing, production, use and finishing with the final disposal – from cradle to grave -

Life Cycle Impact Assessment (LCIA) is a stage to make a probable estimation of the impact on the environmental loads and resources used in the modeled system. The LCIA phase consists of three mandatory elements: selection of impact categories, assignment of LCI results (classifications) and modeling category indicators (characterization).

Methodology is the study of methods and deals with the philosophical assumptions underlying the research process, while a Method is a specific technique for data collection under those philosophical assumptions.

Sustainable construction is a subgroup of sustainable development, which covers subjects like offer, planning and organization of the site, selection of materials, recycling and waste minimization.

Sustainable development: the idea of improving better quality of life for human beings, now and future generations to come. A widely used international definition is 'development which meets the needs of the present without compromising the ability of future generations to meet their own needs.' Also is understood as the improvement of the triple bottom line of the social, economic and environmental aspects.

PAPERS

Ortiz O, Francesc C, Sonnemann G. (2009): Sustainability in the construction industry: a review of recent developments based on LCA. Construction and Building Materials. Volume 23, Issue 1, January 2009, pages 28-39.

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Review

Sustainability in the construction industry: A review of recent developments based on LCA

Oscar Ortiz [a,b,*], Francesc Castells [a], Guido Sonnemann [c]

[a] *University of Rovira i Virgili, Environmental and Analysis Management Group (AGA), Department of Chemical Engineering, Av. Països Catalans 26, 43007 Tarragona, Spain*
[b] *University of Pamplona, Faculty of Engineering and Architecture, Km 1 Vía Bucaramanga, Pamplona N de S, Colombia*
[c] *University of Rovira i Virgili, Visiting Senior Research Fellow, AGA Group (AGA), Spain*

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Abstract

This review brings together research on life cycle assessment (LCA) applied within the building sector. More than ever, the construction industry is concerned with improving the social, economic and environmental indicators of sustainability. By applying LCA it is possible to optimise these aspects, from the extraction of raw materials to the final disposal of waste building materials. Firstly, this review details LCA concepts and focuses on the LCA methodology and tools employed in the built environment. Secondly, this paper outlines and discusses the differences between the LCA of building materials and components combinations versus the LCA of the full building life cycle. Finally, this work can be used by stakeholders as an important reference on LCA including up to date literature on approaches and methodologies to preserve the environment and therefore achieve sustainable development in both developed and developing countries.

The present review has tried to compile and reflect the key milestones accomplished in LCA over the last 7 years, from 2000 to 2007 within the building sector. In summary, it can be stated that the application of LCA is fundamental to sustainability and improvement in building and construction. For industrial activities, SMEs must understand the application of LCA, not only to meet consumer demands for environmentally friendly products, but also to increase the productivity and competitiveness of the green construction markets. For this reason, this review looks at LCA because of its broad international acceptance as a means to improve environmental processes and services, and also for creating goals to prevent adverse environmental impacts, consequently enhancing quality of life and allowing people to live in a healthy environment.

Keywords: Building materials; Building life cycle; Construction industry; LCA; Sustainability; Sustainable development

Contents

* Corresponding author. Address: University of Pamplona, Faculty of Engineering and Architecture, Km 1 Vía Bucaramanga, Pamplona N de S, Colombia. Fax: +57 34 977559621.
E-mail addresses: oscar.ortiz@urv.cat (O. Ortiz), francesc.castells@urv.cat (F. Castells), Guido.Sonnemann@unep.fr (G. Sonnemann).

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1. Introduction

The term sustainable development can be described as enhancing quality of life and thus allowing people to live in a healthy environment and improve social, economic and environmental conditions for present and future generations. Since the world commission on environment and development (WCED), entitled Our Common Future (1987), sustainable development has gained much attention in all nations and a report was published which called for a strategy that united development and the environment and which also made a declaration describing sustainable development as meeting the needs of the present without compromising the ability of future generations to meet their own needs [1]. Sachs [2] believed that the great challenge of the 21st century would be sustainable development. Vollenbroek [3] stated that sustainable development is a balance between the available technologies, strategies of innovation and the policies of governments.

The improving social, economic and environmental indicators of sustainable development are drawing attention to the construction industry, which is a globally emerging sector, and a highly active industry in both developed and developing countries [4–6]. Socially and economically, the European Commission (2006) stated that 11.8 million operatives are directly employed in the sector and it is Europe's largest industrial employer, accounting for 7% of total employment and 28% of industrial employment in the EU-15. About 910 billion euros was invested in construction in 2003, representing 10% of the gross domestic product (GDP) and 51.2% of the Gross Fixed Capital Formation of the EU-15 [7]. By contrast environmentally, this sector is responsible for high-energy consumption, solid waste generation, global greenhouse gas emissions, external and internal pollution, environmental damage and resource depletion [8–10].

In order to overcome the increasing concern of today's resource depletion and to address environmental considerations in both developed and developing countries, life cycle assessment (LCA) can be applied to decision making in order to improve sustainability in the construction industry.

The aim of this review is to systematically examine previous LCA research on the building sector in order to analyse the current situation and to outline the key challenges concerning LCA and the construction industry. Firstly, this paper provides details of LCA and its methodology, which is based on International standard series ISO 14040. Secondly, the review systematically explores and evaluates the different ways of using LCA for building materials and component combinations (BMCC) and LCA of the whole process of the construction (WPC), for example, in urban constructions of dwellings, commercial buildings and other civil engineering projects over the last 7 years, from 2000 to 2007. Following this, we present the discussion of the perceived advantages and limitations of LCA, and finally, we look at the outlook and challenges for ongoing research in LCA and draw some conclusions.

2. Conceptual basis of life cycle assessment (LCA)

Life cycle assessment (LCA) is a methodology for evaluating the environmental load of processes and products (goods and services) during their life cycle from cradle to grave [11–16]. LCA has been used in the building sector since 1990 and is an important tool for assessing buildings [17,18].

Klöpffer [19] stated that LCA has become a widely used methodology because of its integrated way of treating topics like framework, impact assessment and data quality. The description of the LCA methodology is based on the International standards of series ISO 14040 and consists of four distinct analytical steps: defining the goal and scope, creating the inventory, assessing the impact and finally interpreting the results [20]. This paper will now briefly explore LCA methodology.

Firstly, defining goal and scope involves defining purpose, audiences and system boundaries. Secondly, the life cycle inventory (LCI) involves collecting data for each unit process regarding all relevant inputs and outputs of energy and mass flow, as well as data on emissions to air, water and land. This phase includes calculating both the material and the energy input and output of a building system. Thirdly, the life cycle impact assessment (LCIA) phase evaluates potential environmental impacts and estimates the resources used in the modeled system. This phase consists of three mandatory elements: selection of impact categories, assignment of LCI results (classifications) and modeling category indicators (characterization). Classification of the LCI results involves assigning the emissions, wastes and resources used to the impact categories chosen, e.g. CO_2, and CH_4, CO. The converted LCI results are aggregated into an indicator result, which is the final result of the mandatory part of an LCIA. Normalization, grouping, weighting and additional LCIA data quality analysis are optional steps. In a life cycle impact assessment (LCIA), there are essentially two methods: problem-oriented methods (mid-points) and damage-oriented methods (end points) [21]. The mid-points approach involves the environmental impacts associated with climate change, acidification, eutrophication, potential photochemical ozone creation and human toxicity and the impacts can be evaluated using the CML baseline method (2001), EDIP 97& EDIP 2003 and IMPACT 2002+. The end points approach classifies flows into various environmental themes, modeling the damage each theme causes to human beings, natural environment and resources. Ecoindicator 99 and IMPACT 2002+ are methods used in the damage-oriented method.

Finally, the last stage of ISO 14040 is the interpretation. This stage identifies significant issues, evaluates findings to reach conclusions and formulate recommendations. The final report is the last element to complete the phases of LCA according to ISO 14040.

Regarding methodology, various LCA tools have been developed and made available for use in environmental assessment. These tools have been classified according to three levels. Level 3 is called "Whole building assessment framework or systems" and consists of methodologies such as BREEAM (UK), LEED (USA), SEDA (Aus); level 2 is titled "Whole building design decision or decision support tools" and uses LISA (Aus), Ecoquantum (NL), Envest (UK), ATHENA (Canada), BEE (FIN); finally level 1 is for product comparison tools and includes Gabi (GER), SimaPro (NL), TEAM (Fra) LCAiT (SE). Some databases used for environmental evaluation are: CML, DEAM TM, Ecoinvent Data, GaBi 4 Professional, IO-database for Denmark 1999, Simapro database, the Boustead Model 5.0 and US Life cycle inventory database [22–25]. It is observed that previous tools and databases vary according to users, application, data, geographical location and scope. The data represents conditions in industrialized countries. Data from developing and emerging countries, however, is still lacking [26]. For example the use of European and American database may not lead to correct decisions in developing countries. Nevertheless, Frischknecht et al. [27] studied that consistent, coherent and transparent LCA datasets for basic processes make it easier to perform LCA projects, and increase the credibility and acceptance of the LCA results. Huijbregts et al. [28] insisted on evaluating uncertainties such as parameter uncertainty, scenario uncertainty and model uncertainty to improve the application and use of LCA. Hence, LCA does not make any explicit differentiation between the emissions at diverse points of the time. For instance, Hellweg et al. [29] found that if an emission contributes today to the exhaustion of ozone in 200 years, it is treated independently from the period considered in the evaluation of the LCA.

3. Method: state of the art of LCA of building materials and component combinations (BMCC) versus LCA of the whole process of the construction (WPC)

This review of the application of LCA to the construction industry focuses on the two different ways of using LCA for the building material and component combinations (BMCC) and the Whole Process of the construction (WPC). Therefore, this review has considered LCA methodology in the determination of the Functional Unit (FU). Twenty-five case studies have been analysed, 60% of those applying LCA to BMCC and 40% applying LCA to WPC. These case studies have been taken from the last 7 years from 2000 to 2007. Furthermore, other variables for both the BMCC and WPC approaches are discussed, such as who, what, where, why and when.

3.1. Building material and component combinations (BMCC)

Some LCA studies explicitly dedicated to BMCC have been done during the last seven years [30–36]. Those LCA studies presented are not fully comparable; there are differences in the final product and also most studies neglect cost except those works which show the application of shadow prices [37,38]. However, the most recent methodologies which incorporate information regarding environmental impacts and embodied energy in building materials are necessary for sustainable development. To achieve this, the European Commission in 2003 officially released the integrated policy product (IPP) voluntary approach [39]. This policy looks to identify products within the construction sector with the greatest potential environmental impact by focusing on the whole product life cycle and consists basically of three stages: environmental impact products (EIPRO), environmental improvement products (IMPRO) and Policy Implications. Strategies used in the implementation of the IPP are the environmental product declarations (EPD) and Ecodesign. EPD is a strategy adopted for external communication and is committed to reducing the environmental impact of a product [40]. EPDs such as those made on concrete, wood and metals such as aluminium are based on LCA and contain information associated with the acquisition of raw materials, energy use, content of materials and chemical substances, emissions into the air, land and water and waste generation [41–43]. On the other hand, Ecodesign looks at the relationship between a product and the environment. Ecodesign also summarizes techniques to reduce the environmental impact throughout different life cycle stages. Sun et al. [44] and Pujari [45] concluded that common proposals of Ecodesign include ascertaining the environmental impact of the whole production-consumption chain; considering environmental factors during the design of products, processes and activities (dematerialization), given that this is when 60–80% of their life-cycle impact is incurred. However, limited research has been published on Ecodesign in household hazardous waste derived from electrical and electronic equipment (EEE).

Statistics from the U.S. Energy information administration (2003) combined the annual energy required to operate dwelling and commercial buildings with the embodied energy of industry-produced building materials like concrete, ceramic, glass, steel etc., and revealed buildings to be the largest energy consuming and greenhouse gas emitting sector [46], Asif et al. [30] studied eight construction materials for a dwelling in Scotland. These materials were: timber, concrete, glass, aluminium, slate, ceramics tiles, plasterboard, damp course and mortar. The study concluded that the material used in the house with the highest level of embodied energy was concrete, at 61%. The other two materials, timber and ceramic tiles represented 14% and 15%, respectively of the total embodied energy. Concrete was the material responsible for 99% of the total of CO_2 of home construction. However, although there is no doubt that using timber is indispensable for reducing environmental impacts such as CO_2 [31,37], some authors stated that it is incorrect to think of wood as having a negative global warming potential, because sooner or later it will be incinerated or land filled, with the result that the CO_2 balance will be neutral or positive [47].

Alternatively, methodologies for building materials such as reused and eco-materials have been gaining the attention of academics and researchers. Erlandsson and Levin [48] studied a new methodology for reused materials. This study concluded that this strategy is better for the environment than constructing a new building, if the essential functional operation is the same. Additionally, a case study verified that the potential consequences for the environment could be reduced by nearly 70% for heating and 75% for the sewage system. However, when creating classification materials, it is essential to focus on the type of material and their environmental performance. In order to assess products' expected environmental impacts, Ross and Evans [49] performed a LCA case study for a plastic based packaging based on two strategies: re-use versus recycle. By comprehensively reviewing existing literature on building material selection, Sun et al. [50] presented a simplified method to evaluate the environmental loads associated with the material selection of a product. Materials were classified according to glass and ceramics, ferrous metal, no ferrous metal, paper, polymers and woods. Select durable and renewable materials are alternatives for grouping materials and also can promote best practices and economical techniques such as recycling, reusing and recovering materials for optimum waste disposal.

Finally, for eco-materials products, Nie and Zuo [51] studied the importance of investigating and applying building materials. This approach has lead to the development of new materials with low environmental loads during their life cycle. According to Chavan [52], smart building materials such as titanium dioxide can be used for cement and concrete products can be coated for self-cleaning effect due to their strong oxidizing properties. This technique can enable the construction industry to use nanotechnology but due to the increasing use of this field, it is important to examine the life cycle, effects and risk assessment that nanoparticles have on humans and the built environment.

3.2. Whole process of the construction (WPC)

When applied to the full building life cycle, LCA is divided up in three common scenarios: dwellings, commercial buildings and civil engineering constructions.

3.2.1. LCA for dwellings

One of the first analyses during the last seven years on the environmental impact of the dwelling as a whole was performed by Adalberth et al. [53]. The main aim of this study was to evaluate the life cycle of four dwellings located in Sweden with different construction characteristics. The selected functional unit was m^2 of usable floor area. The sensitivity analysis had three parameters: variation of electricity mix, building material data and energy use. The results showed that the factor with the greatest environmental impact was electricity mix. In addition, the paper analysed the importance of knowing which phase in the life cycle has greater environmental impact, if there are similarities between environmental impacts and energy use; or if there are differences between subsisted environmental impacts due to the selection of the construction. Considering an occupation phase of 50 years for the dwellings, this study concluded that the greatest environmental impact occurs during the use phase. Also, 70–90% of the environmental categories arise in this phase. Approximately 85% and 15% of energy consumption occurs during the occupation and manufacturing phases, respectively. SBI's LCA tool was used for the environmental impact of the building.

In a brief analysis on the evaluation of environmental impact of the building life cycle, Peuportier [47] compared three types of houses with different specifications located in France. The functional unit was 1 m^2 living area. The sensitivity analysis was based on the selection of other construction materials (wood versus concrete blocks), the type of heating energy (gas versus electricity) and the transport distance of the wood. EQUER tool was used for the environmental impact of the building. Inventories were taken from the Oekoinventare database. Previous studies in Adalberth et al. [53] and Peuportier [47] showed that the GWP and acidification impacts were highest when the main construction equipment was concrete. The dwellings that had the greatest environmental impacts were not those with the highest m^2 constructed. Hence it is necessary to choose materials with low environmental impact during the pre-construction phase. Furthermore, it can be seen that in Europe the pre-construction step has strong

Table 1
Characteristics of published LCA applied within the building sector for both BMCC and WPC

Reference	BMCC	WPC	Content, country and year.	Environmental loads analysed												
				GW	A	E	OD	HT	EL	WC	DA	W	EC	RS	AR	O
Adalberth et al. [53]		×	Life cycle of four dwellings located in Sweden (2001)	×	×	×	×	×	×							
Ardente et al. [61]	×		LCA of a solar thermal collector, Italy (2005)							×		×		×	×	
Arena and Rosa [62]		×	LCA of energy of the implementation of conservation technologies in school buildings in Mendoza, Argentina (2003)	×		×			×					×		×
Asif et al. [30]	×		LCA for eight different building materials for a dwelling located in Scotland (2005)	×												
Citherlet et al. [63]	×		LCA of a window and advanced glazing systems in Europe (2000)	×	×		×									×
Gustavsson and Sathre [31]	×		LCA Sweden case study: wood and concrete in building materials (2006)													×
Jian et al. [59]		×	LCA of urban project located in Hyogo, Japan (2003)	×					×	×		×				
Junnila [57]		×	LCA for a construction of an office: a Finland case study (2004)	×	×	×			×							×
Koroneos and Dompros [64]	×		LCA of brick production in Greek (2006)	×	×	×						×				×
Koroneos and Kottas [65]		×	LCA for energy consumption in the use phase for a house in Thessaloniki, Greece (2007)	×	×	×	×		×							×
Mroueh et al. [66]		×	A Finnish LCA case study of road construction (2001)											×	×	×
Nebel et al. [32]	×		LCA for floor covering, Germany (2006)	×	×	×	×									×
Nicoletti et al. [33]	×		LCA of flooring materials (ceramic versus marble tiles), Italy (2002)	×	×		×	×			×					×
Nyman and Simonson [54]	×		LCA of residential ventilation units over a 50 year life cycle in Finland (2005)	×	×		×				×				×	
Peuportier [47]		×	Comparison of three types of houses with different specifications located in France (2001)	×	×	×	×	×	×	×	×	×	×	×	×	
Petersen and Solberg [34]	×		LCA by comparing wood and alternative materials in Norway and Sweden (2005)		×	×	×	×								
Prek [68]	×		LCA of heating and air conditioning systems. A Case study for a single family dwelling in a residential building in Slovenia (2004)	×			×									
Ross and Evans [49]	×		An Australian LCA case study for a plastic-based packaging based on two strategies: re-use versus recycle (2003)									×		×		
Saiz et al. [35]	×		LCA for green roofs located in downtown Madrid, Spain (2006)	×	×	×	×	×		×		×				×
Scheuer et al. [58]		×	LCA to a new University building campus with a total area of 7300 m^2 in USA (2003)	×	×		×		×			×				×
Schleisner L [69]		×	LCA Case Study to produce different energy production technologies in Denmark (2000)						×							×
Seppala et al. [36]	×		LCA for Finnish metal products (2002)			×		×	×	×		×				×
Van der Lugt. et al [37]	×		LCA for using bamboo as building material versus steel, concrete and timber in Western Europe (2006)													×
Wu [38]	×		LCA: a Chinese case study for different building materials (2005)	×	×	×	×		×	×						×

Abbreviations: GW, global warming potential; OD, photochemical ozone creation; WC, water consumption; DA, depletion abiotic resource; WPC, whole process construction; A, acidification; HT, human toxicity; W, waste creation; EC, ecotoxicity; BMCC, building and materials components combinations; E, eutrophication; EL, energy consumption; RS, resources consumption; O, others; AR, air emissions.

influence on energy consumption and consequently on the operation phase. For this reason the energy requirements for HVAC are much higher due to the bio-climatic conditions during the operation phase of buildings and are mainly dependent on the behaviour pattern of the citizens and directly linked to construction materials due to the fact that the buildings provide occupants with a healthy indoor environment [54]. Additionally, it can be seen that both works are similar but the sensitivity analysis were done in different scenarios and that other considerations were taken into account such as quality of life, thermal and climate performances to evaluate the entire building life cycle. There is another research done by Jian et al. [59] that analysed the LCA of urban project development through the calculation of CO_2 emissions during construction, maintenance and operation of facilities and public buildings, and their environmental impacts. Data were collected to complete a case study located in the District of Hyogo, Japan. Proposals for the mitigation and simulation of CO_2 reduction were limiting land use of suburban commercial facilities; changing non-wood dwellings to low stored wood dwelling and increasing open spaces such as parks and green areas.

Finally, more specifically, there has been one LCA case study in an indoor environment, Arjen et al. [55] studied the total amount of building materials which humans were exposed to in the use phase of a Dutch home. The emission of radon was 59%, the highest contaminant and harmful to human health; 38.7% for gamma radiating elements; 1.3%, 0.8% and 0.2% formaldehyde, toluene and others, respectively.

3.2.2. LCA for commercial constructions

There has been a fair amount of descriptive work on commercial constructions, but limited research has been published thus far on complete LCA of office buildings, although the first attempts started appearing in 2003 [56]. For example, Junnila [57] studied a construction of an office of 24 000 m^2. Almost 130 different building parts and fifty different building material groups were identified in the inventory phase. The operation phase of the building was divided into operating electricity, operation heat and other services (water use, waste water generation, courtyard care). The energy consumption calculations for the building were performed by a HVAC and electrical design using the WinEtana energy simulation program. The following environmental impacts were studied: climate change, acidification, eutrophication, summer smog and heavy metals by using the Kcl-Eco software with Ecoindicator 95. The data were taken from the Finnish LCA database for energy, LIPASTO, Eco 1999, Simapro and Boustead. The study found that the operating electricity is the most representative of environmental impacts.

Other study done by Scheuer et al. [58] applied LCA to a new university building campus with a total area of 7300 m^2. The research showed that almost 60 building materials were identified for the inventory analysis. The results showed that in the positioning of materials phase (activities required for the design, construction and renovation of a building) the total embodied primary energy was 51×106 MJ over the building life cycle. The operation phase showed 97.7% of the primary energy; the energy required for decommissioning, demolition and transport was 0.2%. The following categories of environmental impacts were studied in the operational phase: global warming (93.4%), nutrification potential (89.5%), acidification (89.5%), ozone depletion potentials (82.9%) and solid waste generation (61.9%). This study also concluded that the operation phase had higher environmental impacts compared with other life cycle phases for the building. Data were taken from Simapro, Franklin associates, DEAM^{TM}, and the Swiss Agency for the Environment, Forests and Landscape.

3.2.3. LCA for civil engineering constructions

LCA have been used in other civil engineering projects. For example, regarding highway constructions, Birgisdottir et al. [60] compared two scenarios with natural versus different types of materials. The method of the LCA was evaluated in ROAD-RES tool, which can be used for LCA in the road construction and waste disposal. Environmental impacts like global warming, acidification and ecotoxicity were analysed. Mroueh et al [66] has carried out a similar study of these impacts. It can be observed in both investigations that the application of LCA pursue strategies to minimize the environmental loads, resource consumption and applied strategies such as recycling and reusing of building materials.

The following Table 1 summarizes the characteristics of some published LCA case studies for both BMCC and WPC with their respective environmental loads.

4. Evaluation of the scenarios analysis

There are practical differences between both scenarios: LCA of building materials and components combinations (BMCC) and LCA of the full building life cycle (WPC).

First, from the reviewed scientific literature it was found that LCA of the full building life cycle as a process is not static; it varies from building to building since each has its own function and different characteristics of engineering [67,70]. For example, construction techniques, architectural style and different conditions such as household size, climate and cultural consumption behaviour vary from country to country. Furthermore, a variation in each design can affect the environment during all life cycle stages of a building. Second, the notation that has been chosen for this review was based on the functional unit. The functional unit for the building material and component combinations was focused on a final product, while for whole building the FU was analysed, taking into account a dwelling, building or m^2 usable floor area. Third, LCA for both scenarios is very industry specific. For instance, construction and building projects have complex processes and many assumptions have to be made, while in building materials and products, processes are based on a single product. Paulsen and Borg [71] stated that characteristic of buildings and building products is their significantly longer life compared to most other building materials and industrial products, and the involvement of many different factors during their life cycle. Furthermore, Gregory and Yost [72] concluded that the direct application of LCA in the construction sector is not a simple or straightforward process. It is expensive and cannot be applied without assumptions or additional modifications. Fourth, most LCA initiatives were focused on evaluating environmental impacts. For example, LCA for the whole building have been evaluated, considering aspects such as cultural consumption behaviours and patterns during the use phase. Promoting better insulation alternatives, replacing materials with less environmental burdens and supporting the application of technologies in renewable energies were the main alternatives evaluated in this scenario. LCA for BMCC have been applied to compare products, promote new products and contribute to better environmental decisions and policies and to improve environmental considerations of products. Fifth, most LCA of WPC data have been taken from architects, engineers, drawings, engineering specifications, suppliers and interviews, while the LCA for BMCC are based in industrial processes. Fig. 1 indicates the life cycle of both scenarios. The phases involved in the building life cycle include raw materials, construction, use and maintenance and finish with final disposal or demolition (cradle to grave). Building materials involve processes such as production, use and final disposal.

5. Discussion of perceived advantages and limitations of LCA

The present review, though not claiming to be exhaustive, demonstrates the progressive evolution of LCA in the building sector during the last seven years. It illustrated how approaches for both BMCC and WPC have been evaluated on scientific evidence. It has been shown that the use of LCA for evaluating building material and LCA for the whole process of the construction and edification is not novel, nor is the use of cost and data sensitivity analysis. However, most analyses of LCA focused on the evaluation and use of sustainability indicators. The results showed that LCA of BMCC and WPC definitely represent an innovative methodology which improves sustainability in the construction sector throughout all stages of the building life cycle. It is also observed that more than 90%–95% of the LCA case studies were focused on evaluating environmental impacts and assisting the decision-making within the building sector. The choice of impact categories was made between loads that are commonly analysed. More environmental burdens identified were global warming potential (GWP), acidification and energy consumption. Nevertheless, other environmental impacts were evaluated such as: inefficient land use, water shortage, air pollution, traffic congestion, deterioration of ecological systems, high consumption of energy, and waste management [73,74]. However the Green Building Challenge Stockholm [75] and Borg [76] declared that aspects like global warming potential (GWP), land use, acidification, eutrophication, stratospheric ozone depletion, abiotic resources and human toxicity are impacts more identified within the building sector. The main influence of climate change were emissions of greenhouse gases. Regarding the selection of the impact categories, Houghton et al. [77] classified the most relevant greenhouse emissions as being carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs).

It has been also seen that global warming potential was the greatest environmental challenge facing the built environment due to the significant period of occupancy occur for the service life caused by the heating, ventilating and air conditioning (HVAC) [78–80].

More generally the review has demonstrated that most LCA studies focus on energy consumption. In response to steadily increasing concern over energy consumption, Kotaji et al. [81] stated that energy consumed during preconstruction accounted from 10% to 20%; during the occupation phase, Adalberth [82] and Bisset [83] stated that energy household activities are estimated between 40% and 50% and for the dismantling phase, Kotaji et al. [81] concluded that energy use is less than 1% through treatment of their final disposition. A detailed study has been found taking into account household energy consumption. For example, Hertwich [26] compared the annual energy consumption per-capita and CO_2 emissions. The results

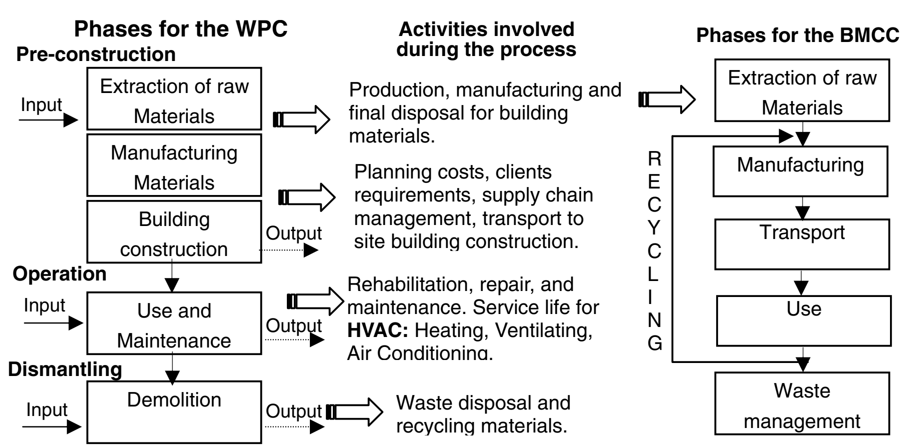

Fig. 1. Schematic representation of the building life cycle.

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showed that the United States is the maximum CO_2 emitter per capita as well as energy consumer. But due to high levels of industrial and economic investment in China, it is unquestionable that this Asian giant will exceed the USA's CO_2 emissions in the coming years. Runming et al. [84] observes that China's building sector currently accounts for 23% of China's total energy use and this is projected to increase to one-third by 2010. Therefore, there is no doubt that reducing the environmental impact of the building sector is important to achieve sustainable development. For example, a proper construction can achieve sustainable development by using fewer natural materials, materials with low environmental impacts, green materials and applying renewable energies to reduce environmental loads and energy and water consumption [85], thereby promoting the principles of sustainable construction [86]. Based on these reflections, there are currently two examples worldwide that could be considered best practices and that fulfilled the requirements and applications integrating the principles of materials and energy as well as the reduced cost required to operate buildings: the European project passive house [87] and the American Off-Grid Zero Emission Buildings [88].

6. SMEs: methodologies applied within the construction industry and perspectives in developing countries

Over the years, it has been observed that there are various methodologies applied within the construction industry in pursuit of continuous improvement for sustainability indicators [89–91]. Despite the application of methodologies as eco-efficiency, cleaner production, extended polluter responsibility, industrial ecology, Eco-label and Environmental Management Systems, there are still a lot of adverse environmental loads emitted by small and medium enterprises (SMEs) and research is required to evaluate the environmental burdens emitted into the atmosphere by SMEs, both globally and locally [92].

Nevertheless, there are pros and cons associated with SMEs. Social and economically, SMEs are a strong base for the economy of any country. For instance, 99.8% and 90% of all companies are SMEs in the UK and Europe, respectively [93]. The European Commission 2006 [94] stated that SMEs in the industrial sector could fluctuate according to macroeconomic indicators like the GDP due to their high indices of investment and contribution to the growth in employment. Some sustainability indicators, for example the Spanish Central Directory of Companies (DIRCE) [95] showed that SMEs 12.79% exert their activity in the construction sector, while the National Statistics Institute (INE) showed that the number of houses built had increased from 302 000 units in 1995 to 750 000 in 2006. In Colombia, the Administrative Department of National Statistics (DANE) [96] stated that the building sector participates in 5.2% of the GDP and SMEs in 2004 contributed to a 96.4% of the industrial activities and that 63% of employment is generated for SMEs. The DANE in 2003 confirmed that 70 000 dwellings for social interest and other 125 000 dwellings for not social interest were built and it is also projected that in 2019, 80% of Colombians will live in urban centers. By contrast, environmentally, Hillary [97] suggested that the industrial sector of SMEs contributes up to 70% of industrial pollution and there is a need to increase the modernization of industrial process in developing countries and promote best practices engineering [98–100].

In order to overcome these adverse environmental impacts and due to the fact that the construction sector must react quickly to changing environmental considerations, lack of knowledge, capacity and initiative to apply a life cycle method to the SMEs, LCAs are sought worldwide and this methodology is not a utopian tool to deploy in developing countries. Although financial supports, technology and technical assistance play a significant role when applying LCA throughout industrial activities in developing countries, in developed countries LCA is the cornerstone for most industrial activities [101–104]. It is, therefore important to apply the nascent LCA methodology in both developed and developing countries to allow sustainable development [105,106].

7. Outlook and challenges for ongoing research in LCA

From the reviewed literature it was proofed that there have been some LCA studies published thus far on complete LCA of the full building life cycle. For example, LCA was applied to evaluate environmental impacts and energy use of a residential home in Michigan [107]. Asif et al. [30] performed a LCA for a dwelling home in Scotland for eight construction materials. Another study by Adalberth et al. [53] has used LCA to evaluate the life cycle of four dwellings located in Sweden. Peuportier [47] compared three types of houses with different specifications located in France. While the previously referenced studies describe in various environmental considerations and energy use detail for dwellings in Europe and USA, there are no comparable studies in the literature from developing countries especially in Latin America.

Therefore, there is no doubt that applying LCA within the building sector can be very important in achieving sustainable development. Curran [108] stated that the most appropriate method for a holistic assessment is LCA, a systematic study of the life cycle (materials manufacturing, construction/ manufacturing processes, use, maintenance, renovation, and end of life treatment) and supply chain environmental effects of products, processes and services. Consequently, LCA is required to promote the best practical methodologies to evaluate, analysis and check the construction life cycle to prevent environmental impacts and assist the field of engineering techniques of buildings.

Finally, the promotion of the principles of sustainable construction in developed and developing countries is important for sustainable development, and the following questions should be considered: which materials can lead towards sustainable construction considering the criteria of sustainable development? How is it possible to get stakeholders in the building sector to apply LCA? How can SMEs improve their processes for their product life cycle? These questions will be answered in future studies in this project, which will consider the evaluation of environmental impacts during the building life cycle in Spanish and Colombian scenarios, as well as analysing whether the practical Ecodesign guidelines used in the sector in Spain and Europe, strong depending on climate conditions, can be applied in tropical areas. Social and economic indicators, the two other legs of sustainability, will also be considered because of their major specific role in developing countries. During this research, key issues will be energy, industrial development, air pollution/ atmosphere and climate change, along with the revision of behavioural patterns in the use phase. The outcome of this research will be used to develop guidelines based on LCA and Ecodesign, which will assist SMEs in developing countries to preserve the environment and contribute to the principles of sustainable construction.

8. Conclusions

The present review compiles and reflects the key milestones accomplished in Life Cycle Assessment over the last 7 years, from 2000 to 2007. It deals with topics such as the differences between LCAs of building materials and components (BMCC) versus LCAs of the whole process of constructions (WPC). LCA is recognized as an innovative methodology which improves sustainability in the construction industry throughout all stages of the building life cycle.

More attention has to be paid to SME's activities in the building sector. The aim for them should be to upgrade their processes and improve their economic and environmental viability. Socially and economically, SME's are a strong base for any country and consequently improvements in environmental behaviour have to be disseminated and applied to them.

It can be seen from the literature reviewed that there has been a large number of LCA studies which deal with a specific part of the building life cycle but few of them deal with the whole life span. Although most LCA case studies have been done in developed countries in Europe and the USA, there are no comparable studies in the literature from developing countries. Therefore, sustainability indicators in design, construction, operations and dismantling need to be developed and used in order to target environmental and energy considerations worldwide.

Among the environmental loads considered in the building sector the operation phase is the most critical in European scenarios. This is because of the higher environmental loads emitted into the atmosphere due to the high-energy requirement for HVAC, domestic hot water and lighting. The contribution made by the operation phase in buildings from tropical zones is not as significant due to lower energy consumption for HVAC. The need to properly evaluate energy requirements for HVAC depending on bioclimatic conditions and the behaviour patterns of citizens is clearly shown.

Finally, governments and environmental agencies should apply construction codes and other environmental policies to improve sustainability in the building sector. The other stakeholders also need to have a serious level of effort and commitment. For this reason, entities involved in the construction industry must be proactive in creating environmental, social and economic indicators, which bring about building sector sustainability and promote the use of sustainable construction practices in both developed and developing countries.

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Sustainability based on LCM of residential dwellings: A case study in Catalonia, Spain

Oscar Ortiz [a,b,*], Cécile Bonnet [c], Joan Carles Bruno [c], Francesc Castells [a]

[a] Environmental and Analysis Management Group (AGA), Department of Chemical Engineering, University of Rovira i Virgili (URV), Av. dels Països Catalans 26, 43007 Tarragona, Spain
[b] Department of Industrial Engineering, University of Pamplona, Km 1 Vía Bucaramanga, Pamplona N. de S., Colombia
[c] Group of Applied Thermal Engineering (CREVER), Department of Mechanical Engineering, University of Rovira I Virgili (URV), Av. dels Països Catalans 26, 43007 Tarragona, Spain

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A B S T R A C T

Life cycle management (LCM) can be applied to the whole construction process, thus making it possible to improve sustainability indicators and also minimize the environmental loads of the full building life cycle. To illustrate this, a case study has been carried out based on the application of the LCM approach to a typical Spanish Mediterranean house located in Barcelona with a total area of 160 m^2 and a projected 50-year life span, which has been modeled according to the Spanish building technical code (CTE). The aim of this research is to use sustainability indicators in the pre-construction and operation (use and maintenance) phases and also to promote and support the adoption of the LCM within the construction industry. This paper concludes that regarding the significant environmental issue of climate change, there was a total emission of 2.34E03 kg CO_2-Eq/m^2 per 50 years, of which about 90.5% was during the operation phase (use 88.9% and maintenance 1.7%) and the pre-construction phase account for a total of 9.5%. In terms of this dwelling's environmental loads, the operation phase is the most critical because of the high environmental loads from energy consumption for heating, ventilation and air conditioning (HVAC), lighting, electrical appliances and cooking.

Additionally, the findings of this study state that the appropriate combination of building materials, improvement in behaviors and patterns of cultural consumption, and the application of government codes would enhance decision-making in the construction industry. Therefore, there is no doubt that applying LCM to the full building life cycle is very important for reducing environmental loads and thereby improving sustainability indicators. Finally, this research will help develop guidelines based on LCM for the construction industry to assist stakeholders in improving customer patterns during the dwelling life cycle.

1. Introduction

In every country the construction industry is currently concerned with improving sustainability indicators [1]. On the one hand, both socially and economically, this sector is highly industrially active and can cause fluctuations in macroeconomic indicators like the gross domestic product (GDP) due to the sector's high rates of investment and contribution to growth in employment. Globally, in 2001 this sector represented 10% of global GDP with an annual output of USD 3000 billion, of which 30% was in Europe, 22% in the United States, 21% in Japan, 4% in the rest of the developed word and 23% in developing countries. It also employed an estimated 111 million workers [2]. In Spain, the construction industry watchdog (SEOPAN) said that in 2005 the construction industry took a lead growth rate of 6%, which accounted for 17.8% of GDP, and contributed almost 11% to the gross value added (GVA). SEOPAN also stated that in 2006 the regions with the highest percentage of housing starts nationwide were Andalusia (19.7%), Catalonia (14.5%) and the region of Valencia (13.8%) [3]. In Catalonia, the Catalan Department for the Environment and Housing stated that the number of houses built had increased from 81.786 units in 2002 to 131.517 in 2006 [4]. On the other hand, this sector is responsible for adverse environmental impacts, high-energy consumption, solid waste generation, greenhouse gas emissions, external and internal pollution, environmental damage and resource depletion [5].

* Corresponding author at: Environmental and Analysis Management Group (AGA), Department of Chemical Engineering, University of Rovira i Virgili (URV), Av. dels Països Catalans 26, 43007 Tarragona, Spain. Tel.: +34 977 55 9644; fax: +34 977 55 9667.

E-mail addresses: oscar.ortiz@urv.cat (O. Ortiz), cecile.bonnet@urv.cat (C. Bonnet), juancarlos.bruno@urv.cat (J.C. Bruno), francesc.castells@urv.cat (F. Castells).

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Table 1
Comparison of LCA studies for residential dwellings

Specification	Blanchard and Reppe [8]	Asif et al. [9]	Adalberth et al. [10]	Peuportier [11]	Koroneos and Kottas [12]
Location	USA	Scotland	Sweden	France	Greece
Year	1998	2005	2000	2000	2005
Type of residential dwelling	Semidetached	Semidetached	Multi-family	Single-family house	Single-family house
Usable floor area	$\approx 228\,m^2$	$\approx 140\,m^2$	$700\,m^2$	$112\,m^2$	$225\,m^2$
Principal building materials	Concrete, gravel and wood	Concrete, timber, ceramics	Concrete, macadam	Concrete blocks	Brick
Wall composition	Double 2 × 4 studs, with a 8.9 cm spacing between the inner wall and outer wall studs. The wall cavity is filled with cellulose insulation	–	Masonry veneer, gypsum plasterboard, mineral wool, polyethylene foil, gypsum plasterboard on the inside of the wall	Concrete blocks and 8 cm internal insulation (polystyrene)	The external wall consists of double brick with interior insulation
Availability of sustainability indicators on energy production	None	None	None	None	Yes
HVAC analysis	Yes	None	None	None	None
Databases employed	DEAM and Óekoinvenatare für Verpackungen	–	Danish	Oekoinventare	–
Energy simulation software	Energy 10	–	Enorm	EQUER	HOT 2000
LCIA approach	Based on EPA600/R-92/245	–	Based on SBI's LCA tool	CML	Ecoindicator 95
Life cycle costing	Yes	None	None	None	None
Application of technical construction codes	Yes	None	None	Yes	Yes
Behaviours patterns during the operation phase	Yes	None	None	None	Yes

To deal with environmental considerations and increasing concern regarding today's resource depletion life cycle management (LCM) can be applied to the whole construction process, thus making it possible to improve sustainability indicators and also reduce the environmental loads of the full building life cycle. Therefore, the application of LCM can be fundamental in pursuing sustainability and improvements in building and construction and implies the use of the environmental management tool of LCA [6].

Life cycle assessment (LCA) within the construction industry is an important methodology for evaluating buildings from the extraction of raw materials, construction, operation and maintenance through to final disposal or demolition (cradle to grave) and also LCA has been gaining attention in the last decade as a means of evaluating building materials explicitly dedicate to residential dwellings [7]. For instance, some studies have already been published on complete LCAs of residential dwellings. One of the first publications evaluated the environmental impacts and energy use of a residential home in Michigan [8]. Asif et al. [9] also applied an LCA to a dwelling in Scotland. Adalberth et al. [10] has used an LCA to evaluate four multi-family buildings located in Sweden. Peuportier [11] compared three types of house with different specifications located in France. Koroneos and Kottas [12] evaluated the annual energy consumption of an existing house in Greece. While these studies describe various environmental considerations and energy use for residential dwellings in the USA and some European countries, there is no evidence from comparable studies in Spain (see Table 1). The LCA investigations presented here are not similar. There are differences in the LCA analyses and in the engineering and physical characteristics. For example, it is observed that some studies did not report the methodology used to evaluate the life cycle impact assessment (LCIA). Additionally, there are dissimilarities in the surface of heated volume, usable floor area, amount of building materials and energy use during occupation. Also, apart from Koroneos and Kottas, most studies did not show results of the environmental impacts of energy production. Therefore, in this study, it has been applied LCM approach to a typical Spanish Mediterranean house located in Barcelona with a total area of $160\,m^2$, split into two storeys and with a projected 50-year lifespan in order to assist the construction industry and also to evaluate environmental burdens at regional level during the full building life cycle. This case study uses current research to develop guidelines based on LCM and apply sustainability indicators within the construction industry. The aim of this research is to use sustainability indicators in the pre-construction and operation (use and maintenance) phases and also to support decision-making within the building sector. Finally, the present research can be used by stakeholders such as engineers, architects, building constructors, environmentalists and LCA advisors as an important point of reference for LCM and energy considerations.

2. LCA as a tool to support LCM

LCA is a methodology used to evaluate environmental loads throughout all stages of the building life cycle, from origin (raw materials) to end of life (disposal waste) [13]. LCA follows the international standard series of ISO 14040. Although there are plenty of valuable sources documenting the technical and practical details, LCA methodology is based on four essentials steps: goal and scope, inventory, impact assessment and interpretation [14]. First, defining the goal and scope involves defining the purpose, audiences and system boundaries. Second, analyzing the inventory includes collecting data regarding all relevant inputs and outputs of energy and mass flow as well as emissions to air, water and land for each part of the process. This phase includes calculating the material and energy input and output of a building system. Third, the impact assessment evaluates potential

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environmental impacts based on the inventory analysis. The purpose of the LCIA phase is to estimate the impact on environmental loads and on the resources used in the system modeled. It consists of three mandatory elements: selection of impact categories, assignment of LCI results (classifications), and modeling of category indicators (characterization). The environmental impact caused by the system being studied may be assessed using impact categories, which are already in common use or by defining new categories. Categories that may be considered more relevant in the building sector are global warming potential (GWP), acidification potential, eutrophication potential and ozone depletion potential [15,16]. The second step involves choosing category indicators corresponding to the impact categories. The category indicator is the quantifiable representation of an impact category. Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), hydro chlorofluorocarbons (HCFCs) and perfluorocarbons (PFCs) all fall within the GWP category and are related to all the relevant outputs in the LCI results which contribute to GWP through characterization factors. The result is a rearranged list of the LCI results in which the data concerning different environmental loads (for example, emissions, wastes, use of resources and energy) is sorted under the different categories. In fact, in a LCIA, there are essentially two methods: problem-oriented methods (mid-points) and damage-oriented methods (end points). The mid-points approach involves the environmental impacts associated with climate change, acidification, eutrophication, potential photochemical ozone creation and human toxicity and the impacts can be evaluated using the CML baseline method (2001), EDIP 97& EDIP 2003 and IMPACT 2002+. The end points approach classifies flows into various environmental themes, modeling the damage each theme causes to human beings, the natural environment and resources. Ecoindicator 99 and IMPACT 2002+ are methods used in the damage-oriented method.

Finally the last step in an LCA is the interpretation. This step maps the environmental impact, identifies the significant issues and formulates recommendations.

2.1. *Case study: system definitions and boundaries*

LCA has been an important tool for evaluating building materials and component combinations as well as for evaluating construction and edification [17]. From this, the building life cycle is illustrated in Fig. 1. The following sections describe the activities and system boundaries for each phase.

2.1.1. *Pre-construction phase*

The pre-construction phase processes mainly involve the production of materials, which implies the use of natural resources, energy and water consumption, and therefore solid waste generation, greenhouse gas emissions, external and internal pollution, environmental damage and resource depletion. The pre-construction phase plays an important role in achieving sustainable construction and thus minimizing the environmental burden before a dwelling has been built. For example, any variation during the pre-construction phase would affect the environmental impact of the final product. Other activities in this phase are the production, manufacturing and final disposal of building materials, planning costs, client requirements, supply chain management and transport to the construction site. The dwelling analyzed in this research, is a typical semidetached Mediterranean house located in Barcelona, Spain. The house selected has a total area of 160 m^2 with two storeys and is made mainly of brick. Table 2a summarizes the principal engineering characteristics of the dwelling studied and Table 2b shows the description of the system for walls (interior and exterior), roof (pitched) and floors, which has been modeled according to the Spanish building technical code (CTE) [18]. During this phase, all the building materials were transported solely by truck and the distance from manufacture to the construction site was 50 km.

2.1.2. *Operation phase*

This phase is divided into two stages: use and maintenance. During the use phase, the environmental impact of the building

Table 2a
Surface distribution of the Spanish residential dwelling

Ground floor usable area	(m^2)	Area of windows (m^2)
Bath 1	11.1	1.4
Dinning–living room	25.3	8.0
Kitchen	13.1	6.5
Hall	11.5	3.1
Corridor+stairs	11.1	–
Total	72.3	19.2
First floor usable area		
Bath 2	11.1	1.4
Bedroom 1	19.0	5.2
Bedroom 2	11.5	4.0
Bedroom 3	19.5	5.3
Corridor	11.1	0.9
Total	72.3	17.0

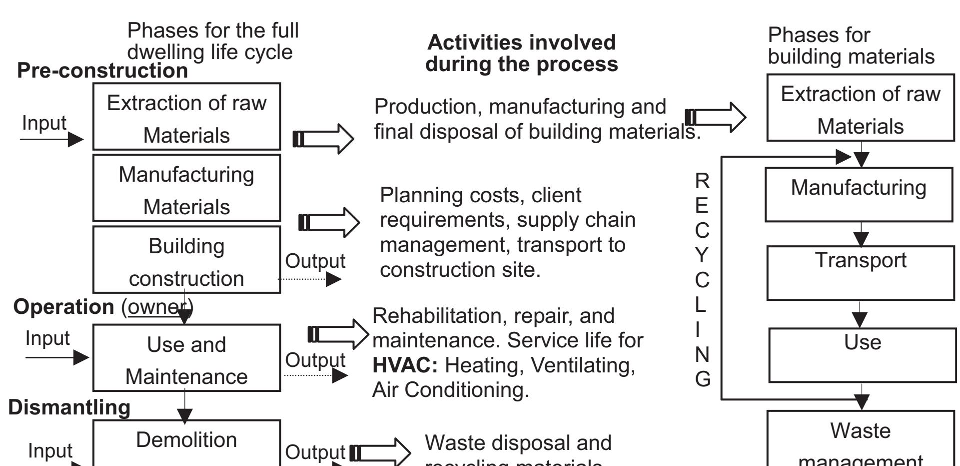

Fig. 1. Schematic representation of the building life cycle.

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Table 2b
Description of systems

System	Characteristics	
	Materials	(kg/m^2)
External walls	Polyethylene (4 cm)	1.2
	Cement	5.9
	Water	2.7
	Sand	20.6
Internal walls	Gypsum plastering	12.3
	Brickwork	165.5
Pitched roof	Clay tile	50.0
	MW stone wool	2.8
	Roofing felt	4.8
First floor	Wooding flooring	6.5
Ground floor	Ceramic	4.5

mainly results from energy consumption for heating, ventilation, air conditioning (HVAC), domestic hot water, lighting, electrical appliances and cooking. Other environmental impacts such as those due to wastewater will not be considered.

The annual energy consumption of the house during the operation phase has been evaluated using the building energy simulation software DesignBuilder [19] and by taking into account typical weather conditions for Barcelona. DesignBuilder is a user interface for the EnergyPlus thermal simulation engine [20].

To evaluate the building's energy consumption during the operation phase, the following parameters have been considered:

- Number of occupants in the home (4 persons = 2.00E–02 pers/m^2).
- Heating and cooling setpoints in the different rooms are presented in Table 3. The dwelling has a split system with a coefficient of performance (COP) of 2.35 for heating and 1.85 for cooling.
- Daily domestic hot water consumption (DHW). This has been estimated at 3.00E01 l/pers/day at a temperature of 60 °C. DHW is produced by an electrical heater with an estimated 95% efficiency.
- Annual energy consumption for cooking. This is estimated at 2.50E02 kWh/pers a (electrical cooking).
- Annual energy consumption for other electrical appliances. This is estimated at 1.20E01 kWh/m^2.
- Annual energy consumption for lighting. Table 4 shows the required lighting level in the different rooms and the lighting power which has been installed. This is estimated at about 1.60E01 kWh/m^2 a.
- The total annual electricity consumption of the dwelling has been evaluated at 1.22E04 kWh/a corresponding to almost 7.65E01 kWh/m^2 a.

In 2006, Spain's total electricity production was 2.68E05 GWh [21]. Fig. 2 illustrates how this electricity was generated and how much electricity each different technology contributed to the total mix. In the present case study, it has been assumed that the energy supply will remain constant during the building's life cycle.

Finally, regarding the maintenance phase, this part takes into account the activities needed to keep the dwelling in good condition during the occupation phase. These activities are related to repainting, reroofing, replacing the cooker and changing all compact florescent light bulbs. Moreover, during the 50-year life span of the dwelling there must be some refurbishing activities. These processes are concerned to the replacement of all flooring, quarry tiles, and replacement of all windows and external doors.

Table 3
Main characteristics of the operation phase

Environmental control					
	Dinning room	Kitchen	Bath	Bedrooms	Corridor+stair
Temperature for heating	21	18	22	18	18
Temperature for ventilation	25	27	24	25	25

Table 4
Level of illumination required for the dwelling

Level of illumination required	Lux
Kitchen	300
Dinning–living room	150
Bath 1	150
Corridor+stairs	100
Bedrooms	100
Potential illumination installed	3.4 W/m^2. 100 lux

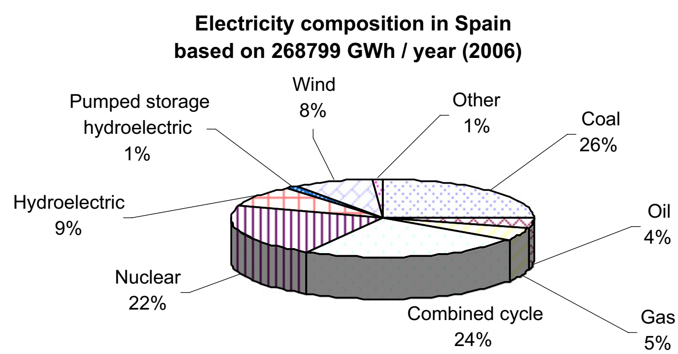

Fig. 2. Spain's total electricity mix production.

2.1.3. *Dismantling phase*

The dismantling phase often results in landfill disposal or recycling of the majority of materials such as concrete, wood, drywall and metal. Due to the lack of data on materials recovery, we have not taken into account the dismantling phase. Nevertheless, of the building's whole life cycle, the dismantling step is not usually significant because most of the environmental effects are generated during the operation phase [22].

2.2. *Limitations*

There are some uncertainties and limitations to the present work. First, Pushkar et al. [23] stated that construction as a process is not static; it varies from building to building since each has its own function and different engineering characteristics. Gregory and Yost [24] concluded that the direct application of LCA in the construction sector is not a simple or straightforward process. It is expensive and cannot be applied without making assumptions or additional modifications. Consequently, variation in each design can affect the environment during all life cycle stages for a building. Paulsen and Borg [25] declared that buildings and building materials are characterized by their significantly longer life compared to most other industrial

Table 5
Classification of some environmental impacts on climate change and acidification potential

Climate change GWP 100–GLO	kg CO_2 Eqv.	Acidification potential generic–GLO	kg SO_2 Eqv.
Carbon dioxide, fossil CO_2 (air)	1.00E00	Ammonia NH_3 (air)	1.88E00
Methane, fossil CH_4 (air)	2.30E01	Nitrogen dioxide (air)	7.00E−01
Dinitrogen monoxide (air)	2.96E02	Sulphur dioxide (air)	1.00E00
Sulphur hexafluoride (air)	2.22E04		
Chloroform (air)	3.00E01		
Carbon oxide CO (air)	1.53E00		

Table 6
Environmental impacts of the final Spanish electricity mix (based on 1 kWh)

Environmental impact	Electricity production by technology at the busbar	Transportation	Total
Acidification (kg SO_2)	3.53E−03	1.00E−03	4.53E−03
Human toxicity (kg 1.4-DCB-Eq)	5.02E−02	8.00E−02	1.30E−01
Depletion of abiotic resources (kg antimony-Eq)	3.51E−03	6.00E−04	4.11E−03
Climate change (kg CO_2-Eq)	4.53E−01	9.00E−02	5.43E−01
Terrestrial ecotoxicity (kg 1.4-DCB-Eq)	7.19E−05	7.00E−05	1.42E−04
Stratospheric ozone depletion (kg CFC-11-Eq)	2.30E−08	3.00E−09	2.60E−08

products, and the involvement of many different factors during their life cycle.

Second, a key issue for the present work is the quality and applicability of data contained in the system. For instance, Frischknecht et al. [26] found that consistent, coherent and transparent LCA datasets for basic processes make it easier to carry out LCA projects and thereby increase the credibility and acceptance of the LCA results. As far as LCA methodology is concerned, some of its tools are available for environmental assessment. These tools have been steadily improving and have been classified according to three levels. Level 3 is called "Whole building assessment framework or systems"; level 2 is called "Whole building design decision or decision support tools". Level 1 is for product comparison. Some of the databases used for environmental evaluation are: CML, DEAM TM, Ecoinvent Data, GaBi 4 Professional, IO-database for Denmark 1999, Simapro, the Boustead Model 5.0 and the US Life cycle inventory [27]. Nevertheless, those tools and database vary according to users, application, data, geographical position and scope. Besides, because of continuing data limitations, and the large range of construction techniques and materials, none of these tools is currently capable of modeling an entire building, or computing the environmental impact of all life cycle phases and processes [28]. As a result, to deal with the LCI analysis, the impact assessment and interpretation, the results of this research were presented in Ecopoints and were developed with the support of LCA Software called LCA-Manager® developed by SIMPPLE (spin out of the URV). Finally, the present project used processes inventoried in the Ecoinvent Database V1.3 in order to provide generic background data of products and processes [29].

2.3. Methodology and application

Determining the functional unit (FU) is crucial when evaluating the goal and scope of LCA for residential buildings. Hence, the present work is based on the m^2 usable floor area of a dwelling with a projected 50-year life span and four people living in the house. The impact assessment in this project is based upon the CML 2 method (2001) developed by Leiden University's Center for Environmental Science due to its broad international acceptance and its common application in the building sector. The CML 2001 method provides operational guidelines for conducting an LCA study step by step on the ISO standards. The CML 2001 method is a midpoint approach, which covers all emissions, and resource-related impacts. In the present case study, we chose climate change, acidification potential, human toxicity, depletion of abiotic resources, terrestrial ecotoxicity and stratospheric ozone depletion in order to assess the environmental impacts. The subcategories for some of the environmental impacts studied are indicated in Table 5.

Table 7
Categorization of the impacts presented in the ecoprofile for the dwelling life cycle studied

Environmental impact	Equivalent ecoprofile	Unit
Acidification potential	1.85E01	kg SO_2-Eq/m^2 per 50years
Human toxicity	7.18E02	kg 1.4-DCB-Eq/m^2 per 50years
Depletion of abiotic resources	1.72E01	kg antimony-Eq/m^2 per 50years
Climate change	2.34E03	kg CO_2-Eq/m^2 per 50years
Terrestrial ecotoxicity	6.82E−01	kg 1.4-DCB-Eq/m^2 per 50years
Stratospheric ozone depletion	1.17E−04	kg CFC-11-Eq/m^2 per 50years

3. Life cycle assessment: results

We have paid particular attention to input variables in electricity consumption. Therefore, the environmental impacts of the electricity consumption has been evaluated based on the Ecoinvent database adapted to the Spanish electricity mix for 2006 and it is out the scope the power plants self, losses and imports [30]. Table 6 summarizes the final environmental impacts based on 1 kWh including the shares of domestic electricity production by the technologies at the busbar. It also includes the transmission, transformation and distribution processes (called transportation).

Next, the LCA results of the full dwelling life cycle will be presented first, followed by a sensitivity analysis across the building life cycle system.

Table 7 shows the total ecoprofile for the building life cycle analyzed.

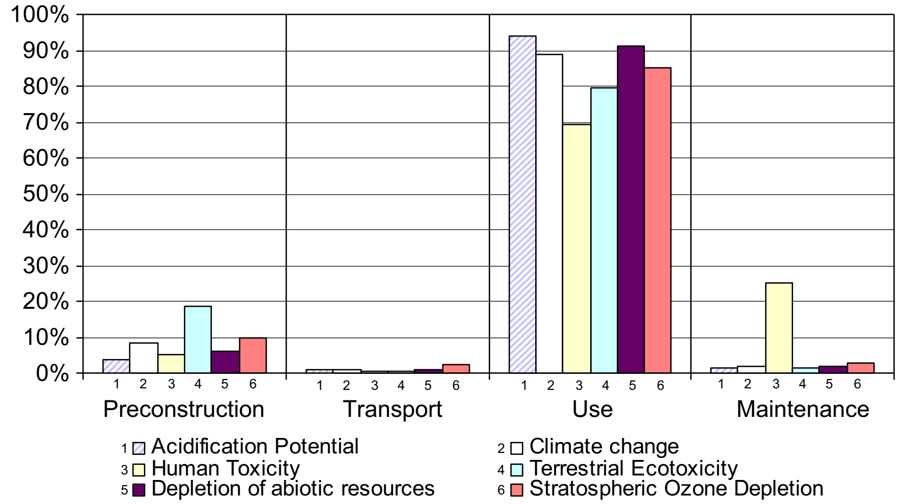

Fig. 3. Distribution of the environmental impacts of the dwelling life cycle studied.

Fig. 3 shows how the life cycle environmental impact is distributed over six categories: acidification potential, human toxicity, depletion of abiotic resources, climate change, terrestrial ecotoxicity and stratospheric ozone depletion. As can be seen in Fig. 3, the time phase with the highest environmental impact is the operation phase; approximately 80–92% of the life cycle's total, except for the human toxicity impact, of which the use accounts for approximately 70% and the maintenance and refurbishing activities contributed up to 25% mainly due to the replacement of all windows. Regarding the environmental issue of terrestrial ecotoxicity, there was a total emission of 6.82E−01 kg 1.4DCB Eq/m^2 per 50 years, of which about 18.5% was during the pre-construction phase due to the use of steel and the operation phase accounts for 82%.

The present work has also studied 12 different building materials in the pre-construction phase. Asif et al. [9] studied eight construction materials for a dwelling home in Scotland. These materials were timber, concrete, glass, aluminum, slate, ceramics tiles, plasterboard, damp course and mortar. The study concluded that concrete had the highest embodied energy in the house at 61%. Two other materials, timber and ceramic tiles represented 14% and 15% of the total of embodied energy, respectively. Concrete was the material responsible for 99% of the total of CO_2 during the home's construction. This supports the results in Fig. 4. This graph depicts that the dwelling had positive and negative values. Positive values mean net CO_2 emissions to the environment while negative values represent a credit of CO_2 due to carbon fixation in wood. Nevertheless, there is no doubt that using timber is indispensable in reducing environmental impacts such as CO_2, although some authors have stated that giving a negative GWP to wood is incorrect, because the wood will sooner or later be incinerated or land filled, resulting in a neutral or positive CO_2 balance [11].

Furthermore, Fig. 4 also shows that the pre-construction phase accounts for 1.96E02 kg CO_2-Eq/m^2 with the resulting effect on global warming. This is due to a large number of different building materials, of which both concrete and steel make up 77.22% and brick accounts for 14.68% of the total, respectively. These results show that the pre-construction phase has a strong influence for selecting sustainable materials with low environmental burdens and good insulation properties. Therefore, even if the contribution of the building materials themselves is low compared with values of the whole life cycle, choosing them carefully, together with an appropriate design of the building structure and orientation, can lead to important energy savings in the operation phase.

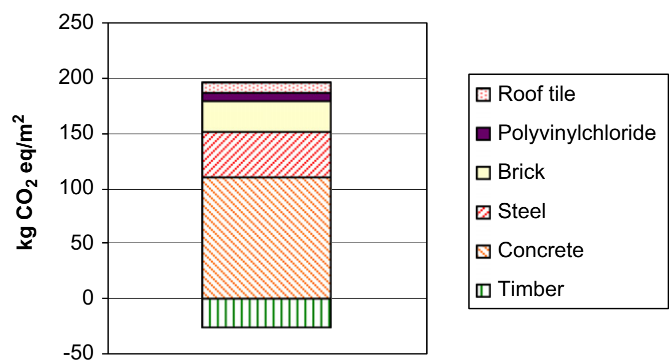

Fig. 4. Global warming potential of 1 m^2 usable floor area for six building materials.

The present case study has dealt particularly with climate change because of its importance within the construction industry both globally and locally and because it is an environmental impact that affects the whole planet [31,32]. Therefore, we did comparative LCA analyses of single buildings to assess the environmental impact during the operation cycle. For instance, Blanchard and Reppe [8] analyzed the total life cycle energy consumption and the GWP of a standard home of 227.8 m^2. The life cycle GWP was 1.01E06 kg CO_2. Adalberth et al. [10] evaluated the life cycle of four dwellings located in Sweden with different construction characteristics. The results concluded that GWP was approximately 1.5 tons CO_2 equivalents/(m^2 per 50 years) for all buildings. Peuportier [11] compared three types of house with different specifications located in France and results showed that the amount of CO_2-Eq/m^2 emitted during their 50-year life cycle was approximately 2.10E03 kg. Finally, in the present research analysis on evaluating the significant environmental issue of climate change, there was a total emission of 2.34E03 kg CO_2-Eq/m^2 per 50 years, of which about 90.5% was during the operation phase (use and maintenance); while pre-construction contributed up to 8.4% and transport accounts for 1.1%.

4. Sensitivity analysis

This paper focuses on a sensitivity analysis based on three initiatives during the full building life cycle. These alternatives are given by real scenarios, whose purpose is to model how the input

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Table 8
Reference house and alternatives versus requirements in the CTE

System	*U*-values (W/m^2 K) (reference house)	Alternative 1 *U*-values (W/m^2 K)	Alternative 2 *U*-values (W/m^2 K)	Alternative 3 *U*-values (W/m^2 K)	*U*-values limit CTE (W/m^2 K)
Wall	0.38	0.60	0.38	0.38	0.73
Roof	0.40	0.40	0.40	0.40	0.41
Floor	0.48	0.48	0.48	0.48	0.50
Windows					
North	3.22	3.22	3.22	2.06	3.40
W/E	3.22	3.22	3.22	2.06	3.90
South	3.22	3.22	3.22	2.06	4.40

Table 9
Effect of using window blinds

Case	Reference house	Alternative 2a	Alternative 2b
Energy demand for heating (kWh/m^2 a)	2.09E03	2.04E03	2.19E03
Energy demand for cooling (kWh/m^2 a)	5.97E03	4.00E03	5.73E03
Energy savings—heating (%)	–	2.0%	−5.0%
Energy savings—cooling (%)	–	33.1%	4.0%
Energy savings—heating+cooling (%)	–	25.1%	1.7%

Table 10
Variations in the windows' characteristics

	Reference house	Alternative 3
Outside pane	Clear 3 mm	Clear 4 mm glass
Air gap	Air gap	Air gap 12 mm
Inside pane	Clear 3 mm	Low-emissivity 4 mm glass

data affects the output data in a small but realistic product system. To accomplish this, it has been taken into account the legal requirements of directive 2002/91/EC of the European Parliament, which in turn promote the energy performance of buildings based on the Spanish building technical code (CTE), the regulation of thermal installations (RITE) [33] and the energy efficiency certification of buildings [34].

This part also addresses the question of whether there is an environmental advantage in using Material A instead of Material B, and compares the typical dwelling (reference house) with three alternatives.

Regarding the heat transfer coefficient (*U*-values) of the reference house, the limit values given by the aforementioned CTE code have been taken into account. Table 8 presents the *U*-values used in this study.

The first alternative was to vary the insulation of the external walls using 8 cm thick expanded polystyrene instead of 4 cm. After the sensitivity analysis had been completed, the results showed a 2.02% increase in the overall greenhouse gas emissions during the pre-construction phase, due to increased quantities of materials, but there is a reduction of 1.83E01 kg de CO_2-Eq (m^2 per 50 years) because the energy demand for heating decreases by 20.7%.

In the second alternative, window blinds are evaluated. In this case, user behavior regarding the blinds is also taken into account. These are aluminum blinds with medium reflectivity slats located on the outside of the windows. Alternative 2a represents a passive user where blinds are always closed. This means that they reduce the solar heat gains in summer but also in winter, leading to a significant reduction in the cooling demand but also a major increase in the heating demand in winter. In alternative 2b user behavior is optimal. Blinds are inside and are closed during the night if there is a heating demand and open during the day if there is a cooling demand. This reduces the cooling demand in summer by reducing solar gains and reduces heat losses through the windows at the night during the winter. Values of energy demand in alternatives 2a and 2b are presented in Table 9.

Finally, in the third alternative, windows with low-emissivity glass were used instead of clear 3 mm glass (reference house) on the internal side of the window, as shown in Table 10.

As a result, windows with low-emissivity glass have a lower heat transfer coefficient (*U*-value) than the conventional windows of the reference house, reducing the energy demand of the building for heating and cooling by 2.2% and 3.1% respectively, and leading to a reduction in the corresponding CO_2-Eq emissions of 2.05 kg of CO_2-Eq (m^2 per 50 years).

Nevertheless, the environmental impact of GWP in kg of CO_2-Eq per 1 m^2 for the construction phase has been measured for the three alternatives considered. Results are presented in Fig. 5.

As can be seen in Fig. 5, alternative 2 had a significant increase in total PFCs of about 150% due to the production of aluminum for the blinds. Even if this alternative presents a relatively high value of CO_2-Eq when compared to the reference value, it is demonstrated that it is the best alternative because of its high-energy savings during the operation phase. In addition, this study has evaluated the effect of the full dwelling life cycle on climate change. Therefore, it can be observed that in all the options the most significant impact comes from the operation phase (see Fig. 6).

Finally, Fig. 7 shows how the impact of household energy in the reference house is distributed. Heating and cooling represent about 34% of the total equivalent CO_2 emissions. The application of alternatives 2a could reduce this impact to about 9% CO_2-Eq/m^2 per year. These results demonstrate the importance of using appropriate building design practices for energy saving during the operation phase. Nevertheless, it is obvious that this type of action must be accompanied by changes in behaviors patterns on the part of the user to reduce the remaining part of the household energy, and not depend on the building design. In the next section this aspect is further developed.

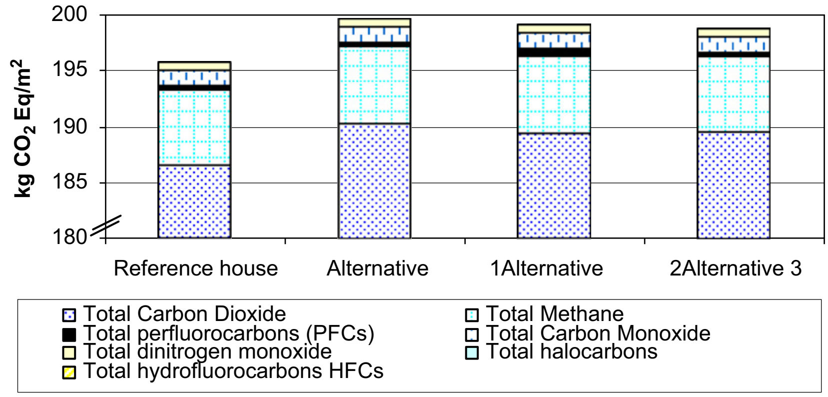

Fig. 5. Greenhouse gas emissions of the dwellings during the pre-construction phase.

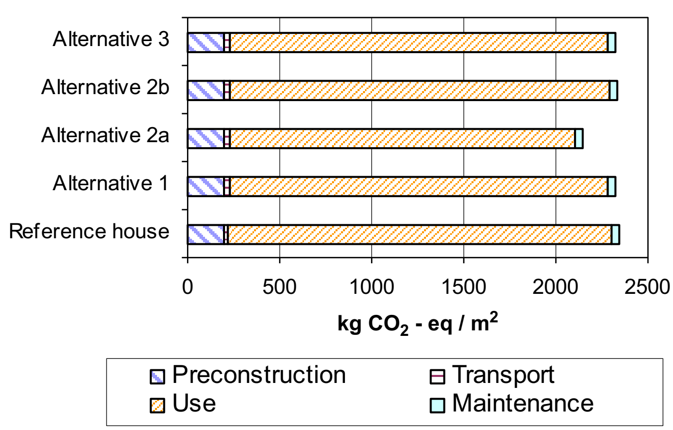

Fig. 6. Incidence of the dwelling life cycle phases of the climate change.

5. Life cycle management: initiatives to improve sustainability within the construction industry

LCM can be applied to the whole construction process, thus making it possible to improve sustainability indicators. For example, a proper design and choice of building materials during the pre-construction phases can improve the energy efficiency during the operation phase and the final distribution of buildings' consumption for heating and cooling. Also applying strategies during the operation phase, such as making changes in consumption patterns, would improve consumption for illumination and household equipment in terms of energy and environmental considerations. Therefore, patterns of consumption have been specifically dealt within this paper. This has meant government policies have been applied to reduce the final energy demand and environmental impacts without compromising quality and the healthy indoor environment for users. The activities that are involved during the operation phase may include direct and indirect patterns. For instance, direct patterns may relate to energy consumption resulting from leaving blinds open. Indirect patterns may include the whole process of producing, transmitting, transforming and distributing the electricity needed to meet the energy consumption of every Spanish household.

Fig. 8 shows the final distribution in the dwelling studied. Lighting represents a significant 21% of the total for the full dwelling energy consumption, while cooling and heating account for 33%, domestic hot water accounts for 21% and house equipment and cooking account for 25%. In this section, we mention some LCM initiatives in the distribution of building's consumption for the reference house and also some of the matters that should be taken into account when trying to improve sustainability indicators for residential dwellings.

Illumination is strictly dependent on consumption behavior, so the reduction and initiatives taken could only be in the area of energy efficiency. Some of the following are proposals to achieve this.

(a) *Lighting*: use sunlight as much as possible and turn off lights whenever not strictly needed. Together these alternatives will be lead to an overall reduction of 15% of the final annual energy consumption.
(b) *Lighting equipment*: Install sensors at indoor and outdoor sites and use suitable lighting throughout the dwelling; lighting energy needs for bedrooms is estimated at 10 W/m^2 and living rooms, and at 20 W/m^2 for kitchens, using incandescent lamps. If fluorescent lamps are used then the energy requirements are 4–5 W/m^2 in bedrooms and 7–10 W/m^2 in kitchens. It is estimated that installing suitable lighting throughout the dwelling will cost approximately 100€. However, the resulting savings are estimated at 10% of the annual lighting energy consumption.

For cooling and heating, combining building products and components for insulation can reduce environmental loads by almost 1.83E01 kg CO_2-Eq/m^2 per year during the use phase. However, in order to achieve this, the owner faces an additional investment cost of about 4800€. Regarding energy savings, heating would have a positive balance, while cooling would be negative. Other aspects that have been taken into consideration are the use of windows with low-emissivity glass. Here, heating and cooling accounted for a total energy saving of 2.9%.

Consumption patterns play an important role in savings and sustainability indicators in the use phase for every aspect of energy consumption. For example, good patterns of use by consumers and users are indispensable for reducing environmental impacts. The advantage of changing users' behavior is that there is no additional cost for this strategy. Energy saving strategies are, for example, not leaving windows open and using blinds correctly and could lead to energy consumption being reduced by up to 25.1% and 1.7% respectively, and save an average of 1.06E02 kg CO_2-Eq/m^2 per 50 years in environmental loads, which represents a savings of 5% in relation to the impact of the reference house (see Table 11).

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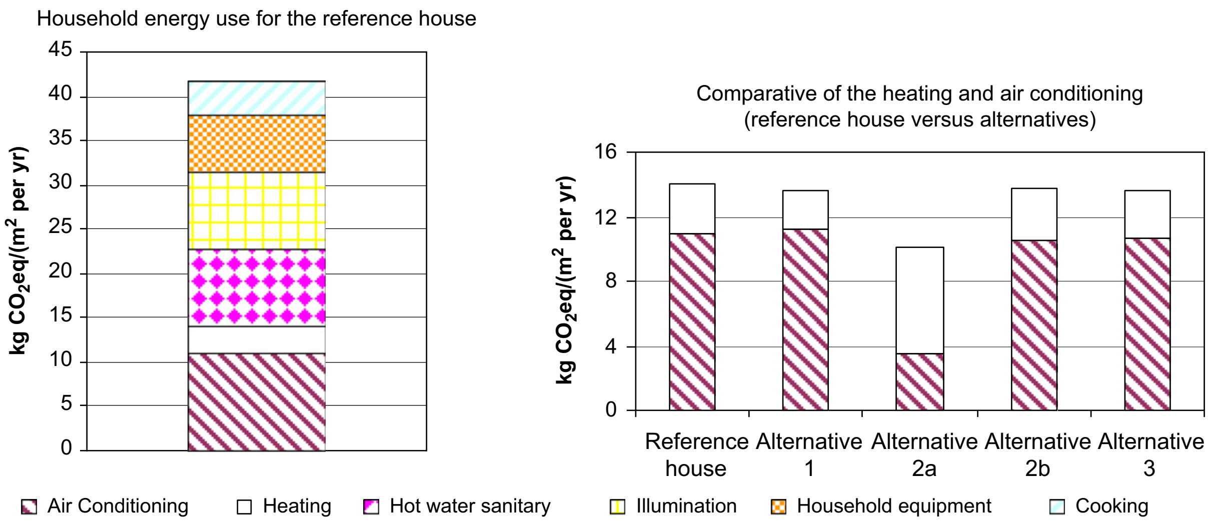

Fig. 7. Household energy consumption for the reference house and alternatives.

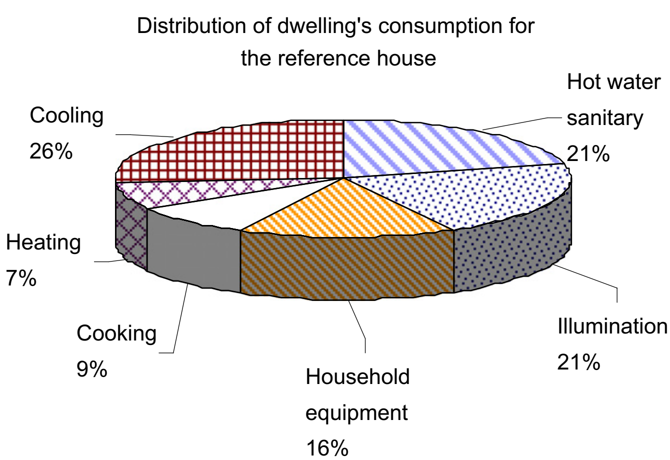

Fig. 8. Distribution of the reference house's consumption.

6. Discussion and outlook

The principal environmental considerations for the full dwelling life cycle based on LCM were to evaluate building materials that were more efficient in terms of their environmental burden and to evaluate the impact of energy consumption during the operation phase. Regarding electrical appliances, the most recent methodologies which incorporate information about environmental aspects, embodied energy and efficiency are necessary for sustainable development. To achieve this, the European Commission officially released the European energy label which rates products from A (the most efficient) to G (the least efficient) [35].

Nevertheless, decision-making regarding any environmental impact depends on global and local environmental quality goals and also on environmental threats identified in research and development by governments. Governments need to apply policies and construction codes that lead to improved quality of life for citizens because these same citizens want assurances that an investment in a dwelling will pay for itself over an acceptable time period. In other words, cost is an important issue for the market in facilitating the best economic and ecological value for society, customers and users.

The present case study has shown that the combination of building materials can lead to reduced environmental impacts. There is a widespread desire to reduce Spanish CO_2 emissions, therefore decisions need to be made with rigorous and appropriate environmental goals set out by the government. This work evaluated and analyzed adverse environmental impacts during the pre-construction and operation phases. LCM has been used in decision-making when applying the environmental management principle of "choose it right first" without compromising the quality of a construction project. Hence, this allowed us to see and evaluate environmental burdens based on combinations of different building materials. Finally, future work in this project will cover aspects of sustainability indicators due to changes in the dwelling energy sources (renewable versus non renewable) and variance in the energy efficiency of electro-domestic equipment and also will consider the construction and demolition waste, and will analyze whether the practical LCM guidelines used in the Spanish sector can be applied in other regions and countries.

7. Conclusions

LCM plays an important role within the Spanish building sector in helping decision-making in order to optimize sustainability indicators. There is no doubt that applying LCM to residential dwellings can be very important for achieving sustainable development. Due to its broad international acceptance, LCM should not be used for improving processes and services, but rather it should be seen as an approach for enhancing quality of life so that people can live in a healthy environment, and for improving social, economic and environmental conditions in both developed and developing countries.

This research concludes that in the whole construction process, the operation phase is the most critical because of the higher environmental burden emitted into the atmosphere.For example, regarding the significant environmental issue of climate change, there was a total emission of 2.34E03 kg CO_2-Eq/m^2 per 50 years, of which about 90.5% was during the operation phase.

Finally, this work has demonstrated that using LCM initiatives on consumption behaviors during the full building life cycle would help to enhance energy, economic and environmental savings, which would in turn accomplish building sector sustainability and promote the use of sustainable construction practices.

Table 11
LCM initiatives of residential dwellings within the Spanish building sector

Phase	Aspect		Normal behaviour reference house	Proposed behaviour	Energy savings			Economic savings		Environmental savings
					kWh/FU		Total energy savings demand (%)	€	Initial investment	kg CO_2 eq/m^2 per 50 years
P–C	IS	D	External walls using 4 cm thick expanded polystyrene	External walls using 8 cm thick expanded polystyrene	20.7[b] SHD	−2.3[b] SCD	3.6	90	4800	1.83E01
P–C	IS	D	Clear glass on the internal side of the window	Windows with low-emissivity glass	2.2[b] SHD	3.1[b] SCD	2.9	60	10,141	2.05E01
U	UB	D	Leaving windows open carelessly	Taking care to close windows	2.0[b] SHD	33.1[b] SCD	25.1	30	0	1.98E02
U	USH	D	Aluminium window blinds with medium reflectivity slats located on the outside of the windows	Blinds are closed during the night if there is a heating demand and open during the day if there is a cooling demand	−5.0[b] SHD	4.0[b] SCD	1.7	30	0	1.46E01
U	E	IN	Electrical cooker	Gas cooker	450[a]		42.2	60	700	5.75E03
U	DHW	IN	Electrical heater	Boiler of natural gas	−220[a]		−8.5	140	1200	3.07E04
M	R	D	Cooker: dirty or clogged orifice	Clean burner orifice	100[a]		9.4	8	0	9.50E02
M	IL	D	Illumination not adequate	Proper illumination	80[a]		3.1	10	100	2.30E03

Abbreviations: P: pre-construction, U: use, M: maintenance, C: construction, IS: insulation, IL: illumination, IN: indirect patterns, D: direct patterns, E: equipment, USH: use of solar heating, UB: user behaviour, R: repairs, a: measured in kWh electric, DHW: domestic hot water, FU: functional unit, b: measured in kWh thermic, SHD: saving heating demand, SCD: saving cooling demand.

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UNIVERSITAT ROVIRA I VIRGILI
SUSTAINABILITY ASSESSMENT WITHIN THE RESIDENTIAL BUILDING SECTOR: A PRACTICAL LIFE CYCLE METHOD
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Operational energy in the life cycle of residential dwellings: The experience of Spain and Colombia

Oscar Ortiz [a,b,*], Francesc Castells [b], Guido Sonnemann [c]

[a] University of Rovira i Virgili, Environmental and Analysis Management Group (AGA), Department of Chemical Engineering, Av. Països Catalanes 26, 43007 Tarragona, Spain
[b] University of Pamplona, Department of Industrial Engineering, Km 1 Vía Bucaramanga, Pamplona, N de S, Colombia
[c] University of Rovira i Virgili, Visiting Senior Research Fellow, AGA Group (AGA), Spain

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ABSTRACT

Life Cycle Assessment (LCA) has been applied within the residential building sector of two buildings, one in each a developed (Spain) and a developing (Colombia) country. The main goal of this paper involves the environmental loads and also brings together the operational energy for activities during the operation phase such as HVAC, domestic hot water, electrical appliances, cooking and illumination. The present research compares two real scenarios: Situation 1, where 100% of the dwelling's energy is supplied with electricity only and Situation 2, where dwellings can be operated with natural gas plus electricity.

The results for the environmental impacts using natural gas plus electricity show that of the Spanish environmental impacts air conditioning had the highest impact with approximately 27–42% due to the electricity used to power it. In Colombian results showed that electrical appliances had the highest environmental impacts in the same order of magnitude with approximately 60% and cooking had the best reduction of emissions due to the use of natural gas, from 10% down to less than 2%.

The origin of the energy source used in each Country plays an important role to minimize environmental impacts, as was demonstrated by the environmental impacts of its use in Colombia where 78% of the electricity came from hydroelectric plants whereas in Spain it is more mixed, fossil fuels represented 55%, nuclear 18% and wind 9%.

In summary, LCA has been applied because this methodology supports the decision making to concern environmental sustainability.

1. Introduction

The United Nations Commission on Sustainable Development (CSD) was created to promote an action plan on the progress of the Agenda 21 (1989) of which Colombia and Spain are signatory countries. The Agenda 21 is a strategic document adopted by the United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro in 1992 of which indicators for monitoring progress towards sustainable development are needed in order to assist decision-makers and policy-makers at all levels and to increase focus on sustainable development [1]. Furthermore, in 2000 the UN General assembly also decided to monitor progress towards Energy and the Millennium Development Goals that should be met by the year 2015 [2]. The challenge for the global energy sector is twofold: first, to dramatically increase access to affordable, modern energy services in countries that lack them, especially for poor communities; and secondly, to find the mix of energy sources, technologies, policies, and behavioral changes that will reduce the adverse environmental impacts of providing necessary energy services [3]. Besides, in recent times, when environmental issues have gained increasing priority with regard to the cost effectiveness of using one fuel rather than another, there is a constant interest to evaluate the environmental value of fuels considering their entire life cycle [4].

The residential building sector is gaining attention through the practice of environmental building performance assessment, of which sustainable development has emerged as one of the key issues due to the significant negative effects of building on the environment. For instance, "buildings, furniture, appliances, and energy for space heating and water together account for 20–35% of the environmental impacts" [5].

There are many studies in the literature dealing with energy analysis in buildings [6], but limited research has been published thus far on evaluate environmental impacts using Life Cycle Assessment (LCA) tool on the operational energy in the life cycle

* Corresponding author. Address: University of Rovira i Virgili, Environmental and Analysis Management Group (AGA), Department of Chemical Engineering, Av. Països Catalanes 26, 43007 Tarragona, Spain. Tel.: +34 660456069; fax: +34 977559621.
E-mail addresses: oscar.ortiz@urv.cat (O. Ortiz), francesc.castells@urv.cat (F. Castells), Guido.Sonnemann@unep.fr (G. Sonnemann).

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of residential dwellings for developing countries in Latin America, although some of the first attempts have started to appear during the last 5 years [7,8]. Furthermore, in developed countries some others LCAs studies for operational energy of residential dwellings were performed in the following studies:

- Sartori and Hestnes [9] performed a literature survey on buildings' life cycle energy use of 60 cases from nine countries. This study concluded that operating energy represents by far the largest part of energy demand in a building during its life cycle.
- Ortiz et al. [10] has applied LCA methodology to evaluate environmental impacts for a Spanish Mediterranean house located in Barcelona with a total area of 160 m^2 and a projected 50 year life span.
- Chung et al. [11] conducted an energy input–output (E-IO) analysis in Korea. The results showed that accounting for energy intensities and green house gas (GHG) emissions intensities is becoming an essential step in proper understanding the energy use structure.
- Thormark [12] in Sweden analyzed within its CEPHEUS project (cost efficient passive houses as European standard) in the European Thermie programe in how far the design phase of housing was relevant with regard to reduce operational energy and how the choice of building materials may affect both embodied energy and recycling potential during the 50 years life span of the building.

In this study, we attempted to quantify the differences in energy consumption and environmental impacts for two residential dwellings located in Spain and Colombia, on the one hand, the Mediterranean dwelling house located in the Province of Barcelona and, on the other hand, a Colombian home with the same constructive characteristics, but with different a location and consumption patters during the operation phase. Therefore, the aim of the present study covers the assessment of environmental impacts using Life Cycle Assessment (LCA) and also brings together the operational energy for activities during the operation phase such as heating, ventilating, air conditioning (HVAC), domestic hot water, electrical appliances, cooking and illumination. Nevertheless, this research has to be considered as a preliminary study evaluating possible measures from the point of view of environmental impacts and energy saving in order to provide new data and environmental sustainability indicators within the residential building sector.

2. LCA methodology and software tool

Life Cycle Assessment (LCA) is an environmental management methodology that evaluates the environmental impacts of a product or service, starting from extraction of raw materials, manufacturing, production, use and finishing with the final disposal, that is, from cradle to grave [13–15]. LCA within the construction and building industry has been used since 1990 and also has been an important tool for evaluating buildings and energy analysis [16–19]; and has become a widely used methodology because of its integrated way of treating issues such as framework, impact assessment and data quality [20]. LCA methodology follows International standards of series ISO 14040 and is based on four essential phases: goal and scope definition, inventory analysis, impact assessment and interpretation [21].

2.1. Goal and scope definition

The overall scope of this paper involves the environmental loads on the operational energy consumed during the full building life cycle and examines the distribution of the household activities of two buildings, one in each a developed (Spain) and a developing (Colombia) country. The present research compares two real scenarios: Situation 1, where 100% of the dwelling's energy is supplied with electricity only and Situation 2, where dwellings can be operated with natural gas plus electricity. The functional unit is defined as building a house and using it considering one square meter of living area with a projected 50 years lifespan. In this research, it has been considered the construction and the use phase. Therefore, the analysis is divided into the following life cycle steps:

- *Construction phase*: evaluates the material and energy consumption associated with the extraction of raw materials, the production and manufacturing of the materials, and the energy used by the building machinery. This phase includes the transport of the raw materials from the factory to the building site and also the internal waste management with the transport of the wastes generated at the building site to their final destination.
- *Use phase*: includes the operation and maintenance activities.
- *Operation phase* covers the full service life for HVAC: Heating, Ventilation and Air Conditioning, and other activities such as illumination, domestic hot water (DHW), electrical appliances and cooking.
- *Maintenance and refurbishment phase* has been calculated including activities such as repainting, PVC siding, kitchen and bathroom cabinet replacement, re-roofing and changing windows.
- *End-of-life phase*: this evaluates the energy consumed by the machinery used during the demolition; also considers the amount of wastes generated during dismantling of the original construction materials, including their transport to the final treatment waste. Due to the lack of information on materials recovery, it is out of scope this phase. Nevertheless, of the building's whole life cycle, this phase is not usually significant because most of the environmental effects are generated during the operation phase [22].

Finally, the following aspects have been assumed:

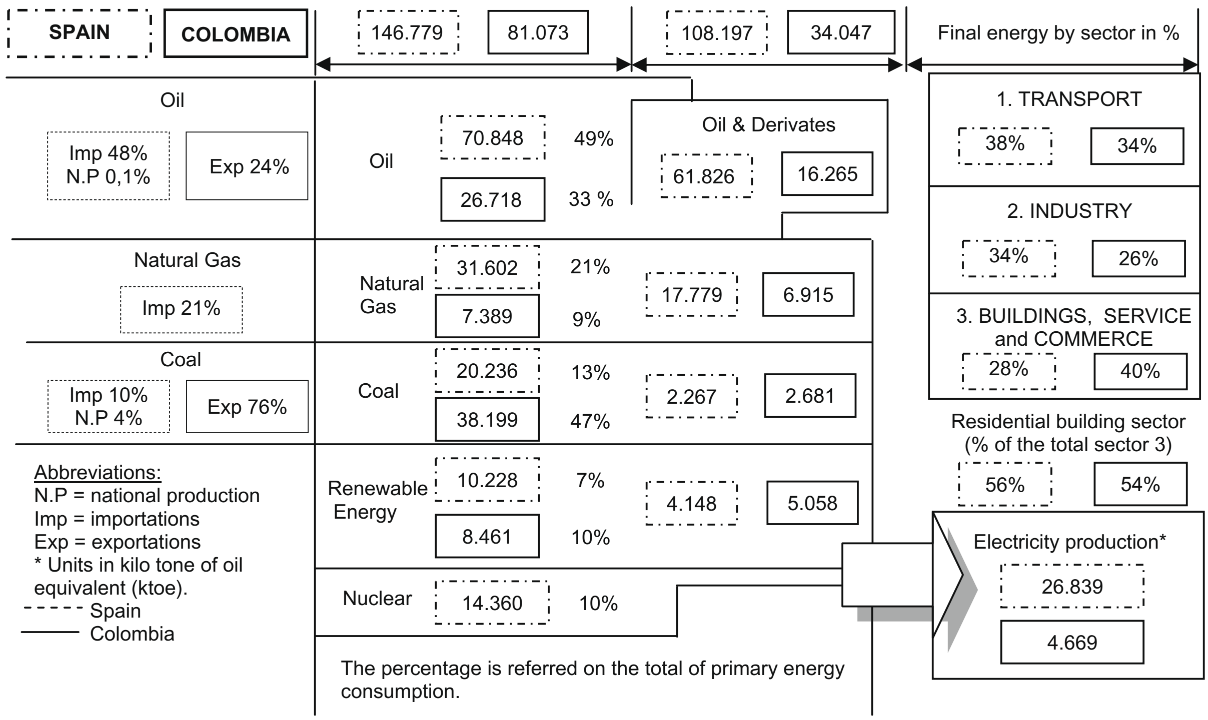
- For each dwelling the mode of transporting building materials is 100% truck and the distances from manufacture to the building site are assumed to be 50 km.
- Environmental impacts such as those resulting from water supply and wastewater treatment will not be considered in the present study.
- All the wastes generated during the construction and maintenance phase were disposed of in landfill and the results include the environmental impact of both the landfill process and transport of the waste to the landfill site. Others two different treatments of waste management such as incineration and recycling will be compared and discussed in future work of this research.

2.2. Inventory analysis

2.2.1. Energy demand in Spain and Colombia

The energy demand management considerations in both countries are summarized in Fig. 1. It illustrates the Sankey diagram which shows the graphic representation of the energy flow considering the methodology of the International Energy Agency (IEA) [23].

It can be seen in Fig. 1 that in 2007, Spain had the primary energy consumption of 146.779 kilo tonnes oil equivalent (ktoe) of which was based on renewable energy with 7% and non-renewable accounted for 93% (mainly oil accounted for 49%, natural gas represented 21%, coal 13% and nuclear 10%). The annual energy consumption was 108.197 ktoe of which the final consumption of petroleum products was 61.826 ktoe, natural gas 17.779 and coal 2.267.



Source: [24], [25].

Fig. 1. Sankey diagram (the energy demand management considerations in both countries).

In 2006 in Colombia, the primary energy consumption was 81.073 ktoe, of which approximately 10% was renewable energy and 90% non-renewable fossil fuels. Moreover, there is an annual final energy consumption of 34.047 ktoe which is about 3 times lower than Spanish consumption. In 2006 the Colombian foreign trade represented a total of 45.879 ktoe, of which the exportation of coal accounted for 76% and oil was 24%. Meanwhile, in Spain there is energy dependence on fossil fuel from overseas, specifically oil (48%), natural gas (21%) and coal (10%), making Spain very vulnerable to potential supply crises. Therefore, it can be stated that Colombia is self-sufficient and less vulnerable that than Spain in a potential supply crisis. But in fact, there is uncertainty regarding energy supply in coming years due to high levels of industrial and economic investment, oil prices worldwide and energy consumption [26].

In Spain, the final energy consumption within the transport sector represented 38%, behind industry sector with 34% and the buildings, service and commerce sector with 28% of which 56% accounted for the residential building sector. In Colombia the higher highest final energy consumption was for the building, service and commerce sector with 40%. For its part the second most important was the transport sector with 34% followed by the industry sector with an average of 26%.

Finally, in Spain the consumption of electricity for end-uses was equivalent to 26.839 ktoe of which the gas represented 31%, coal 24%, nuclear 18% and wind 9% [24]. In Colombia, the net electricity production was about 4.669 ktoe. To respond to this growth in energy demand the highest source is generated by a mix of 78% hydroelectric plants, coal (7%), gas (12%) and others (3%) [25]. Table 1 shows the total electricity production in both countries.

2.2.2. Construction phase

For the inventory analysis of the dwellings, we analyzed two residential buildings, one located in Barcelona, Spain and one situated in the city of Pamplona, Colombia. Table 2 shows the data collection of the principal engineering characteristics and the description of the buildings analyzed during the construction phase.

2.2.3. Operation phase

The calculation of the energy demand for the Mediterranean home was performed using the building energy simulation software DesignBuilder and by taking into account typical weather conditions for Barcelona of which is located on the Mediterranean coast at 41°23 N, 2°11E, and an elevation of 12 m and has a mean annual global horizontal (H) radiation between $13.7 \leqslant H \geqslant 15.1$ MJ/m^2. Therefore, with four persons living in the dwelling the annual electricity consumption is estimated at 1.22E+04 kW h/y.

Regarding the Colombian dwelling, Pamplona city has latitude and longitude of 07°23′N and 72°39′W and elevation of 2.342 m, the annual average temperatures rise between 17 and 20 °C. The average of sunshine per year in Pamplona is 1.300–1.700 h, and the total average radiation value is between 4.0 and 4.5 kW h/m^2/day. Then, the normal behavior is the use of domestic hot water equipments (DHW) without heating and air conditioning loads. In order to assist electricity system planning and end-uses, the monthly energy consumption during the operation phase has been calculated using the following equation:

$$E_t = n * Q * d, \qquad (1)$$

where E_t is the total monthly electricity end-use of the dwelling during the operation phase (kW h); n is the number of electrical appliances operated in the house; Q is the consumption of the appliance (W) and d is the total h/day period used. Hence, with four persons living in the dwelling the annual electricity consumption is estimated at 6.12E+03 kW h/y.

Table 3 depicts the annual distribution for the household energy consumption in kW h/y during the 2007 year where all the energy is supplied by electricity only and the electrical equipment for both houses consists of the following conventional equipment: T.V., D.V.D player, stereo, PC, washing machine, microwave and other small appliances.

Table 1
Input required for the electricity mix in Spain and Colombia.

Production from:	Spanish electricity mix (GW h) in 2007	Colombian electricity mix (GW h) in 2006
Coal	74.712	4.084
Oil	21.270	118
Gas	98.060	6.710
Biomass and waste	4.524	584
Nuclear	55.102	0
Hydro[a]	30.511	42.742
Solar PV	486	0
Wind	27.534	63
Other sources		0
Total production	312.138	54.301
Imports	5.842	21
Exports	−10.900	−1.813
Domestic supply	307.080	52.509

[a] Observation: includes production from pumped storage plants.

2.3. Impact assessment and LCA-software tool

As far as LCA methodology is concerned, some tools and databases have been available for environmental assessment and these vary according to users, application, data, geographical position and scope. To deal with this, data for building materials and energy supply were adapted to the Spanish and Colombian scenarios, and a special LCA-software tool has been developed which creates an ecoprofile for each impact category that provides information on the environmental relevance of the resources used and the emissions associated with the system. Thus, an Excel based tool has been developed to evaluate and map environmental impacts for building materials and over each dwelling's life cycle. The software LCA Manager® (an environmental management tool developed by SIMPPLE, was used to validate the scenarios under study and to make the material balances and the inventory [27].

In order to assess the LCIA, simplified CML 2001 method [28] has been used in order to get information about the inventory data (emissions) for process units. At the same time, obtaining data from the Ecoinvent database V2.01 [29] allows the Life Cycle Impact Assessment (LCIA) to be calculated, thus providing information to carry out the Life Cycle Inventory (LCI) matrix, then emissions are classified and multiplied with characterization factors (quantities $*$ inventories $*$ CF). The final environmental impact indicator is therefore the sum of the impacts defined in the fluxes for each building phase. For the evaluation of the environmental profile we categorized Global Warming Potential (GWP) in (kgCO_2-Eq), Acidification Potential in (kgSO_2-Eq), Stratospheric Ozone Depletion in (kg CFC-11-Eq) and Ionising Radiation in (DALYs). Fig. 2 shows the building system life cycle and the schematic representation of the software principle used for calculating the impacts on the environment produced by the building life cycle.

Table 3
Annual household energy consumption in kW h/y (100% electrical).

Country 100% Electrical	Colombia kW h/y	Spain kW h/y
Heating	0.00E+00	8.87E+02
Domestic hot water	7.15E+02	2.57E+03
Electrical appliances	3.37E+03	1.91E+03
Cooking	6.18E+02	1.07E+03
Illumination	1.42E+03	2.57E+03
Air conditioning	0.00E+00	3.24E+03
Total	6.12E+03	1.22E+04

3. Results

3.1. General results

The present research has assessed the environmental impacts for the energy sources in Spain and Colombia. Regarding the significant environmental challenge of GWP, the major reason why the Colombian technologies emit less CO_2 equivalent is because of the current electricity mix. For instance, in Spain there was a total emission of 5.80E-01 kg CO_2-Eq of which the energy source it is more mixed, gas represented 31%, coal 24%, nuclear 18% and wind 9%. In terms of the Colombian dwelling's technologies, 78% accounts for hydroelectric plants and 12% accounts for gas from a total of 2.28E-01 kg CO_2-Eq.

On the other hand, all the calculated burdens are lower for the Colombian situation during their full building life cycle. For example, the Mediterranean house had emitted approximately 2.46E+03 kgCO_2-Eq/m^2 during the dwelling life cycle of which the use phase represented 92% (operation 90% and maintenance 2%), see Fig. 3.

For the Colombian dwelling, this total was 7.80E+02 kgCO_2-Eq/m^2 of which construction and transport make up 32%, operation 64% and maintenance activities accounts for 4%, see Fig. 4. Therefore, the energy requirements during the household activities are lower in Colombia because the bio-climatic conditions and impacts from operational energy during the operation phase depend mainly on the behavior of citizens as well as the energy consumption due to the use of electrical appliances.

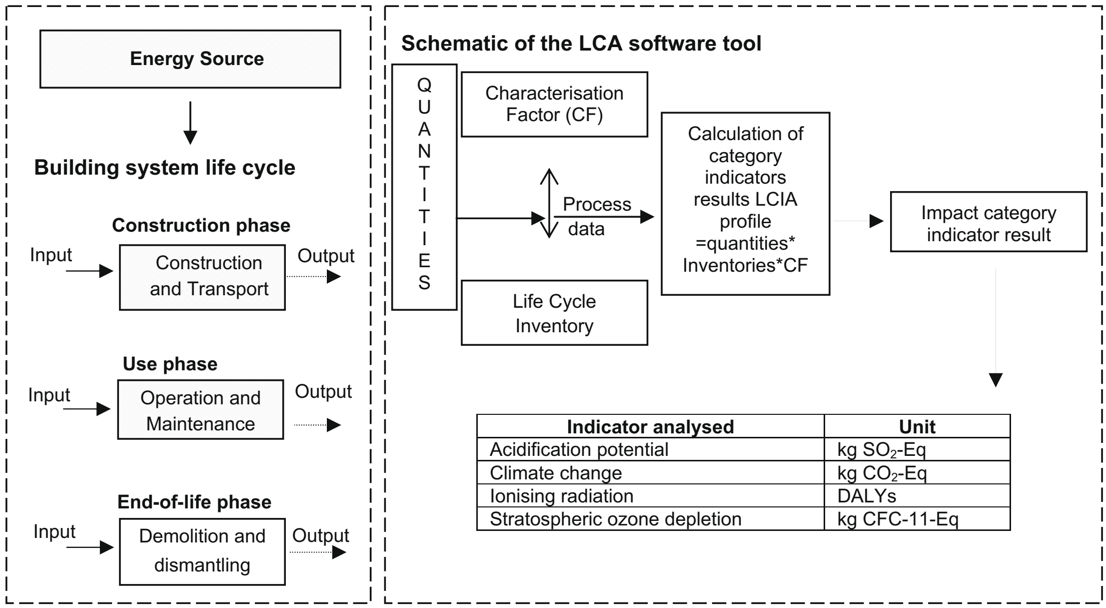
3.2. Results using electricity only: Situation 1

This research has paid particular attention to the environmental impact resulting from the energy requirements during the operation phase of both dwellings. Therefore, the environmental impacts have been assessed in detail.

Fig. 5 shows the environmental impact resulting from the household activities in both countries using 100% electrical. As a result, of all the Spanish environmental impacts resulting from household energy consumption, almost 33% of the electricity was used for HVAC needs (air conditioning 26% and heating 7%), 21%

Table 2
Principal engineering characteristics and description.

Item	Location	Dwelling analyzed	Description and principal engineering characteristics
1	Spain, Barcelona	Mediterranean house located in the city of Barcelona which has an area of 160 m^2 mainly made of brick and is split into two storeys and with a projected 50 year lifespan. The house is insulated with gypsum plasterboard, fiber cement roof slate and polystyrene. Data were adapted from the model used in previous study [9]	Area built ground floor: 60.3 m^2 Area built first floor: 64.7 m^2 Usable-floor area: 125 m^2
2	Colombia, Pamplona	Using architectonical drawings, the dwelling corresponds to a semidetached housing divided up into two storeys, with approximately 140 m^2 of usable-floor area with three bedrooms, living and dining room, kitchen and two baths for a projected 50 years life span. The main construction materials are bricks, concrete and steel, and the upper ceiling is covered with a combination of asbestos and roof tile (0.28 kg/m^2)	Area built ground floor: 52.2 m^2 Area built first floor: 55.3 m^2 Usable-floor area: 107.5 m^2



Note:

1. The grey processes are considered within this study.
2. Inputs are the materials and energy used while the outputs are the waste and emissions emitted during the process's life.

Fig. 2. Building system life cycle and schematic representation of the LCA-software tool.

for DHW, 21% for illumination, 16% for electrical appliances and 9% for cooking. For the environmental burdens in Colombia it is important to stress that electrical appliances are the most important household activity with 55%, illumination accounted for 23%, domestic hot water 12% and cooking 10%.

3.3. Results using a mix of natural gas plus electricity: Situation 2

Due to the fact that in Spain as well as Colombia there is a widespread need to reduce environmental burdens per capita and promote energy savings through housing, this paper deals with the environmental loads of dwellings which have been modelled using natural gas plus electricity with the following requirements and equipments, see Table 4.

Fig. 6 shows the environmental impact resulting from the household activities in both countries using a mix of natural gas

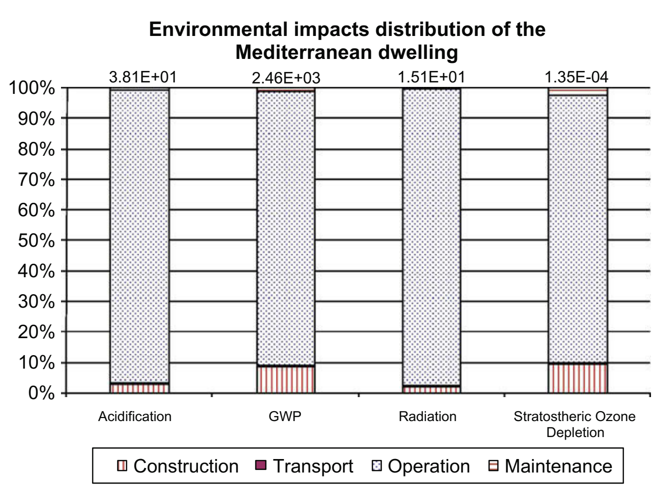


Fig. 3. Distribution of life cycle environmental impacts of the Mediterranean home.

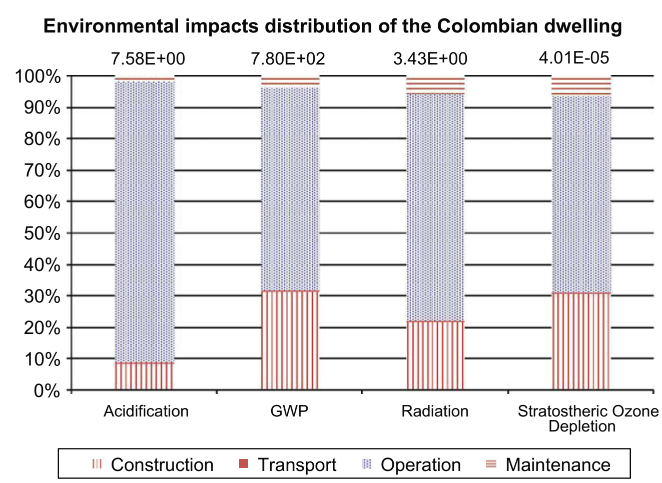


Fig. 4. Distribution of life cycle environmental impacts of the Colombian home.

plus electricity. After the aforementioned LCA-software tool has been re-loaded with the new input data, the results for the environmental impacts using natural gas plus electricity show that of the Spanish environmental impacts air conditioning had the highest impact with approximately 27–42% due to the electricity used to power it. GWP of the remaining household activities such as illumination was 26%, electrical appliances 20%, DHW 12%, cooking 5% and heating 4%.

On the other hand, the Colombian results showed that electrical appliances had the highest environmental impacts in the same order of magnitude with approximately 60%. The environmental impact of GWP for illumination accounted for 25% and domestic hot water for about 13%. Finally, cooking had the best reduction of emissions due to the use of natural gas, from 10% down to less than 2%.

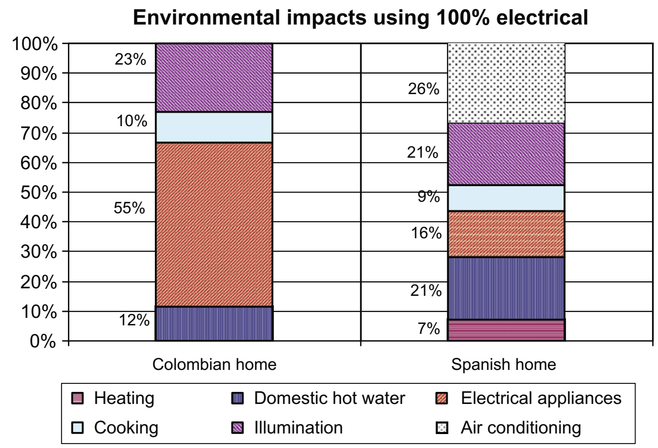


Fig. 5. Environmental impact resulting from the household activities in both countries using 100% electrical.

3.4. Results of the comparison during the operation phase

Two situations have been studied. Situation 1, where the energy demands were met exclusively with electricity, is compared with Situation 2 where the energy demands were met fully partially with natural gas plus electricity.

The results of acidification potential and GWP impact assessment comparing 100% electrical with the mixed of natural gas plus electricity are shown in Table 5. This table shows that the alternatives had favorable and unfavorable values. Unfavorable values mean an increase of emissions to the environment while favorable values represent a reduction of emissions due to the energy use.

In the Spanish Mediterranean home operation of electricity is unfavorable for the GWP impact due to the additional energy consumption with 25%. In Colombia, Situation 2 is more favorable than Situation 1 where 9% of GWP impact from the household activities was incurred during user occupancy. Hence, it can be concluded that the use of natural gas clearly reduces the environmental impacts during the operation phase, however there is a widespread necessity to promote use of renewable energies such as, solar and wind. However, the relationship between environmental impacts that occur during the full building life cycle should also be analyzed. It should be verified whether the improvement of one environmental impact does not cause an adverse effect in another environmental impact.

Finally, a sensitivity analysis has been performed concerning the question of whether there is an environmental advantage to using electricity source X instead of Y. To achieve this, this study focuses on sensitivity analysis which models how the input affects the output data in small but realistic product systems. For this reason, sensitivity analysis was used to determine the difference in output using the GWP indicator.

The first parameter which varied was the energy source composition. This parameter was studied after Spanish and Colombian forecasts for the following year's energy sources on the promotion of renewable energies.

Therefore, in Spain, estimating wind power market penetration is expected to reach 15% by 2020. Results showed that there is a reduction of adverse GWP impact of −10% due to the use of clean energy sources generated by wind power. Meanwhile, in Colombia this analysis is based on the construction of two hydroelectric projects and the results show that there is a reduction of −11% of GWP.

The second parameter which varied was final energy consumption due to the use of technological domestic appliances in both

Table 4
Equipment and energy source (natural gas).

Annual (2007) household energy demand by	Colombia	Spain	Equipment
Heating	–	79 m^3 natural gas	Mixed gas boiler
Domestic hot water	715 kW h electrical	231 m^3 natural gas	Mixed gas boiler
Electrical appliances	3.370 kW h electrical	1.908 kW h electrical	–
Cooking	58 m^3 natural gas	96 m^3 natural gas	Gas hob oven
Illumination	1.418 kW h electrical	2.569 kW h electrical	–
Air conditioning	–	3.240 kW h electrical	Split system COP 1.85

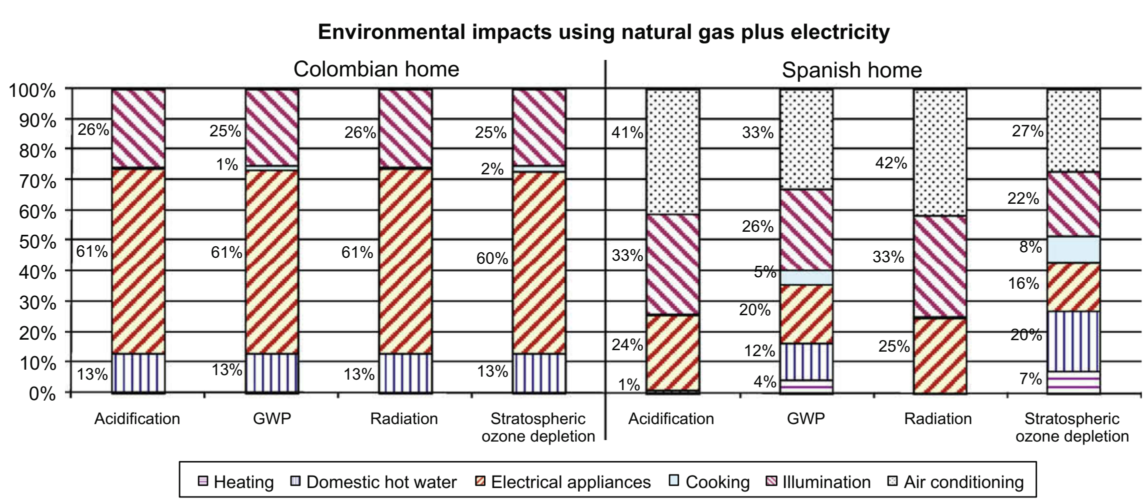


Fig. 6. Environmental impact resulting from the household activities in both countries using electricity plus natural gas.

Table 5
Impact assessment comparing 100% electrical with the mixed energy supply during the operation phase.

Environmental burdens	Spanish home				Colombian home			
	Situation 1: 100% electrical	Situation 2: gas + electricity	[a] %	Concept	Situation 1: 100% electrical	Situation 2: gas + electricity	[a] %	Concept
Acidification potential (kgSO_2-Eq/m^2)	3.73E+01	1.11E+01	70	Favorable	6.77E+00	6.10E+00	10	Favorable
Climate change (kgCO_2-Eq/m^2)	2.22E+03	1.66E+03	25	Favorable	4.99E+02	4.54E+02	9	Favorable

[a] Difference in percentage = ((Situation 1 – Situation 2)/Situation 1) * 100.

countries. This consumption has an emphasis on behavior patterns during the operation phase which represents a saving of 5% of the final energy consumption. The result was a reduction of about 15% in the GWP for dwellings. This was due to the improvement in behaviors and patterns of cultural consumption and the use of electrical appliances released under the European energy label which rates products from A (the most efficient) to G (the least efficient). However, there are other key determinants of energy demand in the household sector that need to be taken into account such as the availability and prices of fuels and appliances, disposable income of households and cultural patterns.

4. Conclusions and outlook

In this study we attempted to quantify the differences in energy consumption and environmental impacts for the dwellings in the two countries. Then, the present research has studied in detail the environmental impact during the operation phase for two residential dwellings located in Spain and Colombia, on the one hand, the Mediterranean dwelling house located in the Province of Barcelona and, on the other hand, a Colombian home with the same constructive characteristics, but with different a location and consumption patters during the operation phase. In this work, we analyzed both dwellings taking into consideration the type of energy used during the operation phase: electricity only versus natural gas plus electricity.

The present case study showed that the adequate combination of energy supplies leads to reduced environmental impacts. The use of efficient energies such as natural gas clearly reduces the environmental impacts during the operation phase.

Furthermore, the origin of the energy source used in each Country plays an important role to minimize adverse environmental impacts, as was demonstrated by the environmental impacts of its use in Colombia where 78% of the electricity came from hydroelectric plants whereas in Spain it is more mixed, 50% coming from fossil fuel combustion. Then, there is a widespread necessity to preserve the environment from the use of fossil fuels (oil and coal) and also to promote the use of renewable energies.

Finally, future research will consider the end-of-life phase of the buildings, and it will be analyzed whether the practical LCA guidelines used in the construction industry for single buildings in Spain, strong depending on climate conditions, can be applied in tropical areas. Social and economic indicators the two other parts of sustainability will also be considered because of their major and particular role in developing countries.

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