EVALUATION OF INITIAL EMBODIED ENERGY, OPERATIONAL ENERGY AND RECYCLING-REUSE POTENTIAL: A CASE STUDY ON CONTEMPORARY HOUSING IN SPAIN

Master in Architecture, Energy and Environment
Master Thesis by:
Duygu MERSIN, Architect

Date of submission: 6th of September 2011
Date of defence examination: 8-9th of September 2011

Supervisor: Prof. Dr. JAUME AVELLANEDA DÍAZ-GRANDE

SEPTEMBER 2011, BARCELONA
EVALUACIÓN DE ENERGIA INCORPORADA INICIAL, ENERGIA DE USO Y POTENCIAL DE RECICLAJE-REUTILIZACIÓN: UN ESTUDIO SOBRE LOS EDIFICIOS RESIDENCIALES CONTEMPORÁNEOS EN ESPAÑA

Máster en Arquitectura, Energía y Medio-Ambiente
Tesina del Máster:
Duygu MERSIN, Arquitecta

Fecha de entrega: 6 de septiembre de 2011
Fecha de presentación: 8-9 de septiembre de 2011

Tutor: Prof. Dr. JAUME AVELLANEDA DÍAZ-GRANDE

BARCELONA, SEPTIEMBRE 2011.
This thesis is dedicated especially to:
Prof. Dr. Rafael SERRA FLORENSA
ACKNOWLEDGEMENTS

Apart from the efforts of me, the success of this investigation depends largely on the encouragement and guidelines of many others. I take this opportunity to express my gratitude to the people who have been instrumental in the successful completion of this thesis.

I would like to show my gratitude to Prof. Dr. Jaume Avellaneda Diaz- Grande for his advice during my master study. I would never have finished without his guidance, knowledge, support and perceptiveness. I thank advisors and researchers of the Architectural Technology-I Department of Barcelona School of Architecture and Valles School of Architecture for their patience, advice and valuable opinion, especially Dr. Jaume Roset Calzada (Physics), for providing me technical support with his talented knowledge during the thermal comfort study. I am really grateful to Dr. Alberto Cuchi Burgos and Dr. Arch. Anna Pages Ramon for their support and to Arch. Camila Burgos Lleiva, Msc. for her cooperation when it is most needed. And also I owe sincere and earnest thankfulness to Prof. Dr. Rafael Serra Florensa and to Prof. Dr. Helena Coch Roura who gave me the opportunity to get lectures from them. I am proud of being a part of the department. Special thanks go to Dr. Arch. Ayşegül Tereci from Middle East Technical University for her support during the thesis study.

I would like to show thanks and respect to my friends from the Master AEM during 2010-2011 for accompanying me in this long journey. I would like to thank everyone that is not named here, but taught me many things. I would like to thank to my best friend Mercan Doğan in particular for all the things we had shared about architecture and life. I also have to thank Arch. Adriana Figueiras Robisco for her friendship and to Arch. Beatriz Lopez Lopez, Arch. Helena Rodriguez Galvez for being with me with their moral support. I would like to express my sincere appreciation to Arch. Gül Güven, Msc. for her endless support and encouragement during my studies.

I am truly indebted and thankful to all members of my family for their understanding, kindness and to Cenker Söğütluoğlu for his personal support, patience and encouragement when it is most required.

Duygu MERSIN, Architect
September 2011, Barcelona
CONTENTS

Table List vi-vi
Figure List vii-viii
Summary ix
Resumen x

1 INTRODUCTION 1
2 ENERGY PROFILES OF THE RESIDENTIAL BUILDINGS 4
   2.1 World Energy Consumption and CO₂ Emissions 4
   2.2 Energy Consumption and CO₂ Emissions in Europe 11
   2.3 Spain's Energy Consumption and CO₂ Emissions 17
   2.4 Energy Related Characteristics of Residential Buildings 22
      2.4.1 Embodied Energy 29
      2.4.2 Operational Energy 34
      2.4.3 Disassembly, Deconstruction, Decomposition and Reuse 37
   2.5 Conclusion 45

3 ENERGY CONSUMPTION AND CO₂ EMISSIONS SOURCED BY
   RESIDENTIAL BUILDINGS 47
   3.1 Antecedents and State of Art of Energy Consumption and CO₂ Emissions
      Sourced by Residential Buildings 47
   3.2 Evaluation of Initial Embodied Energy, Operational Energy during Life-
      Time and Disassembly-Decomposition- Deconstruction-Reuse Potentials 54
      3.2.1 General Frame and Structure of the Case Study 54
      3.2.2. Objectives of the Case Study 63
      3.2.3 Methodology 66
      3.2.4 Limitations and Scope of the Case Study 70
   3.3 Conclusion 72
4 ANALYSIS OF INITIAL EMBODIED ENERGY, OPERATIONAL ENERGY AND DISASSEMBLY-DECOMPOSITION-DECONSTRUCTION-REUSE POTENTIALS OF THREE CASES FROM SPAIN 74

4.1 Operational Energy Calculation 74
  4.1.1 Lightweight Industrialised Module (Steel Frame Structure) 77
  4.1.2 Medium-Lightweight Industrialised Module (3d Concrete Module) 79
  4.1.3 Heavyweight Conventional System (Module) 82

4.2 Initial Embodied Energy Calculation 85
  4.2.1 Lightweight Industrialised Module (Steel Frame Structure) 86
  4.2.2 Medium-Lightweight Industrialised Module (3d Concrete Module) 88
  4.2.3 Heavyweight Conventional System (Module) 90

4.3 Disassembly- Decomposition- Deconstruction- Reuse Potentials Evaluation 92

4.4 Conclusion 100

5 CONCLUSIONS AND DISCUSSION 104
REFERENCES
ANNEX
ANNEX I
ANNEX II
TABLE LIST

Table 2.1: Global energy indexes evolution between 1973 and 2004, Perez-Lombard et al., 2007 according to data obtained from IEA 6
Table 3.1: Schedule of façade, glazed areas and floor plan 54
Table 3.2: U value comparison between Technical Buildings Code of Spain for climate zone of Barcelona, previous studies and case study 58
Table 3.3: Finishing Schedule of three different modules 62
Table 3.4: System Details of three different modules 63
Table 4.1: Exterior temperature values for Barcelona (winter, summer, autumn and spring) (Fabra Observatory, 1971-2000) 76
Table 4.2: Parametric Results for winter (lightweight industrialised system) 77
Table 4.3: Parametric Results for summer (lightweight industrialised system) 78
Table 4.4: Parametric Results for spring (lightweight industrialised) 78
Table 4.5: Parametric Results for autumn (lightweight industrialised system) 79
Table 4.6: Parametric Results for winter (medium-lightweight industrialised) 80
Table 4.7: Parametric Results for summer (medium-lightweight industrialised) 80
Table 4.8: Parametric Results for spring (medium-lightweight industrialised) 81
Table 4.9: Parametric Results for autumn (medium-lightweight industrialised) 81
Table 4.10: Parametric Results for winter (conventional) 82
Table 4.11: Parametric Results for summer (conventional) 83
Table 4.12: Parametric Results for spring (conventional) 83
Table 4.13: Parametric Results for autumn (conventional) 84
Table 4.14: Weight, Energy and Emission values per system for lightweight (steel structure and composite slab) industrialised module (per m²) 86
Table 4.15: Weight, Energy and Emission values per material types for lightweight (steel structure and composite slab) industrialised module (per m²) 87
Table 4.16: Weight, Energy and Emission values per system for medium-lightweight (3d concrete) industrialised module (per m²) 88
Table 4.17: Weight, Energy and Emission values per material types for medium-lightweight (3d concrete) industrialised module (per m²) 89
Table 4.18: Weight, Energy and Emission values per system for heavy weight (reinforced concrete structure) conventional module (per m²) 90
Table 4.19: Weight, Energy and Emission values per material types for heavyweight (reinforced concrete structure) conventional module (per m²) 91
Table 4.20: Colour code scheme for evaluation of materials potential 95
Table 4.21: Evaluation of embodied energy of Lightweight Module 97
Table 4.22: Evaluation of embodied energy of Medium-Lightweight Module

Table 4.23: Evaluation of embodied energy of Heavyweight Conventional Module

Table 4.24: Interior Temperature, Interior Temperature Variation, Energy consumption for heating/cooling and CO₂ emissions of three cases

Table 4.25: Weight (kg/m²), Energy consumption (MJ/m²) and Emission (Kg CO₂ eq/m²) values for three cases

Table 4.26: Potential of reuse, recycling for three cases

Table 4.27: Total emissions per m² at the end of the life time of modules

Table 4.28: Distance rating scheme

Table 4.29: Packing system rating scheme
FIGURE LIST

Figure 2.1: World marketed energy consumption 1990-2035, EIA, International Energy Statistics database 4
Figure 2.2: Primary energy consumption, CO2 emissions and world population, EEA, European Environment Agency 5
Figure 2.3: CO2 emissions per person in different countries in 2004, Department of Environment and Housing of Catalonia (Departament de Medi Ambient i Habitatge de la Generalitat de Catalunya), Construmat, 2007 8
Figure 2.4: World energy consumption by region, EIA 9
Figure 2.5: World energy consumption by sector, EIA, Energy Information Administration, 2006 10
Figure 2.6: Projections of EU-15 and EU-27 emissions during the Kyoto commitment period, EEA 11
Figure 2.7: CO2 emissions caused by domestic consumption sourced by heating and goods in 26 EU Member States, 2004, EEA 14
Figure 2.8: Total greenhouse gas emissions by sector in EU-27, 2008, EEA 15
Figure 2.9: Total greenhouse gas emissions by main source activity in EU-27, 2008, EEA 16
Figure 2.10: Energy Consumption by Industry, by source in Spain, MITYC/IDAED 19
Figure 2.11: Population, Housing and Dwellings in Spain 2001-2007, Ministry of Environment, Rural and Marine, 2008, Perfil Ambiental de Espana 20
Figure 2.12: Energy Consume in Residential Sector by usage in 2006, Spain and UE27 22
Figure 2.13: Original Project of Cerda Plan 23
Figure 2.14: Evolution of building blocks from the Cerda Plan till today 24
Figure 2.15: Orientation of Eixample Building Blocks 24
Figure 2.16: Concrete 3d Module, Banyoles 27
Figure 2.17: Steel Frame Stucture with composite flooring, Callus 27
Figure 2.18: Building Structure Concrete Panel, El Masnau 28
Figure 2.19: System Barcons, Mollet del Valles 28
Figure 2.20: System Pujol, Sant Vicenç dels Horts 28
Figure 2.21: 3d Steel Frame Structure, Torello 29
Figure 2.22: Mix of Production in the Spanish Electric System 31
Figure 2.23: Simple Chart of Early Design Method (EDM), Yohanis et.al, 2000 36
Figure 2.24: Waste generated by activity, 2008 (% of total), Eurostat 37
Figure 2.25: Generated waste by material type in Europe in construction sector (% of total) 38
Figure 2.26: Total quantities of construction and demolition waste per country and capita, 1994-1999, OECD/ Eurostat 40
Figure 2.27: Treatment of construction and demolition waste per capita, Report to the European Commission DG XI.E.3 1999 and ETC/W questionnaire 41

Figure 2.28: Total waste generation in the EU, EFTA, Turkey and Croatia by source, 2006, EEA 41

Figure 3.1: The basic procedure followed in a Life Cycle Assessment, Fraunhofer Institute for Building Physic 47

Figure 3.2: Material flow chart in conventional construction system and in proposed demountable modular construction, Wadel, 2010 52

Figure 3.3: Plan and Sections of Reference Module 55

Figure 3.4: Isotherms of maximum annual temperature of air (T_max in °C), Spain Technical Buildings Code, Annex E Climate Datas, p. SE-AE 41 56

Figure 3.5: Climate Zones in winter, Spain Technical Buildings Code, Annex E Climate Datas, p. SE-AE 42 57

Figure 3.6: Plan and Sections of Lightweight Module 60

Figure 3.7: Plan and Sections of Medium-lightweight Module 60

Figure 3.8: Plan and Sections of Heavyweight Module 61

Figure 3.9: Structure of investigation and interlinking scheme 69

Figure 4.1: Comfort Zones for summer and winter (Baruch Givoni) 76

Figure 4.2: Weight, Energy and Emission values per system for lightweight (steel structure and composite slab) industrialised module (per m² and per cent ratio) 86

Figure 4.3: Weight, Energy and Emission values per material type for lightweight (steel structure and composite slab) industrialised module (per m² and per cent) 87

Figure 4.4: Weight, Energy and Emission values per system for medium-lightweight (3d concrete) industrialised module (per m² and per cent) 88

Figure 4.5: Weight, Energy and Emission values per material type for medium-lightweight (3d concrete) industrialised module (per m² and per cent) 89

Figure 4.6: Weight, Energy and Emission values per system for heavyweight (reinforced concrete structure) conventional module (per m² and per cent) 90

Figure 4.7: Weight, Energy and Emission values per material type for heavyweight (reinforced concrete structure) conventional module (per m² and per cent) 91

Figure 4.8: Interior Temperature, Interior Temperature Variation, Energy consumption for heating/cooling and CO₂ emissions of three cases 100

Figure 4.9: Weight (kg/m²), Energy consumption (MJ/m²) and Emission (Kg CO₂ eq/m²) values for three cases 102

Figure 4.10: Operational and Initial Embodied Carbon Proportions respect to total 107

Figure 4.11: Carbon saving by disassembly respect to total embodied carbon 108

Figure 4.12: Carbon saving by disassembly respect to total initial embodied carbon 109
SUMMARY

EVALUATION OF INITIAL EMBODIED ENERGY, OPERATIONAL ENERGY AND RECYCLING-REUSE POTENTIAL: A CASE STUDY ON CONTEMPORARY HOUSING IN SPAIN

The aim of this study is to understand the relationship between initial embodied, operational energy consumption and CO₂ emissions and recycling/reuse potential of industrialised and conventional systems in architecture. This investigation establishes the impacts of residential buildings and shows the role of early design decisions on this subject. The whole process, from design phase to demolition is evaluated.

In this study, general properties of residential buildings in Catalonia, classification according to principal construction types and major features related with energy/emission character are investigated. Recently constructed residential buildings' properties are compared with three created cases. Reference building is selected as a recently constructed industrialised modular system building in Catalonia and considered as medium-lightweight with minor revisions from the original module. Other two cases are created as lightweight industrialised and heavyweight conventional system with the same building plan of reference case. Three cases are evaluated respect to each other, since thermal masses are different. Impacts of trends in the three cases on the energy consumption and emissions are examined. The relationship between initial embodied energy and life time (fifty years) operational energy are evaluated using unit data values and heating/cooling demand calculation. Recycling/reuse potentials are evaluated with an introduced methodology. However, unit data values are used and indirect effects are not considered.

At the final part of the study, total embodied carbon at the end of the life time for three cases is compared and possible savings are discussed for future applications. Furthermore, required recruitment possibilities for industrialised modules and for conventional system are proposed according to the results of the embodied and operational carbon, as well as the possible savings by recycling/reuse. Transport and packing system rating is discussed and future recommendations are made.
RESUMEN

EVALUACIÓN DE ENERGÍA INCORPORADA INICIAL, ENERGÍA DE USO Y POTENCIAL DE RECICLAJE-REUTILIZACIÓN: UN ESTUDIO SOBRE LOS EDIFICIOS RESIDENCIALES CONTEMPORÁNEOS EN ESPAÑA

El objetivo de este estudio es entender la relación entre la energía y las emisiones de CO$_2$ inicialmente incorporados a su vez también el consumo de energía y las emisiones de CO$_2$ del uso y el potencial de reciclaje/ reutilización de los sistemas industrializados y los sistemas convencionales utilizados en la arquitectura. Esta investigación se establece el impacto de los edificios residenciales y muestra la importancia de las decisiones en la fase principal del diseño sobre este tema. Se ha evaluado el proceso, desde el diseño hasta la demolición.

Se investigan las propiedades generales de algunos edificios residenciales en Cataluña, se clasifican según el tipo de construcción y según las características principales relacionadas con el carácter de la energía/emisiones. Las propiedades de la construcción nueva de edificios residenciales se han comparado con tres casos de estudio. Elegiendo un edificio de referencia, de construcción reciente, el cual posee un sistema industrializado modular, emplazado en Cataluña y se ha considerado como medio-ligero. Los otros dos casos se han construido con un sistema ligero industrializado y convencional pesado con la misma planta del edificio de referencia. Los tres casos se han evaluado con respecto a los otros, ya que las masas térmicas son distintas. Los impactos de las tendencias en el consumo de energía y las emisiones se han examinados en los tres casos. Se ha evaluado la relación entre la energía incorporada inicialmente y la energía de uso durante su vida útil (cincuenta años), utilizando el método de "unit data" y calculando la demanda de calefacción y refrigeración. Se ha evaluado el potencial de reciclaje/ reutilización, con una metodología introducida. Sin embargo, los valores de "unit data" se han utilizados sin considerar los efectos indirectos.

En la parte final de este estudio, se ha comparado el total de carbono incorporado al final de vida útil de los edificios, para los tres casos y se discuten los posibles ahorros para aplicaciones en el futuro. Además, las posibilidades de mejora para los sistemas industrializados y para el sistema convencional se han evaluado. Se proponen los posibles ahorros en reciclaje/ reutilización según los valores de energía incorporada y de uso. También se discute la valoración del transporte y sistema de embalaje, haciendo recomendaciones para el futuro.
1. INTRODUCTION

World demand of non-renovated energy has already head the expected levels due to uncontrolled increase of world population, lack of order in the usage of energy regulations and the absence of consumer awareness. Climate change could be considered as one of the impacts of the increase. It is evident that the climate change is related to the increasing CO₂ emissions. However, the problem cannot be considered as increase in CO₂ emissions only, but it could also include the impacts of disproportional usage of natural resources. World energy demand is projected to increase by 49 % during 2007 and 2035, while emissions are projected to increase by 43 % for the same period (EIA). The population growth is not the only reason for that, since population growth it is a structural factor that increases the energy demand. Behavioural factors could be the most important reasons that are related to the high consumption tendencies like rising living standards, invention of energy-dependent technologies and consuming without renovation. Residential use (i.e. heating, cooling, domestic hot water, domestic devices and lighting) is responsible of more than one-fifth of the total world energy consumption.

In Europe, during 1997-2007, the electricity consumption has increased by 17%. Fuel consumption for construction/manufacturing compromises 12.4 % of the total emissions in EU-27 in 2008 (EEA, 2008). However, with the implementation of EPBD, in regard to the common objective of the Kyoto Protocol, it is expected to decrease.

In Spain, energy demand is similar to other countries of Southern Europe. Energy demand has increased by 60 % in 2003 compared to 1990. However, as the demand increases, it is important to correspond it with the renewable energy resources. Renewable energy consumption has increased by 12.3 % in 2010 compared to 1990 in Spain thanks to its wind and solar potential and implementations of new directives. But there is still potential to decrease the demand, especially in the
construction sector. In Spain, residential buildings have specific importance. Thus, there is a real accumulated stock. Only during 2001-2007, there were increase in the residence stock by 16% (Ministry of Environment, Rural and Marine). The residential buildings were responsible for 16.7% of total energy consumption in 2008. Thus, it is important to implement directives for the existing buildings as well as new constructions. This thesis focuses on the residential buildings and the evaluation of different energy consumption/emission sources of residential buildings in Catalonia, Spain. Till today, general tendency is to decrease the operational energy demand in the buildings, while trying to correspond this demand with renewable energy sources. However, regarding Life Cycle Assessment (LCA) thinking, there is a huge part left. LCA is linked to the whole process, which can start with raw material extraction and continues with construction, use and demolition. For evaluation of possible sources in residential buildings and according to LCA thinking frame, the task has divided to four parts, as following:

- Energy profiles of residential buildings
- Energy consumption and CO₂ emissions sourced by residential buildings
- Analysis of initial embodied energy, operational energy and disassembly-decomposition-deconstruction-reuse potentials of three cases from Spain
- Conclusions and discussion

Energy profile of residential buildings is part of the impact analysis of residential buildings in the world and Europe. These include the profiles of existing buildings in Spain and Catalonia; the systems recently constructed in Catalonia. It also provides an overview of possible sources of energy consumption and emissions of residential building; embodied energy, operational energy as well as demolition; disassembly, deconstruction, decomposition and reuse potentials. It is important to discuss each part separately in order to study the recent construction and conventional systems along with the above mentioned terms.
Energy consumption and CO₂ emissions sourced by residential buildings are consisted of a state of art of the previous studies on the relationship between possible sources. However, after explaining the previous studies, general terms of the thesis are explained including objectives of the case study, methodology and limitations/scope.

In third part; initial embodied energy, operational energy and disassembly-decomposition-deconstruction-reuse potentials of three cases from Spain are analysed. A reference building is selected from Catalonia and two other cases are created. The three buildings are identical in their heat transfer coefficient and interior finishes except the flooring. The study could be summarised in two terms; initial embodied energy and the operational energy calculation as well as evaluation of the three buildings and potential energy returns during demolition. All calculations are made manually, depending on the scale of dwelling. The results of the calculations, evaluation of the three potential energy consumption sources as well as the future considerations are discussed in the conclusion part of the thesis.
2. ENERGY PROFILE OF THE RESIDENTIAL BUILDINGS

2.1 World Energy Consumption and CO$_2$ Emissions

World marketed energy consumption has increased from 355 Btu (quadrillion British thermal units) to 495 quadrillion in 17 years (1990-2007). Also, the current prediction shows that it will rise to 739 Btu by 2035 (See figure 2.1). It means that world energy consumption grows by 49% from 495 Btu to 739 Btu during 2007-2035. The CO$_2$ emissions will increase accordingly as primary energy consumption has grown by 49% from 1984 to 2004, while CO$_2$ emissions have grown by 43%. Average annual increase of the primary energy consumption is 2%, CO$_2$ emission is 1.8%. However, there is also another factor that affects the primary energy consumption and the CO$_2$ emissions which could be described as population (See figure 2.2).

![Figure 2.1: World marketed energy consumption 1990-2035](image)

EIA, International Energy Statistics database
Figure 2.2: Primary energy consumption, CO2 emissions and world population.

EEA, European Environment Agency

It is essential to mention the predicted difference between the primary energy consumption and the population (Perez-Lombard et al., 2007). Relational key consequences were explained by Perez-Lombard according to the analysis of IEA covering the period from 1973 to 2004 (See table 2.1):

- The rate of population growth is well below the GDP, resulting in a considerable rise of per capita personal income and global wealth,
• The primary energy consumption is growing at a higher rate than the population, leading to the increase of its per capita value on 15.7% over the last 30 years,

• The CO₂ emissions have grown at a lower rate than energy consumption showing a 5% increase during this period,

• Electrical energy consumption has drastically risen (more than two and a half times), leading to a percentage increase in the final energy consumption (18 % in 2004),

• Efficiency in exploiting energy resources, shown as the relationship between final and primary energy, has declined by 7% points, especially due to soaring electrical consumption,

• Final and primary energy intensities have dropped because of the higher rate of growth of the GDP over the energy consumption increasing ratio, resulting in an overall improvement of the global energy efficiency.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1973</th>
<th>2004</th>
<th>Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population (millions)</td>
<td>3,938</td>
<td>6,352</td>
<td>61.3</td>
</tr>
<tr>
<td>GDP (GS year 2000)</td>
<td>14,451</td>
<td>35,025</td>
<td>142.4</td>
</tr>
<tr>
<td>Per capita income ($ year 2000)</td>
<td>3,670</td>
<td>5,514</td>
<td>50.2</td>
</tr>
<tr>
<td>Primary energy (Mtoe)</td>
<td>6,034</td>
<td>11,059</td>
<td>83.3</td>
</tr>
<tr>
<td>Final energy (Mtoe)</td>
<td>4,606</td>
<td>7,644</td>
<td>66.0</td>
</tr>
<tr>
<td>Final energy/primary energy</td>
<td>0.76</td>
<td>0.69</td>
<td>−9.4</td>
</tr>
<tr>
<td>Electrical energy (Mtoe)</td>
<td>525</td>
<td>1,374</td>
<td>161.8</td>
</tr>
<tr>
<td>Electrical energy/final energy</td>
<td>0.11</td>
<td>0.18</td>
<td>63.5</td>
</tr>
<tr>
<td>Per capita primary energy (toe)</td>
<td>1.53</td>
<td>1.77</td>
<td>15.7</td>
</tr>
<tr>
<td>Per capita CO₂ emissions (ton)</td>
<td>3.98</td>
<td>4.18</td>
<td>5.0</td>
</tr>
<tr>
<td>Primary energy intensity (toe/GS year 2000)</td>
<td>418</td>
<td>316</td>
<td>−24.4</td>
</tr>
<tr>
<td>Final energy intensity (toe/GS year 2000)</td>
<td>319</td>
<td>218</td>
<td>−31.5</td>
</tr>
</tbody>
</table>

Table 2.1: Global energy indexes evolution between 1973 and 2004

Perez-Lombard et al., 2007 according to data obtained from IEA
The Data and previous analyses show that relationship of population with energy consumption is really hard because there is a considerable rise of value per capita. It is obvious that high energy demand is driven by population growth, additional new high energy demand equipments and behavioural factors. Major population growth predicted to be in urban areas in the near future since energy consumption rise will take place in an architectural scale in a more serious way. As millions of apartments and houses are added to accommodate the growing population, they in turn create new demand for energy to power lights, appliances as well as heating and cooling systems. Types of residences differ from one region to another because of different appliance characteristics and climatic conditions.

Despite the fact of projected rise in energy demand, the population growth will not make much difference as thought. The problem is that as much as we gain; we get wealthier and consume more and more. That is why primary energy consumption is growing at a higher rate than the population growth. Equally, GDO has a higher rate than population as personal wealth seems to rise. Consequences could be concluded as following; there is a pronounced difference between the primary and the final energy, the population growth is about to lost its sense because of the high values per capita and we are about to consume more in any region after 22 years. Figure 2.3 shows that the population cannot be the only indicator to evaluate energy consumption values or CO₂ emissions. As it is shown; in 2004, the developed nations have emitted more than the rest of the world, which has lower rates of population growth, but higher rates of industrialization.

The industrialization cannot be considered as a unique reason for higher consumption in itself. The industrialization should be thought with its extensions in our life-styles as following; there is high demand on transportation, intuited intentions for a bigger house or for a new car. Architects may not decide on behalf of the whole society, but as proved by the history, they can play many roles in changing the society's intuitions. It is projected to have the same for sustainability in the future and now; at least that is what it should be.
World energy consumption can also be seen per region (See figure 2.4). Even the values of emerging nations are smaller than those of developed nations; it is predicted to be equal by 2020. The reason for the increase could be linked to 3.2 % average annual growth rate of emerging nations while developed nations only have 1.1 % average annual growth rate.

It is clear that an increase will occur in the CO₂ emissions if the type of energy usage or source does not change, the population continue growing at such speed and if we continue to consume in an endless way as we did during the last century. Since the growth and consumption rates are hard to change, it is necessary to focus on the main

**Figure 2.3:** CO₂ emissions per person in different countries in 2004, Department of Environment and Housing of Catalonia (Departament de Medi Ambient i Habitatge de la Generalitat de Catalunya), Construmat, 2007
indicators of the energy consumption. It seems to be essential to relate indicators with each other in terms of sustainability.

![Graph showing world energy consumption by region](image)

**Figure 2.4:** World energy consumption by region

EIA

The final energy consumption could be classified by sectors as; industry, commercial, residential and transportation. There are more sectors like agriculture and services. Absence of a common terminology for the classification causes confusion in the analysis of different regions.

The construction sector, comprising residential and commercial consumers, accounts for about one-fifth of the world’s total delivered energy consumption (excluding transportation values). One-fifth of the energy consumption is sourced by heating, cooling, domestic hot water, food preparation and lighting. It is essential to sum the amount of energy needed to produce construction materials, which is an important part of the energy consumption in the industry sector. Also, if we consider
construction as a global sector, transportation of materials can be added to this value. It could be concluded that the residential and commercial usage of energy and its relevant consumptions, exceeds one-fifth of the total energy consumption of the world's total delivered energy consumption (See figure 2.5).

**Figure 2.5:** World energy consumption by sector

EIA, Energy Information Administration, 2006
2.2 Energy Consumption and CO₂ Emissions in Europe

According to Kyoto Protocol, Europe has started implementing the European Performance of Buildings Directive (Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002) in 2002, which is re-casted in 2010. It is the key element to ensure that buildings consume less according to the objective of 2020. Efforts to avert increment of global temperature more than 3 degrees (concentrations lower than 550ppm of CO₂ -eq) will imply reductions of CO₂ emissions before 2030, and the proposed objective for the European Union is to emit 20% lower emissions than those generated in 1990 (See figure 2.6).

![Graph showing CO₂ emissions from 1990 to 2020 for EU-15 and EU-27.

Figure 2.6: Projections of EU-15 and EU-27 emissions during the Kyoto commitment period, EEA]
There are also agreements as final purpose that permits to maintain a continual stabilization of atmospheric CO₂ concentration, implying more than 80% reduction in the annual emissions generated in 2000. According to the European Union Country Report; the EU believes that its support to improve energy efficiency will provide decisive for competitiveness, security of supply and meeting the commitments under Kyoto Protocol (Implementing the EPBD, Featuring Country Reports, 2010). As it is known and believed, there is a 40 % consumption of buildings, 36% of construction sector sourced CO₂ emissions, and there is a real potential to reduce. The EPBD classifies this process around 5 main items, as following:

- Certification of Buildings
- Inspection of Boilers and Air-Conditioning systems
- Training of Experts
- Procedures for characterisation of Energy Performance
- Information Campaigns

Each item has been explained widely in the report, not only advantages but also the disadvantages of every step were discussed. One of the difficulties encountered in every item is the different regulations or rating systems for buildings energy usage in different countries of Europe. Marking the problems seems to be difficult in the European legislative network; the solutions also will also be difficult not only to propose but to implement as well (Thullner, 2010). A comparison is made by Katharina Thullner from Lund University between low-energy building regulations in 9 European Countries. Conclusions show that; comparison of energy rating is really hard since different related areas, differently included energy posts and different terms and definitions cause confusion. The confusion is not only in comparing the different countries, but it also occurs within one county. Apart from
that, it shows that there is nearly neither a regulation system about embodied energy or the decomposition potential in buildings, nor a rating system. Absence of those items in 9 European Union countries' regulation and rating systems show that the area needed to be studied and more complete regulation systems needed to be implemented. Thus, there are so many discussions about 'Life Cycle Assessment (LCA)' and its relationship with the current rating systems, which generally rates the lower energy demand in operational energy (Spain, Energy Class Certification).

In Europe; northern countries have considerably high values compared to other countries. EU-27 final electricity consumption per capita has been steadily increasing between 1997 and 2007. In 2007, it reached 5742 kWh per capita, which presents a 17 % increase compared to 1997. All Member States increased their final electricity consumption per capita over this period. In 2007, Finland, Sweden and Luxembourg had the highest final electricity consumptions per capita, at least double the EU-27 average since Northern Europe has high level of industrialization and high energy demand. United Kingdom, Netherlands, Ireland, Finland, Denmark and Belgium could be considered within this group. Other Mediterranean countries like Spain, Italy and Portugal could be sorted under another group. Another factor for having relatively low values in Southern Europe could be due to better weather conditions in winter. Figure 2.7 shows the CO2 emissions per person in 2004 in different European countries sourced by domestic emissions for heating and the production of natural goods for domestic consumption and embodied in importation for domestic consumption.

Besides the total emissions created by different countries that are sourced by heating and goods, emissions could be grouped by the source of different sectors. Fuel combustion of manufacturing/ construction has a 12.4 % portion of all emissions in EU-27 in 2008 (See figure 2.8 and figure 2.9).

Despite the fact that manufacturing and construction industries sector has so many extensions, as main source activity it has 10 % of the total emissions in EU-27 in
2008. It will be seen that it emits more, if the real per cents of construction related portions of the residential sector and road transportation were known. Every mentioned item is not related to the activity of construction and manufacturing, but they are related to the 'embodied energy' of the buildings. This is because no complete study has been conducted to show this relationship, it is not possible now to evaluate the total emissions related to all activities of construction. Although there is no precise value, it could be concluded that the construction sector is responsible more than 10 %, and as known, there is a real potential to decrease.

**Figure 2.7:** CO₂ emissions caused by domestic consumption sourced by heating and goods in 26 EU Member States, 2004, EEA
Figure 2.8: Total greenhouse gas emissions by sector in EU-27, 2008

EEA
Figure 2.9: Total greenhouse gas emissions by main source activity in EU-27, 2008, EEA
2.3 Spain's Energy Consumption and CO₂ Emissions

Energy consumption per person in Spain is similar to other countries of Southern Europe, except some years with warmer winters; it follows the trend and continues rising every year. Only in 2003, the final energy consumption has showed 60 % increase in respect to the value obtained in 1990. The general tendency of the primary energy consumption in the years ahead seems to be as following:

- Petroleum will be the dominant combustible as of today,

- Nuclear energy will not be a choice, the European Countries have problems in the management of hazardous residues and public acceptance of the nuclear centrals after the big danger occurred in Fukushima Nuclear Central after the tsunami in Japan (2011),

- Natural gas will continue to increase, in 2010, by 23.5 % of total consumption obtained from natural gas,

- Carbon consumption tends to decrease. It has decreased from 17 % in 2000 to 7.8 % in 2010, and

- Renewable energy consumption will increase. It has increased from 5.6 % in 2000 to 12.3 % in 2010, thanks to great wind and solar potential in Spain.

Energy consumption in the Spanish industrial sector grew by an average of 1.2 % during 1990- 1999, and grew by 5.6 percent/year on an average over the period from 2000 to 2005. Between 2005 and 2009, the industrial energy consumption dropped by an average of 6.8 percent/year (-4 % in 2008 and -12 % in 2009, following the economic crisis). The share of electricity in the industrial energy consumption is increasing on a regular basis. In 2009, it reached 35 %, compared with 27 % in 1990. The shares of coal and oil have fallen dramatically (to 1 % and 21 % in 2009
compared with 18% and 29% in 1990, respectively), benefiting the natural gas, which saw its share doubled to 36% in 2009.

The contribution of energy intensive industries remained stable since 1990; at around 60% of the final industrial energy consumption. The share of the steel industry in energy consumption decreased to 14% in 2008 (from 19% in 1990), despite the stable consumption of this sector. That relative decline is also linked to the increase in energy consumption by the non-metallic minerals industry (+48% between 1990 and 2008). The decrease in industrial energy intensity (consumption per unit of industrial value added) was accelerated since 2000 (2 percent/year); the average decrease over the period from 1990 to 2008 was just 0.9 percent/year.

The largest energy efficiency improvements were made in cement and steel production (on average 3.1 and 2.2 percent/year respectively during 1990 - 2008). The share of combined heat and power generation in Spain is high (29% in 2009). It stands above the EU average (17%). The industrial CHP spread rapidly between 1990 and 1999 (+29 percent/year on an average) and remained relatively stable since then at around 30% of the industrial consumption of electricity. While the energy intensity of industry as a whole is decreased. The intensity of the manufacturing industry (excluding construction) showed a reverse trend; it increased by 0.3 percent/year over the period from 1990 to 2008 (+0.9 percent/year during 2000-2008). That increase is limited by changes observed in the industry structure. That structural effect made it possible to limit the increase in the energy intensity of the manufacturing sector (+0.9 percent/year during 1990-2000).

It is important to mention the values of industry in Spain because 'embodied energy' of building materials are mostly related to those values. However, it is needed to group them and classify the values that are related to the construction and manufacturing. The values of industry can still give an idea. Thus, the commonly used construction materials have limited origins like steel, bituminous, stony and minerals (See figure 2.10).
Figure 2.10: Energy Consumption by Industry, by source in Spain

MITYC/IDAE

According to the Energy Mix Fact Sheet of the European Commission in 2007:
Spain strongly depends on energy imports, while domestic production is mainly related to nuclear energy. Energy demand has increased significantly since 1990. Transport and industry are the most significant energy-consuming sectors. In the electricity sector, coal is still the main fuel, but the contribution of gas, nuclear and renewable sources are remarkably high. Gas has exhibited the most significant increase in the share in electricity generation. Spain has a significant share of electricity generated by renewable sources. It has become the second largest country in the world in terms of installed wind capacity. The increase of both gas and renewable sources in the electricity mix are important in terms of climate change.

Residential sector is responsible for 16.7 % of the total consumption in Spain. In 2008, the consumption was decreased to 2.1% to 16,471 ktoe. Lower demand in 2008 was driven by the lower consumption of oil products and particularly coal. The demand on this sector is steadily decreasing in regard to the usage of renewable energies and natural gas. Natural gas has registered a rise in demand by 10.6 %. Renewable energy usage demand is 13 % of the total consumption in primary energy
use. It has already penetrated to sector. Although there will be a considerable decrease in the consumption of residential sector by the usage of renewable energy source; the demand to construct dwellings is increasing constantly (See figure 2.11). During 2001-2007, more than three millions of dwellings were constructed elevating the park to 24.5 millions. Approximately, 16.7 million correspond to principal or primary dwellings and 7.5 million to secondary dwelling or not principals. Increment has created some environmental impacts such as; land, water and materials consumption, the increase of traffic or passenger impact and more in energy demand and the emissions related to the operation and construction of those dwellings.

![Figure 2.11: Population, Housing and Dwellings in Spain 2001-2007](image)

Ministry of Environment, Rural and Marine, 2008, Perfil Ambiental de Espana

Beside the fact of the increase in construction of dwellings, projections for the future show that Spain has a growing profile on renewable energy implementation especially in the residential sector. Till today, Spain is obliged to implement the EPBD with decrees. Implementation of the EPBD is under responsibility of the Ministry of Industry, Tourism and Commerce as well as the Ministry of Housing or the ministries related to building and energy. Development could be seen by the decrees (EPBD, CA Featuring Country Report, 2010);


The code includes an obligation to obtain 30-70% of the domestic hot water demand from solar thermal energy. The code is to be applied to all new
buildings. The variation of the solar fraction between 30 and 70% depends on the assumed volume of hot water demand and the geographical location of the building. Large buildings in the tertiary sector (for instance office buildings > 4,000 m²) will also be obliged to install photovoltaic systems. The solar photovoltaic sector has witnessed a rapid growth with an average annual growth rate of 50% during the period from 1997 to 2005 of. Electricity generation from the solar PV in Spain shows again the second highest level in the EU27, following Germany.

- Royal Decree 47/2007, dated 19th January, approving the basic procedure for the energy certification of new build. Currently; the Energy Performance Class is the usual certificate and the Autonomous Communities are in charge of registration, inspection and control. Annual primary energy consumption and apart from the energy rating and global CO₂ emissions rating, is valid for ten years.

- Royal Decree 1027/2007, dated 20th of July, approving the Thermal Building Regulations.

The above mentioned decrees show that there is a considerable development to decrease the emissions sourced by construction. There will be also a revision in the Technical Building Code regarding the energy efficiency for rehabilitation. For the time being, the code is applied to new buildings only.
2.4 Energy Related Characteristics of Residential Buildings

Residential buildings could be described as an end-use sector that consists of living quarters for private households. Common uses of the energy associated with this sector include space heating; water heating; air conditioning; lighting; refrigeration; cooking; and running a variety of other appliances. The residential sector excludes institutional living quarters. The residential sector is disaggregated into single family detached buildings, multi-family dwellings, and apartments (EIA description). Structural change can affect energy efficiency. Structural change is a change in "other explanatory factors" that affects the energy intensity that is unrelated to the efficiency with which energy is used. The population migration could be a factor for residential buildings. Migration of population can increase the demand for new residences. On the other hand it can be even advantageous for Spain to use the existing residence stock. However, it is not a key factor for energy efficiency of residences. Thus, a change in the structure does not change the efficiency of energy use in the residential sector.

The main energy consumption source in the residential buildings in Spain is space heating which is 47.3 % of total consumption (See figure 2.12). It is below the average of the European Countries since the average of Europe is 67 %. This is related with better winter conditions in Spain compared to the average of European Countries. It is expected, however, that an increase will occur in the future, mainly due to the tendency to have better equipments and the gradual penetration of the individual heating systems in general, which is less efficient than collective systems.

**Figure 2.12:** Energy Consume in Residential Sector by usage in 2006, Spain and UE27

- Heating: Spain: 47.3 %, UE27: 66.9%
- Hot water: Spain: 26.7 %, UE27: 15 %
- Electro domestics: Spain: 14 %, UE27: 11 %
Besides the tendency of having individual equipments in residential buildings, the demand for heating is determined by the architectural design. Type of the building, its structure and wall configuration, design of the building envelope, orientation, the capacity for gain from sun (direct or indirect), design of the sun protection in summer affects the demand for heating or cooling.

Common types of dwellings in the centre of Barcelona are adjacent blocks with a common gallery in Eixample District. The Eixample refers to the extension of the city, starting with a demand for an extended city that was described as a more suitable configuration than the existing to 'dynamic' life style of the industrialized community of 1850s. Ildefons Cerdà i Sunyer, introduced a new geometrical system to extend the city from the old city centre to districts like Gracia and Sants (See figure 2.13). Building blocks configuration was studied, but there was a considerable change since then because of the higher density. The change took place vertically, adding more flats, and in the galleries (See Figure 2.14). Today, the galleries are used as a common empty space without any function of recreation.

![Figure 2.13: Original Project of Cerda Plan](image)

23
The geometrical design of the blocks are designed in order to benefit as much as possible from the sun light (See figure 2.15). The long façades are oriented to North-East, North-West, South-East and South-West. The streets were planned to be 20m width to allow sun light penetration. The short North Façade (15m) is advantageous to decrease of the heat losses. However, there are heating and lightning problems resulted by the orientation of the blocks, shown as following:

- As the scheme shows, the eastern façade (83m) should have sun light equal to the western façade (83m), which is not the case. Since summer days are longer, the western façade will have more sun light and needs more protection than the eastern façade to evade overheating,
- Shifting on the axis of the North-South will block the possible heat gain of the South Façade.

**Figure 2.14**: Evolution of building blocks from the Cerda Plan till today

**Figure 2.15**: Orientation of Eixample Building Blocks
Doubtless, façade (building envelope) is one of the important elements for a building. It is not only in a structural or visual manner but also the protection from radiation, separation of interior from exterior. Because of these given functions, it was evolved a lot over the centuries. There are grand varieties of construction types of façades commonly in use in Barcelona, but the conventional façades could be considered as following;

- Façade with massive bricks, revested with plaster, bricks to be entangled in every layer,

- Double skin façade with brick finish, with air chamber and thermal insulation. Thermal insulation is between air chamber and exterior brick layer, adjacent to the exterior brick layer

- Double skin façade with brick finish, the air chamber and the thermal insulation. Thermal insulation is located between the air chamber and the exterior brick layer, adjacent to the inner brick layer

- Double skin façade with brick finish, with air chamber and thermal insulation. The thermal insulation is located between the interior space and the inner brick layer,

- Double skin façade with brick finish, ventilated air chamber and thermal insulation. The thermal insulation is located between the ventilated air chamber and the exterior brick layer, adjacent to the inner brick layer

The most common conventional type is the ventilated façade with brick finish. However, in contemporary dwellings, the brick finish is substituted with lighter layers and the connections are more technological. But the principal of the façade, which is suitable for this type of climate, is still the same; the exterior layer provides protection from radiation and the ventilated air evades humidity. The mentioned
types are also common in other southern European countries like Italy and Portugal. It is also very common in England as the exterior layer could be called 'rain screen'.

More than conventional types and contemporary structures, the industrialized types are becoming popular in terms of sustainable architecture because of time gain and systems' properties. Most commonly used industrial construction types in Catalonia are as following:

- Structure of the prefabricated concrete; columns, beams, pavements or alternative solutions,
- Structure of the prefabricated concrete, bearing walls,
- The metallic structure,
- Three dimensional modules,

Those types have a variety of production and application process; a unit produced on factory and montaged on site, structure only produced on factory and finishes can be made on site, finishing materials or walls that can be either fabricated or produced on site. This process depends on the selected system and as the industrial systems have flexibility in montage and fabrication, the innovative solutions could be proposed without facing any serious obstacles.

In 2006 and 2007, INCASOL (l'Instut Catala del Sol) introduced a competition to encourage innovative and industrialised solutions (CIT, 2007). It is essential to analyse in order to get an idea about the 'contemporary' solutions for the industrialized architecture. The construction types of winner projects could be summarised as following;
• Banyoles, Catalonia.
  System: COMPACT HABIT
  Architects: Xavier Tragant and Miguel Morte
  30 houses in total.
  3d Concrete module, all finishes were made in factory. Transported to site from factory and the montage of modules was made on site.

  ![Figure 2.16: Concrete 3d Module, Banyoles](image)

• Callus, Catalonia.
  System: TECCON
  Architects: Arau-Medievilla scp.
  27 houses in total.
  Steel frame structure with composite flooring and with bearing panels of TECCON with substructure. Montage was made on site.

  ![Figure 2.17: Steel Frame Structure with composite flooring, Callus](image)

• El Masnau, Catalonia.
  System: BSCP (Building Structure Concrete Panel)
  Architects: Eduard Calafell and Laia Orovà
  36 houses in total.
  Reinforced concrete massive panels with BSCP System, the modulation of each element was produced in factory and montage was made on site.
Figure 2.18: Building Structure Concrete Panel, El Masnau

- Mollet del Valles, Catalonia.
  System: BARCONS
  Architect: Vigum Project SL
  90 houses in total.
  Vertical and horizontal elements of structure and interior divisions made of concrete. Construction module of system Barcons high pressure was used.

Figure 2.19: System Barcons, Mollet del Valles

- Sant Vicenç dels Horts, Catalonia.
  System: Pujol
  Architects: Andreu Arriola, Carme Fiol and Xavier Vilalta
  42 houses in total.
  Façade consists of two layers; prefabricated ceramic and prefabricated high formatted glass.

Figure 2.20: System Pujol, Sant Vicenç dels Horts
• Torello, Catalonia.
  System: TAC
  Architects: Estudi TAC, Eduardo Gasgon and Jordi Roig
  36 houses in total.
  3 dimensional steel structure module. Constructed in factory including the
  finishes and the montage of the modules were made on site. Façade with
  sandwich panels.

  ![Figure 2.21: 3d Steel Frame Structure, Torello](image)

### 2.4.1 Embodied Energy

Embodied energy is defined as the commercial energy (fossil fuels, nuclear, etc) that is
used in the work of making any product, introducing into market, and disposing it.
Embodied energy is an accounting methodology, which aims at finding the sum total
of the energy necessary for an entire product lifecycle. This lifecycle includes raw
material extraction, transport, manufacture, assembly, installation, disassembly,
deconstruction and/or decomposition. In this study, disassembly, deconstruction and
decomposition are considered as a different part, since a different methodology is
introduced.

Embodied energy analysis is interested in what energy goes to supporting a
consumer, and so all energy depreciation is assigned to the final demand of the
consumer. Different methodologies use different scales of data to calculate energy
embodied in products and services of nature and human civilization. International
consensus on the appropriateness of data scales and methodologies is pending. This
difficulty could give a wide range in embodied energy values for any given material.
The main methods of embodied energy accounting as used today grew out of Wassily Leontief's input-output model and are called Input-Output Embodied Energy analysis (Leontief, 1966). Leontief's input-output model is in turn an adaptation of the neo-classical theory of general equilibrium with application to 'the empirical study of the quantitative interdependence between interrelated economic activities'. According to Tennenbaum, Leontief's Input-Output method is adapted to embodied energy analysis by Hannon to describe ecosystem energy flows (Tennenbaum, 1988). Hannon’s adaptation tabulated the total direct and indirect energy requirements (the energy intensity) for each output made by the system (Hannon, 1973). The total amount of energies, direct and indirect, for the entire amount of production is called the embodied energy.

Embodied energy is a concept for which the scientists have not yet agreed on absolute universal values because there are many variables to take into account, but most of them agree that the products could be compared to each other to see which one has more and which has less embodied energy. Comparative lists contain average absolute values and explain the factors that have been taken into account when compiling the lists. Typical embodied energy units used are MJ/kg (mega joules of energy needed to make a kilogram of product), tCO₂ (tonnes of carbon dioxide created by the energy needed to make a kilogram of product). Converting MJ to tCO₂ is not straightforward because different types of energy (oil, wind, solar, nuclear and so on) emit different amounts of carbon dioxide. So the actual amount of carbon dioxide emitted when a product is made will be dependent on the type of the energy used in the manufacturing process. In Spain, according to BOE (n: 45, p.9926, Annex II, 2008), 1kWh (3.6 MJ) is equal to 0.62 kg CO₂ (there are different values given by different companies, however this value is given as an average national value), due to the mix, which is made during the production of electricity (See figure 2.22).
Figure 2.22: Mix of Production in the Spanish Electric System

The SB Tool, UK Code for Sustainable Homes and USA LEED are methods by which the embodied energy of a product or material is rated, along with other factors to assess a building's total environmental impact.

Databases of listed materials with their impact, generally energy and emissions, are obtained by tools such as Life Cycle Assessment (LCA). Life cycle refers to consecutive and interlinked stages of a product or service system, from the extraction of natural resources to the final disposal while Life cycle Assessment could be described as a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy as well as the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle. Life cycle assessment determines the environmental impacts of products, processes or services, through production, usage, and disposal (ISO 14040.2 Draft: Life Cycle Assessment - Principles and Guidelines). The procedures of life cycle assessment (LCA) are part of the ISO 14000 environmental management standards: in ISO 14040:2006 and 14044:2006 (ISO 14044 replaced earlier versions of ISO 14041 to ISO 14043). LCA technique for assessing the potential environmental
aspects and potential aspects associated with a product (or service), could be described by:

- Compiling an inventory of relevant inputs and outputs (LCI),

- Evaluating the potential environmental impacts associated with those inputs and outputs (LCIA), and

- Interpreting the results of the inventory and impact phases to the objectives of the study (due to LCI and LCIA).

There are two basic types of LCA tools;

- Software packages: There are two principal tools; GaBi Software, developed by PE International, and SimaPro, developed by PRé Consultants.

- Tools with the LCA in the background intended for those who want LCA-based results without having to actually develop the LCA data and impact measures: The whole building design level and different tools are available in different parts of the world. For example, the ATHENA® Impact Estimator for Buildings is capable of modelling 95% of the building stock in North America. Envest is developed by the Building Research Establishment to meet the UK needs while EcoQuantum is available in the Netherlands. As regards the Netherlands, extensive databases (open access) are available on the so called eco-costs and carbon footprint of buildings and its components. The European Council of Construction Economists is planning to develop such open source databases for other European countries as well. At a building assembly level (e.g., exterior walls) the free ATHENA® EcoCalculator for Assemblies is an example of a tool that serves North America and the Whole Building Design Guide is an example of a tool applicable to the UK.
In Spain, there is no rating system applied to buildings yet, but there is a database for environmental impact of the construction materials called Metabase, Banco Bedec. The Metabase is a set of databases that include information on building products that contains price information, specifications, technical information, certification, product images and environmental data as energy consumption and emissions. The database is created by the Institute of Construction Technologies of Catalonia (ITEC - Institut de Tecnologia de la Construccio de Catalunya).

It is essential to know basic types of the LCA data while evaluating the data obtained from the LCA databases, since there are two types of the LCA data;

- **Unit process data:**
  Unit process data is derived from direct surveys of companies or plants producing the product of interest.

- **Environmental input-output data (EIO-LCA):**
  Input–output analysis is a top-down linear macroeconomic approach to describe industrial structure. EIO-LCA involves the use of aggregate sector-level data quantifying how much environmental impact could be directly attributed to each sector of the economy and how much each sector purchases from other sectors in producing its output. In addition to direct effects, developments cause environmental pressure indirectly through the consumption of goods and services, and the activities of the numerous producing industries in the national as well as foreign economies. Indirect effects are of infinite order: impacts on vegetation, wildlife and the physical environment, as well as the land occupied by producers of construction machinery, steel plants producing the steel for the machinery and by mining operations providing the iron ore for the steel factory, by manufacturers of mining equipment, and so on. These impacts are generally off-site, and may even occur in foreign countries (Lenzen et al., 2003).
'Product usage factor' could be one of the important items in the LCA for buildings. This is because the life cycle considered usually consists of a number of stages including: materials extraction, processing and manufacturing, product use, and product disposal. If the most environmentally harmful of these stages is determined, then the impact on the environment could be efficiently reduced by focusing on making changes for that particular phase. Life Cycle Assessment for buildings could be determined not only at the material level, but as a whole organism. Thus, life time of a building is minimum fifty years, the durability of materials become important. However, within the frame of sustainability, the energy demand to operate is generally rated, but the relationship between life cycle and the operational energy could better explain an organism and the total consumption and emissions.

In this investigation, particular analysis and indirect effects have not been considered. The study is divided into two parts; initial embodied energy to compare energy consumption and the emissions of each material in total and secondly; the deconstruction-decomposition and disassembly potential on an architectural frame. While evaluating the initial embodied energy; data is obtained for each material from Metabase- BancoBedec of ITEC, comparative excel lists are prepared in manually written data.

2.4.2 Operational Energy

Operational energy of a building could be described as the total energy required to operate a building. It could be summed up as energy necessary for space heating, space cooling, lighting, water heating, electro-domestics and other appliances. Operational energy load depends on some given inputs in early designing period. Some indicators are given as following (Yohanis et al., 2000):

- Glazing ratio, glazing transmission, window framing, room dimensions, internal reflections, external reflections, UHA, OSV,
- Site latitude, orientation, daily difference vertical radiation,

- Occupied hours, incidental gains,

- U values, external temperature,

- Thermal mass,

- Air exchange rate,

- Solar radiation,

- Comfort temperature, and

- Density, heat specification and thickness of materials.

Some of the above mentioned items are directly and some indirectly related with (See figure 2.23); daylight factor in reference points, hourly ambient illuminance, non-lighting gains, lighting gains, internal gains, lighting load, fabric heat losses, average daily comfort temperature, ventilation heat losses, gross solar gains, solar utilization, heat losses and finally with heating load and cooling load (Yohanis et al., 2000).

In this investigation, related values are used. Nevertheless, input values are similar in any operational load calculation. The below simple chart is important to show the relationship between the total embodied energy and the operational energy.
Figure 2.23: Simple Chart of Early Design Method (EDM), Yohanis et.al, 2000
2.4.3 Disassembly, Deconstruction, Decomposition and Reuse

It is essential to mark the potential waste generated in the future by the existing stock of residential buildings and new construction. In Spain, there is a considerable residential building stock accumulated, even new construction rate is projected to rise by factors of population or personal wealth. In Europe, residential sector represents 46% of the total EU production (EUROCONSTRUCT, 1994). The building service is characterised by a long service life of fifty years and even more. The statistics show that the replacement rate of the building stock in Europe is about 1% per year and building demolition is about twenty times less than new construction (Housing statistics in the European Union, 2004). The European low energy house market is in rapid growth with approximately 1000 new dwellings per year but this represents only 0, 1% of the total new construction today. This means that, there is a real stock accumulated especially in Spain while new construction continues with the obligations to decrease the energy demand. On the other hand, new construction is already incorporated in more recent technical solutions. So, it will affect sustainability issues on the long term. However, the waste generated by construction and demolition is generally counted together in the statistics due to the absence of detailed values for each member state in Europe. In 2008, the waste generated by construction is nearly equal to the waste generated by industry in 27 member states (See Figure 2.24).

![Figure 2.24: Waste generated by activity, 2008 (% of total), Eurostat](image-url)
In Europe, Construction and demolition waste makes up approximately 25% of all waste generated in the EU with a large proportion arising from the demolition and renovation of old buildings. It is made up of numerous materials including concrete, bricks, wood, glass, metals, plastic, solvent, asbestos and excavated soil. Many of which could be recycled in one way or another (See figure 2.25).

**Figure 2.25:** Generated waste by material type in Europe in construction sector (% of total)

Waste generated by construction and demolition is considered as the main theme for the European Commission. However, terms used in each country differs from each other. Therefore, making a comparison seems to be difficult. Explanation of Waste Framework Directive could be used in order to analyse obtained values in the waste generation by construction and demolition: The 70% recycling target for C&D waste in the new Waste Framework Directive includes "preparing for reuse, recycling and other material recovery, including backfilling operations...". Furthermore, the definition of recycling explicitly excludes '… the reprocessing into materials that are to be used as fuels or for backfilling operations' (Waste Framework Directive 2006/12/EC and amendments).

If we consider that more than 50% of all materials extracted from earth are transformed into construction materials and products, it is expected to have high
energy consumption and emissions during raw material extraction, transformation and transportation. However, in terms of waste generation and waste management, it is not marked as only raw material transformation level. OECD/Eurostat Joint Questionnaire on Waste explain waste, waste generation and waste management as following:

'... Waste refers here to materials that are not prime products (i.e. products produced for the market) for which the generator has no further use for own purpose of production, transformation or consumption, which he discards, intends or is required to discard. Wastes may be generated during the extraction of raw materials during the processing of raw materials to intermediate and final products, during the consumption of final products, and during any other human activity...'

'Waste management means the collection, transport, treatment and disposal of waste, including after-care of disposal sites...'

Construction and demolition waste has been identified as a priority waste stream by the European Union. This means that particular attention will be paid to policies and measures to ensure increased recycling of construction and demolition waste. However, there is still a potential to decrease even the values per capita that are lower than its rate in 1999 (See figure 2.26). Till today, there has been a considerable development in European countries in implementing the 'Waste Framework Directive' and treatment the construction and demolition waste. It is shown that, countries with high waste generation also have higher values in the treatment of waste. In 1999, Spain generated lower than one thousand kg of waste per capita. But approximately all has used for land filling (See figure 2.27). Statistics show that construction of buildings in Catalonia is responsible for 30-40 % solid residue generation (PROGROC). Development of waste management in Spain could be explained by new directives. Elaboration of Management Plan of Residues with the entry of Real Decreto 105/2008, in the construction site, it is obligated to separate residues according to their properties to facilitate its subsequent recovery. In Europe, the situation is similar to Spain. All materials placed on the market are destined to
become waste at one time or another. Every production process generates some form of waste. At present, 49% of EU municipal waste is disposed through landfill, 18% is incinerated and 33% is recycled or composted (EU Waste Management System). In construction sector; construction and demolition waste had the 33 % of waste generations resulted by buildings in 2004 (See figure 2.28). Manufacturing waste is 13 % and mining and quarrying waste is 22 % of the total waste. Although, there is no data showing the waste generated during recycling of materials, the difference of energy consumption and emissions for a material as well as energy consumption and emissions after recycling of the same material, could give an idea about the process between demolition and recycling. The process is linked to energy consumption and emissions caused by generated waste during the recycling and the power needed for recycling.

**Figure 2.26:** Total quantities of construction and demolition waste per country and capita, 1994-1999, OECD/ Eurostat
Figure 2.27: Treatment of construction and demolition waste per capita, Report to the European Commission DG XI.E.3 1999 and ETC/W questionnaire

Figure 2.28: Total waste generation in the EU, EFTA, Turkey and Croatia by source, 2006, EEA
Waste management is becoming an obligation in Europe with implementations of related directives. Waste management contributes to a total cycle of a material or a product (could be an architectural product). It is summarized in two ways; waste prevention and waste treatment or waste reduction. Waste prevention policy actions could be visualised on the axes 'phase in the life cycle' and 'kind of instrument' (EC, Final Report, Analysis of the evolution of waste reduction and the scope of waste prevention) are as following:

- The life cycle contains the steps: design, extraction, production, distribution, consumption/use, waste, and end-of-waste.
- The instruments are defined as: legal, economic, communication, technical and other instruments.

In the near future, possible potential actions could be taken by institutions or individuals like architects or contractors in the process of rehabilitation or demolition of accumulated stock or new construction could be as follows:

- Accumulated residential building stock
  - Waste generation by demolition
    Potential should be analysed and actions should be taken including disassembly, deconstruction and decomposition of components or materials.
  - Waste generation by rehabilitation
    Potential should be analysed to reduce the potential waste by types of components. Energy needed to prepare for reuse should be analysed since it depends on the context of the rehabilitation.

- New construction
  - Waste generation materials
    Prevention in design of extraction, transformation to components and transport to site,
- Waste generation by demolition in the future

Preventive action should be taken in the design process. Design should be made as non-waste concept or disassembly, deconstruction and the decomposition plan should be considered.

- Waste generation by rehabilitation

Potential to prevent the future waste should be considered. Thus economical, esthetical and durability discussion in components are made.

Reuse is a concept which seems to be applicable to some components of building or to the whole building. It is actually a preventive action. However, types of the reuse are differ from each other in terms of energy need (Parker et al., 2007):

- Straight reuse; possibly by someone else and in a different way.

- Refurbishment; cleaning, lubricating or other improvements,

- Repair; rectifying a fault,

- Redeployment & cannibalisation; using working parts elsewhere,

- Remanufacturing; to guarantee the performance of the finished object.

Since the durability of some components or materials of construction are higher than the demand for residential buildings; straight reuse could be an option. It prevents the generation of waste in demolished buildings or in rehabilitation projects while it prevents the new material production and its impacts in new construction. Other options should be analysed in terms of energy consumption balance and possible emissions. Furthermore, in life cycle assessment frame, the whole process should be designed. Closing the cycle during the process is important. Closing the cycle of the materials is a process, which starts with the transformation of the raw material into materials or components for construction. However, closing the cycle could be in
material level; starting firstly with disassembly/deconstruction of the components and later on the decomposition of materials or at the component level like reuse (structure, façade, divisions and finishes) as well as at the building level itself like reuse.

In this case; disassembly refers to the act of taking apart components into its constituent pieces. Deconstruction is breaking the components down into smaller parts while decomposition is the act or process of resolving the constituent parts of a compound body or substance into materials of elementary parts; separation into constituent part; analysis; the decay or dissolution consequent on the removal or alteration of some of the ingredients of a compound; and disintegration; like the decomposition of wood, rocks, etc. Construction waste is consisted of two parts; the first part occurs during on site construction and the other one occurs during manufacturing. Waste sourced by the demolition of buildings could be considered as an on site waste.

In Spain, treatment and management of residues of construction and demolition has started already with revisions of directives and new obligations. There are companies with waste recycling plants. They are dedicated only to construction sector and holding the mission to raise the awareness of the need to recycle. The existence of those plants is important because they offer waste recycling and alternatives for final producers like reuse for builders, developers and individuals who are responsible for generated residues. Furthermore, it is still essential to get the exact values regarding the total waste generated by construction.
2.5 Conclusion

Total energy demand tends to be continued in the world the next years. Population growth will increase with a bigger rate, but the most important impact on Spain will be the global migration from colder climates to warmer parts of the world. If other scenarios of climate change occur such as the increase in temperature, lack of access to potable water in several parts of the world, before the indicators are discovered and described well, these impacts can occur at a deeper level in Spain as a Mediterranean country.

Europe has prepared so many studies for future scenarios of the climate change as well as possible precautions for possible items. Due to the progress reports, after the implementation was started in Spain, there is a real development in terms of renewable energy usage. Thus Spain had become the second country in wind energy source usage.

In the construction sector, thanks to Buildings Technical Code of Spain, 2006, solar energy usage for hot water services and photovoltaic panel integration caused decrease in consumption and emissions. However, there are still so many parts of buildings that could be more efficient. Operational energy is well studied. Thus; the demand is decreasing every year with design in buildings; with gains from sun in winter or with providing protection on summer to avoid overheating. On the other hand, life-cycle assessment is one of the items which to be related with operational and embodied energy.

Residential sector is one of the important activities of the construction sector in Spain, though there is a real stock accumulated. Besides the stock, there is an intellectual demand to try new types as; industrialized modules, new configurations of construction systems, technological construction materials in order to reach more efficient buildings types in Catalonia. Industrialized types were very common in the history of architecture when a country or city have a rapid and unexpected
immigration because of their advantage in the construction period. While sustainable construction has started to be an objective, they come to the design scene again. Industrialised systems have started new discussions on efficiency, though they made us re-think about previous intentions like;

- Time gain in construction,
- Transport of building materials to the factory instead of construction site,
- Controlled montage process,
- Decomposition potential thanks to common application of dry systems,
- Flexible reuse potential

All such items could not be related to the operational energy efficiency, nor could be considered as a structural change like population, since it is necessary to evaluate the relationship between different types of energy consumption and CO₂ emissions. Evaluation could be made to conventional construction system and new techniques.
3 ENERGY CONSUMPTION AND CO₂ EMISSIONS SOURCED BY RESIDENTIAL BUILDINGS

3.1 Antecedents and State of Art of Energy Consumption and CO₂ Emissions Sourced by Residential Buildings

Several studies were realized about the total consumption of residential sector by several authors. There is no doubt that; the general context has started with the design of frame of Life Cycle Assessment (LCA), which involves the whole process of construction starting with raw material extraction and continues with closing the cycle of all terms (See figure 3.1). Embodied energy analysis has a major share of the literature and there are few studies made with the context of the whole process due to the variety of data in every step of LCA of a building, taking into consideration that data is not available and viable in every phase.

Figure 3.1: The basic procedure followed in a Life Cycle Assessment, Fraunhofer Institute for Building Physics
It is essential to define each of the embodied energy analysis of building materials and the embodied energy analysis for a building. Embodied energy for building materials could be described in three terms (Hammond et al., 2008):

- Cradle to grave: Includes extraction of material till the end of the products lifetime (includes energy from manufacturing, transport, energy to manufacture capital equipment, heating and lighting of factory, maintenance, disposal...etc.),

- Cradle to gate: Includes all energy (in primary form) until the product leaves the factory gate, and

- Cradle to site: Includes all of the energy consumed until the product reaches the point of use.

Life Cycle Assessment of building also could be described in similar terms, but it is needed to add cradle to occupation or cradle to demolition. However, in previous researches, embodied energy description varied a lot and the embodied energy concept differed from each other.

There are several authors who have studied the relationship between the initial embodied energy and the operational energy in different terms. One of the important points while relating operational energy and embodied energy is the effect of the thermal mass (Hacker et al., 2008). A study was made on a 65m² semi-detached house in south-east in England analysing the effect of thermal mass with possible climatic conditions regarding climate change. Four weights of thermal mass were considered from lightweight timber frame to heavyweight concrete frame. For each case, embodied and predicted operational energies were calculated and analysis was made under a simulation of 100 years of climate change conditions. However, only the summer performance of each case was discussed. The reasoning was made according to a previous research on the importance of thermal mass in commercial
and domestic buildings. The research showed that thermal mass is important in summer for buildings that have concrete as a construction type (Palmer, 2005; cited by Hacker et al., 2008). The analysis could be framed as cradle to occupation. The study shows that heavier weight case has higher embodied energy initially but reduced operational energy. Payback of the time of initial embodied energy for the medium lightweight case was only 11 years while for heavier cases; it was 23-25 years. However, no 'optimum weight' was found yet that could have a better performance in the relationship between initial embodied energy and operational energy. It is important to mention that lightweight case was configured by timber frame which is not a common construction system in Catalonia.

Another case study was conducted in England about an embodied carbon and energy analysis of modern methods of construction in housing using lifecycle assessment framework (Monahan et al., 2011). The process based LCA methodology was used. The study was made by a 83m² semi-detached house in Norfolk, England and analysed the effect of on-site (conventional) and off-site (fabricated modular system) common construction systems. Three systems were studied as following; MMC timber frame larch cladding, MMC timber frame brick cladding and masonry. Investigation was made to compare the different approaches to find out carbon consequences of the new housing system and identifying areas that could deliver reductions in embodied carbon. The analysis could be framed as cradle to site. The study showed that using a panelised timber frame MMC construction reduces embodied carbon by 34 % when compared to a traditional masonry structure. Timber has a major usage in the structure and the brick cladding in façade in England. However, the case study with timber structure and cladding showed that there can be a reduction by 24 % when brick cladding replaced with timber. In addition to the previous studies; in this analyse, waste generation was discussed. It is mentioned that off site construction of the structure generates less waste and total waste generated by the structure implies only 4 % of total embodied carbon. However, a wide conclusion was not obtained due to the absence of data on the waste generated on site. The embodied carbon was found to be associated with the construction of the
substructure, the foundations and the ground floor. The high values were related to the usage of carbon intensive materials in those sections. The material usage was discussed. Although the brick was unfired, it had a high embodied carbon factor. Cement production was also considered as a reason of high values. The steel piles were considered as a high embodied carbon factor while the recycling and the reuse potential was mentioned as positive factors. Avoiding the usage of cement in buildings or other high carbon factored materials where no additional benefit to their usage is possible was discussed. But it was mentioned that embodied energy analysis should not be isolated from the other items like operational energy reduction benefit of the concrete usage (VanGeem et al., 2008 and Brown et al., 2001). Finally, consideration of embodied energy was introduced as an element that needs to be integrated in the earliest design stage. Potential embodied carbon savings methodology was also explained as increasing the off-site manufacturing, considering sustainable materials, designing the materials within the structure according to their properties and implementing strategies to minimise on-site waste.

Is Catalonia, Spain, the industrialised construction system was analysed; it was asked if they are better in terms of reducing CO₂ emissions (Pages et al., 2007). The study was made with 84 m² single family building in Barcelona, Spain for 60 years of lifetime. Four cases were organised for comparison as following; lightweight industrialised, heavyweight industrialised, light-heavy weight industrialised and conventional systems. The study could be considered cradle to occupation since the disassembly potential considered as a concept only. Rather than the previous studies, the CO₂ emissions were compared according to building operation between winter, summer and the intermediate seasons. Heavyweight was the best performance in the all seasons as in previous studies. Another case was organised adding 5 cm more insulation to walls, floors and roof. But it didn't make any difference compared to the 4 cases, although all of them had a better thermal comportment. In the construction phase, lightweight industrialised system had the highest values of emission, but it was considered more advantageous than the other three cases in terms of disassembly potential in the demolition stage. However, no precise study was made according to
exact potential for disassembling. The conclusion made for the climatic region was; %38-52 of CO₂ emissions over a building life time linked to the construction phase and conventional system was still the best in terms of overall emissions. Improving the lightweight industrialised system in this region, could be made with more insulation and adding thermal mass still.

Lightweight systems were discussed for their thermal comportment. Although they have less thermal mass, but are still in use due to other advantages in a sustainable frame. Investigations are underway to get better lightweight system with phase change materials (PCM) (Fraser, 2009). Phase change materials were offered as a solution to lightweight systems because of their properties. They can store latent heat energy, as well as sensible energy. As the temperature increases, the material changes phase from solid to liquid. As this reaction is endothermic, the PCM absorbs heat. Similarly, when the temperature decreases, the material changes from liquid to solid. As this reaction is exothermic, the PCM releases heat (Kuznik et al., 2008; cited by Fraser, 2009). It was mentioned that materials with those properties could be effective. However, current results considered to be discouraging to product these materials commercially. It was indicated that there are materials in the market like wall linings or construction chemicals, but they are nearly ten times expensive than common construction materials.

Another study about construction materials was focused on closing the materials cycle in the industrialised architecture (Wadel et al., 2010). The research focused on a productive model from the ecological industry, based on the biosphere as a recycling machine. The given hypothesis was as following: using technology presently available, represented by the lightweight modular construction that is commercialised by renting (making it possible to return the modules to the factory once their useful life is over, therefore recuperating resources) and a management system capable to close the material cycle at least to 90% could be developed (conventional building construction currently manages a recycling value of 10% of the used resources). The idea depended on a proposed system of renting and
demountable modules usage in the current market. According to the proposal, after
the life-time of the module is finished, the module is to be reused with some
recuperation. After deconstruction, the module's materials are to be rehabilitated or
the materials should be sent to the factory for recycling (See figure 3.2). It showed
that the material flow could be an interlinking chart in order to have a conventional
construction system which is programmed to generate waste. The study could be
framed as cradle to demolition but the building use or the thermal comportment of
the lightweight industrialised systems were not considered as an obstacle as in the
previous studies.

![Diagram]

**Figure 3.2:** Material flow chart in conventional construction system and in proposed
demountable modular construction, Wadel, 2010

There are several studies that frame the industrialised architecture with different
focuses. However, it seems hard to compare because of the different focuses. But it
shows that evaluation of the whole process as cradle to demolition is hard because
there are no many viable values yet, especially on waste generation while the
construction systems and materials of each system differs a lot.
In all reviewed studies, the main focus differs between cradle to occupation and cradle to demolition. But there are few that have extended their context. As regards Catalonia, it is necessary to evaluate different kinds of the recent industrial systems with conventional system in all terms such as: Initial embodied energy, operational energy (use) and existing potential, in order to discontinue generating waste sourced to demolition or construction. Previous studies showed that studying with total embodied energy is hard because of two reasons; the construction process of buildings is too long while there are few viable data given by companies of construction materials or the plants. Therefore, this investigation is divided into two main parts: comparison of initial embodied energy with operational energy of three cases and evaluation of the existing potential in three cases in order not to generate waste which was held only in the previous study from Catalonia (Wadel, 2010). A quantitative study is made during the evaluation process but the conclusion is made as qualitative, which could be a more viable reference for future studies.
3.2 Evaluation of Initial Embodied Energy, Operational Energy during Life-Time and Disassembly- Decomposition- Deconstruction- Reuse Potentials

3.2.1 General Frame and Structure of the Case Study

The relationship between initial embodied energy, maintenance energy and disassembly- decomposition- deconstruction potentials were studied with a moduler industrialised apartment in Banyoles, Catalonia. The case study was made with three different types of present construction systems in Catalonia.

The reference building was constructed in Banyoles in 2010, which consists of concrete modules and in-situ constructed comun areas. Total floor area of the selected module is approximately 50 m² and its total volume is 172.5 m³. The floor plan and sections are presented in Figure 3.3 and Table 3.1. The module has two façades oriented to East and West as constructed. It is an intermediate module between the 2nd floor and 3rd floor. An intermediate module was selected as a reference module in order to obtain similar comportment in case of extreme conditions in the three cases.

---

Orientation
The building is oriented to East and West.
West is the main façade with an access balcony while the East provides main access from the main open corridor of the building. North and South façades are considered as conjunction with other modules since the selected module is an intermediate.

| Façade Areas (including glazed areas): | East: 17.5 m², West 17.5 m² |
| Glazed Areas: | East: 4m², West 4m² |
| Floor Area | 50m² |

Table 3.1: Schedule of façade, glazed areas and floor plan
Figure 3.3: Plan and Sections of Reference Module
Reference building was constructed in Banyoles near Girona in Catalonia. Case studies were made according to the climate conditions in Barcelona Capital to make estimation for possible climate conditions in the centre. Barcelona Capital is in the C2 Climatic Zone (same as Banyoles) according to the current Technical Buildings Code of Spain, altitude was given as 1 m (CTE, Appendix D, Climatic Zones, p. HE1-31). The values are given as maximum annual temperature of air and climate zones in winter. Maximum temperature could be taken from the data on the map in the absence of precise empiric data. Minimum temperature is to be taken from the climate zones in winter and the altitude factor should be considered (figure 3.4 and figure 3.5). In the case study minimum and maximum temperature was taken from a meteorological observatory station in the centre of Barcelona to study the parameters more precisely (Observatory Fabra, 1971-2000).

![Figure 3.4: Isotherms of maximum annual temperature of air (T_max in °C)](image)
Figure 3.5: Climate Zones in winter


The specifications were standardised as much as possible in the three cases (e.g. with the same external cladding, insulation materials and interior finishing) to evade any extent of exposed thermal mass in the interior spaces.

Three cases have the same heat transfer coefficients (U values- W/ m²K) of external walls, internal walls, flooring and ceiling. The values are in accordance with the limits of current Technical Buildings Code of Spain (CTE). Also a comparison of the heat transfer coefficient values were made between previous the studies on this topic and the current regulation of construction in Spain (CTE) for the climate zone of Barcelona (table 3.2). The U values are as following:

- External Walls: 0.41 W/ m²K
- Internal Walls: 0.31 W/m²K
• Floor & Ceiling (intermediate module): 0.48 W/m²K

<table>
<thead>
<tr>
<th></th>
<th>U value of External Walls (W/m² K)</th>
<th>U value of Glass and Frame (W/m² K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Buildings Code of Spain, U values for Climate Zone C2 (CTE p.944)</td>
<td>0.73</td>
<td>4.4*</td>
</tr>
<tr>
<td>Pages et al.</td>
<td>0.34-0.70**</td>
<td>N.A</td>
</tr>
<tr>
<td>Case study</td>
<td>0.41</td>
<td>3.9</td>
</tr>
</tbody>
</table>

**Table 3.2:** U value comparison between Technical Buildings Code of Spain for climate zone of Barcelona, previous studies and the case study

* The values are explained as percentage relation to the total area of the façade. For façades oriented to East and West, with a 10% opening ratio value is 4.4 W/m²K

** The U values were taken between 0.34 and 0.70. Different construction types have different U values of a minimum of 0.34 and maximum of 0.70 (Pages et al., 2007)

The reference module is supposed to be occupied by three persons (one as a child). The house is in occupancy by two persons during the day time and three persons during night (20:00-08:00).

Household non-renewable energy consumption is assumed to be as following:

• Lighting and services; two fluorescents of 80 W; one hour during day time. Five fluorescents of 80 W; three hours during night time,

• Electro domestic devices; one computer 70 W; three hours during day time and three hours during night time (total 6 hours a day). One television 204 W;
three hours during day time and three hours during night time (total 6 hours a
day). One coffee machine 1000 W; half an hour during day time. One electric
oven 2652 W; two hours during day time and other small electro domestic
devices for twenty minutes during day time,

- Hot water services: In Spain according to current regulations, hot water
should be a mix of the system and solar panels. The case study buildings were
constructed according to this regulation. However, in the future it is expected
that all hot water necessities will be provided by renewable energy resources.
Through this assumption, in this study, all hot water necessity is assumed to
be sourced by renewable energies,

- Heating and Ventilation; are examined and compared in the case studies.
While in the three cases, the consumption could be different from each other,
the final consumption should be added as household energy consumes in the
final lists to each of them in the case of obtaining from non-renewable energy
sources.

During the plantification of the other two cases; architectural design of this module
was not changed, but construction types were changed in order to make a comparison
between the different types. Construction types are similar to the two different
buildings constucted in 2010 in Catalonia. The construction type and weight of case
studies could be grouped as following;

- Lightweight industrialised system (535 kg/m²) (See figure 3.6)
Construction type of structure (the main reason of emissions in conventional
buildings) was inspired by a recently constructed building in Callus,
Catalonia (CIBSE, 2010). The building have composite flooring and the
structre is considered as steel profile frame. Interior finishes were not
changed except floor finish (from wood panels to terrazzo tiles) in order to
evade any extent of exposed thermal mass in the interior spaces. The façade
finish is fibro-cement tiles and the façade finish configuration is the same as the reference model building except the sub-structure. The main reason to analyse this type is to evaluate an intermediate module between the industrialized and the in-situ production. Thus, the module has steel frame as the structure and the in-situ produced part, which is composite flooring, as its concrete was casted on site.

**Figure 3.6: Plan and Sections of Lightweight Module**

- **Medium lightweight industrialised system (722 kg/m²)** (See figure 3.7) The original module of a unifamiliar apartment in Banyoles, Catalonia. Only small modifications were made in the façades in order to evade any over heating from sun and any obstacles. The floor finish is wooden panels. The interior finishes including the false ceiling are gypsum board. The façade finish is fibro-cement tiles.

**Figure 3.7: Plan and Sections of Medium-lightweight Module**
• Conventional construction system (1150 kg/m²) (See figure 3.8)

Conventional construction is considered with fabric brick walls and reinforced concrete structure as it has been very common in Catalonia. The interior finishes are not changed except the floor finish (from wood flooring to terrazzo tiles) although the façade finish is considered as fibrocement tiles as in the reference building module.

![Figure 3.8: Plan and Sections of Heavyweight Module](image)

The main difference between the three cases are in the structure (construction type) and the wall configurations. The intention is to standardise as much as possible, in order to compare the effect of thermal mass (See table 3.3). Also system details are given in order to explain constructive details for each case (See table 3.4).
<table>
<thead>
<tr>
<th></th>
<th>Lightweight Industrialised</th>
<th>Medium Lightweight Industrialised</th>
<th>Heavyweight Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structure</strong></td>
<td>Steel box profiles, Composite slab</td>
<td>3 d Reinforced Concrete (including walls)</td>
<td>Reinforced Concrete Columns, Beams, Slab</td>
</tr>
<tr>
<td><strong>Divisions and Finishes</strong></td>
<td>Ceiling: Galvanised Steel Substructure, Rockwool, Plasterboard</td>
<td>Ceiling: Galvanised Steel Substructure, Rockwool, Plasterboard</td>
<td>Ceiling: Galvanised Steel Substructure, Rockwool, Plasterboard</td>
</tr>
<tr>
<td></td>
<td>Flooring: Plasterboard (special), laminated wood</td>
<td>Flooring: Mortar, terrazzo tiles</td>
<td>Flooring: Mortar, terrazzo tiles</td>
</tr>
<tr>
<td></td>
<td>Partition Walls and Frames: Plywood and MDF board</td>
<td>Partition Walls and Frames: Plywood and MDF board</td>
<td>Partition Walls and Frames: Plywood and MDF board</td>
</tr>
<tr>
<td></td>
<td>Walls: Galvanised steel substructure, plasterboard, Rockwool</td>
<td>Walls: Concrete bearing walls, plasterboard, Rockwool (exterior part)</td>
<td>Walls: Fabric brick walls, plasterboard, Rockwool (exterior part)</td>
</tr>
<tr>
<td></td>
<td>Double glazing with aluminium frame</td>
<td>Double glazing with aluminium frame</td>
<td>Double glazing with aluminium frame</td>
</tr>
<tr>
<td><strong>Façade</strong></td>
<td>Fibrocement Finish with substructure of aluminium profiles, air chamber, plywood and Rockwool.</td>
<td>Fibrocement Finish with substructure of aluminium profiles, air chamber, plasterboard with galvanised steel substructure and Rockwool, isolation membrane, plasterboard as interior finish</td>
<td>Fibrocement Finish with substructure of aluminium profiles, air chamber, fabric brick wall and Rockwool, isolation membrane, plasterboard as interior finish</td>
</tr>
<tr>
<td><strong>Complementary Elements</strong></td>
<td>PVC Solar shading with aluminium box</td>
<td>PVC Solar shading with aluminium box</td>
<td>PVC Solar shading with aluminium box</td>
</tr>
</tbody>
</table>

**Table 3.3:** Finishing Schedule of three different modules
### Table 3.4: System Details of three different modules

<table>
<thead>
<tr>
<th>Lightweight Industrialised</th>
<th>Medium Lightweight Industrialised</th>
<th>Heavyweight Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Lightweight Industrialised" /></td>
<td><img src="image2" alt="Medium Lightweight Industrialised" /></td>
<td><img src="image3" alt="Heavyweight Conventional" /></td>
</tr>
</tbody>
</table>

#### 3.2.2 Objectives of the Case Study

The aim of this study is as following:

- To evaluate the relationship between the initial embodied energy and the operational energy of a recently constructed building, and

- To examine the meaning of embodied energy not in the construction material context, but also in a building scale in terms of disassembly-decomposition-deconstruction potential and reuse.
Frame of the investigation is beyond the implementation strategies of European Union Building Energy Performance Directive (EU, EPBD, 2010) in Spain. This is because the relationship between the embodied energy and the operational energy is studied with a building which was constructed after implementation had started.

The main intent of the investigation is to constitute a precedent for future residential buildings. The reference building has a scale which could be considered as 'small'. However, it is essential to specify three important points for the general context of the investigation, as following:

- Conclusions are made according to the study of a small scale residential building while the discussions are made apart from the scale,
- Studied reference building and the other two construction system comparison is made according to recently constructed buildings' construction types in Catalonia, Spain. This will extend the 'time' context of study to the future, and
- The investigation focuses on impacts of trends in non-renewable energy consumption in the residential buildings. Thus, the impacts of methodology, construction material selection and the construction type selection are discussed.

Specific questions addressed are:

- In terms of thermal mass:

  Do conventional dwellings have better thermal comportment than the lightweight? If so:
  - How many years in a buildings' life-time are needed to compass the high embodied energy?
- What is the relationship between its recycling potential and the embodied energy and the operational energy?

Do lightweight dwellings have worse thermal comportment than heavyweight conventional buildings? If so:
- In which terms the lightweight dwellings could be considered advantageous?
- How do low embodied energy and high operational energy relate with each other?
- What is the relationship between its recycle potential, the embodied energy and the operational energy?

- In terms of initial embodied energy:

- Does embodied energy is related to the amount of materials (mass)? Or there are more items that drive to have higher values; if so, what are those items?

- Is the problem of higher values related to industrial production process of the materials or the configuration of construction system? If it is related to configuration of construction system, what are the indicators?

- In terms of disassembly-deconstruction-decomposition and reuse potential:

- Up to which point the disassembly-deconstruction-decomposition could be advantageous for the efficiency in conventional buildings?

- How can we evaluate the disassembly-deconstruction-decomposition in a more practical way in order to convert it to a common part of sector?

- Could the industrial modules be reused? How to evaluate this process?
The evaluation is made according to energy consumption and the CO₂ emission in the three themes in order to reach a complete conclusion. Complementary objectives are as following:

- Evaluate the energy performance of the three dwellings that have different construction types in Catalonia.

- Does the given 'U' value by the Technical Building Code of Spain is sufficient to operate the buildings in a passive way? Or, dwellings will require conditions of comfort with the given 'U' values?

- Do the dwellings act better in winter or in summer? In the case of additional heating or cooling needed, in which season will they consume more?

- Which one of the three cases acts better in winter? Which one of the three cases acts better in summer?

- Possible effect of increase in thermal mass is examined. Does the thermal mass affects the inner temperature or oscillation in any season?

### 3.2.3 Methodology

The research consists of a number of investigation modules such as; calculation of the initial embodied energy consumption and the CO₂ emissions, the energy consumption and the CO₂ emissions sourced by operational energy and evaluation of the disassembly-deconstruction-decomposition as well as the reuse potential. Different methodologies were used to obtain the final value for each item which could be explained respectively, as following:
- Organization of data and analysis
  Materials used in every system; façades, structure (vertical and horizontal),
divisions and finishes were organized separately and the values were
calculated for every system as MJ/m² (energy consumption) and kgCO₂eq/m²
(emissions). Also, the tables and graphics were created according to the
values in order to analyse each system separately. The split graphics were
made only for the material types according to classification; organic,
synthesis, metal and stony.

- The materials used in every system; façades facing to exterior, façades facing
to other local space, floor, ceiling were organized due to the arrangement of
every layer. Calculation was made according to the method described in
'Arquitectura y Energia Natural' pages 378-381 (Serra, R Coch, H., 2001).
The key design values of above mentioned methodology are as following:
- Barcelona Climate data for winter, summer, spring and autumn. Minimum
  exterior temperature, maximum exterior temperature and mean average
temperature was taken from Fabra Meteorological Observatory Station in
- Average Radiation data on a vertical surface in south façade: 125 W/m² in
  January, 104 W/m² in July.
- Total value of the interior heat generators like lighting fixtures, electro-
domestic devices, considering their functioning time separately as day and
night.
- Occupation; separately as day and night.
- Coefficients of thermal exchange (W/ C m³), direct and indirect gain from
  sun, coefficients depending on orientation and obstructions, exchange with
  transmission, exchange for ventilation, coefficient depending on situation of
  façade and exchange of air per hour.
Organization of data and analysis
- List of the materials which are recyclable was made for the three cases. Values of the energy and emissions were used in the first step to evaluate the total consumption and emission. Progressed with given values for the same material but with values after recycling.
- The construction types were evaluated due to the parts that could be reusable. Extra energy needed for rehabilitation was not added.
- The module itself was evaluated according to the criteria of reuse; economical value, esthetical value and durability.

At the end of the whole process, an interlinking scheme was generated to relate each item (See figure 3.9). The conclusions depend on this relationship, since every separate item could be discussed apart as different investigation themes. Linking the process function is as following:

- Initial Embodied Energy and Operational Energy
  - Horizontal Relationship;
  Initial embodied energy values were compared for the three cases and the operational energy was compared for the three cases,
  - Vertical Relationship;
  Values for each case were compared. For steel frame structure; the embodied energy value and the operational energy value was compared. For concrete module; the embodied energy value and the operational energy value was compared. For conventional system; the embodied energy value and the operational energy value was compared, and

- Disassembly-deconstruction-decomposition, reuse potential
  Horizontal and Vertical Relationship;
  All values were compared for the three buildings as well as separately for each building in respect to the previously obtained embodied and operational energy consumption values.
Figure 3.9: Structure of investigation and interlinking scheme
3.2.4 Limitations and Scope of the Case Study

Energy consumption rates and CO₂ emissions are given for the sectors by statistical agencies. However, there is no certain classification for the construction sector yet. The more common and current design and build process described is as following; architectural design, structure project preparation, mechanical and electrical projects preparation, order -purchase of all materials, production of materials, transport of materials to montage, build process, test and commissioning and demolition at the end of the life time of the building. The important items could be; the material production, transportation and demolition. This is because the construction sector links to a process, which could be considered as preliminary part as mentioned above and after these preliminary parts, depending on design, the energy consume demand during life-time and demolition part follows. It is hard to get certain values for exact process separately. Regarding absence of values, it is essential to study the relationship between them to get a decrease in energy consumption and CO₂ emissions in total. The study is marked with some limitations as following:

- Buildings common areas such as open corridor, staircase, and entrance were out of scope because of diversity in the design. Only one module was studied in order to determine the case for future studies,

- Reference Module for all cases was considered as one space since operable partition between living area and bedroom is lower than the false ceiling level. Humidity produced in the bathroom was not added to space thermal comportment calculation. The main focus was to emphasize the possible effect of the thermal mass,

- The Roof and the ground floor were considered as out of scope because selected module is an intermediate module between other flats. Since, there are variety of materials and systems that could be used in the roof and the
ground floor, energy change is more complicated and differences between four seasons will be greater,

- Transport of materials, transport of demolished parts and transport of module itself in industrialized systems were considered out of scope because there are various types of transportation. Also, it is not an easy controllable variable; raw material could be imported or could be produced in Spain, montage could be made in-situ or in the factory,

- Climate change scenarios were considered as out of scope. Although the change in heating days and temperatures are predicted, the study of thermal comportment was made according to last fifty years climatic values. Discussion was made through a future climate change scenario in the conclusion part in order to provide an interpretation for future studies,

- Extreme types of current construction in Barcelona, Catalonia were not selected in order to obtain conclusions for more common types. The extreme types described as following; dwellings constructed with imported materials, dwellings with high energy demand, dwellings that are constructed before the current Technical Buildings Code of Spain (CTE), dwellings with complex and special designs, dwellings that are furnished with high-energy demanded electro-domestics and lighting fixtures, dwellings that have no basic concepts of sustainable buildings (site, orientation, form, shading control, building envelope). However, an interpretation was made in the conclusion part to emphasize the importance of all the above mentioned items, and

- Hazardous material production, impact of those materials and analyse of chemicals in the construction materials were considered out of scope.
3.3 Conclusion

Most of the high demand to construct residential blocks took place in the last century due to the immigration from villages to urban areas and during last 20 years because of the demand on immigration from other countries to Spain. As population is a structural change, it does not relate directly to the building's energy efficiency itself, but it increases demand in the necessity of residential buildings. Apart from this indirect indicator in high-energy demand and emissions, it is required to explore the main reasons of consumption and the CO₂ emissions in the residential buildings;

- Unlike commercial buildings, the main reason of consumption and emissions are not the basic concepts of energy efficiency design in residential buildings. Those basic concepts link to; site selection, optimum orientation, form, building envelope and sun protection in summer. Residential buildings could be considered as 'small scale buildings' compared to the commercials, although the operational energy demand could be solved through passive design solutions. Thus, except some special designs, there is no need to space scheduling programming. Users are more controlled in residential buildings as well as the time of occupation of the building.

- Similar to the design of commercial buildings, there is a public tendency in the residential buildings design to use advanced construction methods, or building optimization. It is a positive tendency that all buildings should have for a sustainable feature, but;
  - Residence owners want a residence that consumes lower than the others,
  - Residence owners want a residence that looks more 'trendy' than the rest, and
  - Institutions want a sustainable building that is designed according to sustainable building criteria.
Considering that the difficulty to change the structure of thinking of the public; a research problem could be created about the great confusion in regard to 'sustainable building image and criteria'. The confusion could be summarized as following:

- A high energy demanded materials are used, low energy demanded residence is more sustainable than a low energy demanded materials used, low energy demanded residence?

- If the construction material industry remains as high energy demanded materials, then?

- Architects can intervener the theme with innovative solutions? If so; can it be the design of construction types with high deconstruction potential?

In an architectural frame, it is believed that; the most critical decisions are to be made in the design phase of the dwelling and a balance should be made between possible sources of consumptions and emissions.
4 ANALYSIS OF INITIAL EMBODIED ENERGY, OPERATIONAL
ENERGY AND DISASSEMBLY-DECOMPOSITION-DECONSTRUCTION-
REUSE POTENTIALS OF THREE CASES FROM SPAIN

4.1 Operational Energy Calculation

Operational energy load was calculated according to the methodology of Rafael
Serra and Helena Coch as explained in 'Arquitectura y Energia Natural'. But it is
essential to define the key items of methodology according to the book; static and
dynamic methods. The objective of the calculation is to find average temperature in
interior spaces and the temperature oscillations of a building with natural behaviour
in certain climate conditions (January for winter, July in summer). The static method
(or balance situation) seeks to obtain an average interior temperature (temperature of
balance) in certain climate conditions assuming that all actions are constant during
the time. Value is guidance regarding the general conditions of the architecture
respect to the climate. However, no reflects the temporal variations which can be
very important in the temperate climates. The basic expression for calculating the
average temperature inside is:

\[ T_i = T_e + \frac{(I + D)}{G} \]

Where: 
- \( T_e \) = Average outside temperature for that month (January or July)
- \( I \) = Average gain from solar radiation (W/m\(^3\)),
- \( D \) = Internal heat loads (W/ m\(^3\)),
- \( G \) = Coefficient of thermal exchange in W/ (°C m\(^3\)).

The dynamic method pretends to obtain oscillation value of the interior temperature
in respect to the average temperature obtained by balance method. This value of
oscillation will influence the variation of conditions caused by the situation day and
night difference, as well as the variation that occurs in a sequence of extreme days
that deviate from the mean of the month. Furthermore, effects of the two variations,
daily and sequential oscillations, could be accumulated in a given time. Base formula is as following:
\[
\Delta T_i = (\Delta T_e + (I + D) / G - (I' + D') / G') \left(1 - e^{-\frac{t}{G'}}\right)
\]
Where:
- \(\Delta T_i\) = Oscillation of the interior temperature, in °C
- \(\Delta T_e\) = Effective oscillation of temperature exterior, in °C (\(T_{e_{\text{max}}} - T_{e_{\text{min}}} / 4\))
- \(I', D', G'\) = Values of mentioned parameters in the period of variation (day-night or between extreme temperatures)
- \(t\) = Time of the duration of oscillation, in seconds
- \(M\) = Unitary thermal mass, in J/°Cm³

In this study, effects of thermal mass were discussed with three different cases. The different cases are identical except of their thermal mass. Also for each case, the thermal performance in each season was discussed and approximate total consumption for heating and cooling was calculated as kWh/m² and kg CO₂/m². The calculation was made according to following formula;
\[
\text{A.U.} \frac{\{\Delta T\}.h}{1000} = \text{A.U.} \{(T_i + \Delta T_i / 2) - T_{i_{\text{comfort}}}.h\} / 1000
\]
Where:
- \(A\) = Surface area, in m²
- \(U\) = Average heat transfer coefficient of walls
- \(\Delta T = (T_i \pm \Delta T_i/2) \pm T_{i_{\text{comfort}}}\) difference respect to comfort conditions, considering interior temperature and interior temperature oscillation value
- \(h\) = Duration of the calculation period, in hours

Converting from kWh to kgCO₂ was made according to the average national value of electric production: 1kWh (3.6 MJ) is equal to 0.62 kg CO₂

Thermal mass affects the natural behaviour of the buildings according to variations of exterior temperatures. The oscillation value study was calculated as day-night and sequential. However, the sequential oscillation was considered as more identical for comparison between case studies.

Interior Space comfort conditions according to Baruch Givoni is as following; for winter between 18-23 °C and for summer between 21-26 °C (See Figure 4.1).
Exterior mean temperatures for Barcelona are as following; winter 8 °C, summer 26 °C, autumn 18 °C, spring 16 °C (See table 4.1).

**Figure 4.1:** Comfort Zones for summer and winter (Baruch Givoni)

<table>
<thead>
<tr>
<th>Barcelona, Spain</th>
<th>$T_e$ (minimum)</th>
<th>$T_e$ (maximum)</th>
<th>$T_e$ (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>20</td>
<td>28</td>
<td>26</td>
</tr>
<tr>
<td>Winter</td>
<td>3</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Autumn</td>
<td>14</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>Spring</td>
<td>13</td>
<td>20</td>
<td>16</td>
</tr>
</tbody>
</table>

**Table 4.1:** Exterior temperature values for Barcelona (winter, summer, autumn and spring) (Fabra Observatory, 1971-2000)
4.1.1 Lightweight Industrialised Module (Steel Frame Structure)

Lightweight industrialised module was analysed in terms of balance and variability values for winter, summer and intermediate seasons. The values are as following:

- Balance temperature and variability values
  Winter (See table 4.2): Balance ($T_i$) = 10 °C, Variability ($\Delta T_i$) = 3 °C
  Summer (See table 4.3): Balance ($T_i$) = 28 °C, Variability ($\Delta T_i$) = 10 °C
  Spring (See table 4.4): Balance ($T_i$) = 18 °C, Variability ($\Delta T_i$) = 5 °C
  Autumn (See table 4.5): Balance ($T_i$) = 20 °C, Variability ($\Delta T_i$) = 7 °C

- Approximate energy demand needed for heating/cooling
  Winter: 61 kWh/m² and 38 kg CO₂/m²
  Summer: 52 kWh/m² and 32 kg CO₂/m²
  Spring: 15 kWh/m² and 9 kg CO₂/m²
  Autumn: 12 kWh/m² and 8 kg CO₂/m²
  Total: 140 kWh/m² and 87 kg CO₂/m²

<table>
<thead>
<tr>
<th>CLIMATE</th>
<th>VENTILATION</th>
<th>GAINS (DAY)</th>
<th>GAINS (NIGHT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e$</td>
<td>Gt</td>
<td>0.536872458</td>
<td>I 0.34099942</td>
</tr>
<tr>
<td>$T_{e,\text{min}}$</td>
<td>Gv</td>
<td>0.725</td>
<td>D 2.18087923</td>
</tr>
<tr>
<td>$T_{e,\text{max}}$</td>
<td>R 104</td>
<td>Unitary Thermal Mass: 111594.04 J/°Cm³</td>
<td></td>
</tr>
<tr>
<td>Occupation</td>
<td>3</td>
<td>BALANCE</td>
<td>Ti 10.0 °C</td>
</tr>
</tbody>
</table>

$$\Delta T_i = \left( \Delta T_e + \frac{I}{G} - \frac{I'+D'}{G'} \right) \left( 1 - e^{-\frac{G'}{M}} \right)$$

| VARIABILITY | $\Delta T_i$ | 3 °C |

Table 4.2: Parametric Results for winter (lightweight industrialised system)
### Table 4.3: Parametric Results for summer (lightweight industrialised system)

<table>
<thead>
<tr>
<th>CLIMATE</th>
<th>VENTILATION</th>
<th>GAINS (DAY)</th>
<th>GAINS (NIGHT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te</td>
<td>Gt</td>
<td>0.610899366</td>
<td>I 1.84434783</td>
</tr>
<tr>
<td>Te, min</td>
<td>Gv</td>
<td>1.74</td>
<td>D 2.18087923</td>
</tr>
<tr>
<td>Te, max</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>125</td>
<td>Unitary Thermal Mass: 111594.04 J/ºCm³</td>
<td></td>
</tr>
<tr>
<td>Occupation</td>
<td>3</td>
<td>BALANCE</td>
<td>Te 28 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VARIABILITY</td>
<td>∆Ti 10 °C</td>
</tr>
</tbody>
</table>

\[
\Delta T_i = \left( \Delta T_e + \frac{I + D}{G} - \frac{I' + D'}{G'} \right) \left( 1 - e^{\frac{-t}{M}} \right)
\]

### Table 4.4: Parametric Results for spring (lightweight industrialised)

<table>
<thead>
<tr>
<th>CLIMATE</th>
<th>VENTILATION</th>
<th>GAINS (DAY)</th>
<th>GAINS (NIGHT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te</td>
<td>Gt</td>
<td>0.610899366</td>
<td>I 1.84434783</td>
</tr>
<tr>
<td>Te, min</td>
<td>Gv</td>
<td>1.74</td>
<td>D 2.18087923</td>
</tr>
<tr>
<td>Te, max</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>125</td>
<td>Unitary Thermal Mass: 111594.04 J/ºCm³</td>
<td></td>
</tr>
<tr>
<td>Occupation</td>
<td>3</td>
<td>BALANCE</td>
<td>Ti 18 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VARIABILITY</td>
<td>∆Ti 5 °C</td>
</tr>
</tbody>
</table>

\[
\Delta T_i = \left( \Delta T_e + \frac{I + D}{G} - \frac{I' + D'}{G'} \right) \left( 1 - e^{\frac{-t}{M}} \right)
\]
### Parametric Results - Autumn

<table>
<thead>
<tr>
<th>Climate</th>
<th>Ventilation</th>
<th>Gains (Day)</th>
<th>Gains (Night)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te</td>
<td>Gt</td>
<td>I</td>
<td>I'</td>
</tr>
<tr>
<td>18</td>
<td>0.610899366</td>
<td>1.84434783</td>
<td>1</td>
</tr>
<tr>
<td>Te_min</td>
<td>Gv</td>
<td>D</td>
<td>D'</td>
</tr>
<tr>
<td>14</td>
<td>1.74</td>
<td>2.18087923</td>
<td>0.63</td>
</tr>
<tr>
<td>R</td>
<td>Unitary Thermal Mass:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>111594.04 J/°Cm³</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Occupation</th>
<th>Balance</th>
<th>Ti</th>
<th>20 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
\Delta T_i = \left( \Delta T_e + \frac{I + D}{G} - \frac{I' + D'}{G'} \right) \left( 1 - e^{-\frac{t}{M}} \right)
\]

<table>
<thead>
<tr>
<th>Variability</th>
<th>ΔTi</th>
<th>7 °C</th>
</tr>
</thead>
</table>

Table 4.5: Parametric Results for autumn (lightweight industrialised system)

### 4.1.2 Medium-Lightweight Industrialised Module (3d Concrete Module)

Medium-LW industrialised module was analysed in terms of balance and variability values for winter, summer and intermediate seasons. The values are as following:

- **Balance temperature and variability values**
  - Winter (See table 4.6): Balance (T_i) = 10 °C, Variability (ΔTi) = 2 °C
  - Summer (See table 4.7): Balance (T_i) = 28 °C, Variability (ΔTi) = 7 °C
  - Spring (See table 4.8): Balance (T_i) = 18 °C, Variability (ΔTi) = 4 °C
  - Autumn (See table 4.9): Balance (T_i) = 20 °C, Variability (ΔTi) = 5 °C

- **Approximate energy demand needed for heating/cooling**
  - Winter: 58 kWh/m² and 36 kg CO₂/m²
  - Summer: 43 kWh/m² and 26 kgCO₂/m²
  - Spring: 13 kWh/m² and 8 kgCO₂/m²
  - Autumn: 10 kWh/m² and 6 kgCO₂/m²
  - Total: 124 kWh/m² and 76 kgCO₂/m²
### PARAMETRIC RESULTS-WINTER

<table>
<thead>
<tr>
<th>CLIMATE</th>
<th>VENTILATION</th>
<th>GAINS (DAY)</th>
<th>GAINS (NIGHT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te</td>
<td>Gt 8</td>
<td>I 0.535848446</td>
<td>I' 0.34099942</td>
</tr>
<tr>
<td>Te, min</td>
<td>Gv 3</td>
<td>D 0.725</td>
<td>D' 2.18087923</td>
</tr>
<tr>
<td>Te, max</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Unitary Thermal Mass: 186687.53 J/ºCm³

### PARAMETRIC RESULTS-SUMMER

<table>
<thead>
<tr>
<th>CLIMATE</th>
<th>VENTILATION</th>
<th>GAINS (DAY)</th>
<th>GAINS (NIGHT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te</td>
<td>Gt 26</td>
<td>I 0.609709365</td>
<td>I' 1.84434783</td>
</tr>
<tr>
<td>Te, min</td>
<td>Gv 20</td>
<td>D 1.74</td>
<td>D' 2.18087923</td>
</tr>
<tr>
<td>Te, max</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Unitary Thermal Mass: 186687.53 J/ºCm³

\[
\Delta T_i = \left( \Delta T_e + \frac{I + D}{G} - \frac{I' + D'}{G'} \right) \left( 1 - e^{-\frac{t \cdot G'}{M}} \right)
\]

### Table 4.6

Parametric Results for winter (medium-lightweight industrialised)

| VARIABILITY | ∆Ti | 2 °C |

### Table 4.7

Parametric Results for summer (medium-lightweight industrialised)

| VARIABILITY | ∆Ti | 7 °C |
### PARAMETRIC RESULTS - SPRING

<table>
<thead>
<tr>
<th>CLIMATE</th>
<th>VENTILATION</th>
<th>GAINS (DAY)</th>
<th>GAINS (NIGHT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te</td>
<td>16</td>
<td>Gt 0.609709365</td>
<td>I 1.84434783</td>
</tr>
<tr>
<td>Te, min</td>
<td>13</td>
<td>Gv 1.74</td>
<td>D 2.18087923</td>
</tr>
<tr>
<td>Te, max</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occupation</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Unitary Thermal Mass: 186687.53 J/°Cm³

**BALANCE**

<table>
<thead>
<tr>
<th>Ti</th>
<th>18 °C</th>
</tr>
</thead>
</table>

**VARIABILITY**

<table>
<thead>
<tr>
<th>ΔTi</th>
<th>4 °C</th>
</tr>
</thead>
</table>

Table 4.8: Parametric Results for spring (medium-lightweight industrialised)

### PARAMETRIC RESULTS - AUTUMN

<table>
<thead>
<tr>
<th>CLIMATE</th>
<th>VENTILATION</th>
<th>GAINS (DAY)</th>
<th>GAINS (NIGHT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te</td>
<td>18</td>
<td>Gt 0.609709365</td>
<td>I 1.84434783</td>
</tr>
<tr>
<td>Te, min</td>
<td>14</td>
<td>Gv 1.74</td>
<td>D 2.18087923</td>
</tr>
<tr>
<td>Te, max</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occupation</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Unitary Thermal Mass: 186687.53 J/°Cm³

**BALANCE**

<table>
<thead>
<tr>
<th>Ti</th>
<th>20 °C</th>
</tr>
</thead>
</table>

**VARIABILITY**

<table>
<thead>
<tr>
<th>ΔTi</th>
<th>5 °C</th>
</tr>
</thead>
</table>

Table 4.9: Parametric Results for autumn (medium-lightweight industrialised)

A study was conducted for medium-lightweight building in ARCHISUN 3.0 computer programme in order to compare final values with manual calculation. Results were similar with mentioned values (ANNEX-I).
4.1.3 Heavyweight Conventional System (Module)

Heavyweight industrialised module was analysed in terms of balance and variability values for winter, summer and intermediate seasons. The values are as following:

- **Balance temperature and variability values**
  - Winter (See table 4.10): Balance ($T_i$) = 10 °C, Variability ($\Delta T_i$) = 1 °C
  - Summer (See table 4.11): Balance ($T_i$) = 28 °C, Variability ($\Delta T_i$) = 5 °C
  - Spring (See table 4.12): Balance ($T_i$) = 18 °C, Variability ($\Delta T_i$) = 3 °C
  - Autumn (See table 4.13): Balance ($T_i$) = 20 °C, Variability ($\Delta T_i$) = 3 °C

- **Calculated energy demand needed for heating/cooling**
  - Winter: 56 kWh/m² and 35 kg CO₂/m²
  - Summer: 38 kWh/m² and 24 kg CO₂/m²
  - Spring: 12 kWh/m² and 7 kg CO₂/m²
  - Autumn: 8 kWh/m² and 5 kg CO₂/m²
  - Total: 114 kWh/m² and 71 kg CO₂/m²

<table>
<thead>
<tr>
<th>CLIMATE</th>
<th>VENTILATION</th>
<th>GAINS (DAY)</th>
<th>GAINS (NIGHT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e$</td>
<td>$g_t$</td>
<td>$I$</td>
<td>$I'$</td>
</tr>
<tr>
<td>$T_e$, min</td>
<td>$g_v$</td>
<td>0.725</td>
<td>$D$</td>
</tr>
<tr>
<td>$T_e$, max</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R$</td>
<td>104</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occupation</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.10: Parametric Results for winter (conventional)
### PARAMETRIC RESULTS-SUMMER

<table>
<thead>
<tr>
<th>CLIMATE</th>
<th>VENTILATION</th>
<th>GAINS (DAY)</th>
<th>GAINS (NIGHT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te</td>
<td>26 Gt</td>
<td>I 1.84434783</td>
<td>I' 1</td>
</tr>
<tr>
<td>Te, min</td>
<td>20 Gv</td>
<td>D 2.18087923</td>
<td>D' 0.63</td>
</tr>
<tr>
<td>Te, max</td>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>125</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Unitary Thermal Mass: 288386.46 J/°Cm³

Occupation 3

<table>
<thead>
<tr>
<th>BALANCE</th>
<th>Ti 28 °C</th>
</tr>
</thead>
</table>

\[
\Delta T_i = \left( \Delta T_e + \frac{I + D}{G} - \frac{I' + D'}{G'} \right) \left( 1 - e^{-\frac{t \cdot G'}{M}} \right)
\]

<table>
<thead>
<tr>
<th>VARIABILITY</th>
<th>ΔTi 5 °C</th>
</tr>
</thead>
</table>

**Table 4.11:** Parametric Results for summer (conventional)

### PARAMETRIC RESULTS-SPRING

<table>
<thead>
<tr>
<th>CLIMATE</th>
<th>VENTILATION</th>
<th>GAINS (DAY)</th>
<th>GAINS (NIGHT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te</td>
<td>16 Gt</td>
<td>I 1.84434783</td>
<td>I' 1</td>
</tr>
<tr>
<td>Te, min</td>
<td>13 Gv</td>
<td>D 2.18087923</td>
<td>D' 0.63</td>
</tr>
<tr>
<td>Te, max</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>125</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Unitary Thermal Mass: 288386.46 J/°Cm³

Occupation 3

<table>
<thead>
<tr>
<th>BALANCE</th>
<th>Ti 18 °C</th>
</tr>
</thead>
</table>

\[
\Delta T_i = \left( \Delta T_e + \frac{I + D}{G} - \frac{I' + D'}{G'} \right) \left( 1 - e^{-\frac{t \cdot G'}{M}} \right)
\]

<table>
<thead>
<tr>
<th>VARIABILITY</th>
<th>ΔTi 3 °C</th>
</tr>
</thead>
</table>

**Table 4.12:** Parametric Results for spring (conventional)
### Parametric Results—Autumn

<table>
<thead>
<tr>
<th>CLIMATE</th>
<th>VENTILATION</th>
<th>GAINS (DAY)</th>
<th>GAINS (NIGHT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te</td>
<td>18</td>
<td>Gt 0.610053824</td>
<td>I 1.84434783</td>
</tr>
<tr>
<td>Te, min</td>
<td>14</td>
<td>Gv 1.74</td>
<td>D 2.18087923</td>
</tr>
<tr>
<td>Te, max</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>125</td>
<td></td>
<td>Unitary Thermal Mass: 288386.46 J/ºCm³</td>
</tr>
<tr>
<td>Occupation</td>
<td>3</td>
<td>BALANCE</td>
<td>Ti 20 ºC</td>
</tr>
</tbody>
</table>

\[
\Delta T_i = \left( \Delta T_e + \frac{I + D}{G} - \frac{I' + D'}{G'} \right) \left( 1 - e^{-\frac{t}{M}} \right)
\]

| VARIABILITY | \(\Delta T_i\) | 3 ºC |

**Table 4.13:** Parametric Results for autumn (conventional)
4.2 Initial Embodied Energy Calculation

Initial embodied energy of the module, in the three cases, was calculated according to the total energy consumption and emissions. Tables and graphs were prepared for each of them in order to detect the source of the energy consumption and emissions. The main source could be the type of material, the component or the system. The organisation was made according to:

- Material classification; organic, synthesis, metal and stony (general classification of materials such as natural stones, loams, materials with mineral binders, ceramics and glass).

- System classification; structure, façades and divisions/finishes.

- Structure; vertical (columns, bearing walls, steel profiles,...etc) and horizontal (beams, secondary beams, concrete or composite slab...etc)

- Façades; opaque elements, transparent elements, frames and complementary elements.

- Division/ Finishes; wall finishes (including substructures), ceiling finishes (including substructures), floor finishes (including base material), interior divisions (including substructures) and interior frames.

Evaluation was made for each of these cases and a comparative study was conducted in the conclusion part regarding the total final values.
4.2.1 Lightweight Industrialised Module (Steel Frame Structure)

Steel frame structure and composite slab module (lightweight) was calculated as 535 kg/m², and initial embodied energy was calculated as 4044 MJ/m² and the emissions were as 340 kgCO₂eq/m² (See table 4.14). Values are represented by systems; divisions/finishes, structure and façade. In this case, the structure is five times heavier than the divisions and finishes but this value decreases in energy consumption. This is because the finish materials consume more than structure (per m³ and per kg). In emissions, the difference is still not representative of weight, while the structure is nearly three times higher in emissions (See figure 4.2).

<table>
<thead>
<tr>
<th>Divisions/Finishes</th>
<th>Weight - kg/m²</th>
<th>Energy - MJ/m²</th>
<th>Emissions - kg CO₂ eq/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divisions/Finishes</td>
<td>71.80</td>
<td>1007.81</td>
<td>60.89</td>
</tr>
<tr>
<td>Structure</td>
<td>419.25</td>
<td>2147.61</td>
<td>168.64</td>
</tr>
<tr>
<td>Façade (East)</td>
<td>22.10</td>
<td>444.64</td>
<td>54.98</td>
</tr>
<tr>
<td>Façade (West)</td>
<td>22.10</td>
<td>444.64</td>
<td>54.98</td>
</tr>
<tr>
<td>Total</td>
<td><strong>535.25</strong></td>
<td><strong>4044.70</strong></td>
<td><strong>339.50</strong></td>
</tr>
</tbody>
</table>

**Table 4.14:** Weight, Energy and Emission values per system for lightweight (steel structure and composite slab) industrialised module (per m²)

**Figure 4.2:** Weight, Energy and Emission values per system for lightweight (steel structure and composite slab) industrialised module (per m² and per cent ratio)
If every system is interpreted according to material types; it could be seen that metals have higher energy consumption and emission, although concrete is heavier than metals (See table 4.15). The values show that the synthesis materials have higher values per m³ or for 1kg, but as their usage is not wide as concrete or metal, the values are behind compared to other material types (See figure 4.3).

<table>
<thead>
<tr>
<th>Family</th>
<th>Material</th>
<th>Weight - kg/m³</th>
<th>Energy - MJ/m²</th>
<th>Emissions - kg CO₂ eq/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
<td>20% recycled steel</td>
<td>4.12</td>
<td>144.31</td>
<td>14.84</td>
</tr>
<tr>
<td></td>
<td>Galvanized Steel</td>
<td>75.03</td>
<td>1800.84</td>
<td>127.56</td>
</tr>
<tr>
<td></td>
<td>Aluminium (primary)</td>
<td>2.27</td>
<td>362.71</td>
<td>58.94</td>
</tr>
<tr>
<td>Stony (natural stones, loams, materials with mineral binders, ceramics and glass)</td>
<td>Fibrocement</td>
<td>9.98</td>
<td>89.80</td>
<td>8.88</td>
</tr>
<tr>
<td></td>
<td>Fibreglass Polyester</td>
<td>1.37</td>
<td>153.02</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Flat Glass</td>
<td>3.92</td>
<td>74.40</td>
<td>3.68</td>
</tr>
<tr>
<td></td>
<td>Plasterboard</td>
<td>26.65</td>
<td>68.49</td>
<td>6.40</td>
</tr>
<tr>
<td></td>
<td>Concrete (H-300)</td>
<td>348.66</td>
<td>408.01</td>
<td>40.80</td>
</tr>
<tr>
<td></td>
<td>Terrazzo Tiles</td>
<td>33.89</td>
<td>338.86</td>
<td>18.30</td>
</tr>
<tr>
<td></td>
<td>Mortar</td>
<td>1.88</td>
<td>1.88</td>
<td>0.19</td>
</tr>
<tr>
<td>Organic</td>
<td>Rockwool</td>
<td>16.06</td>
<td>321.14</td>
<td>27.99</td>
</tr>
<tr>
<td></td>
<td>Plywood Board</td>
<td>0.04</td>
<td>0.19</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>MDF Board</td>
<td>9.55</td>
<td>133.64</td>
<td>12.89</td>
</tr>
<tr>
<td>Synthesis</td>
<td>Polyurethane</td>
<td>0.00</td>
<td>0.24</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>PVC (primary)</td>
<td>1.84</td>
<td>147.19</td>
<td>19.01</td>
</tr>
<tr>
<td>Grand Total</td>
<td></td>
<td>535.25</td>
<td>4044.70</td>
<td>339.50</td>
</tr>
</tbody>
</table>

**Table 4.15:** Weight, Energy and Emission values per material types for lightweight (steel structure and composite slab) industrialised module (per m²)  

![Diagram](https://via.placeholder.com/150)

**Figure 4.3:** Weight, Energy and Emission values per material type for lightweight (steel structure and composite slab) industrialised module (per m² and per cent)
4.2.2 Medium-Lightweight Industrialised Module (3d Concrete Module)

3d concrete module (medium-lightweight) had 723 kg/m², and the initial embodied energy was calculated as 3103 MJ/m², the emissions were 306 kgCO₂eq/ m² (See table 4.16). The values are represented by systems; divisions/finishes, structure and façade. In this case, the structure is nearly six times heavier than the divisions and finishes but in energy consumption this difference disappears regarding the materials used in the interior space. In emissions, the difference is still not representative of weight, since the structure is only twice higher in emissions (See figure 4.4).

<table>
<thead>
<tr>
<th>Divisions/Finishes</th>
<th>Weight - kg/m²</th>
<th>Energy - MJ/m²</th>
<th>Emissions - kg CO₂ eq/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>100.46</td>
<td>933.86</td>
<td>67.05</td>
</tr>
<tr>
<td>Façade (East)</td>
<td>578.14</td>
<td>1280.47</td>
<td>129.83</td>
</tr>
<tr>
<td>Façade (West)</td>
<td>22.10</td>
<td>444.64</td>
<td>54.98</td>
</tr>
<tr>
<td>Total</td>
<td>722.80</td>
<td>3103.61</td>
<td>306.85</td>
</tr>
</tbody>
</table>

Table 4.16: Weight, Energy and Emission values per system for medium-lightweight (3d concrete) industrialised module (per m²)

![](image1)

**Figure 4.4:** Weight, Energy and Emission values per system for medium-lightweight (3d concrete) industrialised module (per m² and per cent)

If every system is interpreted according to the material types; it could be seen that metals have higher energy consumption than concrete, though 20 % recycled metal is used (See table 4.17). Also, the difference between recycled steel and aluminium is
considerably high (See figure 4.5). In organic group, fabric boards have a higher energy consumption sourced by the production process and the usage of glue.

<table>
<thead>
<tr>
<th>Family</th>
<th>Material</th>
<th>Weight (\text{kg/m}^2)</th>
<th>Energy - MJ/m²</th>
<th>Emissions (\text{kg CO}_2\text{ eq/m}^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
<td>20% recycled steel</td>
<td>17.85</td>
<td>624.81</td>
<td>64.27</td>
</tr>
<tr>
<td></td>
<td>Galvanized Steel</td>
<td>10.78</td>
<td>258.74</td>
<td>18.33</td>
</tr>
<tr>
<td></td>
<td>Aluminium (primary)</td>
<td>2.27</td>
<td>362.71</td>
<td>58.94</td>
</tr>
<tr>
<td>Stony</td>
<td>Fibrocement</td>
<td>9.98</td>
<td>89.80</td>
<td>8.88</td>
</tr>
<tr>
<td>(natural</td>
<td>Fibreglass Polyester</td>
<td>1.41</td>
<td>156.80</td>
<td>0.00</td>
</tr>
<tr>
<td>stones,</td>
<td>Flat Glass</td>
<td>3.92</td>
<td>74.40</td>
<td>3.68</td>
</tr>
<tr>
<td>loams,</td>
<td>Plasterboard</td>
<td>81.42</td>
<td>209.25</td>
<td>19.54</td>
</tr>
<tr>
<td>materials</td>
<td>Concrete (H-300)</td>
<td>560.29</td>
<td>655.66</td>
<td>65.57</td>
</tr>
<tr>
<td>with</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mineral</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>binders,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ceramics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>and glass)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organic</td>
<td>Rockwool</td>
<td>10.29</td>
<td>205.70</td>
<td>17.93</td>
</tr>
<tr>
<td></td>
<td>Plywood Board</td>
<td>0.04</td>
<td>0.19</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>MDF Board</td>
<td>22.72</td>
<td>318.13</td>
<td>30.68</td>
</tr>
<tr>
<td>Synthesis</td>
<td>Polyurethane</td>
<td>0.00</td>
<td>0.24</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>PVC (primary)</td>
<td>1.84</td>
<td>147.19</td>
<td>19.01</td>
</tr>
<tr>
<td>Grand Total</td>
<td></td>
<td>722.80</td>
<td>3103.61</td>
<td>306.85</td>
</tr>
</tbody>
</table>

**Table 4.17:** Weight, Energy and Emission values per material types for medium-lightweight (3d concrete) industrialised module (per m²)

**Figure 4.5:** Weight, Energy and Emission values per material type for medium-lightweight (3d concrete) industrialised module (per m² and per cent)
4.2.3 Heavyweight Conventional System (Module)

Conventional case (heavyweight) had 1151 kg/m², and initial embodied energy was calculated as 3671 MJ/m², emissions were 330 kg CO₂ eq/m² (See table 4.18). The values are represented by systems; divisions/finishes, structure and façade. In this case, the energy consumption of divisions and finishes are much higher than the structure. Thus in structure, only concrete and steel bars are used as in the traditional systems, but the difference is mainly sourced by the usage of fabricated brick in the walls and terrazzo tiles as flooring. (See figure 4.6).

<table>
<thead>
<tr>
<th>Divisions/Finishes</th>
<th>Weight - kg/m²</th>
<th>Energy - MJ/m²</th>
<th>Emissions - kg CO₂ eq/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>685.59</td>
<td>1247.23</td>
<td>126.04</td>
</tr>
<tr>
<td>Façade (East)</td>
<td>70.64</td>
<td>493.10</td>
<td>56.65</td>
</tr>
<tr>
<td>Façade (West)</td>
<td>70.64</td>
<td>493.10</td>
<td>56.65</td>
</tr>
<tr>
<td>Total</td>
<td>1150.39</td>
<td>3671.49</td>
<td>329.46</td>
</tr>
</tbody>
</table>

Table 4.18: Weight, Energy and Emission values per system for heavy weight (reinforced concrete structure) conventional module (per m²)

Figure 4.6: Weight, Energy and Emission values per system for heavyweight (reinforced concrete structure) conventional module (per m² and per cent)

If every system is interpreted according to the material types; it could be seen that metals have higher energy consumption and emission though concrete is heavier than

90
metals (See table 4.19). Another source of energy consumption and emissions is the fabricated brick. Stony materials are responsible for 96% of the total weight while in energy consumption, they only have 60% of the total consumptions (See figure 4.7).

<table>
<thead>
<tr>
<th>Family</th>
<th>Material</th>
<th>Weight - kg/m²</th>
<th>Energy - MJ/m²</th>
<th>Emissions - kg CO₂ eq/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
<td>20% recycled steel</td>
<td>13.15</td>
<td>460.33</td>
<td>47.35</td>
</tr>
<tr>
<td></td>
<td>Galvanized Steel</td>
<td>7.39</td>
<td>177.33</td>
<td>12.56</td>
</tr>
<tr>
<td></td>
<td>Primary Aluminium</td>
<td>2.27</td>
<td>362.71</td>
<td>58.94</td>
</tr>
<tr>
<td>Stony (natural stones, loams, materials with mineral binders, ceramics and glass)</td>
<td>Fibrocement</td>
<td>9.98</td>
<td>89.80</td>
<td>8.88</td>
</tr>
<tr>
<td></td>
<td>Fibreglass Polyester</td>
<td>1.37</td>
<td>153.02</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Plane Glass</td>
<td>3.92</td>
<td>74.40</td>
<td>3.68</td>
</tr>
<tr>
<td></td>
<td>Plasterboard</td>
<td>26.65</td>
<td>68.49</td>
<td>6.40</td>
</tr>
<tr>
<td></td>
<td>Concrete (H-300)</td>
<td>672.44</td>
<td>786.90</td>
<td>78.69</td>
</tr>
<tr>
<td></td>
<td>Terrazo Tiles</td>
<td>23.72</td>
<td>237.20</td>
<td>12.81</td>
</tr>
<tr>
<td></td>
<td>Mortar (M-40)</td>
<td>1.88</td>
<td>1.88</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>Fabricated Brick</td>
<td>368.98</td>
<td>791.72</td>
<td>52.71</td>
</tr>
<tr>
<td>Organic</td>
<td>Rockwool</td>
<td>14.20</td>
<td>284.05</td>
<td>24.75</td>
</tr>
<tr>
<td></td>
<td>Plywood Board</td>
<td>0.04</td>
<td>0.19</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>MDF Board</td>
<td>2.56</td>
<td>35.86</td>
<td>3.46</td>
</tr>
<tr>
<td>Synthesis</td>
<td>Polyurethane</td>
<td>0.00</td>
<td>0.24</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Primary PVC</td>
<td>1.84</td>
<td>147.19</td>
<td>19.01</td>
</tr>
<tr>
<td></td>
<td>Polyethylene (d tyvek)</td>
<td>0.00</td>
<td>0.19</td>
<td>0.00</td>
</tr>
<tr>
<td>Grand Total</td>
<td></td>
<td>1150.39</td>
<td>3671.49</td>
<td>329.46</td>
</tr>
</tbody>
</table>

**Table 4.19:** Weight, Energy and Emission values per material types for heavyweight (reinforced concrete structure) conventional module (per m²)

![Figure showing weight, energy, and emissions per material type](image1.png)

**Figure 4.7:** Weight, Energy and Emission values per material type for heavyweight (reinforced concrete structure) conventional module (per m² and per cent)
4.3 Disassembly- Decomposition- Deconstruction- Reuse Potentials Evaluation

Evaluation of disassembly, decomposition and deconstruction material was made in order to determine the existing/embodied potential of materials and components. Analyse was made for three cases, since the initial embodied energy of three buildings are different. Different colours were used to describe different potentials (See table 4.20). Reuse potential is generally applicable to components more than single materials. But aesthetical, economical and duration analysis were made for the components to be reused. Considered components for reuse are as following:

- **Fibreglass polyester**, used in the bathroom module. The material duration is more than 50 years (lifetime of modules are considered as 50 years), since fibreglass polyester was considered as reusable. It is a prefabricated module; the displacement facility because of its lightness, future application flexibility and dismounting capacity are considered as positive properties.

- **Plywood and MDF boards**, used in interior partitions. The boards were considered as appropriate for reuse. Generally, they have glue between wooden particles and recycling of those materials are not economically validated. Thus, the raw material does not have an important impact compared to glue used in production.

- **Primary aluminium**, used as substructure of fibrocement panels. Properties of the aluminium and its modular configuration were considered as a positive factor for reuse.

- **Fibrocement panels**, used as façade finish. Durability and modular design of the panels were considered as acceptable for its re usage.

- **PVC used as solar shading**. Durability of the material was considered as acceptable for re usage.
• Aluminium box used for solar shading. The modular design and function was considered as appropriate to reuse.

All metals, including steel bars inside of concrete slabs, columns, beams, were considered as recyclable. Also, they could be considered as reusable but a modular or precast system should be applied in the design process. In three cases, in situ casted concrete was used, since reuse of concrete with reinforcement cannot be applied.

Concrete could be crushed and used as coarse aggregate in roads as a substitute for gravel. Furthermore, it can be used to form new concrete. In this study, the reinforced concrete was held as; steel bars and concrete. In some of the previous studies, generally no energy saving was considered for the decomposition of concrete (Thormark, 2001) but the environmental impact of the recycling was considered as a positive effect. However, in this investigation, in-situ casted concrete as well as terrazzo tiles, bricks and mortar recycling were considered as a possible saving from the initial embodied energy. Possible recycling of concrete, brick, terrazzo tiles and mortar were evaluated as following:

• Concrete was considered to be crushed and to be used as aggregate as base or subbase. It was not considered to be recycled to form new concrete. Thus, energy saving from the initial embodied energy by recycling was considered as; the difference between concrete and 0 % recycled content formed aggregate (the energy needed to transform concrete to aggregate is counted).

• Brick, terrazzo tiles and mortar (base for terrazzo tiles in flooring) were considered to be used as base or subbase aggregate. Thus, energy saving from the initial embodied energy values were; difference between embodied energy of mentioned materials and 0 % recycled content formed aggregate (the energy needed to transform mentioned materials to aggregate is counted).
Materials/components considered as waste (not possible to reuse or recycle) are as following:

- Rockwool, used in ceiling, walls and façade as thermal and acoustical insulation. Decomposing the material was not validated economically and durability of the material is not as much as to reuse (special care from water is needed, etc).

- Plasterboard, used in ceiling and walls. Gypsum plaster board could be used as raw material for the production of new board or reused. The environmental benefits of the material recycling are mainly in the decreased use of the raw gypsum stone and the transport of raw gypsum stone from the quarry to the factory. However, reuse of plasterboards was not considered as a common and recent application in Catalonia. In this investigation, no energy saving was accounted for this component.

- Glass, used as a transparent element of façades. Reuse or recycling is difficult because it is not applicable to every case. Furthermore, the low-e glass usage is becoming wider in buildings and only few percent of low-e glasses are recyclable.

There is another option for modules that could be considered as reuse of the module itself. However, the 3d concrete module was found to be more appropriate than the lightweight industrialised and conventional system. The reasons are as following:

- 3d concrete module has a structure system which is reinforced concrete. In other cases, walls, slab and structure are considered as different components while in concrete module it is the whole piece. However, in the other two cases, durability of different components is different than each other. Furthermore, the properties of each component (thermal conductivity, natural behaviour, aesthetical and economical values) are different. 3d concrete
module was considered as appropriate to reuse when it was compared to those terms.

- For reuse potential, previous evaluations were generally made in three terms: technical, aesthetical and economical (Thormark, 2001). The economical evaluation was made for each system. For example, if aesthetical value is not found sufficient at the end of the buildings life, renovation or refurbishment is needed. Impact of renovation/ refurshishment implies energy consumption, money, emissions and indirect effects on natural resources. Technical value for the architecture is generally linked to durability, in which the concrete module has a positive value when compared to the other two cases.

<table>
<thead>
<tr>
<th>-</th>
<th>Recycling</th>
<th>Reuse</th>
</tr>
</thead>
</table>

**Table 4.20:** Colour code scheme for evaluation of materials potential

Three cases were analysed according to the mentioned potentials for each material/ component. Reuse and recycling potentials were held according to disassembly, decomposition and disassembly potentials of each. The recycling potential could be described as a process that enables an amount of total embodied energy to be conserved through. The reuse potential refers to a reduction from the total embodied energy when considered as appropriate in terms of aesthetical, technical and economical. Frame of reuse links to the reuse of material or component for the same purpose. In this study, the recycling and reuse potentials were held as general concepts without discussing the types of recycling or the types of renovations needed to reuse. However, concept of energy saving through recycling was introduced as a qualitative concept in order to evaluate existing potential. As a quantitative manner, simplifications were made in order to compare three cases.
Evaluation of reuse, recycle potential of materials and components were analysed with unit data methodology. Unit data values were used for recycled materials and the total gain from initial embodied energy is calculated. The question was considered as; how much energy from the initial embodied amount could be conserved by recycling or reuse. Unlike common systems in Spain, a system was created to value disassembly potential. An intermediate person will take part between the demolishing site and the recycling plant or site where components will be reused. However, no maximum cases were considered but an applicable system has thought. The energy savings were made for the future applications without creating extreme future conditions.

- **Lightweight (steel frame structure) (See table 4.21):**
  Initial embodied energy: 4044.7 MJ/m², Initial CO₂ emissions: 339.50 kg CO₂ eq/m²
  Saving- Energy: -1873.1 MJ/m², - Emissions: -161.9 kg CO₂ eq/m²
  Total embodied energy after reduction; Energy 2171.6 MJ/m², Emissions: 177.6 kg CO₂ eq/m²

- **Medium-Lightweight (3d concrete structure) (See table 4.22):**
  Initial embodied energy: 3103.6 MJ/m², Initial CO₂ emissions: 306.85 kg CO₂ eq/m²
  Saving- Energy: -1535.9 MJ/m², - Emissions: -163.2 kg CO₂ eq/m²
  Total embodied energy after reduction; Energy 1220.9J/m², Emissions: 143.6 kg CO₂ eq/m²

- **Heavyweight (conventional system) (See table 4.23):**
  Initial embodied energy: 3671.4 MJ/m², Initial CO₂ emissions: 329.46 kg CO₂ eq/m²
  Saving- Energy: -1167.3 MJ/m², - Emissions: -128.1 kg CO₂ eq/m²
  Total embodied energy after reduction; Energy 2504 MJ/m², Emissions: 201.3 kg CO₂ eq/m²
<table>
<thead>
<tr>
<th>Lightweight (Steel Frame Structure)</th>
<th>Weight kg/m²</th>
<th>Energy MJ/m²</th>
<th>Emissions Kg CO₂ eq/m²</th>
<th>Energy MJ/m²</th>
<th>Emissions Kg CO₂ eq/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divisions and Finishes</td>
<td>71.80</td>
<td>1007.81</td>
<td>60.89</td>
<td>-291.37</td>
<td>-10.07</td>
</tr>
<tr>
<td><strong>Ceiling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galvanized Steel</td>
<td>7.39</td>
<td>177.33</td>
<td>12.56</td>
<td>-88.67</td>
<td>-5.17</td>
</tr>
<tr>
<td>Rockwool</td>
<td>4.07</td>
<td>81.31</td>
<td>7.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasterboard</td>
<td>2.94</td>
<td>7.56</td>
<td>0.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Wall</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rockwool</td>
<td>9.55</td>
<td>190.95</td>
<td>16.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fibreglass Polyester</td>
<td>0.30</td>
<td>34.00</td>
<td>0.00</td>
<td>-34</td>
<td></td>
</tr>
<tr>
<td>Plasterboard</td>
<td>8.12</td>
<td>20.86</td>
<td>1.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Flooring</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terrazzo tiles</td>
<td>33.89</td>
<td>338.86</td>
<td>18.30</td>
<td>-13.18</td>
<td>-1.4</td>
</tr>
<tr>
<td>Mortar (M-40)</td>
<td>1.88</td>
<td>1.88</td>
<td>0.19</td>
<td>-0.47</td>
<td>-0.04</td>
</tr>
<tr>
<td>Fibreglass Polyester</td>
<td>1.07</td>
<td>119.01</td>
<td>0.00</td>
<td>-119</td>
<td></td>
</tr>
<tr>
<td><strong>Frame</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plywood Board</td>
<td>0.04</td>
<td>0.19</td>
<td>0.00</td>
<td>-0.19</td>
<td></td>
</tr>
<tr>
<td><strong>Interior Partition</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MDF Board</td>
<td>2.56</td>
<td>35.86</td>
<td>3.46</td>
<td>-35.86</td>
<td>-3.46</td>
</tr>
<tr>
<td><strong>Structure</strong></td>
<td>419.25</td>
<td>2147.61</td>
<td>168.64</td>
<td>-891.44</td>
<td>-57.14</td>
</tr>
<tr>
<td><strong>Horizontal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 % recycled steel</td>
<td>4.12</td>
<td>144.31</td>
<td>14.84</td>
<td>-74.22</td>
<td>-8.66</td>
</tr>
<tr>
<td>Galvanized Steel</td>
<td>37.54</td>
<td>900.86</td>
<td>63.81</td>
<td>-450.42</td>
<td>-26.28</td>
</tr>
<tr>
<td>Concrete (H-300)</td>
<td>348.66</td>
<td>408.01</td>
<td>40.80</td>
<td>-19.58</td>
<td>-1.95</td>
</tr>
<tr>
<td><strong>Vertical</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galvanized Steel</td>
<td>28.94</td>
<td>694.44</td>
<td>49.19</td>
<td>-347.22</td>
<td>-20.25</td>
</tr>
<tr>
<td><strong>Façades (East and West)</strong></td>
<td>44.20</td>
<td>889.28</td>
<td>109.96</td>
<td>-690.54</td>
<td>-94.68</td>
</tr>
<tr>
<td><strong>Frame</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary Aluminium</td>
<td>0.92</td>
<td>146.38</td>
<td>23.78</td>
<td>-125.34</td>
<td>-21.4</td>
</tr>
<tr>
<td><strong>Opaque Elements</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galvanized Steel</td>
<td>1.18</td>
<td>28.20</td>
<td>2.00</td>
<td>-14.10</td>
<td>-0.82</td>
</tr>
<tr>
<td>Primary Aluminium</td>
<td>1.02</td>
<td>162.66</td>
<td>26.44</td>
<td>-162.66</td>
<td>-26.44</td>
</tr>
<tr>
<td>Fibrocement</td>
<td>9.98</td>
<td>89.80</td>
<td>8.88</td>
<td>-89.80</td>
<td>-8.88</td>
</tr>
<tr>
<td>Rockwool</td>
<td>2.44</td>
<td>48.88</td>
<td>4.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MDF Board</td>
<td>6.98</td>
<td>97.78</td>
<td>9.42</td>
<td>-97.78</td>
<td>-9.42</td>
</tr>
<tr>
<td>Plasterboard</td>
<td>15.58</td>
<td>40.06</td>
<td>3.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Transparent Elements</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plane glazing</td>
<td>3.92</td>
<td>74.4</td>
<td>3.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Complementary Elements</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary Aluminium</td>
<td>0.34</td>
<td>53.68</td>
<td>8.72</td>
<td>-53.68</td>
<td>-8.72</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>0.00</td>
<td>0.24</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary PVC</td>
<td>1.84</td>
<td>147.18</td>
<td>19.00</td>
<td>-147.18</td>
<td>-19</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>535.25</td>
<td>4044.70</td>
<td>339.50</td>
<td>-1873.1</td>
<td>-161.9</td>
</tr>
</tbody>
</table>

**Table 4.21:** Evaluation of embodied energy of Lightweight Module
<table>
<thead>
<tr>
<th>Divisions and Finishes</th>
<th>Weight kg/m²</th>
<th>Energy MJ/m²</th>
<th>Emissions kg CO₂ eq/m²</th>
<th>Energy MJ/m²</th>
<th>Emissions kg CO₂ eq/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galvanized Steel</td>
<td>2.22</td>
<td>53.20</td>
<td>3.77</td>
<td>-26.60</td>
<td>-1.55</td>
</tr>
<tr>
<td>Rockwool</td>
<td>3.29</td>
<td>65.89</td>
<td>5.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasterboard</td>
<td>2.94</td>
<td>7.56</td>
<td>0.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galvanized Steel</td>
<td>7.39</td>
<td>177.33</td>
<td>12.56</td>
<td>-88.67</td>
<td>-5.17</td>
</tr>
<tr>
<td>Rockwool</td>
<td>4.55</td>
<td>90.93</td>
<td>7.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fibreglass Polyester</td>
<td>0.34</td>
<td>37.78</td>
<td>0.00</td>
<td>-37.78</td>
<td></td>
</tr>
<tr>
<td>Plasterboard</td>
<td>4.06</td>
<td>10.43</td>
<td>0.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flooring</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MDF Panels</td>
<td>13.18</td>
<td>184.49</td>
<td>17.79</td>
<td>-184.49</td>
<td>-17.79</td>
</tr>
<tr>
<td>Fibreglass Polyester</td>
<td>1.07</td>
<td>119.01</td>
<td>0.00</td>
<td>-119.01</td>
<td></td>
</tr>
<tr>
<td>Plasterboard</td>
<td>58.83</td>
<td>151.19</td>
<td>14.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plywood Board</td>
<td>0.04</td>
<td>0.19</td>
<td>0.00</td>
<td>-0.19</td>
<td></td>
</tr>
<tr>
<td>Interior Partitions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MDF Board</td>
<td>2.56</td>
<td>35.86</td>
<td>3.46</td>
<td>-35.86</td>
<td>-3.46</td>
</tr>
<tr>
<td>Structure</td>
<td>578.14</td>
<td>1280.47</td>
<td>129.83</td>
<td>-352.81</td>
<td>-40.6</td>
</tr>
<tr>
<td>Horizontal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20% recycled steel</td>
<td>11.05</td>
<td>386.88</td>
<td>39.79</td>
<td>-198.96</td>
<td>-23.22</td>
</tr>
<tr>
<td>Concrete (H-300)</td>
<td>346.62</td>
<td>405.61</td>
<td>40.56</td>
<td>-12.01</td>
<td>-1.3</td>
</tr>
<tr>
<td>Vertical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20% recycled steel</td>
<td>6.80</td>
<td>237.92</td>
<td>24.47</td>
<td>-122.36</td>
<td>-14.28</td>
</tr>
<tr>
<td>Concrete (H-300)</td>
<td>213.68</td>
<td>250.05</td>
<td>25.00</td>
<td>-19.48</td>
<td>-1.8</td>
</tr>
<tr>
<td>Façades (East and West)</td>
<td>44.20</td>
<td>889.28</td>
<td>109.96</td>
<td>-690.54</td>
<td>-94.68</td>
</tr>
<tr>
<td>Frame</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary Aluminium</td>
<td>0.92</td>
<td>146.38</td>
<td>23.78</td>
<td>-125.34</td>
<td>-21.4</td>
</tr>
<tr>
<td>Opaque Elements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galvanized Steel</td>
<td>1.18</td>
<td>28.20</td>
<td>2.00</td>
<td>-14.10</td>
<td>-0.82</td>
</tr>
<tr>
<td>Primary Aluminium</td>
<td>1.02</td>
<td>162.66</td>
<td>26.44</td>
<td>-162.66</td>
<td>-26.44</td>
</tr>
<tr>
<td>Fibrocement</td>
<td>9.98</td>
<td>89.80</td>
<td>8.88</td>
<td>-89.80</td>
<td>-8.88</td>
</tr>
<tr>
<td>Rockwool</td>
<td>2.44</td>
<td>48.88</td>
<td>4.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MDF Board</td>
<td>6.98</td>
<td>97.78</td>
<td>9.42</td>
<td>-97.78</td>
<td>-9.42</td>
</tr>
<tr>
<td>Plasterboard</td>
<td>15.58</td>
<td>40.06</td>
<td>3.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transparent Elements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plane glazing</td>
<td>3.92</td>
<td>74.4</td>
<td>3.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complementary Elements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary Aluminium</td>
<td>0.34</td>
<td>53.68</td>
<td>8.72</td>
<td>-53.68</td>
<td>-8.72</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>0.00</td>
<td>0.24</td>
<td>0.04</td>
<td>-0.24</td>
<td>-0.04</td>
</tr>
<tr>
<td>Primary PVC</td>
<td>1.84</td>
<td>147.18</td>
<td>19.00</td>
<td>-147.18</td>
<td>-19</td>
</tr>
<tr>
<td>Total</td>
<td>1220.9</td>
<td>143.6</td>
<td></td>
<td>722.80</td>
<td>-1535.9</td>
</tr>
</tbody>
</table>

Table 4.22: Evaluation of embodied energy of Medium-Lightweight Module
<table>
<thead>
<tr>
<th>Heavyweight (Conventional System)</th>
<th>Weight kg/m²</th>
<th>Energy MJ/m²</th>
<th>Emissions kg CO₂ eq/m²</th>
<th>Energy MJ/m²</th>
<th>Emissions kg CO₂ eq/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Divisions and Finishes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceiling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galvanized Steel</td>
<td>7.39</td>
<td>177.33</td>
<td>12.56</td>
<td>-88.67</td>
<td>-5.17</td>
</tr>
<tr>
<td>Rockwool</td>
<td>3.29</td>
<td>65.89</td>
<td>5.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasterboard</td>
<td>2.94</td>
<td>7.56</td>
<td>0.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fabricated Brick</td>
<td>263.55</td>
<td>565.51</td>
<td>37.65</td>
<td>-18.83</td>
<td>-1.70</td>
</tr>
<tr>
<td>Rockwool</td>
<td>8.64</td>
<td>172.76</td>
<td>15.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fibreglass Polyester</td>
<td>0.30</td>
<td>34.00</td>
<td>0.00</td>
<td>-34</td>
<td></td>
</tr>
<tr>
<td>Plasterboard</td>
<td>8.12</td>
<td>20.86</td>
<td>1.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flooring</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terrazo Tiles</td>
<td>23.72</td>
<td>237.20</td>
<td>12.81</td>
<td>-9.22</td>
<td>-0.9</td>
</tr>
<tr>
<td>Mortar (M-40)</td>
<td>1.88</td>
<td>1.88</td>
<td>0.19</td>
<td>-0.47</td>
<td>-0.04</td>
</tr>
<tr>
<td>Fibreglass Polyester</td>
<td>1.07</td>
<td>119.01</td>
<td>0.00</td>
<td>-119</td>
<td></td>
</tr>
<tr>
<td><strong>Frame</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plywood Board</td>
<td>0.04</td>
<td>0.19</td>
<td>0.00</td>
<td>-0.19</td>
<td></td>
</tr>
<tr>
<td><strong>Interior Partitions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MDF Board</td>
<td>2.56</td>
<td>35.86</td>
<td>3.46</td>
<td>-35.86</td>
<td>-3.46</td>
</tr>
<tr>
<td><strong>Structure</strong></td>
<td>685.59</td>
<td>1247.23</td>
<td>126.04</td>
<td>-274.67</td>
<td>-31.61</td>
</tr>
<tr>
<td>Horizontal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20% recycled steel</td>
<td>11.08</td>
<td>387.92</td>
<td>39.90</td>
<td>-199.5</td>
<td>-23.27</td>
</tr>
<tr>
<td>Concrete (H-300)</td>
<td>608.29</td>
<td>711.83</td>
<td>71.18</td>
<td>-34.17</td>
<td>-3.7</td>
</tr>
<tr>
<td>Vertical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20% recycled steel</td>
<td>2.07</td>
<td>72.41</td>
<td>7.45</td>
<td>-37.4</td>
<td>-4.34</td>
</tr>
<tr>
<td>Concrete (H-300)</td>
<td>64.15</td>
<td>75.07</td>
<td>7.51</td>
<td>-3.60</td>
<td>-0.3</td>
</tr>
<tr>
<td><strong>Façades (East and West)</strong></td>
<td>141.28</td>
<td>986.2</td>
<td>113.30</td>
<td>-586.44</td>
<td>-85.24</td>
</tr>
<tr>
<td>Frame</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary Aluminium</td>
<td>0.92</td>
<td>146.38</td>
<td>23.78</td>
<td>-125.34</td>
<td>-21.4</td>
</tr>
<tr>
<td><strong>Opaque Elements</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary Aluminium</td>
<td>1.02</td>
<td>162.66</td>
<td>26.44</td>
<td>-162.66</td>
<td>-26.44</td>
</tr>
<tr>
<td>Fabricated Brick</td>
<td>105.42</td>
<td>226.20</td>
<td>15.06</td>
<td>-7.54</td>
<td>-0.76</td>
</tr>
<tr>
<td>Fibrocement</td>
<td>9.98</td>
<td>89.80</td>
<td>8.88</td>
<td>-89.80</td>
<td>-8.88</td>
</tr>
<tr>
<td>Rockwool</td>
<td>2.26</td>
<td>45.40</td>
<td>3.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyethylene (d tyvek)</td>
<td>0.00</td>
<td>0.18</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasterboard</td>
<td>15.58</td>
<td>40.06</td>
<td>3.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Transparent Elements</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plane Glazing</td>
<td>3.92</td>
<td>74.40</td>
<td>3.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Complementary Elements</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary Aluminium</td>
<td>0.34</td>
<td>53.68</td>
<td>8.72</td>
<td>-53.68</td>
<td>-8.72</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>0.00</td>
<td>0.24</td>
<td>0.04</td>
<td>-0.24</td>
<td>-0.04</td>
</tr>
<tr>
<td>Primary PVC</td>
<td>1.84</td>
<td>147.18</td>
<td>19.00</td>
<td>-147.18</td>
<td>-19</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2504/ 201.3</td>
<td>1150.39</td>
<td>3671.49</td>
<td>329.46</td>
<td>-1167.3</td>
<td>-128.12</td>
</tr>
</tbody>
</table>

Table 4.23: Evaluation of embodied energy of Heavyweight Conventional Module
4.4 Conclusion

Operational energy of each module was analysed in terms of interior temperature ($T_i$), and variability (response of natural behaviour of each building to sequential oscillations of exterior temperature) ($\Delta T_i$) for each season, consumption as kWh/m$^2$ and emissions as kgCO$_2$/m$^2$ (See Figure 4.8 and See table 4.24)

Interior temperature ($T_i$) of each module was equal. Effect of the thermal mass could be seen in variability ($\Delta T_i$) values. Heavyweight conventional system responded better to any kind of oscillation (day-night and sequential) than the other two cases. Also, the response was similar for summer and winter conditions while there were more differences in the variability for other cases. Lightweight industrialised system was the worst in consumption and emissions due to the lower levels of thermal mass. Medium-lightweight had the intermediate value in respect to other cases. However, no significant differences were considered in respect to the heavyweight case. Considerable difference could be marked as natural behaviour of the building due to exterior temperature oscillations.

![Figure 4.8: Interior Temperature, Interior Temperature Variation, Energy consumption for heating/ cooling and CO$_2$ emissions of three cases](image)

100
Table 4.24: Interior Temperature, Interior Temperature Variation, Energy consumption for heating/cooling and CO₂ emissions of three cases

Initial embodied energy of each module was analysed in terms of weight (kg/m²), energy (MJ/m²) and emissions (kgCO₂/m²) (See figure 4.9 and See table 4.25). Lightweight industrialised system is the lightest one, but it had the highest values of initial embodied energy. The reason could be linked to the usage of metal profiles as vertical structure and composite slab. Module configured with conventional system is the heaviest, but it had higher values of consumption and emissions than the 3d concrete module. The reason was related to the selection type of the medium-lightweight module, which was formed by reinforced concrete. In consumption
values, concrete had a considerable impact, though the initial embodied energy of conventional system and the 3d module were not proportional to the weight. However, used materials affect the initial embodied energy values more than the weight of the building. It could be said that, concrete module has the best results in terms of scaled usage of concrete and steel if compared with the other two cases.

![Graph](image)

**Figure 4.9**: Weight (kg/m²), Energy Consumption (MJ/m²) and Emissions (kg CO₂ eq/m²) values for three cases

<table>
<thead>
<tr>
<th></th>
<th>Lightweight Industrialised</th>
<th>Medium-Lightweight Industrialised</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kg/m²)</td>
<td>535</td>
<td>722</td>
<td>1150</td>
</tr>
<tr>
<td>Energy C. (MJ/m²)</td>
<td>4044</td>
<td>3103</td>
<td>3671</td>
</tr>
<tr>
<td>Emissions (kg CO₂ eq/m²)</td>
<td>339</td>
<td>307</td>
<td>329</td>
</tr>
</tbody>
</table>

**Table 4.25**: Weight (kg/m²), Energy consumption (MJ/m²) and Emission (kg CO₂ eq/m²) values for three cases
Evaluation of reuse, recycle potential of materials and components were analysed with unit data methodology. The unit data values were used for recycled materials and the total gain from initial embodied energy was calculated. The question was raised as following; how much energy from the initial embodied amount could be conserved by recycling or re-using (See table 4.26).

In the lightweight industrialised module, 46 % of the initial embodied energy can be saved by recycling/reuse while this proportion for the medium weight industrialised module is 49 % and for the conventional module is only 30 %. It can be seen that the potential of disassembly is better in the lightweight case, however, in total embodied energy, it still not has the best results. It shows that; though the disassembly potential is higher in proportion, if the initial embodied energy is high; it is not possible to get lower values in total. In the lightweight industrialised case; a big part of energy and carbon saving linked to recycling while in other two cases this links to reuse. This can be reasoned to usage of steel frame structure and composite slab in the lightweight case. The other two modules include the reinforced concrete structure, brick, and terrazzo tiles that were assumed to be recycled to form aggregates. Therefore, energy needed to form the concrete like cement production, to produce brick and terrazzo tiles are continuing embodied even they are recycled to form aggregate.

<table>
<thead>
<tr>
<th>Potential</th>
<th>Lightweight Industrialised</th>
<th>Medium-Lightweight Industrialised</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy (MJ/m²)</td>
<td>Emissions (kg CO₂ eq/m²)</td>
<td>Energy (MJ/m²)</td>
</tr>
<tr>
<td>Initial Embodied</td>
<td>4044</td>
<td>339</td>
<td>3103</td>
</tr>
<tr>
<td>Reuse</td>
<td>-740</td>
<td>-76</td>
<td>-928</td>
</tr>
<tr>
<td>Recycling</td>
<td>-1133</td>
<td>-86</td>
<td>-608</td>
</tr>
<tr>
<td>Total</td>
<td>2172</td>
<td>178</td>
<td>1221</td>
</tr>
</tbody>
</table>

Table 4.26: Potentials of reuse and recycling for three cases
5 CONCLUSIONS AND DISCUSSION

The conclusions are made in four parts: initial embodied emissions, operational emissions, recycling/reuse potential in terms of emissions and overall conclusions for three cases (See table 4.27). In the discussion part, impacts of methodology, construction material selection and construction type selection and recommendation for future studies are made according to conclusions. The conclusions are as following:

- Impact of the initial embodied energy was measured as CO₂ (kg of CO₂ emissions/built up for m²) for three modules. The most efficient system was the 3d concrete module, with 307 kg CO₂ eq/m² (or 3103 MJ/m² in terms of energy). The worst could be considered as the lightweight system with 339 kg CO₂eq/m² (or 4350 MJ/m² in terms of energy). The embodied energy was not proportional to the amount of materials (mass). However, the conventional module was approximately twice heavier than the lightweight module. In emissions, this difference was not representative. There were items that drive to have higher values such as unit emission values for selected materials, construction process and configuration of the construction system. Lightweight system was configured with metal frames and the composite slab, medium-lightweight was configured with concrete including walls. If the configuration of the construction systems and unit values for selected materials are compared, it could be seen that the conventional module had intermediate values. Thus, total metal and concrete amount was proportioned between two other cases. The unit value is higher in metals than concrete or synthetic materials. This could be the reason for the higher values in lightweight system though beams are not configured with metal structure. In respect to the above mentioned items, no considerable difference was noticed between the emissions related to the initial embodied energy. The
considerable difference could be considered as the relationship between weight and the initial embodied energy/ emissions.

- Operational emissions for 50 years were calculated approximately, according to the emissions sourced by heating/ cooling and including lighting and electrodomestic devices. As the three modules were identical in lighting, internal loads and heat transfer coefficient, the difference was linked to the heating and cooling load. There was a significant difference between lightweight and the other two modules; heavyweight module consumes approximately 10% less than the lightweight module and 5% less than medium-lightweight module. This difference was related to the different thermal mass. Heat transfer coefficients were considered according to limits of Spanish Technical Code and were identical in the three cases. However, the given coefficients were not found sufficient to operate a building in a passive way. The thermal mass affected the behaviour of the modules in different conditions. Interior temperatures were equal while variation in the interior temperature differed. For winter and summer conditions conventional module with its higher thermal mass, had the best results, while the lightweight module had higher variations in day-night and sequential oscillations. Emissions were considered higher in lightweight module for both seasons while conventional system responded with lower emissions in both seasons. The greatest difference in emissions between the three cases could be seen in summer. Conventional module consumes 10% less than the lightweight module while in winter this difference decreases to 4%. In the future, the Mediterranean zone is considered to be more hot and dry in summer while more precipitation is projected for the winter. Due to the projected scenario; summer interior conditions of the three analysed cases will be more different and the importance of thermal mass will be important. However, there are studies in order to increase the thermal performance of any type of lightweight buildings such as using phase change materials. Other important items that could be considered as design input values are shading,
orientation, building envelope, site selection, etc. In the analysed cases, building envelope was considered without any obstructions and the sun shadings were provided as usual in the Mediterranean climate. Also, a study was conducted during investigation to see the effect of the orientation. Orientation of the module was changed from east-west direction to the south-north. However, in this scale of modules (5m*10m*3.45m height), no considerable effect was noticed (ANNEX-II). However, it could be critically important in bigger volumes of residential buildings.

- Disassembly-deconstruction-decomposition and reuse potentials were evaluated for each of the cases (See table 4.27). In the recycling potential, the lightweight industrialised module was considered as the best. However, in reuse potential, it was worse than medium-lightweight industrialised module. In total, the reuse gained in all cases than recycling. Thus, the recycling needs more energy input for transformation while reuse has only rehabilitation of components as input. The conventional system was the worst case both in recycling and in reuse potentials evaluation. Thus, stony materials had more proportion than the other types with that energy savings could be achieved. However, medium-lightweight system also had lower rates in the recycling. The reason could be linked to selected type, which was a 3 dimensional concrete module and the recycling of concrete to aggregate values were considerably low when compared with metals.
<table>
<thead>
<tr>
<th></th>
<th>Lightweight Industrialised</th>
<th>Medium-Lightweight Industrialised</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Embodied kgCO₂/m²</td>
<td>339</td>
<td>307</td>
<td>329</td>
</tr>
<tr>
<td>Operational (50 years) kgCO₂/m²</td>
<td>4350</td>
<td>3800</td>
<td>3550</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recycling/ Reuse Potentials at the end of the life time kgCO₂/m²</th>
<th>Recycling -86</th>
<th>Reuse -76</th>
<th>Recycling -70</th>
<th>Reuse -94</th>
<th>Recycling -67</th>
<th>Reuse -62</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>-162</td>
<td>Total</td>
<td>-178</td>
<td>Total</td>
<td>-128</td>
<td></td>
</tr>
<tr>
<td>TOTAL kgCO₂/m²</td>
<td>4527</td>
<td>3929</td>
<td>3751</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.27:** Total emissions per m² at the end of the life time of modules

Three cases were evaluated in relation with the initial embodied and operational emissions during life time. Lightweight industrialised module needed to be operated 12.8 years, medium lightweight industrialised module needs 12.3 years and conventional module needs 10.8 years. Although lightweight industrialised module had higher embodied energy, more operational years are needed in order to compass when compared with other cases regarding its higher initial embodied energy. In proportion to total consumption in 50 years; lightweight buildings operational energy is 92.2 %, medium lightweight is 91.9 % and conventional is 90.7 % respect to total of initial embodied and operational emissions. (See Figure 4.10).

![Figure 4.10: Operational and Initial Embodied Carbon Proportions respect to total emissions](image-url)
If an overall comparison held, it could be seen that; lightweight industrialised module had higher values in initial embodied emissions and during operation time. In savings by recycling, it was the most advantageous but reuse potential was lower than other two cases. Medium lightweight module was more potential in reuse potential. However, in total, it had intermediate values for the initial embodied energy and the operational energy.

Disassembly potentials for the lightweight, medium lightweight and conventional module, respect to total carbon at the end of the life time, are as following; %3.4, %3.9, %3.1 (See Figure 4.11). This values of savings corresponds to 1.8 years operational carbon saving for the lightweight, 2.1 years operational carbon saving for the medium-lightweight and 1.7 years operational carbon saving for the conventional case. The initial embodied energy has % 7.7, %8 and % 9.2 respect to total embodied carbon at the end of the lifetime. Relationship between initial embodied energy and the recycling/ reuse potential is 39 % for heavyweight case while for the medium-lightweight this value increases to 58 % and for the lightweight is % 48 (See figure 4.12).

**Figure 4.11:** Carbon saving by disassembly respect to total embodied carbon
**Figure 4.12:** Carbon saving by disassembly respect to initial embodied carbon

It could be seen that, at the end of the lifetime, the conventional module had the best results and lower embodied carbon respect to others. The main reason can be linked to lower initial embodied carbon and lower operational energy demand. In the recycling potential, it had the worst results. However, indirect effects were not considered as an input to evaluate. In case of the indirect effects were added as an input, industrialised modules could be more advantageous in following terms:

- Time gain in construction process

- Controlled consumptions like water and electricity, preconsumed materials life cycle, etc.

- Flexible design possibility in order to increase disassembly potential

The conventional building could be advantageous in the indirect effects, if design to disassembly potential could be added in earlier design phase. The industrialised modules could be better in total carbon, if thermal comportment could be improved by design and the initial embodied carbon could be decreased.
Transport was considered as out of scope in the case studies of undetermined variables and the difficulty of evaluation of the conventional case. However, it is essential to discuss, up to which point the transport can affect the total emissions of a residential building. There is no doubt that the industrialised systems could have better values than traditional construction systems if transport configuration was also designed. Transport parameters could be as following:

- Distance (See table 4.28)
  - Traditional construction site
    From factory to site for every material; distance is rated between <50 km and >150 km circle range.
  - Industrialised construction types
    From factory to site for every component/module; distance is rated between <50 km and >150 km circle range.

<table>
<thead>
<tr>
<th>Distance (circle)</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;50 km circle</td>
<td>A</td>
</tr>
<tr>
<td>&gt;50 km circle</td>
<td>B</td>
</tr>
<tr>
<td>&gt;150 km circle</td>
<td>C</td>
</tr>
</tbody>
</table>

**Table 4.28:** Distance rating scheme

- Packing System (See table 4.29)
  - From factory to traditional construction site; if the materials or the components are appropriate for compact packing, rating is considered as A. An example can be the concrete, as a semi-liquid packing or the mountable steel profiles instead of transporting as casted or mounted.
  - For industrial case, transport of module or components from factory to site is rated. The materials transport to factory is not included to rating system because of undetermined variety of inputs. In this case, the 3d modules are lower rated because of the high volume occupation, while components with compact packing like U shaped modules are rated as highest. U shaped
volumes can be finished on site by mounting. Transporting only frame structure with wall finishes in a building which has composite slab (on-site casted) can be an example to those types.

<table>
<thead>
<tr>
<th>Types of elements</th>
<th>Rate of proper packing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Components which are appropriate for compact packing</td>
<td>A</td>
</tr>
<tr>
<td>Components (ready to montage on site)</td>
<td>B</td>
</tr>
<tr>
<td>3 dimensional modules</td>
<td>C</td>
</tr>
</tbody>
</table>

**Table 4.29: Packing system rating scheme**

This investigation could be described as an evaluation between energy consumption and emission sources in residential buildings. However, in the future, an investigation including more parts can be done. Possibilities for future studies could be as following:

- More types of industrialised or conventional systems could be evaluated in terms of initial embodied energy, operational energy and disassembly potential,

- Evaluation of cases could be made with an LCA frame, considering indirect effects of all the emissions and the usage of natural resources with possible effects on ecosystems.

- Water usage on site for traditional construction sites and in the factory for industrialised cases could be evaluated. However, water is considered to be an important item in the future predictions even in the Mediterranean climate zone.
- Investigation could be made in the on-time values for each of the cases. It means that a long-term study could be conducted with different buildings but with on-site, on-factory and recent/real values.

- Investigation could be made including the transport. However, real values are not required to consider the transport making an interpretation. A systematic plan design is needed in order to evaluate all transport values. In industrial construction, the transport of raw materials and the transport of materials of components to the factory should be considered. Considering only transport values of module to site will not be sufficient in order to make an evaluation between industrial and conventional.
REFERENCES


Buildings Performance Institute Europe (BPIE), 2010, Implementation of the EPBD in Member States, Spain, pp.60-61


Código Técnico de la Edificación (CTE), 2006, Appendix D, Climatic Zones, pp.HE1-31

Código Técnico de la Edificación (CTE), 2006, Appendix E, Climate Datas, Isotherms of maximum annual temperature of air (T_{max} in °C), pp.SE-AE 41

Código Técnico de la Edificación (CTE), 2006, Appendix E, Climate Datas, Climate Zones in Winter, pp.SE-AE 42

Código Técnico de la Edificación (CTE), 2006, U values for Climate Zone C2, pp.944


EN ISO 14040, 1997, Environmental management, Life Cycle Assessment, Principles and framework

EN ISO 14040.2 Draft: Life Cycle Assessment - Principles and Guidelines

EN ISO 14041, 1999, Environmental management, Life Cycle Assessment, Goal and Scope definition and inventory analysis


Hammond, G., Jones, C., 2008, Inventory of Carbon and Energy (ICE), Version 1.6, Sustainable Energy Research Team (SERT), Department of Mechanical Engineering, University of Bath, UK


Institute for Diversification and Saving of Energy (IDAE), available at: www.idae.es

International Energy Agency (IEA), 2010, Key World Energy Statistics


Ministry of Industry, Tourism and Commerce of Spain, available at: www.mityc.es


National Centre of Renewable energy (Cener-Centro Nacional de Energias Renovables), available at: www.cener.com


Thullner, K., 2010, Low-energy buildings in Europe - Standards, criteria and consequences- A study of nine European countries, Lund University


WEB REFERENCES


http://salmedinatri.com/, Treatment and Management of Demolition Residues, Madrid

http://scp.eionet.europa.eu/definitions, European Topic Centre on Sustainable Consumption and Production, access: July, 2011


http://www.fabra.cat, Fabra Meteorological Observatory Station
http://www.greenspec.co.uk/embodied-energy.php, Embodied Energy Definition, access: July, 2011

http://www.gremirecuperacio.org/10revista.asp, Magazine Recupera (Revista Recupera)


http://www.idae.es, Institute for Diversification and Saving of Energy (IDAE)


http://www.meteo.cat, Meteorological Service for Catalonia, Spain (In Catalan)

http://www.salvoweb.com/, Information about antique, reclaimed, salvaged and green material and dealers

http://www.secbe.org.uk/gwaste/data_collection, Waste- Data Collection, South East Centre for Built Environment (SECBE), access: July, 2011


http://www.worldenergy.org, World Energy Council (WEC), access: July, 2011

http://www20.gencat.cat/docs/incasol/Home/INCASOL/Documentaci%C3%B3/Publicacions/LLibre_CIT_OK.pdf, Libre CIT, access: July, 2011
ANNEX

ANNEX-I
ARCHISUN 3.0 computer simulation values for medium-lightweight industrialised module (3d concrete module)

ANNEX- II
Thermal Calculation for medium-lightweight industrialised module with north-south orientation (control case for change in orientation from east-west direction to north-south direction)
ANNEX-I

ARCHISUN 3.0 computer simulation values for medium-lightweight industrialised module (3d concrete module)
ANNEX- II

Thermal Calculation for medium-lightweight industrialised module with north-south orientation (control case for change in orientation from east-west direction to north-south direction)

### PARAMETRIC RESULTS-SUMMER

<table>
<thead>
<tr>
<th>CLIMATE</th>
<th>VENTILATION</th>
<th>GAINS (DAY)</th>
<th>GAINS (NIGHT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te</td>
<td>Gt</td>
<td>0.532789467</td>
<td>I 1.0753623</td>
</tr>
<tr>
<td>Te, min</td>
<td>Gv</td>
<td>1.74</td>
<td>D 2.1808792</td>
</tr>
<tr>
<td>Te, max</td>
<td>R</td>
<td>28</td>
<td>D' 0.63</td>
</tr>
<tr>
<td>R</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occupation</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BALANCE</td>
<td>Ti</td>
<td>28 °C</td>
<td></td>
</tr>
</tbody>
</table>

\[ \Delta T_i = \left( \Delta T_e + \frac{I + D}{G} - \frac{I'+D'}{G'} \right) \left( 1 - e^{-\frac{t - G'}{M}} \right) \]

VARIABILITY \[ \Delta T_i \] 7 °C

### PARAMETRIC RESULTS-WINTER

<table>
<thead>
<tr>
<th>CLIMATE</th>
<th>VENTILATION</th>
<th>GAINS (DAY)</th>
<th>GAINS (NIGHT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te</td>
<td>Gt</td>
<td>0.524401383</td>
<td>I 0.42624928</td>
</tr>
<tr>
<td>Te, min</td>
<td>Gv</td>
<td>0.725</td>
<td>D 2.1808792</td>
</tr>
<tr>
<td>Te, max</td>
<td>R</td>
<td>9</td>
<td>D' 0.63</td>
</tr>
<tr>
<td>R</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occupation</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BALANCE</td>
<td>Ti</td>
<td>10 °C</td>
<td></td>
</tr>
</tbody>
</table>

\[ \Delta T_i = \left( \Delta T_e + \frac{I + D}{G} - \frac{I'+D'}{G'} \right) \left( 1 - e^{-\frac{t - G'}{M}} \right) \]

VARIABILITY \[ \Delta T_i \] 2 °C
### Parametric Results-Spring

<table>
<thead>
<tr>
<th>Climate</th>
<th>Ventilation</th>
<th>Gains (Day)</th>
<th>Gains (Night)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e$ 16</td>
<td>$G_t$ 0.532789467</td>
<td>$I$ 1.07536232</td>
<td>$I'$ 1</td>
</tr>
<tr>
<td>$T_e$, min 13</td>
<td>$G_v$ 1.74</td>
<td>$D$ 2.1808792</td>
<td>$D'$ 0.63</td>
</tr>
</tbody>
</table>

Unitary Thermal Mass: 186687.53 J°C/m³

**Occupation**: 3

| Balance | $T_i$ | 18 °C |

**Variability**: $\Delta T_i = \left( \Delta T_e + \frac{I + D}{G'} - \frac{I'+D'}{G'} \right) \left( 1 - e^{\frac{-t}{M}} \right)$

### Parametric Results-Autumn

<table>
<thead>
<tr>
<th>Climate</th>
<th>Ventilation</th>
<th>Gains (Day)</th>
<th>Gains (Night)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e$ 18</td>
<td>$G_t$ 0.532789467</td>
<td>$I$ 1.07536232</td>
<td>$I'$ 1</td>
</tr>
<tr>
<td>$T_e$, min 14</td>
<td>$G_v$ 1.74</td>
<td>$D$ 2.1808792</td>
<td>$D'$ 0.63</td>
</tr>
</tbody>
</table>

Unitary Thermal Mass: 186687.53 J°C/m³

**Occupation**: 3

| Balance | $T_i$ | 20 °C |

**Variability**: $\Delta T_i = \left( \Delta T_e + \frac{I + D}{G'} - \frac{I'+D'}{G'} \right) \left( 1 - e^{\frac{-t}{M}} \right)$