LIFE CYCLE ENVIRONMETAL IMPACT ASSESSMENT OF A MULTI-STOREY RESIDENTIAL BUILDING IN IZMIR

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İZMİR

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ABSTRACT

LIFE CYCLE ENVIRONMETAL IMPACT ASSESSMENT OF A MULTI-STOREY RESIDENTIAL BUILDING IN IZMIR

For a sustainable development, it is essential to improve the building stock and sector which are majorly affiliated with the negative impacts on environment. The analysis of current situation and establish the basic problems in order to decrease the environmental impacts of buildings. Life Cycle Assessment (LCA) is a holistic and scientific method in the area of environmental impact assessment. While the LCA may be applied to individual building components or specified life cycle phases, it is also possible to assess the environmental impacts of a building from cradle to grave with an integrated approach toward whole life cycle.

The purposes of this study are to evaluate the current position of the LCA method, which is a vital component of the sustainability assessment in building sector, and to make a quantitative assessment on the environmental impacts of multi-storey-mass housing which has the primary share of recent residential building stock in Turkey. One residential unit of a mass housing development in Izmir constructed at the last decade, at the edge of the expanding city boundary, was selected as the case object of this study.

The life cycle of building is fundamentally examined in three phases, which are: pre-use phase, use phase and end-of-life phase. The Simapro software 7.3.3 and Ecoinvent 2.2, up-to-date database, were selected for the LCA simulation. In addition, as a local input to database, energy data for Turkey was created.

As a result of this study, the environmental impacts during the life cycle of a multi-storey building residential unit have been ascertained and the life phases, building components and operational processes which have the heaviest impact on the environment have been determined.

ÖZET

İZMİR’DE ÇOK KATLI BİR KONUT YAPISININ YAŞAM DÖNGÜSÜ ÇEVRESEL ETKİ DEĞERLENDİRMESİ

Çevreye negatif etkiler ile ilişkilendirilen yapı stoku ve yapı sektörünün iyileştirilmesi, sürdürülebilir kalkınma için önem taşımaktadır. Güncel durumun analiz edilmesi ve temel sorunların belirlenmesi, günümüzde binaların çevresel etkilerini azaltmak için bir gerekliliktir. Yaşam döngü değerlendirmesi (YDD) çevresel etki değerlendirmesi alanında yaygın olarak kullanılan bütüncül ve bilimsel bir yöntemdir. YDD tekil bir yapı bileşeni veya belirli bir yaşam dönemine uygulanabileceği gibi bir yapının çevresel etkilerini beşikten mezara tüm yaşam döngüsü boyunca bütüncül bir yaklaşımla değerlendirmek de mümkündür.

Bu çalışmanın amacı yapı sektöründe sürdürülebilirlik değerlendirmesinin çok önemli bir parçası haline gelen YDD metodunun güncel durumunu değerlendirmek ve Türkiye konut stokunda önemli bir paya sahip toplu konut projelerinin çevresel etkilerini YDD yöntemi ile değerlendirmektir. Son on yıl içerisinde İzmir’de inşa edilmiş bir toplu konut yerleşkesinin bir konut birimi uygulama alanı olarak seçilmiştir.

Yapının yaşam döngüsü temel olmak üzere üç fazda incelenmiştir. Bu fazlar; kullanım öncesi fazı, kullanım fazı ve yaşam sonu fazlarıdır. Simapro 7.3.3. yazılımı ve güncel Ecoinvent 2.2. veritabanı YDD simülasyonu için seçilmiştir. Veri tabanına olarak, Türkiye’nin enerji verisi yerel girdi olarak yaratılmıştır.

Bu çalışmanın sonucunda Türkiye’de son yıllık periyoda inşa edilmiş bir toplu konut biriminin yaşam döngüsü çevresel etkisi değerlendirilmiş, yaşam döngüsü fazlarının ve yapı bileşenlerinin çevresel etkilerdeki payları, kritik etki noktaları belirlenmiştir.

To Deniz and Derin

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AC:	Air condition
ADP:	Abiotic resource depletion potential
AP:	Acidification potential
BMCC:	Building material and component combinations
CH_4:	Methane
CML:	Institute of Environmental Sciences of the University of Leiden
CO_2:	Carbon dioxide
COP7:	Seventh session of the Conference of the Parties
DALY:	Disability adjusted life years
EI:	Eco-indicator
EN:	Energy consumption
EP:	Eutrophication potential
EPA:	Environmental protection agency
EQ:	Ecosystem quality
ET:	Eco-toxicity
FU:	Functional unit
GHG:	Green house gases
GWP:	Global warming potential
HFC:	Hydroflourocarbons
HH:	Human health
HT:	Human toxicity
ICF:	Insulated concrete form
ILCD:	International reference life cycle data system
IPCC:	Intergovernmental Panel on Climate Change
ISO:	International standardization organization
JRC:	Joint research center
LCA:	Life cycle assessment
LCI:	Life cycle inventory
LCIA:	Life cycle impact assessment
MRI:	Midwest research institute

N_2O:	Nitrous oxide
NGO:	Non-governmental organization
NP:	Nutrification potential
NR:	Non-renewable resources
O:	Others
ODP:	Ozone layer depletion potential
OECD:	Organization for economic co-operation and development
PFC:	Perflourocarbons
POCP:	Photochemical ozone creation potential
PS:	Photo-smog
REPA:	Resource and Environmental Profile Analysis
RS:	Resources consumption
SETAC:	Society of Environmental Toxicology and Chemistry
SF_6:	Sulphur hexafluoride
UCTE:	Union for the Co-ordination of Transmission of Electricity
UNCBD:	United nations convention on biological diversity
UNCCD:	United nations convention to combat desertification
UNEP SBCI:	United nations environmental programme sustainable building and climate initiative
UNFCCC:	United nations framework convention on climate change
UNOPS:	United Nations Office for Project Services
VOC:	Volatile organic compound
W:	Waste creation
WMO:	World Meteorological Organization
WPC:	Whole process construction

CHAPTER 1

INTRODUCTION

1.1. Problem Statement

Environmental debates today are arising on the basis of facts as ozone and resource depletion, global warming, eutrophication of lakes and rivers, deforestation, and ecotoxicity. “A rapidly rising global population, combined with accelerating development and resource use, surging energy demand and ever-expanding need for water and food are creating huge stress on natural environment” (Hardisty 2010, p. 1).

Global warming is the principle subject of contemporary environmental debates. Greenhouse gases (GHG) arising from intense human activities such as industrial production, burning fossil fuels and deforestation accumulate in the higher layers of atmosphere, and cause the problem of global warming (Asif et al 2007).[1] In the last decades, GHG emissions are put forward by researchers and policy makers as more readily quantified impacts than others in the environmental assessment. Yet, it is essential to notice that GHG emissions are just one part of the parameters that should be considered in assessing environmental impacts (Khasreen 2009). Although global warming has dominated the environmental agenda in recent years, there is also growing awareness on preservation of ecosystems as a whole including natural and built environment. In other words, there is a need for holistic approach integrating social, cultural, and economic as well as ecological aspects of sustainable development for a prosper future (Hardisty 2010).

2011 world population data indicates that 51% of the total population is living in urban areas (Population 2011).[2] While northern countries’ percentage of urban population is more today, it is expected that southern countries will have the most urban population growth in near future. Therefore urbanization will inevitably cause a significant stress on natural environment depending on the density and character of

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[1] Green house gases (GHG) are CO_2 (carbon dioxide), CH_4 (methane), N_2O (Nitrous Oxide), PFCs (perflourocarbons), HFCs (hydroflourocarbons), SF_6 (sulphur hexaflouride) as well as the indirect greenhouse gases such as SO_2, NO_x, CO and NMVOC (UN Framework 2012).

[2] Averages of urban population in different regions of the world are 39% in Africa, 80% in Americas, 44% in Asia, 71% in Europe, and 66% in Oceania (Population Reference 2011).

construction activities, transportation, industrial production and amount of urban waste that are intense more than ever.

In order to understand the impact of urbanization on natural environment, it is important to have a close look at the construction sector, responsible from the significant resource consumption and waste production during the whole life cycle of buildings. Common Carbon Metrics (UNEP SBCI and WRI 2010) states that the environmental footprint of construction sector includes 40% of energy use, 30% of use of raw materials, 25% of solid waste, 25% of water use, and 12% of land use.

According to Turkey Construction Sector Report 2010 (YEMAR 2010), the average growth prospect of construction sector in northern countries is about 3.2%, while it is 7.2% for developing countries in 2010-2020 period. The construction sector in Turkey will be one of the fastest growing ones in the world with a 7.3% growth rate in the next decade.

Construction industry as the leading sector for Turkish economy indeed is one of the key sectors that should be considered to reach sustainable development targets. Especially, the weight of residential buildings is about 60% in total building construction (TUIK Building 2010). Turkey Energy and Energy Efficiency Report (ENVER and Iconomy Vezir Consultancy 2010) presents that residential building related energy use accounts for 32% of the total energy consumed in Turkey. Furthermore, Turkey population has reached 73 million and remains one of the fastest growing populations among the OECD countries (TUIK 2012). 76% of the total population lives in urban areas (Population Reference 2011). Besides, major migrations from rural areas to urban areas still continue. As a result, Turkey confronts with the challenge of ensuring that economic growth driving by the construction sector should be associated with environmental and social progress, namely the sustainable development.

1.2. Research Aims and Objectives

For a sustainable development, it is important to improve the building stock and the building industry which are majorly affiliated with the environmental impacts. It is required to analyze the current situation and establish the basic problems in order to decrease the environmental impacts of buildings.

Life cycle analyses of existing whole buildings are essential to identify and evaluate how key design parameters will influence a building's environmental sustainability. It is seen that previous whole building LCA studies have been conducted in a broad international range, except Turkey. There is a need in whole building LCA research in Turkey's conditions to give a rise of implementation of this internationally accepted method.

The aim of this study is to quantify potential environmental impacts caused by a residential dwelling in a multi-storey building in Izmir, during its life cycle. This study contributes to the growing international literature of whole process construction (WPC) LCA. The objectives of the study are to;

- Identify and quantify environmental impacts of a residential dwelling with unweighted, transparent results,
- Determine the life cycle phases and elements that contribute most to the life cycle impacts (identifying hotspots),
- Provide information about the connection between different life cycle elements of the building and environmental aspects,
- Specify critical environmental impact categories,
- Make a review of recent position of LCA in literature.

1.3. Method of Study

In the frame of determined aims and objectives, this research has been compiled in five chapters which are introduction, life cycle methodology, method application on a case study, detailed LCA results and conclusion.

Introduction draws a general framework of fundamentals and the research aim and objectives described as well as an overview of how this research is structured. Limitations and assumptions forms the system boundary of the research are indicated. A comprehensive conceptual background is given with a retrospective view on sustainable development and environmental issues. Relation between sustainability an LCA is briefly clarified.

Life cycle methodology provides a deep understanding on fundamentals and background of LCA. An extensive literature review on building LCA is performed to determine the state of the art of the LCA in building sector. Method of LCA is defined in detail covering four principle steps of LCA according to international standards. Various LCA tools and databases are also evaluated.

Method application covers the presentation of the case study and the application of described LCA method in detail according to life cycle phases. Goal and scope definition, determining inventory inputs, life cycle phases, impact assessment method and database are the essential parts of this chapter.

Life cycle impact results according to life cycle give detailed results on environmental impact potential of the case according to objectives of the study. Characterized and normalized values are provided transparently, without weighting or scoring.

Conclusion closes the thesis with interpreting obtained detailed results, determining problems and defining potentials for future research provided by this work.

1.4. Limitations and Assumptions

The limitations and Assumptions of LCA Methodology:

The life cycle impact analysis is an assessment technique; therefore, like other assessment techniques, the LCA has also particular limitations. The ISO 14040 (1997) determines the general potential limitations in the application of LCA. According to this early determination, subjectivity may occur in making choices and assumptions in the LCA, e.g. system boundary setting, selection of data sources, and impact categories. Besides, the local conditions may not be adequately represented by regional or global conditions. In addition, the accuracy of LCA studies may be limited by accessibility or availability of the relevant data.

The application of LCA in buildings has also specific limitations parallel to the general framework. Ortiz (2009) states that the implementation of LCA in building sector is a complex process in which the LCA cannot be applied without making assumptions and additional modifications. Thus there is a need for coherent, consistent and transparent data sets to simplify application process and to increase the acceptance of the LCA results. The absence of an industry standard for conducting a LCA study in building sector results a considerable variation in the scope and system boundaries of LCA studies. It causes some limitations in comparison among the LCA studies in the literature. Furthermore, the whole building decision support tools and databases varies according to users, application, data, geographical position and scope. Therefore these tools are not capable of modeling entire building or computing all environmental impact of all life cycle phases and process.

With the aim of application of LCA methodology in a building while regarding these limitations, the present research are computed in the transparent and flexible LCA software, Simapro 7.3.3, and used processes and materials inventoried in Ecoinvent 2.2 Database in order to provide generic and most appropriate background data of products and processes.

The Limitations and Assumptions of Thesis:

The LCA methodology is intended to implement in a case, characterized by a multistory building constructed in the last decade, i.e. between 2000 and 2010, with the aim of reflecting environmental impacts of the recent construction techniques and multi-storey buildings as the most constructed type of residential buildings in Turkey. Evaluation of architectural qualities or occupational behavior of the residential unit is out of the scope of this thesis. The aim is to determine all environmental impacts in a detailed and transparent way for all life cycle phases. The case study is selected as an existing building in the vicinity of city boundary, i.e. in a suburban area located on the southern development axis of Izmir.

The LCI life cycle inventory (LCI) data for Turkey, unfortunately, is not available in any accessible databases. Therefore Ecoinvent 2.2 database consisting of the generic European data is chosen to provide most possible and convenient inventory data, regarding geographical and technological similarities. However, the country electricity mix used in material production processes considerably varies from one country to another. Ecoinvent 2.2 does not contain the electricity production mix of Turkey. To minimize discrepancies on results and to localize data, the electricity production mix of Turkey is modeled according to 2009 data and implemented in the inventory. The resource mix supplying electricity to the building was considered to be static for the building lifetime. The life span of building is assumed as 50 years regarding similar studies from the literature.

Building operational energy data is obtained by observing monthly electricity and heating bills for a one year period between January 2011-2012. Data limitations on the Turkey residential component replacement lifetimes led to the utilization of appropriate data from literature.

The LCI input amounts for construction materials are accounted from building implementation project. It is assumed that all materials came from a 50 km distance by truck because of the lack of the detailed certain data. It is hard to achieve back-ward looking information in Turkey construction practice. The machine energy data needed in on-site construction phase is estimated following the construction guide of the Ministry of Environment and Urban Planning.

The end of life phase was in the system boundary of this study at preliminary plan. But it’s found that a database for building demolition energy in Turkey is not available. Also there is no literature on building demolition energy of multistory reinforced concrete buildings. Input data for demolition energy couldn’t be achieved. There is no distinctive legislation and statistical data on waste management of building demolition wastes. It was only possible to account the impact of landfill of building demolition waste. Due to its contribution to total impact less than 0,5% it is applied a cut of for this phase.

Although a one year simultaneous measurements on thermal comfort conditions of residential unit and local climatic conditions of the housing settlement area was carried out in order to develop improvement options by simulating variable alternatives on materials and energy sources, this is left for a future study because of the time limitation.

CHAPTER 2

LIFE CYCLE METHOD

2.1. Conceptual Background: Retrospective View on Sustainable Development and Environmental Issues

The emergence of concept of sustainable development is a consequence of gradual awakening of individuals, NGOs and governments about negative impacts of humankind on natural environment. First actions of environmental awareness in public and governmental levels emerged in the 60s. During the next decade, loss of biodiversity, city smog and contamination of natural water sources became major subjects of environmental discussions which, then, lead to pressure on industrial production processes (Hardisty 2010).

The concept of sustainability was first expressed in the United Nations (UN) Conference on Human Environment in 1972.[3] The conference focused on the necessity of a common perspective and principles which can globally lead and inspire people in protecting the nature. In the same year, Club of Rome which was founded in 1968 as an informal association of independent leading personalities, sharing a common concern for the future of humanity and the planet, published the famous report, i.e. Limits to Growth. Understanding the limits of earth ecosystem and its restraints, which impose on human population and activities, were two main objectives of this report (Malaska and Vapaavouri 2005). In fact, the report presents the provisional results of a mathematical model of the world development system, based on the interaction between several key factors, i.e. population growth, food production, industrialization, resources depletion, and pollution. It states that “economic and industrial growth would come to a stop in the near future due to the exiguity of natural resources, with a consequent decline in the population level and in the industrial system” (Giudice et al 2006, p. 2). Meadows (1972) also points out that “if the actual line of development continues unchanged in these five principal sectors, humanity is destined to reach the natural limits of

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[3] The United Nations Conference on Human Environment was organized at Stockholm, Sweden between June 5 and 16, 1972. Representatives of the 113 states, invited in accordance with General Assembly Resolution 2850 (XXVI), took part in the conference including Turkey.

development within the next 100 years.” In conclusion, by this report, the idea that economic development must be combined with environmental protection was underlined (Allacker 2010).

Another report of the World Commission on Environment and Development, Our Common Future, declared in 1987, officially introduced the terminology and notion of sustainable development.[4] Here the term of sustainable development was defined as “the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs’’ (UN Commision 1987, p. 24). International cooperation and institutional reform, highlighting the importance of institutional and legal change, was one of the four essential topics of this report. Here, the UN Environment Programme (UNEP) has been intended to be the principle agent on critical environment and natural resource protection issues.[5]

After two decades from the first UN Conference, in 1992, the second one on Environment and Sustainable Development, known as The Earth Summit, met at Rio de Janeiro, Brazil. The goal of this conference was built on the declaration of Stockholm Conference. The message was “nothing less than a transformation of our attitudes and behavior would bring about the necessary changes” (UN Conference 1997, p. ND). Durmuş Arsan (2003, p. 39) states the results of this conference that “it mobilized governments to move the sustainability issue to the center of development planning, economic and sectoral policy and decision-making. It was clearly understood that the protection of the environment and social and economic development are fundamental to sustainable development, based on the Rio Principles.” The importance given to climate change, forests and biodiversity indicated that the summit, as a largest organization with 30.000 participants, has been a vital step toward sustainable development. The Convention on Biological Diversity (UNCBD), Framework Convention on Climate Change (UNFCCC), Principles of Forest Management (UNCCD) and Local Agenda 21 were the outcomes of this summit which became major legal bases of the notion of sustainable development (UN Commission 2007). The establishment of the UN

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[4] The Report of World Commission on Environment and Development, Our Common Future, is also known as the Brundtland Report by the name of chairman of Commission, Gro Harlem Brundtland.

[5] The Principle 93 (UN Report 1987, p.?) declares that “governments should also reinforce the roles and capacities of environmental protection and resource management agencies. This is needed in many industrialized countries, but most urgently in developing countries, which will need assistance in strengthening their institutions. The UN Environment Programme (UNEP) should be strengthened as the principal source on environmental data, assessment, and reporting and as the principal advocate and agent for change and international cooperation.”

Commission on Sustainable Development was also proposed. The environmental impact assessment was one of the significant topics of Earth Summit. It is pointed out that “environmental impact assessment, as a national instrument, shall be undertaken for proposed activities that are likely to have a significant adverse impact on the environment and are subject to a decision of a competent national authority’’(UN Conference 1997 p. ND).

Five years later, in 1997, The Kyoto Protocol was adopted in Kyoto, Japan, and came into force by February 2005. The detailed rules for the implementation of the Protocol were adopted at the 7th Conference of the Party’s to the UN Framework Convention on Climate Change (COP7), called as the Marrakesh Accords. In Marrakesh in 2001, The Kyoto Protocol is an international agreement linked to the UN Framework Convention on Climate Change. Its major feature was to set binding targets for 37 industrialized countries and the European community for reducing greenhouse gas emissions. The Annex B emissions target and the Party’s emissions of GHGs in the base year determine the Party’s initial assigned amount for the Kyoto Protocol’s five-year first commitment period, i.e. 2008 – 2012, (UN Framework 2008). These amounts to an average of five percent below against 1990 levels over the five-year period for 2008 – 2012 (Table 2.1). With the aim of a truly global emission reduction regime that will stabilize GHG emissions, and providing the essential structure for any future international agreement on climate change, the Kyoto Protocol has been seen as a significant first step.

Table 2.1. Countries Included in Annex B of the Kyoto Protocol and Their Emission Targets (Source: UNFCC 2008)

Country	**Reduction Target**
EU-15, Bulgaria, Czech Republic, Estonia, Latvia, Liechtenstein, Lithuania, Monaco, Romania, Slovakia, Switzerland	-8%
US	-7%
Canada, Hungary, Japan, Poland	-6%
Crotia	-5%
New Zealand, Russian Federation, Ukraine	0
Norway	1%
Australia	8%
Iceland	10%

The process paving the road toward the Kyoto Protocol begins with the establishment of Intergovernmental Panel on Climate Change (IPCC) by UNEP and the World Meteorological Organization (WMO) in 1988. Türkeş and Arıkan states that this process parallel with the sustainable development can be examined in four essential stages such as gathering the scientific data, strategies for action and obligations, and institutional structuring. The period after the Kyoto Protocol came into force is stated as the stage of implementation and new obligations.

While the Earth Summit underlined global environmental change, including the problems of biodiversity, resource depletion, and climate change, Kyoto Protocol only focused on climate change and reduction of GHG emissions. On the other hand, after eight year from Earth Summit, the UN Millennium Summit at New York in 2000, the environmental sustainability appeared as one of the eight goals, instead of a central subject. Other goals of the Millennium Summit related to human development are as follows (UNOPS, 2011):

- To eradicate extreme poverty and hunger,
- To achieve universal primary education,
- To promote gender equality and empower women,
- To reduce child mortality,
- To improve maternal health,
- To combat HIV/AIDS, malaria and other diseases,
- To develop a global partnership for development by the year of 2015.

The Johannesburg Summit 2002, i.e. the World Summit, on Sustainable Development was held in Johannesburg, South Africa in August 2002. This summit sets an action agenda with a sense of urgency. The major outcome of the summit was to put a plan for implementation of targets and timetables to foster action on access to clean water and sanitation, preserving biodiversity by 2015 and phasing out of toxic chemicals by 2005 (UN Press Releases 2002).

The UN climate change conferences have been convened each year since 1996 up to day. These conferences draw more attention since the first commitment period of the Kyoto Protocol ended by 2012. What will happen beyond 2012 is one of the key issues for governments of the 195 Parties to the Convention. The Intergovernmental Panel on Climate Change (IPCC) clearly indicated that a new international framework needs to be negotiated and ratified with the stringent emission reductions.

At the point reached by the Kyoto Protocol, it is clear that climate change becomes a focused environmental problem standing out from the others. The protocol enabled a general acceptance that the GHG emissions are essential environmental indicators in the environmental assessment. Consequently, global warming potential (GWP) appeared as the most common environmental impact category.

2.1.1. Sustainability and Life Cycle Assessment

Adams (2006) stated that definition of sustainability evolved since its first emergence. He emphasized that the sustainability definition of Brundtland report was vague even though it cleverly captured two fundamental issues, the problem of the environmental degradation that so commonly accompanies economic growth, and yet the need for such growth to alleviate poverty.

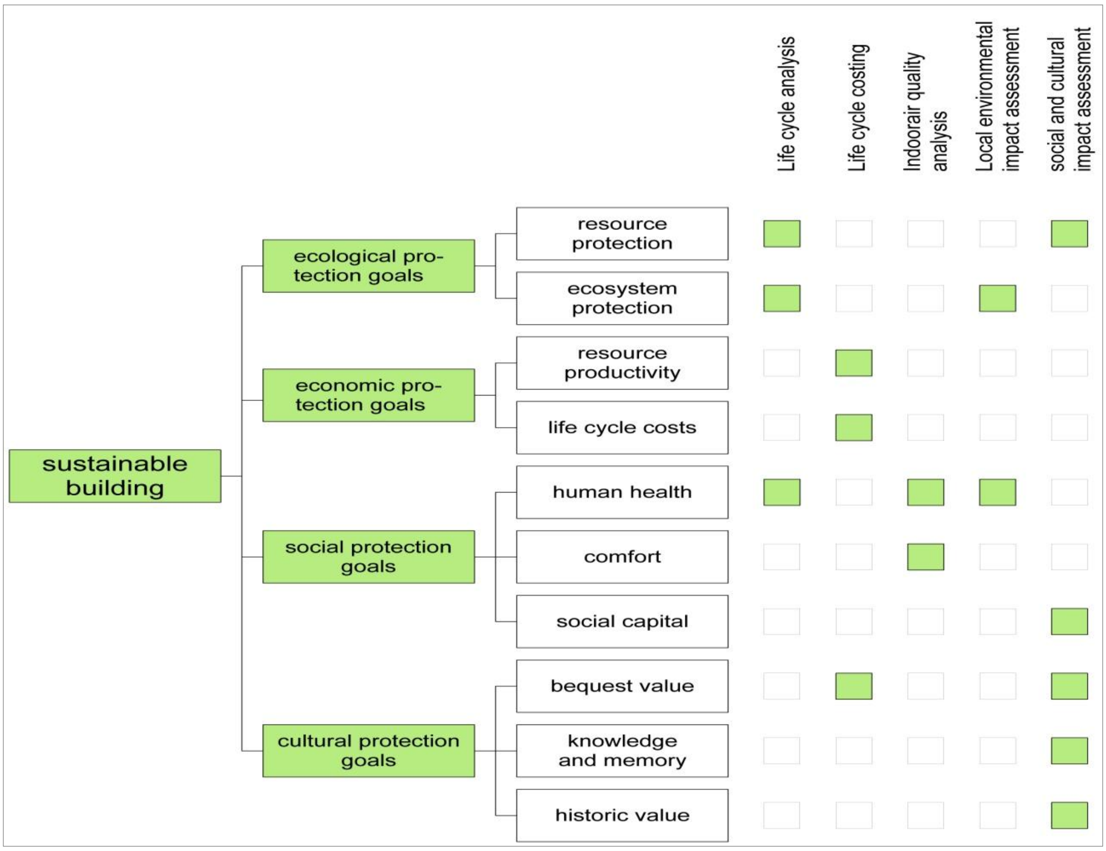
Faber at al, (2005) concluded that ‘’the earliest definitions of sustainability had a construct, absolute and static view on what sustainability is about. However, the sustainability discussion developed further to the point where sustainability shifted from an entity towards a construct orientation, from an absolute towards a relative perspective and from a static towards a dynamic perspective on sustainability’’.

Sustainability covers several dimensions as ecological, economic, social and cultural. While ecologic dimension of sustainability focuses on preservation of environment and limiting the world resources depletion to protect the basis of life, economic dimension concerns the adaptation of the production and consumption processes to meet ecological requirements as a long term cost-avoidance strategy. Social sustainability is a multilayer dimension in itself which is mainly covers the maintenance of human-health and general well-being directly depending on ecological and economic dimensions. Cultural sustainability concerns the preservation of the cultural diversity of the societies for future generations. In terms of built environment as a product of human history aims to protect a non-renewable resource (Köning et al. 2010).

Sustainability assessment can be carried out by various analytical methods [6]which include life cycle analysis. In these analytical methods the most important need is data and information on the interactions between society, nature and economy.

Ortiz et al. (2009) states that ‘’more than ever, the construction industry is concerned with improving the social, economic and environmental indicators of sustainability. By applying LCA it is possible to optimize these aspects, from the extraction of raw materials to the final disposal of waste building materials’’. The question of sustainable development therefore acquires special importance for the field of construction.

Köning et al. (2010) indicates that the construction currently responsible for the largest of all man-made material flows and it defines a building sustainability being parallel with sustainability definition in figure below.



		Life cycle analysis	Life cycle costing	Indoorair quality analysis	Local environmental impact assessment	social and cultural impact assessment
ecological protection goals	resource protection	🟩				🟩
	ecosystem protection	🟩			🟩	
economic protection goals	resource productivity		🟩			
	life cycle costs		🟩			
social protection goals	human health	🟩		🟩	🟩	
	comfort			🟩		
	social capital					🟩
cultural protection goals	bequest value		🟩			🟩
	knowledge and memory					🟩
	historic value					🟩

Figure 2.1. Protection Goals and Certification Procedures for Sustainable Building
(Source: Köning et al. 2010)

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[6] Analytical methods: environmental assessment, urban ecology assessment, material flow analysis, risk analysis, life cycle assessment, product-line analysis, cost-benefit analysis (Köning et al. 2010)

2.2. Life Cycle Assessment (LCA)

Fundamentals of life cycle assessment are given in the fallowing parts to provide a clear understanding on life cycle concept in sustainability assessment.

2.2.1. Definition of LCA

Life cycle assessment (LCA) is a process of the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle (ISO 14040:1997).

It is a methodology for evaluating the environmental load of processes and products (goods and services) during their life cycle from cradle to grave (Ortiz 2009). Life cycle assessment is a structured, comprehensive and internationally standardized method. It quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or service (European JRC 2010).

US EPA (1993) defines LCA as a concept and methodology to evaluate the environmental effects of a product or activity holistically, by analyzing the whole life cycle of a particular product, process, or activity. It is important to notice that an LCA assesses potential instead of actual impacts.

According to European JRC (2010) an LCA can be settled on three main goal situations. Decision support on micro-level is typically for product-related questions which are assumed to have only limited and no structural consequences outside the decision context. Meso-macro level decision support is counted as a strategic level having results on large scale consequences and accounting which is described as a purely descriptive documentation of the system under analysis.

Curran (2006, p. 3), determines the benefits of a LCA performance as fallowing: “Providing a systematic evaluation of the environmental consequences associated with a given product; quantifying environmental releases to air, water and land in relation to each life cycle stage and/or major contributing process; assisting in identifying significant shifts in environmental impacts between life cycle stages and environmental media; assessing the human and ecological effects of material consumption and environmental releases to the local community, region and the world; comparing the health and ecological impacts between two or more rival products/processes or identifying the impacts of a specific product or processes; identifying impacts ton one or more specific environmental areas of concern”.

An LCA can assist in decision making in industry, governmental and non-governmental organizations, selection of relevant environmental indicators and adequate measurement techniques, marketing opportunities for products by supporting product certification.

2.2.2. Standardization of LCA

International standards assists in the specification, definition, method and protocols associated with undertaking, reviewing and reporting LCA studies (Horne et al. 2009). ISO 14040 describes the principles and framework for life cycle assessment.

The development of the international standards for life cycle assessment, ISO series 14040:1997, ISO 14041:1999, ISO 14042:2000, ISO 14043:2000, is important step to combine procedures and methods of LCA. Their contribution to the general acceptance of LCA by all stakeholders and by the international community was crucial. (Finkbeiner et al. 2006). To achieve needed readability and removal of errors and inconsistencies, this first generation of LCA standards is replaced with two new LCA standards ISO 14040:2006 and ISO 14044:2006. By this publication four existing standards are revised, cancelled and replaced.

As is mentioned on the website of ISO: “ISO 14040:2006 describes the principles and framework for LCA including: definition of the goal and scope of the LCA, the LCI phase, the LCIA phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements”. ISO 14044:2006 specifies requirements and provides guidelines for life cycle assessment.

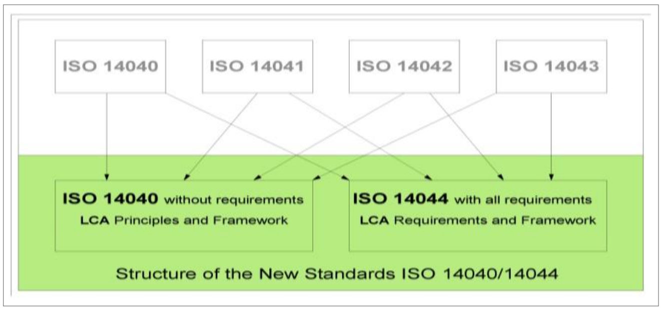

Figure 2.2. General Outline of the New Standards
(Source: Finkbeiner et al. 2006)

European Commission Joint Research Centre (JRC) has also developed an ILCD (International Reference Life Cycle Data System) Handbook published in 2010 by the European Platform on Life Cycle Assessment providing technical guidance for detailed LCA studies and technical basis to derive product-specific criteria, guides, and simplified tools. The handbook consists of a set of documents that are in line with the international standards on LCA (ISO 14040/44): general guide for life cycle assessment, specific guide for Life Cycle Inventory (LCI) data sets, the life cycle impact assessment (LCIA) guide, and the guide on “review schemes for life cycle assessment.

2.2.3. History

Environmental life cycle analysis has shown a rapid development in last three decades. Guinee et al. (2010) states that ‘’whereas LCA developed from simply energy analysis to a comprehensive environmental burden analysis in the 1970’s, full-fledged life cycle impact assessment and life cycle costing models were introduced in the 1980s and 1990s, and social-LCA and particularly consequential LCA gained ground in the first decade of the 21th century’’.

The roots of the LCA are based on 1960’s. Limitations of raw material and energy use triggered a tendency in finding ways to cumulatively account for energy use and to project future resource supplies. EPA (2006) reports that a study on calculation of cumulative energy requirements for the production of chemical intermediates and the products published in World Energy Conference 1963, is one the first publication in its kind.

Foundation of the current methods of the life cycle inventory analysis is based on the internal study for the Coca-Cola Company in US, 1969 which was conducted by Midwest Research Institute (MRI). Objectives of this study were; choosing glass or plastic for the product bottling, making a choice between internal and external bottle production and end of life options for the chosen bottle. This study was taking into account of the whole environmental impacts, from the raw material extraction to the waste disposal.

The first works on LCA in early 1970s, appears simultaneously in Europe and USA independently. According to EEA report (1997), in 1972, in the UK, a scientist Ian Boustead calculated the total energy used in the production of various types of beverage containers, including glass, plastic, steel, and aluminum. Over the next few years, Boustead consolidated his methodology to make it applicable to a variety of materials.

Other companies in both the United States and Europe performed similar comparative life cycle inventory analyses in the early 1970’s. EPA (2006, p. 4) states that “ the process of quantifying the resource use and environmental releases of products became known as a Resource and Environmental Profile Analysis (REPA), as practiced in the United States. In Europe, it was called an Ecobalance. With the formation of public interest groups encouraging industry to ensure the accuracy of information in the public domain, and with the oil shortages in the early 1970’s, approximately 15 REPAs were performed between 1970 and 1975’’.

After this period, while oil crisis was faded its influence, energy issues declined in prominence. Between 1975s and 1980s environmental concerns shifted to issues of hazardous and household waste management. Guinee et al. (2010) emphasizes that after this period of decreasing public interest in LCA, there has been a rapidly growing interest in the subject from the early 1980s on. In 1984 the Swiss Federal Laboratories for Materials Testing and Research (EMPA) published a report presenting a comprehensive list of the data needed for LCA studies which was paving the road for broader application of LCA.

By the mid-1980s, multi-criteria analysis had branched out to nappies, appliances, automobiles and housing. During this time, European interest grew with the establishment of an Environment Directorate (DG X1) by the European Commission parallel to interest in USA. In 1988 solid waste turned out to be an international issue and LCA came up again as a tool for environmental assessment.

Society of Environmental Toxicology and Chemistry (SETAC) organized an international workshop in1990. The term ‘life cycle assessment’ was first proposed and agreed in this workshop, USA. This was an important step which gives a start of rapid growth of LCA between 1990-2000. In this period, worldwide scientific and coordination activities smoothed the way for development of standards, handbook, guidelines and publishing of the first scientific LCA journals. EPA (2006, p. 5) interprets that “the action, along with pressure from other environmental organizations to standardize LCA methodology, led to the development of the LCA standards in the International Standards Organization (ISO) 14000 series (1997 through 2002)”. In this decade, LCA also came into use in policy and legislations, starting with legislations on packaging in EU and Japan Guinee et al. (2010). Well-known LCA methods are originated in this period.

The last ten years between 2000-2010, is a decade of elaboration. The United Nations Environmental Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) launched the UNEP/SETAC Life cycle Initiative in 2002, with an international partnership to assist development of LCA. The aim of initiative was to enable users to put life cycle thinking into practice, in Europe, USA and Japan (Horne 2009). Accordingly, environmental policy gets increasingly life-cycle based all over the world. For example, several life cycle-based carbon footprint standards have been established.

Accordign to Guinee et al. (2010), the next decade will be called the decade of life cycle sustainability analysis. It will broaden the scope of current LCA from mainly environmental impacts only to covering all three dimensions of sustainability (people, planet, and prosperity).

2.3. Literature Review: State of the Art of the LCA within the Construction Sector

Sustainable development indicators defined by the UNEP/SETAC Initiative, designate the construction sector as the globally emerging sector for both northern and southern countries.[7] Even though it ensures huge capacity of employment, the

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[7] According to Turkey Construction Materials Sector Report, 2011, the global construction sector growth forecast for 2009-2014 period demonstrates the growth rate of 7.9% for the Asia Pacific, 7.2% for the

construction sector is the single biggest contributor to GHG emissions. Besides, it is responsible for solid waste generation, high energy consumption, environmental damage and resource consumption (Ortiz 2009, UNEP SBCI 2011). Yet, at the same time, it also holds the greatest potential to reduce its impacts over the environment. Increasing environmental awareness in the construction sector has resulted in the proliferation of environmental assessment tools for buildings and application of life cycle assessment (LCA) methodologies (SETAC).

The potential users of LCA methodology in construction sector are the consultants of municipalities, e.g. urban designers setting benchmarks at municipal level, property developers and clients setting environmental targets, architects comparing design alternatives in terms of geometry, orientation and technical choices, and engineers comparing design solutions in collaboration with architects (Bribian 2009). The LCA methodology has also been applied in such different areas of construction sector as policy making in national or regional level, evaluation of existing building stock, and environmental labeling and /or certification of buildings. Furthermore, according to Ortiz (2009), the LCA can be utilized in decision making process in order to improve sustainability in the construction sector, and to overcome increasing environmental concerns of today.

European commission Research Center and Seventh Framework Programme for Research has funded EeBguide Project in 2012 as the operational guidance for life cycle assessment studies of the energy efficient buildings initiative.

EeBGuide (2012) states that “Several European projects dealing with LCA and buildings have been conducted over the past few years. Most of them were aimed at adapting the methodological rules for LCA studies in the construction sector and enabling the development of user-friendly tools that can be used by building stakeholders, who are usually not LCA experts”. REGENER, Annex 31 IEA, PRESCO, IMPRO-Building, ENSLIC Building and LoRe-LCA are examples of these projects.

Khasreen et al (2009) states that the application of LCA in building sector has become a distant working area within the LCA practice. He underpins this statement by introducing five dynamics:

- complexity of buildings,

Eastern Europe, 6.1% for the South America, 6.0% for the North America, 5.2% for the Africa and 1.4% for the Western Europe. In this picture, Turkey is one of the fastest growing markets with 8.5% growth forecast between 2006 and 2014.

- long life time of buildings,
- possible changes during life time of buildings,
- significance of using phase performance depending on critically design and material selection,
- presence of many stake holders in construction sector.

The LCA is indeed a powerful and widespread method to quantify complex environmental impacts over its whole life cycle of a building material, building component or whole building by looking at from a range of different environmental impact categories (Szalay 2007). There are three basic options for bringing the LCA into building design decisions: at the product level, the assembly level and whole building level. Moreover, in terms of common application areas of LCA into the construction sector, the studies focus on either on the whole processes of construction (WPC) or the building material and component combinations (BMCC). While the WPC can provide holistic screening of all the material processes and building life cycle phases, in other words, whole process of construction, the BMCC is concerned with a part of the building, building component or material.

The following part introduces a comprehensive literature review conducted over seventy one LCA case studies published between 1998 and 2012 from twenty seven countries. The aim of this review is principally to discuss the WPC versus BMCC LCAs as two different approaches of the LCA application in the construction sector, in terms of characteristics, differences, advantages and limitations. Providing an up to date literature by broadening previous reviews such as by Ortiz (2009), Khasreen (2009) and Sharma (2011) is the second objective of this review, since the LCA literature related to building sector is rapidly growing.

Seventy one LCA case studies published between years 1998-2012, from twenty seven countries have been analyzed. It is seen that majority of the cases are from Europe and USA, as northern countries. Published LCA case studies show a rapid increase starting in 2005 up today. While 57% of the cases have been applied to WPC, 43% of the cases have been applied to BMCC.

2.3.1. Comparison of Whole Process Construction versus Building Material and Component Combination

The comprehensive literature review indicated that the majority of case areas are from the Europe and the U.S.A., i.e. the northern countries. The published LCA case studies demonstrate a rapid increase starting with 2005. 57% of the cases have been applied to the WPC approach, while the rest had the BMCC one. The WPC cases cover different functions of buildings like residential, office, educational and retail. The review results point out that the widest examined functional group is the residential buildings with a 73% rate, followed by office buildings with 19% (Table 2.2).

The LCA for WPC studies has variable character, in other words, they have more than one aim. While the whole impact analysis of building is the most common and principal goal, there are many other goals and focus points in parallel to complexity of buildings.

From the reviewed scientific literature it was found that comparative LCA, hotspot determination and evaluating building footprint are the main approaches in performing whole process construction LCAs. Comparison in WPC studies is divided up in two common types: building comparison and scenario comparison. Comparative building LCAs are mostly performed between buildings:

- With the same function in different geography (countries, climates regions)
- With the same function with different material, component or structure properties.

Scenario comparison approach is generally performed as:

- A building versus its improved versions
- A building versus its different material, component, structure or system options.
- Energy performance improvements versus environmental impacts

Hotspot determination is another significant approach in WPC LCA which can be also a part of the comparative LCA. This approach provides determination of the most effective points over the building total environmental impact. The focus point can be:

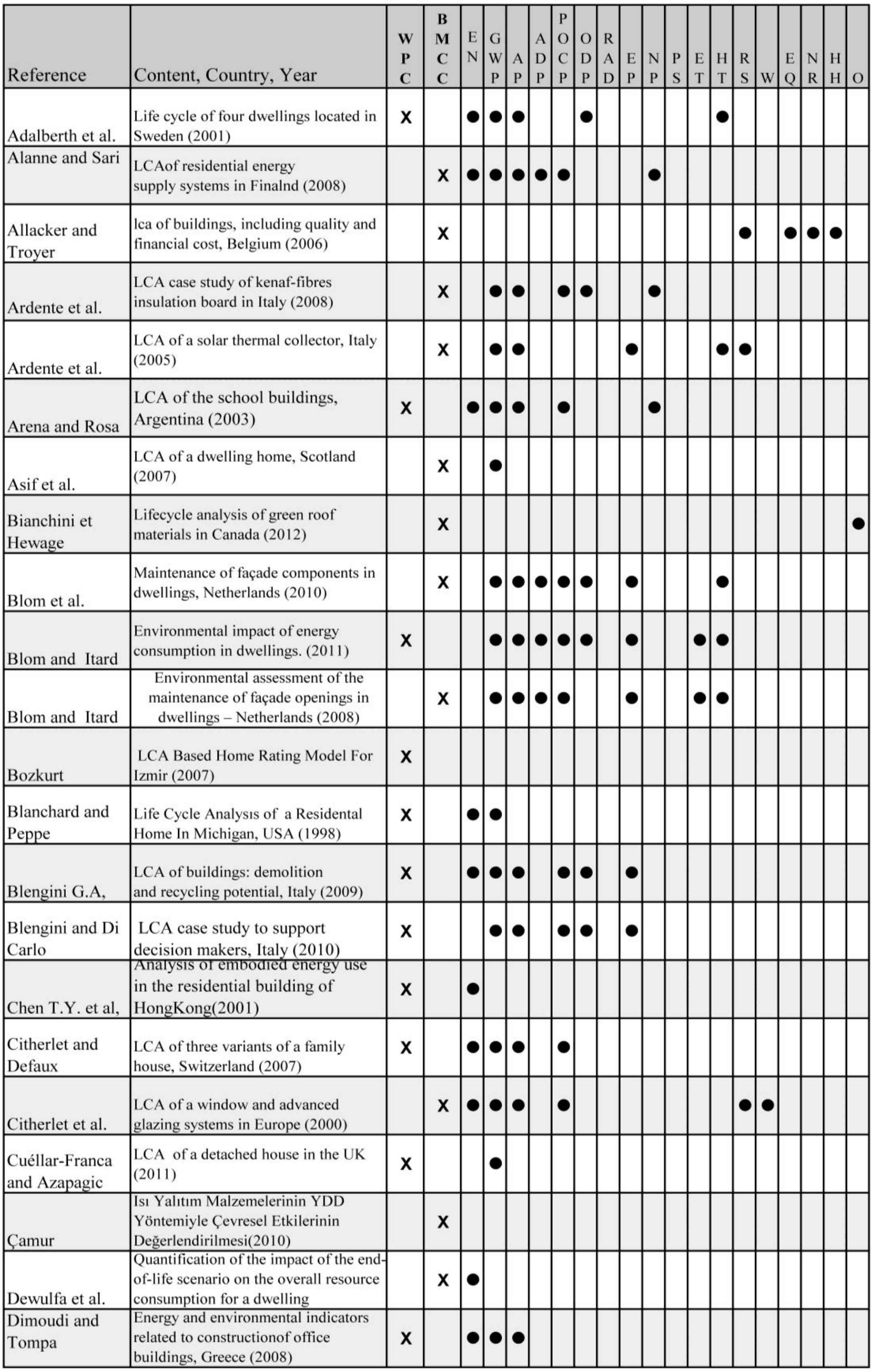
- A specific life cycle phase or phases,
- A specific building material/component,
- A specific building material/component in a specific life cycle phase.

Building total footprint is a holistic approach providing detailed environmental impact analysis. The main goal is not to compare or to determine hotspots but it can contain these approaches also. It provides environmental information from a further aspect without the aim of judgment whether the building is “good” or “bad”.

BMCC studies focuses on building materials and components or systems in particular. Khasreen (2009, p. 689) states that “many industrialized countries have made steps towards environmental improvement of the construction process, building occupation and demolition, and these steps differ to the extent that building construction is strongly determined by local traditions, local climate and locally available natural resources. As a result, many LCA studies calculating the environmental impacts of BMCC have been done during the last fifteen years “.

It is found that the functional unit (FU) for the whole building can be a building or m2 usable floor area for a specified life span. According to the goal of the LCA functional unit can be expended with additional parameters as occupancy, performance or site.

Table 2.2. Published LCAs Applied within the Building Sector in World Wide Between 1998-2012 with Additional Information.



Reference	Content, Country, Year	WPC	BMCC	EN	GWP	AP	ADP	POCP	ODP	RAD	EP	NP	PS	ET	HT	RS	W	EQ	NR	HH	O
Adalberth et al.	Life cycle of four dwellings located in Sweden (2001)	X		●	●	●			●						●						
Alanne and Sari	LCAof residential energy supply systems in Finalnd (2008)		X	●	●	●	●	●				●									
Allacker and Troyer	lca of buildings, including quality and financial cost, Belgium (2006)		X													●		●	●	●	
Ardente et al.	LCA case study of kenaf-fibres insulation board in Italy (2008)		X		●	●		●	●			●									
Ardente et al.	LCA of a solar thermal collector, Italy (2005)		X		●	●					●				●	●					
Arena and Rosa	LCA of the school buildings, Argentina (2003)	X		●	●	●		●				●									
Asif et al.	LCA of a dwelling home, Scotland (2007)		X		●																
Bianchini et Hewage	Lifecycle analysis of green roof materials in Canada (2012)		X																		●
Blom et al.	Maintenance of façade components in dwellings, Netherlands (2010)		X		●	●	●	●	●		●				●						
Blom and Itard	Environmental impact of energy consumption in dwellings. (2011)	X			●	●	●	●	●		●			●	●						
Blom and Itard	Environmental assessment of the maintenance of façade openings in dwellings – Netherlands (2008)		X		●	●	●	●			●			●	●						
Bozkurt	LCA Based Home Rating Model For Izmir (2007)	X																			
Blanchard and Peppe	Life Cycle Analysıs of a Residental Home In Michigan, USA (1998)	X		●	●																
Blengini G.A,	LCA of buildings: demolition and recycling potential, Italy (2009)	X		●	●	●		●	●		●										
Blengini and Di Carlo	LCA case study to support decision makers, Italy (2010)	X			●	●		●	●		●										
Chen T.Y. et al,	Analysis of embodied energy use in the residential building of HongKong(2001)	X		●																	
Citherlet and Defaux	LCA of three variants of a family house, Switzerland (2007)	X		●	●	●		●													
Citherlet et al.	LCA of a window and advanced glazing systems in Europe (2000)		X	●	●	●		●								●	●				
Cuéllar-Franca and Azapagic	LCA of a detached house in the UK (2011)	X			●																
Çamur	Isı Yalıtım Malzemelerinin YDD Yöntemiyle Çevresel Etkilerinin Değerlendirilmesi(2010)		X																		
Dewulfa et al.	Quantification of the impact of the end-of-life scenario on the overall resource consumption for a dwelling		X	●																	
Dimoudi and Tompa	Energy and environmental indicators related to constructionof office buildings, Greece (2008)	X		●	●	●															

(cont. on next page)

Table 2.2. (cont.)

Reference	Content, Country, Year	WPC	BMCC	EN	GWP	AP	ADP	POCP	ODP	RAD	EP	NP	PS	ET	HT	RS	W	EQ	NR	HH	O
Dodoo and Gustavsson	Life cycle primary energy implication of retrofitting a wood-framed apartment building, Sweeden (2010)	X		●																	
Gustavsson et al.	Life cycle primary energy use and carbon emission of a wood-framed apartment building, Sweeden (2010)	X		●																	
Gustavsson and Sathre	LCA Sweden case study: wood and concrete in building materials, Sweeden (2006)		X	●																	●
Gerillaa et al.	An environmental assessment of wood and steel reinforced concrete housing construction, Japan (2007)	X		●	●																
Gervásio and Silva	Influence of end-of-life scenarios on the environmental performance of a residential dwelling, Portugal (2008)	X														●		●	●	●	
Glaumann et al.	Basic LCA Application :Residential Building Case Study - Gronskar, Sweden (2008)	X		●	●																
Haapio and Viitaniemi	Environmental effect of structural solutions and building materials to a building, Finland (2008)	X		●	●											●	●				
Haynes	Embodied Energy Calculations within Life Cycle Analysis of Residential Buildings(2010)	X		●	●																
Huberman and Pearlmutter	A life cycle energy analysis of building materials in the Negev desert, Israel (2007)		X	●												●					
Iyer-Raniga et Wong	Evaluation of whole life cycle assessment for heritage buildings in Australia (2012)	X		●	●			●			●										●
Junnila et al.	Comparative LCA of office buildings in Europe and the United States, Finlanf-USA (2006)	X		●	●																
Junnila	LCA for a construction of an office, Finland (2004)	X			●	●					●		●								
Jonsson et al.	LCA of Concrete and Steel Building Frames, Sweeden (1998)	X		●	●											●					
Koroneos et al.	LCA of an office building in Greece (2007)	X			●	●	●	●	●	●	●										
Koroneos and Dompros	LCA of brick production in Greece (2007)		X		●	●					●		●			●	●				
Koroneos and Kottas	LCA for energy consumption in the use phase for a house in Thessaloniki, Greece (2007)	X		●	●	●			●		●										●
Kosareo et al.	Comparative environmental life cycle assessment of green roofs, USA (2007)		X		●	●			●		●										
Marceau and Vangeem	Comparison of the LCA of an insulating concrete form house and a wood frame house, USA (2008)	X			●	●			●	●	●			●	●	●	●				
Matasci	LCA of 21 buildings, Switzerland (2006)	X														●		●	●	●	
Monahan and Powell	An embodied carbon and energy analysis of modern methods of construction in housing, UK (2011)	X		●	●																
Nebel et al.	LCA for floor covering, Germany (2006)		X	●	●	●		●	●		●										
Nemry and Uihlein	Environmental Improvement Potentials of Residential Buildings (IMPRO-Building) (2008)	X		●	●	●		●	●		●										

(cont. on next page)

Table 2.2. (cont.)

Reference	Content, Country, Year	**WPC**	**BMCC**	EN	GWP	AP	ADP	POCP	ODP	RAD	EP	NP	PS	ET	HT	RS	W	EQ	NR	HH	O
Nicoletti et al.	LCA of flooring materials (ceramic versus marble tiles), Italy (2002)		X		●	●	●	●	●			●			●						●
Nyman and Simonson	LCA of residential ventilation units over a 50 year life cycle in Finland (2005)		X		●	●		●													
Ortiz	Sustainability based on LCM of residential dwellings: A case study, Spain(2009)	X			●	●	●		●						●	●					
Ortiz et al.	The environmental impact of the construction phase: An application to composite walls from a life cycle		X	●	●	●										●					
Peuportier	Comparison of three types of houses with different specifications located in France (2001)	X		●	●	●	●	●	●		●		●	●	●	●	●				
Petersen and Solberg	LCA by comparing wood and alternative materials in Norway and Sweden (2005)		X	●		●			●		●				●						
Prek	LCA of heating and air conditioning systems for a single family dwelling in Slovenia (2004)		X		●				●												
Ramesh et al.	Life cycle energy analysis of a residential building with different conditions in India (2012)	X		●																	
Saiz et al.	LCA for green roofs located in downtown Madrid, Spain (2006)		X		●	●	●	●	●		●			●	●						
Scheuer et al.	Life cycle energy and environmental performance of a new university building: modeling challenges and	X		●	●	●			●			●					●				
Shah et al.	Life cycle assessment of residential heating and cooling systems in four regions in the United States (2008)		X		●													●	●	●	
Seppala et al.	LCA for Finnish metal products (2002)		X		●	●			●		●										
Somtua and Yossapol	Comparative LCA of Residential Buildings in Thailand Using Two LCIA Methods-P (2009)	X																●	●	●	
Tae et al.	Life cycle CO2 evaluation on reinforced concrete structures, Korea (2011)		X																		
Thiers and Peuportier	Life Cycle Assessment of a positive energy house in France (2009)	X		●	●	●				●	●		●	●		●	●			●	
Thormark	LCA of residential houses in Sweden (2001)	X		●																	
Trusty and Mail	Building Life Cycle Assessment: Residential Case Study, Canada	X		●	●									●		●	●				
Van Ooteghem et Xu	The life-cycle assessment of a single-storey retail building in Canada(2012)	X		●	●																
Wallhagen et al.	An LCA Case study on an office building in Sweden.(2011)	X		●	●																
Van der Lugt. et al	LCA for using bamboo as building material versus steel, concrete and timber in Western Europe (2010)		X																		●
Wang et al.	A Building LCA Case Study Using Autodesk Ecotect and BIM Model USA (2011)		X	●	●																●
Welz	Environmental impacts of lighting technologies, LCA and sensitivity analysis, Switzarland (2011)		X	●	●																

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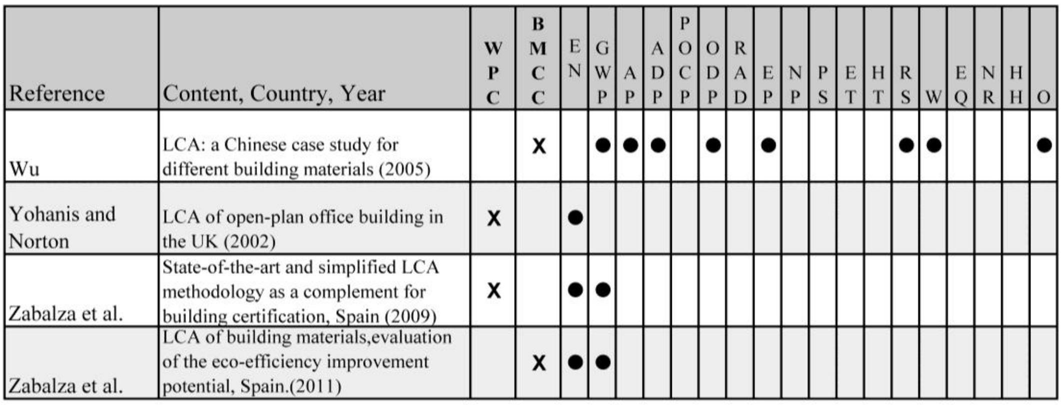
Table 2.2. (cont.)



Reference	Content, Country, Year	WPC	BMCC	EN	GWP	AP	ADP	POCP	ODP	RAD	EP	NP	PS	ET	HT	RS	W	EQ	NR	HH	O
Wu	LCA: a Chinese case study for different building materials (2005)		X		●	●	●		●		●					●	●				●
Yohanis and Norton	LCA of open-plan office building in the UK (2002)	X		●																	
Zabalza et al.	State-of-the-art and simplified LCA methodology as a complement for building certification, Spain (2009)	X		●	●																
Zabalza et al.	LCA of building materials,evaluation of the eco-efficiency improvement potential, Spain.(2011)		X	●	●																

Abbreviations: WPC, whole process construction; BMCC, building and materials components combinations; EN, energy consumption; GWP, global warming potential; AP, acidification; ADP, depletion abiotic resource; POCP, photochemical ozone creation; ODP; ozone layer depletion; RAD, radiation; EP, eutrophication; PS: photo-smog; ET, eco-toxicity; HT, human toxicity; RS, resources consumption; W, waste creation; EQ, ecosystem quality; NR, non-renewable resources; HH, human health; O, others.

The functional unit for the building material and component combinations is mostly focusing on the kg or m^2 of the product. If the subject is a component FU can be also a number of product and FU can be expended with a defined geometry and a specified performance.

Application of the whole process construction LCA is basically divided in three common phases as pre-use, use and end of life.[8] While nearly half of the WPC studies from literature cover all phases, there are also studies which are neglecting one phase or focusing to a single phase. Each life cycle phase has also sub-phases and some of the studies which cover all life cycle phases could be not covering all sub-phases.

Table 2.3. Building Life Cycle Phases (by Author)

PRE-USE	material production
	transportation
	construction
USE	operation
	maintanence
	refurbishment
END of LIFE	deconstruction/demolition
	transport
	recycling/reuse
	disposal

---

[8] According to CEN 350 the building´s life cycle stages include: product stage, construction stage, use stage and end-of-life stage. But these stages can be simplified considering product and construction stages can be interpreted in one stage as pre-use.

Table 2.3 shows the detailed sub-stages of these three main life cycle phases of a building. Pre-use phase consists of material production (raw material extraction, production of materials, transportation, and manufacturing of building components), transportation (transportation of building materials and components to the site) and construction (energy used for on-site construction works, on-site waste management). Use phase covers operation (operational energy, waste, resource consumption and transportation of occupants), maintenance and refurbishment sub-stages. End-of-life phase mainly includes demolition/deconstruction (energy for demolition/deconstruction works), and waste management (recycling/reuse/disposal) sub-stages. There are also studies which uses simplified LCA for buildings.

WPC shows a character which is not static; it varies according to scope and boundaries of each case. Whereas 'cradle to gate or cradle to grave' is the major differentiation in determining main approach in BMCC LCA studies. Cradle to gate is an industry specific approach for general products. When cradle to gate is applied to building materials and components, performance during life span is also important.

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

2.3.2. Whole Process Construction

Life cycle assessment studies focusing whole process construction (WPC) are evaluated by grouping according to building types as dwellings and offices.

2.3.2.1. LCA for Dwellings

From the reviewed scientific literature it is found that 31 of the studies listed in Table 2.2. deal with dwellings which constitutes 43% of the all studies and 75% of the WPC studies. This significant ratio demonstrates the general trend in LCA of buildings concentrated on dwellings.

Blancahard and Peppe (1998), state that historically, focus has been on understanding energy use during the operational period of the home (use phase) which was neglecting the embodied energy of construction materials and end of life impacts and argue that to understand overall environmental impacts of the building, as a complex product, all life cycle stages should be inventoried. In this review there are 16 studies following this approach.

Blancahard and Peppe (1998), conducted a scenario comparison LCA on a standard home (SH) versus the Energy Efficient Home (EEH) based on SH plan, in Michigan, USA. The object of study was a 2,450 ft2 home selected because of its close size of new homes built in the US and standard construction materials and techniques. The functional unit was a home with a 50 life span. Determining the relationship between material production/construction (pre-use) phase energy, and use phase energy, as energy efficiency strategies are applied to various home systems is the main goal of the study. Pre-use, use and end of life phases are particularly studied. While GWP and primary energy are two environmental indicator focused in this study, a life cycle cost study is also conducted. The results show that total life cycle energy of a new residential home can be reduced by a factor of 2.8 by making incremental design changes that reduce the embodied energy, and the use-phase energy consumption of the home.

An LCA case study carried out by Blengini and Di Carlo (2010) to support decision makers in Piedmont Region Italy, in terms of energy policies and low energy buildings. A recently built low-energy individual family house was selected as an outstanding example of resource efficient building. The aim of this study is to determine the benefits corresponding to the reduction of operational energy could be confirmed in a life cycle perspective. The functional unit is 1 m^2/year for a 250m^2 building with 70 year life span. In parallel to the Blanchard and Peppe's study, a comparative LCA study is performed regarding the LCA model of the low-energy house (LEH) versus a second model relevant to the same house (SH), but with standard winter energy requirement and conventional equipment. Hotspots in material-related and life cycle phase impacts also evaluated by using midpoint indicators with Simapro software and ecoinvent database. While the winter heat requirement was reduced by a ratio of 10:1, the life cycle energy was only reduced by 2.1:1 and the carbon footprint by 2.2:1.

Citherlet and Defaux (2007), studied the energy and environmental comparison of three variants of a family house during its whole life span. An individual family house for two occupants is the subject of the study. Comparative scenario analysis of three variants of the family house as SIA standard, Minergie and low-energy to evaluate the total environment impacts during the whole life cycle is the main goal of the study. A contribution analysis for life cycle phases of each variant is also conducted to evaluate hotspots in a phase-scenario relation. A midpoint approach is fallowed in impact assessment and data is taken from ESU database. This study generally confirmed, the indirect impact is important when the total energy demand is lower than about 150 $MJ/m^2/y$ for Swiss mix electricity production and lower than about $50MJ/m^2/y$ for UCTE mix. When the energy demand is higher than these values, it is preferable to stress the reduction of direct impacts first, such as improving the envelope insulation or promoting the use of renewable sources of energy.

Life cycle assessment of a typical detached housed in UK, is studied by Cuellar and Azapagic (2010). The principal goal of the study is to evaluate the life cycle carbon footprint of a detached brick house with the aim of identifying the hot spots and improvement opportunities along the supply chain. All life cycle phases are under consideration and the chosen functional unit is the performance of a detached house of 222 m2 of floor area over 50 years life span. It is found that the total carbon footprint over the life time of the house is equal to 835 t CO2 eq. While operation of the house ids responsible 90%of this amount, 9% comes from construction, and 1% is from the end-of-life stage.

Gustavsson et al. (2010), calculated life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building, recently built in Sweden. Alternative scenarios with different energy supply systems are also investigated. They concluded that it is important to adopt a life cycle perspective involving both material and energy supply when evaluating the primary energy and climatic impacts of buildings.

Gerillaa et al. (2007) conducted a comparative environmental assessment of wood (conventional and prevalent construction type in Japan) and steel reinforced (rising tend) concrete housing construction. LCA of the two different housing construction types is traced, environmental impacts are determined and three improvement assessment scenarios are simulated. Kilogram of emission per year per square meter is the functional unit of this study focusing to the emissions to air during whole life stages of the house. GWP, AP, EP and HT are evaluated midpoint environmental indicators. GWP has the highest contributor to environmental impact for both type of construction and SRC construction has a higher environmental impact compared to that of the wooden type of housing construction. Analysis of the improvement options confirmed that combination of a 75 year design life and the use of solar energy in the operation phase of the household give about an 84% reduction in total life cycle carbon emission.

Haapio and Viitaniemi (2008), analyzed the effect of different structural solutions and building materials on the results of the environmental assessment of a whole building over the building's life cycle. 78 single-family houses were evaluated for this study with a building environmental assessment tool ATHENA. The focus of the study is on the envelopes of the buildings while the interiors of the buildings are assumed to be identical. Different life span alternatives from 60 up to 160 years are also investigated as a further research.

Eight residential heritage buildings in Victoria, Australia with different envelopes, structural framework, construction, age and climatic locations are evaluated by Iyer-Raniga and Wong (2012), regarding whole life cycle assessment. The functional unit of this comparative study is one square meter floor area of a building. While life cycle environmental footprint and life cycle primary energy of these eight houses is compared, a comparative scenario analysis for improvement options is also conducted. According to findings of this study lower life cycle primary energy consumption does not necessarily lead to lower carbon emissions as carbon reduction depend on a combination of primary energy consumption, magnitude of heating and cooling, fuel mix profile and efficiency of the conventional grid.

One of the earlier studies of LCA of buildings was carried out by Jonsson et al. in (1998). They conducted an LCA study in Sweden, comparing concrete and steel building frames to learn about the environmental impact of these structural frames in buildings throughout the life cycle. Seven representative buildings covering offices and dwellings are the subject of this study. One square meter of floor area during the lifetime (50 years) of the building based on Swedish building standards, is defined as functional unit appropriate for comparison. Global warming potential, energy and resource consumption are the environmental indicators. It is found that the choice of frame construction is only a small part of the total impact of the building.

Marceau and Vangeem (2008), from Portland Cement Association studied an LCA of concrete construction compared to wood-framed construction conducted on a single family house modeled with two types of exterior walls: a wood-framed wall and an ICF wall. Climate scenarios for five representative cities in US (Miami, Phoenix, Seattle, Washington (DC), and Chicago) were applied to the house model to evaluate these two options energy performance under this representative range of US climates.

DOE-2 was used to evaluate building performance and Simapro for LCA. They concluded that for a given climate, wood house has a greater impact than IFC house in each environmental category. The impacts from electricity and natural gas production and also the use of these energy sources in the houses by the occupants are founded more significant than the construction materials.

A life cycle assessment study of 21 existing buildings in Switzerland, aiming to analyze different life phases and highlighting of the main causes of their impact on the environment carried out by Matasci (2006). Subject buildings consisting different building types are categorized as single occupancy houses (EFH), apartment houses (MFH), service buildings (DLG) and manufacturing buildings (PRG). Construction techniques are also varying as reinforced concrete, wood, brick and steel. A square meter of gross external floor area is chosen as functional unit for this comparative LCA study and data taken from Ecoinvent. All life cycle phases are taken into account and an endpoint impact assessment method is used. As one of the significant results the use phase has the greatest impact fallowed by renovation, construction and disposal.

‘Environmental improvement potential of residential buildings in Europe’ (IMPRO-Building) project which is a scientific contribution of the JRC to the European Commission’s IPP framework seeking to minimize the environmental impacts of buildings conducted by Nemry and Uihlein (2008). IMPRO-Building is a comprehensive and systematic study containing household dwellings, from single-family houses to multi-apartment buildings, including existing and new dwellings in the EU-25. Midpoint impact indicators and primary energy (renewable and non-renewable) are calculated. The functional unit of the LCA is the use of 1 m^2 of the building’s living area over a 1 year period. This study emphasizes that energy use has an important share in quantified environmental impacts as a result of space heating and building products h fallowing as second important contributor. They stated if the measures examined are carried out on the buildings considered, the emissions of greenhouse gasses from these buildings may be cut by around 30 to 50% over the next 40 years and also they emphasize that the information in this study provides the basis for discussions on measures and steps that can be taken in that direction.

Peuportier (2001), applied life cycle assessment for the comparative evaluation of single family houses in the French context. The principal goal of this study was to apply the developed environmental assessment tool EQUER linked to the thermal simulation tool COMFIE. It is emphasized the importance of dynamic simulation rather than the correlation. A house being selected in a solar house competition in France (Observ'ER house), is compared with a typical standard French house (reference house) and a well insulated wooden frame house (CNDB house). The inventory data are from REGENER and Ecoinvent database. All life cycle phases are taking into account. Midpoint method (CML) is used for impact assessment and 12 indicators are investigated. It is found that high thermal insulation, use of renewable energy and choice of an efficient heating system remain appropriate measures to reduce the environmental impacts of buildings.

Thiers and Peuportier (2009), conducted a recent LCA study focusing on environmental performance of a ‘positive energy house’, which are often questioned whether techniques, materials and components used to reach a positive energy house requires more amount and energy than a standard one regarding whole life cycle phases. The building under study is the first “Passive-House” buildings in France built in 2007, which constitutes a group of two attached houses with an inhabitable area of 132 m2, for a family of four people. A combination of Equer-Comfie software and Ecoinvent database are used in performing LCA. Three different heating solutions are studied: an electric heat-pump, a wood pellet condensing boiler and a wood pellet micro-cogeneration unit. This study concluded that the PEH building presents high energy and environmental performance, like a GWP limited to about 11 kg CO_2 q./m_2/yr. Although the building is a PEH, the majority of the environmental impacts remain positive during the operation phase. None of the three heating solutions studied found optimal, but it is determined that the PEH can contribute to reduce the radioactive waste production, especially if heat is not provided by a heat pump.

Life cycle assessment of a low energy building ((45 kWh (162 MJ) =m2) in Sweden focusing to the recycling potential and to relate the recycling potential to the energy used for production and operation of the building, is studied by Thormark (2002). The housing under study consists of 20 apartments with a net residential floor area 120m^2. Determined functional unit is m2 residential floor area of an average apartment for 50 years. Energy for erection and demolition was not included in this study. Operational energy calculated by DEROB-LTH software. The recycling potential is calculated for two scenarios; maximum material recycling/combustion and maximum reuse. It is found that the embodied energy accounts for a considerable part about %40 of the total energy need in low energy houses. While the recycling potential found about 35% for material recycling/combustion scenario, for the reuse scenario it was about

39%. They concluded that the recycling potential in the two scenarios accounted for 15% and 17%, respectively, of the total energy use over 50 years.

While nearly half of the residential studies cover all life cycle phases, there are also studies which are focusing on the environmental impacts of the use phase or pre-use-end of life phases depending on their goals.

Chen et al. (2001) conducted a study on the analysis of embodied energy use in the residential building of Hong Kong. Two typical high-rise residential building designs for lower-income groups in Hong Kong are studied. Both buildings have 40-storey. Harmony Block (H1) built in 1992 and New Cruciform Block (NCB) built in 1984. Goals of this study are to develop a model for estimating embodied energy of residential buildings in Hong Kong, to determine embodied energy usage profiles and to provide data on the embodied energy which can be implemented to regionally energy policy on buildings. It is emphasized that while the building material used in the largest quantity is concrete, energy embodied in steel and aluminum may account for more than three-quarters of the total embodied energy in a residential building in Hong Kong.

Blom et al. (2011) performed the environmental impact assessment of building-related and user-related energy consumption for each type of energy in dwellings in Netherlands. It is aimed to understand how to reduce the environmental impact of the energy from gas and electricity delivered to dwellings, considering all production processes. Six different scenarios for annual gas and electricity are compared and energy consumption categorized as building related and user related and a comparative study is also conducted focusing on this. It is concluded that electricity consumption has a higher impact on the environment than gas per MJ of energy. The residential gas consumption found significantly contributed to the environmental impact categories of Abiotic depletion, Global warming, Ozone layer depletion and Human toxicity while for other categories there is a parallel contribution amount with electricity consumption. The analysis shows that the amount of electricity consumed is mainly user-related.

Glaumann (2008), applied a basic LCA approach on a residential building case study in Gronskar, Sweden. Basic MS Excel tool is developed.

Ortiz (2009), carried out a LCA case study on residential dwellings in Catalonia, Spain. A typical Spanish Mediterranean house located in Barcelona with a total area of 160m2 and a projected 50 year life span, which has been modeled according to the Spanish building technical code (CTE) is understudy. The aim of this research is to use sustainability indicators in the pre-construction and operation (use and maintenance) phases and also to support decision-making within the building sector. Functional unit (FU) for this case is m^2 usable floor area of a dwelling with a projected 50-year life span and four people living in the house. Pre-use phase containing material production, transport, construction sub-phases and use phase containing operation and maintenance sub-phases are focused life cycle phases in this research. End-of life phase is neglected because of the lack of data on materials recovery. CML method is used as a midpoint approach. Design builder interface and Energy Plus software are used to evaluate annual energy use in operation phase. Life cycle assessment is performed using LCA-Managers software by SIMPPLE and Ecoinvent database for life cycle inventory. Ecopoints is preferred for final presentation. According to distribution of the environmental impacts of the dwelling life cycle, use phase is responsible for 80-92% of the impacts.

Somtua and Yossapol (2009), studied comparative life cycle assessment of residential buildings in Thailand using two LCIA methods. This is one of the few studies from Far East in this review. Four Thai style single residential buildings are assessed with a functional unit 1 m^2 of useable space of the house over 50 years. BEES and Ecoindicator 99 methods are chosen for environmental assessment. While BEES focuses on environmental, economic and material aspects, EI 99 assesses damages on human health, ecosystem quality and resources. Pre-use (material production, transport, construction) and use (maintenance, operational energy) phases is understudy. Life cycle inventory database appears as a limitation for Thailand case and existing databases available in BEES and Simapro are used. It is found that Northeastern house has the biggest environmental impact for both methods.

Trusty and J. K. Meil from ATHENA Sustainable Materials Institute presented a partial comparative life cycle assessment study of a three alternative material designs of a custom 2400 sq. ft. single-family home built for the Toronto market. Softwood lumber and wood I-joist framing, light frame steel for structure and uses insulated concrete forms (ICF) for the basement and exterior walls and Hambro floor system are three design alternatives.

A case study aiming integration between LCA and building certification in Spain is conducted by Bribian et al. (2009). A simplified methodology has been developed to complement the results provided by the Spanish building certification software with an LCA approach. Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential of building materials are performed by this proposed simplified approach which has been developed on an Excel spreadsheet. The case is a single-family home (terraced) of 222 m2 with a total volume of 502 m3, in Zaragoza. The house has a combined heating and air conditioning system made up of a conventional 28 kW natural gas boiler with a nominal performance of 92%. According to simulation results performed by CALENER VYP programme, building energy classification obtained as ‘’B’’ which means At the use stage, the total emission is 15 kg of CO^2 per m2 per year and the primary energy consumption is 71.1 kWh/m2 per year. According to simplified LCA results embodied energy represents 31% of the total energy requirement during the building’s life span. It is emphasized that this significant amount of energy is ignored in the building certification. While the major energy consumption occurred by heating the second is the building materials.

In some studies use phase is neglected and pre-use and end of life phases are studied. This approach usually reflects the embodied energy analysis in life cycle assessment and evaluated environmental impact category is only the global warming potential.

Chen et al. (2001), conducted an analysis of embodied energy use in the residential building of Hong Kong. Analysis of building envelopes are studied by developed model for estimating the intensities of the embodied and demolition energy. Two typical high-rise residential buildings, The Housing Authority Harmony 1 and the New Cruciform blocks, are understudy. It is found that steel and aluminum are the major contributors to calculated embodied energy for more than three-quarters of the total despite the concrete has the largest amount in total materials used. It is also emphasized that imported building materials has a significant impact on embodied energy use.

Gervásio and Silva (2008), studied the life cycle analysis of a light weight steel dwelling in Portugal to determine the significance of the Influence of different options for end of life stage and how it affects the overall results of the analysis. A one family dwelling containing 2 main floors, with an area of 165 m2 each, and a smaller top floor with an area of 115 m2 is the subject of this study. The functional unit is a lightweight steel dwelling designed for a service life of 50 years. While pre-use and end-of-life phases are considered with all sub-phases, use phase is neglected. Ecosystem quality, resources and human health are evaluated by a damage oriented method Eco-indicator 99. The inventory data needed for the analysis is gathered from Ecoinvent, ETH-ESU and Buwal 250 databases supplied by Simapro software. Flowcharts for each phase are presented and hotspots are determined. Results for construction stage represents that steel production is responsible for highest impacts with a 2.88 kPt and a share of more than 50%. Damage assessment for the construction is also show that steel production is the largest contributor to damages on human health, ecosystem quality and resource consumption. Comparative scenario analysis for three end of life options as landfill, recycle and reuse is conducted. It is found that landfill scenario causes the most environmental damage.

2.3.2.2. LCA for Office Buildings

Dimoudi and Tompa (2008), investigated energy and environmental indicators related to construction of office buildings. Two office buildings in Athens with different morphology and size but under the same national standard are studied. The aim of this research is to determine the embodied energy and equivalent emissions of different construction materials in office buildings. Building-1 is a five story office building with 1891 m^2 usable area. It has a reinforced concrete structure and double brick walls (0.27m thickness) with core thermal insulation, a 5-cm thick extruded polystyrene layer and mortar as composite external wall. Building-2 is a three-storey office building with a 400 m^2 useable floor area which has a reinforced concrete structure. The external wall composition constitutes double brick walls (0.27m thickness), with core thermal insulation of a 5-cm thick mineral wool layer and aluminum composite panel. It is found that the embodied energy of building-1 reaches the value of 3647 GJ while for building-2 the corresponding value is 1309 GJ, corresponding with 378 tn CO_2 and 1.5 tn SO_2 for building-1 and 116 tn CO_2 and 0.5 tn SO_2.

Comparative LCA study of office buildings in Europe and the United States is performed by Junnila et al. (2006). A typical new office building in Southern Finland and a typical new office building in the Midwest region of the United States are studied in terms of total energy and environmental impacts. Investigating the relative contribution of each building life cycle phase to the total energy and environmental effects and identifying environmental hotspots are emphasized as the major subjects of this study. Full life cycle phases are studied and identical for both cases. The European building is a new office with 4,400 m^2 of gross floor area, having four floors and a structural frame with a steel-reinforced concrete system. The U.S. building has 4,400 m2 of gross and a structural frame with steel-reinforced concrete beam-and-column system with shear walls at the core.

Junilla (2004), studied life cycle assessment of environmentally significant aspects of an office building in Finland. Goal of this study was to quantify and compare the potential environmental impacts of an office building' life cycle. Determination of the most significant life cycle phases and environmental aspects was the related purposes to the main goal. The case building was a new nine storey office building which had 24000 m^2 of gross floor area and volume of 110000 m^3. The buildings was evaluated as sophisticated in terms of building services system which provides energy efficiency with a double façade, computer-controlled valves and shutters. It is stated that calculated heating energy consumption of the building is 15 $kWh/m^3/yr$ which is some 55% below the average heat consumption of new office buildings in Finland and the electricity consumption $39kWh/m^3/yr$ which is some 37% above the average in Finland. WinEtana energy simulation program was used for annual energy estimations. Whole life cycle phases are understudy.

The study found that the operating electricity causes most of the environmental impact during the life-cycle of the office building. The other significant life-cycle phases were the manufacturing of building material, the operating heat and maintenance. The significant environmental aspects of the building life cycle were found to be the electricity in outlet, heating, ventilating and air conditioning, and lighting, the internal surfaces in maintenance and manufacturing, the structural frame in manufacturing, and complementaries in maintenance. The significant aspects were quite predominant since in seven life-cycle elements out of forty they produced over 50 % of the life-cycle impact. The findings of this study support previous arguments that operating energy is a major environmental issue in the life-cycle of an office building, and that some specific building materials are also significant.

Jonsson et al. (1998) conducted an LCA study of seven concrete and steel building frames representing technology of the day in Sweden. Multi-storey offices and dwellings were studied. One average square meter of floor area during the lifetime of a building, based on Swedish building standards defined as functional unit of the study. Whole life cycle phases as pre-use (material production, transport, construction), use (operational energy), end of life (demolition, disposal) are studied. It is found that over the life cycle, building production from cradle to gate accounted for about the same contribution to total environmental loads as maintenance and replacement of heat losses through external walls during service life, whereas demolition and final disposal accounted for a considerably lower contribution.

LCA of a standard office building in Athens, Greece is performed by Koroneos et al. (2007). The functional unit of this study is one office building for 80 years life span which is the type of functional unit particularly chosen in non-comparative studies. While life cycle assessment of the building includes pre-use and use phase of the building, end of life phase is not included due to the lack of comprehensible data. LCA simulation is performed in Gabi Software. Impact assessment method is CML 2001. It is found that the environmental impacts in use phase were more than 92% and the construction phase contributed by 8% to the total environmental score. ADP, AP, EP, GWP, ODP, POCP, RAD[9] were the studied impact categories and GWP has the largest contribution to the overall score by 78,8% percentage. While the ground floor was found having the largest environmental impact in construction phase, the energy consumption for heating cooling and lighting is responsible for the largest percentage of impacts in use phase.

Wallhagen et al. (2011) conducted a simplified LCA study of a new office building in Sweden. The main goal of the study is to determine the way to reduce energy use and climate change contributions by decisions taken in early building design phases. The basic ENSLIC[10] tool is used to apply a simplified LCA on this existing office building to explore different improvement measures. The building has four stories and 3537m^2 heated area. Structure of the building consists of reinforced concrete, steel load bearing system and glue-laminated wood roof beams. It is stated that selected energy source is the main determinant factor of contributions to climate change. Accordingly, a number of energy source alternatives by replacing the Swedish electricity mix and Gävle district heating with Swedish electricity mix and district heating Stockholm, Nordic electricity mix and district, electricity and heating from coal and building material alternatives are tested.

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[9] . Abiotic Depletion (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP 100 years), Ozone Layer Depletion Potential (ODP), Photochem. Ozone Creation Potential (POCP), Radioactive Radiation (RAD)

[10] ENSLIC definition: Energy Saving through Promotion of LIfe Cycle Assessment in Buildings Project promotes the use of life cycle assessment (LCA) techniques in design for new buildings and for refurbishment, in order to achieve an energy saving in the construction and operation of buildings. This action draw on the existing information generated from previous research projects regarding: design for low energy consumption, integrated planning, environmental performance evaluation of buildings, design for sustainability and LCA techniques applied to buildings (Circe overview, 2012).

The most important measures proved to be changing to CO_2 free electricity, changing construction slabs from concrete to wood, using windows with better U-values, insulating the building better and installing low energy lighting and white goods. Introduction of these measures was estimated to reduce the total contribution to climate change by nearly 50% compared with the original building and the operational energy use by nearly 20% (from 100 to 81 kWh/m^2 yr). Almost every building is unique and situated in a specific context. Making simple analyses of different construction options showed to be useful and gave some unexpected results which were difficult to foresee from a general design experience. This process acts as an introduction to life cycle thinking and highlights the consequence of different material choices.

2.3.3. Building Materials and Component Combination

Alanne and Saari (2008), conducted a study to estimate the environmental burdens of residential energy supply systems through material input and emission factors. Energy supply system of a group of low energy single-family houses in Finland

A LCA case study of kenaf-fibres insulation based on a natural fibre composite material board performed by Ardente et al. (2008), to define the energy and environmental profile of the product. The functional unit of this BMCC study is the mass (kg) of insulating board which involves a thermal resistance R of 1 (m^2 K/W). Cultivation and crop of kenaf, transports along all phases, kenaf fibres refining and manufacturing of the insulation board, installation, maintenance, use and end of life phases are considered. Contribution to the midpoint impact categories is assessed and it is found that GHG emissions are the main contributors to the environmental release. Distribution of the GHG impact percentages by life cycle phases shows that production of polyester fibers phase is the largest contributor for 39% of the total. The other phase's contribution fallows as disposal for 24.9%, transport for 23.1%, fertilizers 8.1%, electricity and methane for 3.4% and cultivation for 1.9% of the total. A comparative study is also conducted to assess the life cycle performance of a kenaf fiber insulation board versus the performances of various replaceable products, as polyurethane, glass wool, flax rolls, stone wool, mineral wool and paper wool. According this comparison highest impacts are related to synthetic materials, while the better performances are due to mineral wools.

Asif et al. (2005) worked on the life cycle assessment of a 3-bed room semi detached dwelling home in Scotland. The aim of the study is to determine embodied energy and associated environmental impacts of the five construction materials i.e. wood, aluminum, glass, concrete and ceramic tiles. The only environmental impacts category assessed is the global warming potential. It is concluded that most significant material in terms of quantity used, embodied energy and accordingly environmental impacts is concrete which is accounted for about 61% of total the total embodied energy of the dwelling. Timber and ceramic tiles fallows concrete in terms of embodied energy by 13% and 14% of the total. It is calculated that the total embodied energy of the dwelling is 227.4 GJ. It is emphasized that although the concrete has smaller values of embodied energy and environmental impacts as a material when compared to other construction materials like glass, aluminum and ceramic tiles in this study, it appears as responsible for a large share of the total values because of its large amount in the construction. Concrete and mortar are also responsible for the 99% of the total CO_2 of the dwelling.

Bianchini and Hewage (2012) performed an LCA study focusing on the analysis of green roof materials. Environmental benefits of green roofs gathered from extensive literature review presented as reduction of energy demand for heating and cooling, mitigation of urban heat island, reduction and delay of storm water runoff, improvement in air quality, replacement of displaced landscape, enhancement of biodiversity, provision of recreational and agricultural spaces, and insulation of a building for sound.

The aim of the study is to drawn attention to the subject that green roofs are considered as a sustainable practice even though the layers of a green roof contains polymers of which production process is highly polluting and assess the life cycle impacts of these materials. Layers of a typical green roof are stated as root barrier layer, drainage layer, filter layer, water retention layer, growing medium layer, vegetation layer. LCA of the polymers is conducted by using Simapro software. Eco-indicator method is used for impact assessment considering four main polluting substances (NO_2, SO_2, O_3 and PM_{10}). It is concluded that air pollution due to the polymer production process can be balanced by green roofs in 13-32 years but manufacturing process of low density polyethylene and polypropylene has many other negative impacts to the environment than air pollution. The current green roof materials needed to be replaced by more environmentally friendly and sustainable products. Green roofs can be sustainable only in long-term base.

Blom et al. (2010) studied the environmental impact of dwellings in use by focusing on maintenance of façade components of a Dutch reference apartment building. The goal of the study stated as assessing the environmental impact of different maintenance strategies for façade components and identifying main contributor factors to the environmental impact categories during this stage. The functional unit of the LCA is the maintenance and replacement of façade components in the reference building for a 70 years period of dwelling operation, including transportation of maintenance workers. The case building for this research is a gallery flat constructed between 1966-1988 which is representative for approximately 208,000 dwellings of this type exist in the Netherlands. A comparative scenario analysis is performed to determine environmental impacts of different maintenance options. Energy performance is also taking into account which is affected by the replacement on the façade components and calculated by Vabi EPA-W software. Ecoprofiles of components and maintenance processes gathered from Ecoinvent Database. CML 2000 Method was used for the impact assessment. It is found that replacing existing single and double glazing with high efficiency double glazing is the most effective scenario for the reduction of environmental impacts. Choosing timber frame instead of PVC frame with a steel core is the second significant scenario.

A comprehensive life cycle assessment study of a window and advanced glazing systems in Europe carried out by Citherlet et al. (2000) within the framework of the European Project IMAGE[11]. This study consists of two parts. In the first part the glazing systems have been decomposed into their main components to perform their LCAs considering whole life cycle phases. The second part is a thermal balance study which aims to compare chosen specific test-windows, in terms of energy costs, in a room containing this window for different climates and orientations. Glass unit components which are panes, gas gap and spacers are evaluated in the frame of first part of the study. It is found that laminated and diffused glass shows the highest value but spacers' environmental impact is of the same order of magnitude as clear float glass despite spacers mass is lower than the panes. Impacts of wood frames are differentiated from plywood principally in production phase. It is found that the aluminum has the highest energy consumption in production phase. From thermal balance study, it is

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[11] IMAGE: The framework and project of Implementation of Advanced Glazing systems in Europe which offers LCA of the glazing system production, maintenance phase and a thermal balance of its utilization phase for glass industry, engineers, architects.

concluded that advanced windows have slightly higher environmental impact during their life cycle but this difference is not significant compared to the energy gains they provide during the utilization phase due to their insulation properties.

Gustavsson and Sathre (2006), conducted an LCA study of wood and concrete in building materials with the aim of identifying factors effecting their CO_2 and energy balances. The study carried out on a 4 story apartment building in Sweden, with an 1190m2 usable area. On-site construction and operation phases are neglected. It is found that the wood-framed building had lower energy and CO2 balances than those of the concrete-framed building. It is emphasized that wood products has a couple with greater integration into energy systems effective means of reducing fossil fuel use and net CO2 emission to the atmosphere.

LCA of residential ventilation units for a single family house in Finland, taking into account the manufacturing process, fan energy consumption and the energy recovered by air-to-air energy exchangers, performed by Nyman and Simonson (2005). Ventilation units are pointed out as an important building service component which affected building energy consumption primarily, accounting for 30% to 50% of the energy consumed in buildings. The main focus of on the effect of heat recovery, frosting and different frosting control strategies on the energy use and environmental impact of the ventilation unit. The functional unit of this study is providing an outdoor ventilation airflow of 50 l/s, which corresponds to the recommended ventilation rate of 0.5 ach in Finland for a house with a floor area of 120–150m^2. Two different ventilation units manufactured in Finland are compared. It is concluded that the greater effectiveness provides the greater positive impact on the environment.

The environmental impact of the construction phase focusing on the application to composite walls studied by Ortiz et al. (2010). This research investigates the construction phase of a reference building and effect of different construction scenarios for external and internal walls, in detail. The functional unit for this study defined as the construction of 1m2 horizontal living area over the period of 50 years (y), when the reference building is assessed, and the construction of 1m2 vertical area over the period of 50 years (y) for the composite walls assessment, and the evaluation of the waste management scenarios for these composite walls. The construction phase is covering the fabrication, transport and the waste management resulting from the disposal of material and packaging wastes in the working site. Three possible treatment scenarios as land filling, incineration and recycling have been considered. CML 2000 method was chosen for impact assessment. Ecoinvent database and LCA Manager Software were used for modeling. Environmental impact of global warming potential for sub-phases of construction phase are calculated as 85% during the fabrication, due to the energy consumed 8%, transport 6% and waste management 1%. The total resources consumption distribution is for 36% foundation and basement, 19%, and walls (internal and external) 19%. Different external (8) and internal wall (7) scenarios are considered. It is seen that recycling materials has a significant environmental impact regarding high resource consumption in fabrication process.

A comparative assessment of standard and green roofs in Madrid, Spain is conducted by Saiz et al. (2006). Life cycle impact of a multi-storey residential building which is representative for multi-unit residential building stock in Madrid is evaluated by focusing on the influence of roof alternatives. Madrid standard gray gravel roof (BFR) is compared with two alternatives that are green roof (BGR) and a reflective white roof (BWR). An eight storey reference building which has 34 dwelling units, a commercial space in the ground level and two levels of underground parking is studied.
Even though assessment approach is WPC, the focus of the study is a component of the building therefore this study is evaluated as BMCC. Life cycle phases considered are material production, building operation and building maintenance. Building energy simulation is performed with ESP-r Software, while LCA simulation conducted with Simapro and Ecoinvent Database. It is found that preferring green roof instead of common flat roof provides reduction of environmental impacts between 1.0 and 5.3%. It is also emphasized that similar reductions might be achieved by using a white roof with additional insulation for winter.

Life cycle assessment of residential heating and cooling systems in four regions (Minnesota, Oregon, Pennsylvania and Texas) in the United States carried out by Shah et al. (2008). Three heating and cooling systems as : (a) central natural gas furnace heating and conventional central air-conditioning, (b) natural gas powered hydronic heating and conventional central air-conditioning, and (c) electric air–air heat pump for heating as well as cooling are evaluated. This systems applied in a two story L shaped reference house which has 181 m^2 living area, occupied by a family of two adults and two children. Functional unit of the LCA study is the system installed in a new single family residential house and operated over a life of 35 years. Extraction of raw materials, manufacturing and transportation of the system components, operation and disposal phases are considered. The operational energy consumption from fuel for 35 years is calculated with a simulation of the house for 1 year period. Human health, ecosystem quality, resources and global warming are the evaluated environmental indicators. Franklin USA and ETH-ESU 96 databases are used with Simapro software.

According to the findings the largest impacts associated with appliances and distribution systems occurred for the boiler and AC system. In the case of heat pump electricity sources is very important. It is found that in the regions where electricity mostly derived from fossil fuels the heat pump has the maximum impact. For these regions furnace and AC system indicated as best choice.

2.4. LCA Methodology

Life Cycle Assessment (LCA) method analyses the complex interaction between a product or system and the environment. Life cycle perspective, environmental focus, relative approach-functional unit, iterative approach, transparency, comprehensiveness, priority of scientific approach are the fundamental principles in conducting an LCA which are set by ISO series (Finkbeiner et al. 2006). Life cycle assessment considers the whole life cycle of a product/system. LCA addresses the environmental aspects and impacts of a product system while the economic and social aspects and impacts are, typically, outside the scope of the LCA. But integrated LCA studies can be performed for more extensive assessments. The structure of a LCA study is based on a functional unit to that all subsequent analyses are relative. Each phases of an LCA use results of the other phases, iteratively. Due to this complex structure of LCA transparency appears as an indispensable principle (Finkbeiner et al. 2006).

According to International standards of series ISO 14040 and ISO 14044 LCA methodology consists of four iterative steps as illustrated in Figure 2.4. (ISO 14040, 2006).

- Goal and scope definition
- Life cycle inventory (LCI)
- Life Cycle Impact Assessment (LCIA)
- Interpretation of the results

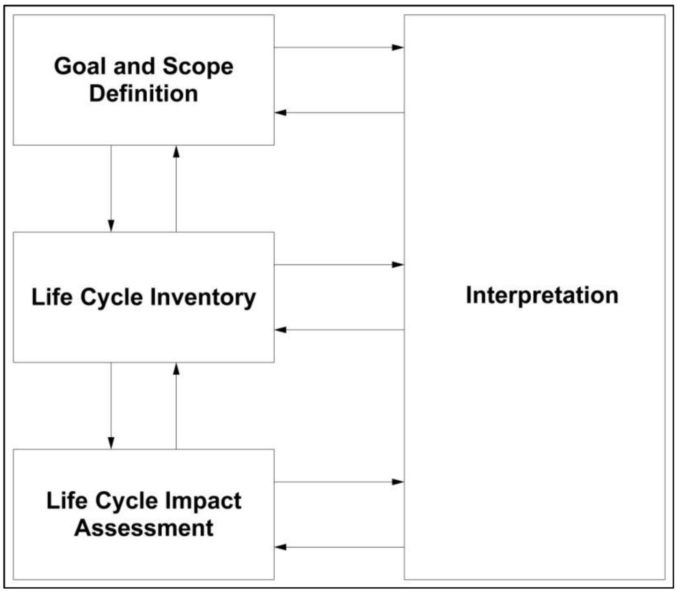


Figure 2.4. Iterative Steps of LCA (by Author, Source: ISO 14044)

2.4.1. Goal and Scope Definition

The goal and scope definition is a crucial phase which form basis for the further progress of an LCA. This step consists in defining the subject matter (objects of study), the target group and the content of which the latter is to be notified. Fundamental question of this step is ‘’who is aiming to have a controlling influence on which system and the interest in doing so (to which purpose) is of fundamental importance in an LCA.’’ The main issues of this part are:

- goal
- scope
- functional unit
- system boundaries

Goal definition is the first stage of any life cycle assessment in which six major aspects are determined, namely, intended applications, limitations, reasons for the study and decision context, target audience of the study and type of audience, comparisons and commissioner (ILCD 2010).

Scope definition is a clarifying step of which main question is “what to analyze and how “. “The definition of the scope of the life cycle assessment sets the borders of the assessment - what is included in the system and what detailed assessment methods are to be used” (EEA 1997).

In this stage fallowing items are described: function of the product system, functional unit, system boundaries, allocation procedures, and types of impacts, methodology, data requirements, assumptions, limitations, and data quality requirements, type of critical review, type and format of the report (ISO14040 2006).

Functional unit which has defined in ISO 14040 as a “quantified performance of a product system for use as a reference unit in a life cycle assessment study” is the central element of an LCA. The functional unit is used as a basis for calculation and usually also as a basis for comparison between different systems fulfilling the same function (Guinée 2002 cited in Ortiz 2009).

System boundary is an Interface between a product system and environment or other product systems. The system boundaries determine which unit processes is included within the LCA. Setting the study boundaries defines coverage as time, geographical, technology and justifies limits as focus on select phases, omitting small inputs.

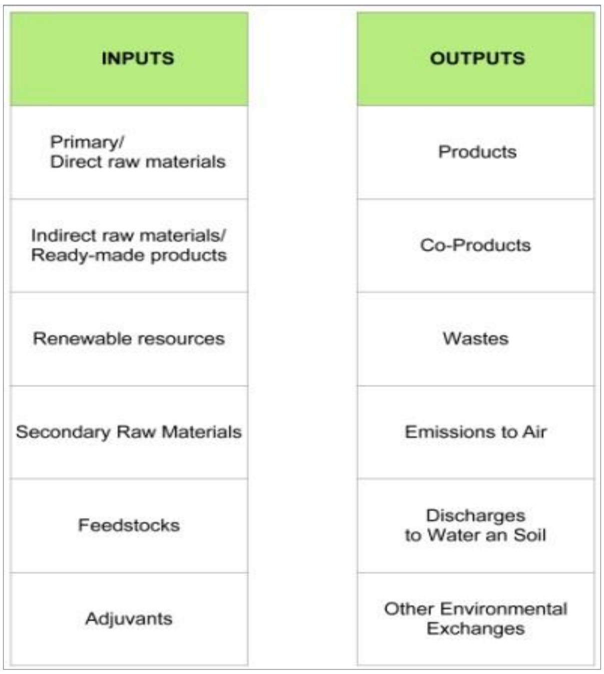
2.4.2. Life Cycle Inventory

Inventory phase basically covers the input/output data operations as collection of data and calculation procedure to quantify related inputs and outputs of a product system for all phases of the life cycle (ISO 14040 2006). Input data involve all natural resources, while the output data include products and all environmental exchanges illustrated in Table 2.4. (Allacker 2009).

Throughout the inventory examination which is a repetitive process of collecting data and getting more experienced with the system, it may be understood that collection of additional data is required or certain restrictions on the analysis process may become obvious. This whole process may result in the necessity of more advanced or extra data collection or the clear determination of the system limits.

Simplified procedures for life cycle inventory analysis step are given in Figure 2.5. Data collection according to goal and scope definition is one of the main part of this step. These collected data are relating to the unit process and functional unit of the system. Inventory is calculated by aggregation of these data. Based on the iterative character of the LCA, after the calculation of the inventory data a check can be done if there is a need in additional data or unit process. According to this final control, system boundaries should be refined.

Table 2.4. Input Output Data (by Author)



INPUTS	OUTPUTS
Primary/ Direct raw materials	Products
Indirect raw materials/ Ready-made products	Co-Products
Renewable resources	Wastes
Secondary Raw Materials	Emissions to Air
Feedstocks	Discharges to Water an Soil
Adjuvants	Other Environmental Exchanges

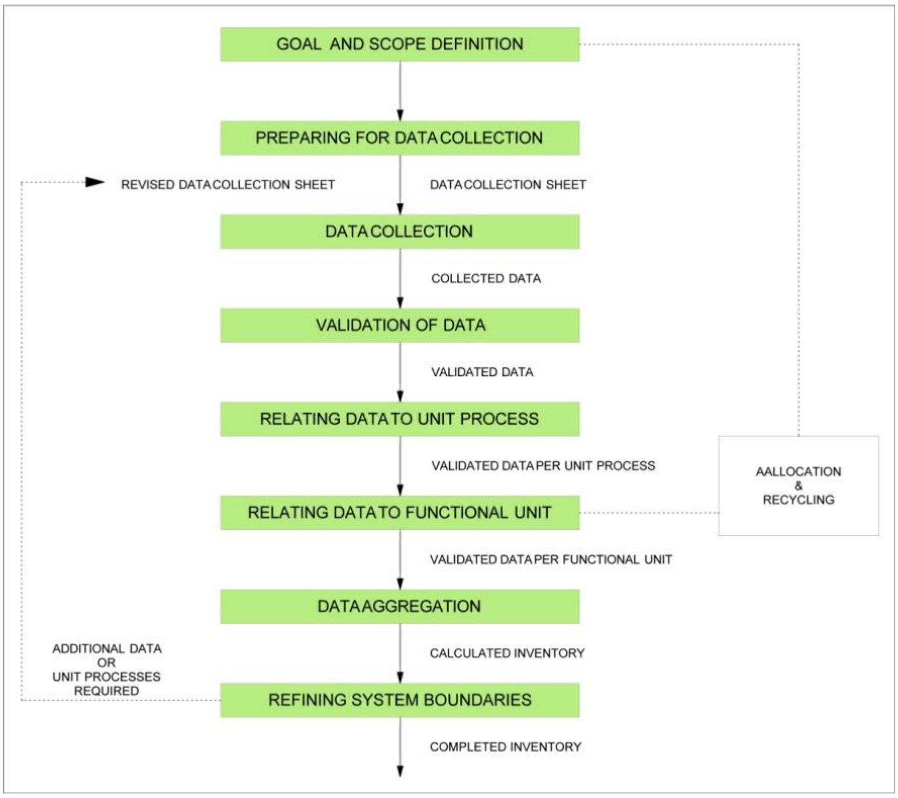


Figure 2.5. Simplified Procedures for Inventory Analysis (Source; ISO 14044 2006)

2.4.3. Life Cycle Impact Assessment

The purpose of the impact assessment phase of an LCA study is to evaluate significance of potential environmental impacts using the results of the life cycle inventory analysis (ISO 14044 2006). Life Cycle impact assessment (LCIA) is composed of five steps which are: impact category definition, classification, characterization, normalization, and valuation.

While definition, classification and characterization steps are obligatory, normalization, and valuation are optional.

The impact assessment framework is a multi-step process, starting by selecting and defining impact categories, which are relevant to the study. Common environmental impact categories maintaining in UNEP, SETAC and LC Initiative documents are: resource and land use; climate change; stratospheric ozone depletion; photooxidant formation; acidification; eutrophication; human toxicity; ecotoxicity. (118) Classification as the second step of (LCIA) life cycle impact assessment covers the assignment of life cycle inventory (LCI) parameters to the impact categories.[12] ‘’Characterization is the assessment of the magnitude of potential impacts on the chosen impact categories’’ (Curran, 1996). This is the calculation step of category indicators.

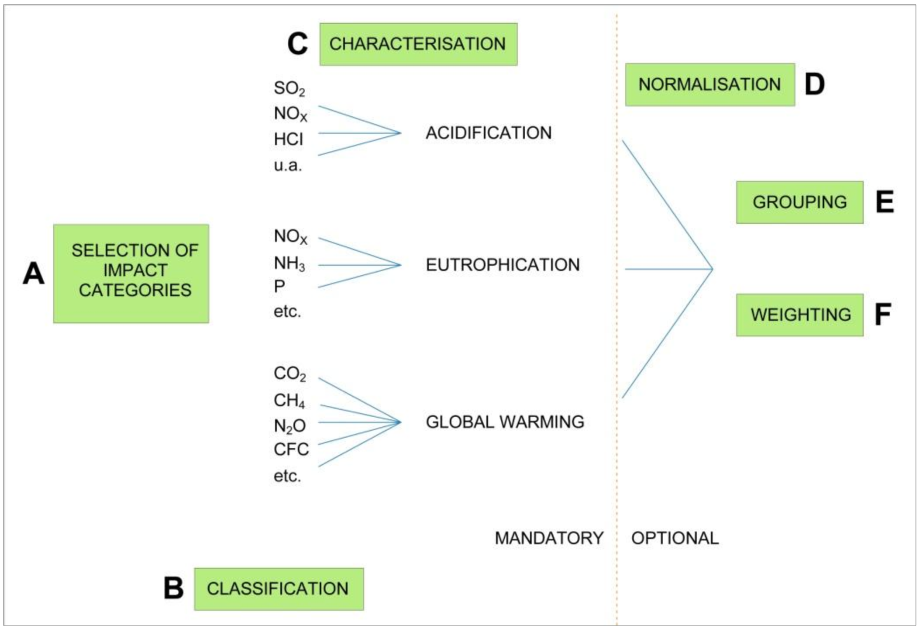


Figure 2.6. Steps of Life Cycle Impact Assessment (by Author)

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[12] ‘’e.g. CO2 emissions are related to global warming, SO2 emissions are related to acidification and respiratory effects ‘’ (Allacker 2009)

Normalization and valuation are optional steps under ISO 14044:2006 to support the interpretation of the impact profile and are steps towards a fully aggregated result. Normalization ‘‘relates the micro world of an LCA study to the macro world in which the product/service is embedded’’ (Lindeijer 1996 cited in Bare 2010). In other words, ‘’it relates the environmental impact of a product system to the impact of a reference system.’’ (Allacker 2010, p 19). After normalization the impact category indicators all get the same unit, which makes it easier to compare them. Normalization can be applied on both characterization and damage assessment results.

The valuation process can be conducted for grouping and/or weighting. Weighting involves assigning distinct quantitative weights to all impact categories expressing their relative importance. According to ISO data prior to weighting should remain available.

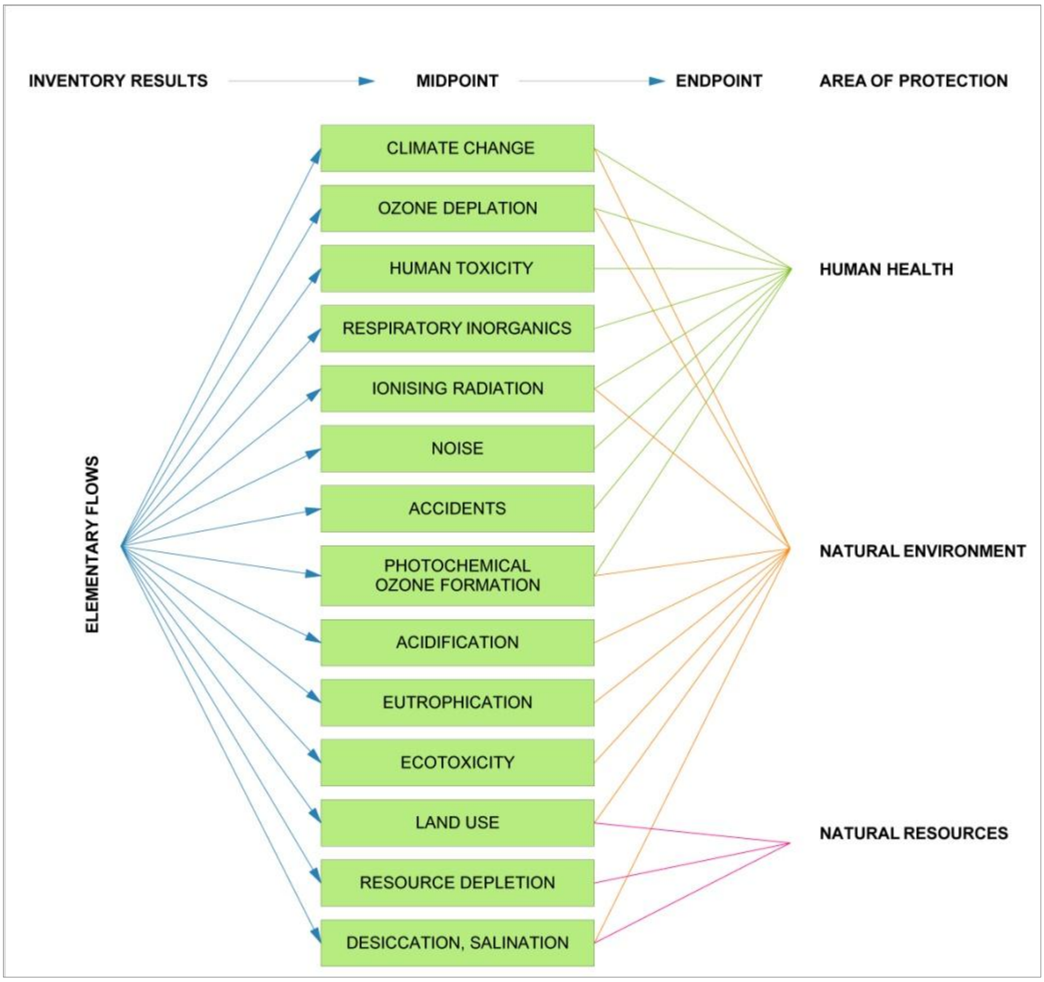


Figure 2.7. Flow Diagram of the Impact Assessment Phase (by Author).

Life cycle impact assessment (LCIA) quantifies the potential for environmental impacts over all (Bare 2010). There are a number of life cycle impact assessment methods. LCIM is described as a set of principles, models and characterization factors to calculate characterization results for a certain impact category by ILCD Handbook-Recommendations for Life Cycle Impact Assessment in the European context. There are essentially two assessment approaches: problem-oriented methods (mid-points) and damage-oriented methods (end points).

Problem oriented methods aim at simplifying the complexity of hundreds of flows into a few environmental areas of interest. The EDIP or CML 2000 methods are examples of problem-oriented methods.

The damage-oriented methods also start by classifying a system's flows into various environmental themes, but model each environmental theme's damage to human health, ecosystem health or damage to resources. For example, acidification - often related to acid rain - may cause damage to ecosystems (e.g., in the Black Forest in Germany), but also to buildings or monuments. In essence, this method aims to answer the question: Why should we worry about climate change or ozone depletion? EcoIndicator 99 is an example of a damage-oriented method.

Problem-oriented methodologies are based on internationally and scientifically accepted approaches when possible. But some categories, such as human toxicity or aquatic toxicity, remain difficult to model and are currently under development and require careful evaluation when used. Even more difficulties with scientific relevance exist with damage-oriented methods, hence careful evaluation is necessary.

Bare and Gloria (2008) states that the midpoint represents a point on the cause-effect chain between stressors and endpoints. Midpoint models generally enjoy a higher level of scientific consensus than models conducted at the endpoint and damage levels, while endpoints are those physical elements which society determines are worthy of protection, but are linked to stressors (and possibly midpoints) with very little value-based parameters or models incorporated (as opposed to damage and weighting).

2.4.3.1. Life Cycle Impact Assessment Methods in Detail

A number of impact assessment methods are used to calculate impact assessment results especially originated from Europe and North America. The basic structure of impact assessment consists of characterization, damage assessment, normalization and weighting as it was mentioned before. Because of the last three steps are being optional, they are not used in all methods.

Life cycle impact assessment is generally categorized in two approach; mid-point (problem oriented) and end-point (damage oriented). Table 2.5. gives a detailed information on methods and their assessment approaches. While CML 2001, Ecological Footprint, Ecological Scarcity 2006, EDIP 2003, EPD 2007, IPCC 2007, TRACI 2 and Athena are categorized as mid-point methods, BEES, EcoIndicator 99, EPS 2000 and LIME are categorized as end-point methods. Impact 2002+ and ReCipie impact assessment methods contain both mid-point and end-point approaches.

Table 2.5. Life Cycle Impact Assessment Methods and Approaches (by Author)

Impact Assessment Methods	**Mid-point**	**End-point**
BEES		🟩
CML 2001	🟩	
Ecoindicator 99		🟩
Ecological Footprint	🟩	
Ecological Scarcity 2006	🟩	
EDIP 2003	🟩	
EPD 2007	🟩	
EPS 2000		🟩
Impact 2002+	🟩	🟩
IPCC 2007 (GWP)	🟩	
TRACI 2	🟩	
Athena	🟩	
ReCipie	🟩	🟩
LIME		🟩

The most common impact assessment methods for whole building LCA studies derived from literature will be explained in detail below.

CML 2001 (Baseline)

CML 2001 methodology developed by the Center of Environmental Science (CML) of Leiden University, is the set of impact categories defined for the midpoint approach. Impact categories are ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, rerrestrial ecotoxicity, photochemical oxidation, global warming 100a, acidification, abiotic depletion, eutrophication. For each baseline indicator, normalisation scores are calculated for the reference situations:

the world in 1990, Europe in 1995 and the Netherlands in 1997. Grouping and weighting are optional. Impact categories in CML method are:

- Abiotic Depletion Potential : This impact category is dependent on extraction of minerals and fosil fuels. Simply it measures the gradual depletion of non-renewable non-organic resources. The geographic scope of this indicator is at global scale.
- Global Warming potential: Greenhouse gases (CO2, CH4, N2O and CFCs) emissions to the atmosphere causes global warming. Climate change can affect ecosystem health, human health and material welfare. Intergovernmental Panel on Climate Change (IPCC) expressed characterization factor as GWP for time horizon 100 years, in kg CO_2/kg emissions.
- Ozone Depletion Potential: Depletion of stratospheric ozone layer decreases filtration of UV radiation. This can be harmful for human health, animal health, terrestrial and aquatic ecosystems and biochemical cycles. World Meteorological Organization (WMO) defines ozone layer depletion of different gases as kg CFC-11 equivalent/ kg emission. The geographic scope of this indicator is at global scale.
- Human Toxicity: This category related to the exposure of toxic substances on human environment. Its characterization factor is human toxicity potential (HTP) and for each toxic substance HTP's are expressed as 1,4 – dichlorobenzene equivalents/ kg emission. The geographic scope of this indicator can vary between local and global scale.
- Fresh Water Aquatic Eco-toxicity: This impact category measures the exposure of toxic substances on fresh water ecosystems. Eco-toxicity potential characterization factor (FAETP) is expressed as 1,4 –dichlorobenzene equivalents/ kg emission. This indicator's scope can be global/continental/regional or local scale.
- Marine Eco-toxicity: Impacts of toxic substances on marine aquatic ecosystem is the concern of this category. Eco-toxicity potential characterization factor (FAETP) is expressed as 1,4 –dichlorobenzene equivalents/ kg emission. This indicator's scope can be global/continental/regional or local scale.
- Terrestrial Eco-toxicity: This category refers to impacts of toxic substances on terrestrial fauna and flora. Eco-toxicity potential characterization factor

(FAETP) is expressed as 1,4 –dichlorobenzene equivalents/ kg emission. This indicator's scope can be global/continental/regional or local scale.

- Photochemical Oxidation: Photo-oxidant formation is the formation of reactive substances (mainly ozones) including nitrogen oxides and VOCs. These are affected on human health, ecosystems, crops. Photochemical Ozone Creation Potential (POCP) for emission of substances to air is calculated with the UNECE Trajectory model (including fate), and expressed in kg ethylene equivalents/kg emission.
- Acidification Potential: Acidifying substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings). Acidification Potentials (AP) for emissions to air describes the fate and deposition of acidifying substances. AP is expressed as kg SO2 equivalents/ kg emission. The time span is eternity and the geographical scale varies between local scale and continental scale.
- Eutrophication: Eutrophication (also known as nutrification) includes all impacts due to excessive levels of macronutrients in the environment caused by emissions of nutrients to air, water and soil. Nutrification potential (NP) expressed as kg PO4 equivalents/ kg emission. The geographical scale varies between local and continental scale (Simapro Goedkoop 2008)

Eco-indicator 99

Eco-indicator 99 is the first damage oriented method which is the successor of the Eco-indicator 95. The weighting concept is the source of the Eco-indicator method.

This model is applied for the following impact categories: carcinogens (DALY/kg emission), respiratory organics (DALY/kg emission), climate change (DALY/kg emission), radiation (DALY/kg emission), ozone layer depletion (DALY/kg emission), ecotoxicity ((PAF)*m2*year/kg) emission, acidification ((PAF)*m2*year/kg), eutrophication((PAF)*m2*year/kg), landuse (PDF)*m2*year/m2 or m2a, minerals (Surplus energy per kg mineral), fosil fuels (Surplus energy per extracted MJ, kg or m3 fossil fuel).

Instead of weighting a large number of impact categories, damage types caused by these impact categories are weighted. There are three damage categories:

HH Human Health - (unit: DALY= Disability adjusted life years; this means different disability caused by diseases are weighted)

EQ Ecosystem Quality- (unit: PDF*m2yr; PDF= Potentially Disappeared Fraction of plant species)

R Resources- (unit: MJ surplus energy Additional energy requirement to compensate lower future ore grade)

The EcoIndicator 99 comes in three versions: egalitarian, individualist and hierarchist.

2.4.4. Interpretation

Interpretation as the final stage of life cycle impact assessment (LCIA) of ISO 14040 presents results, analyses of findings and aims reaching conclusions and formulating recommendations. Identification significant impacts and significant life cycle stages is also subject of this stage. The results, data, methods, assumptions and limitations are presented as a final report.

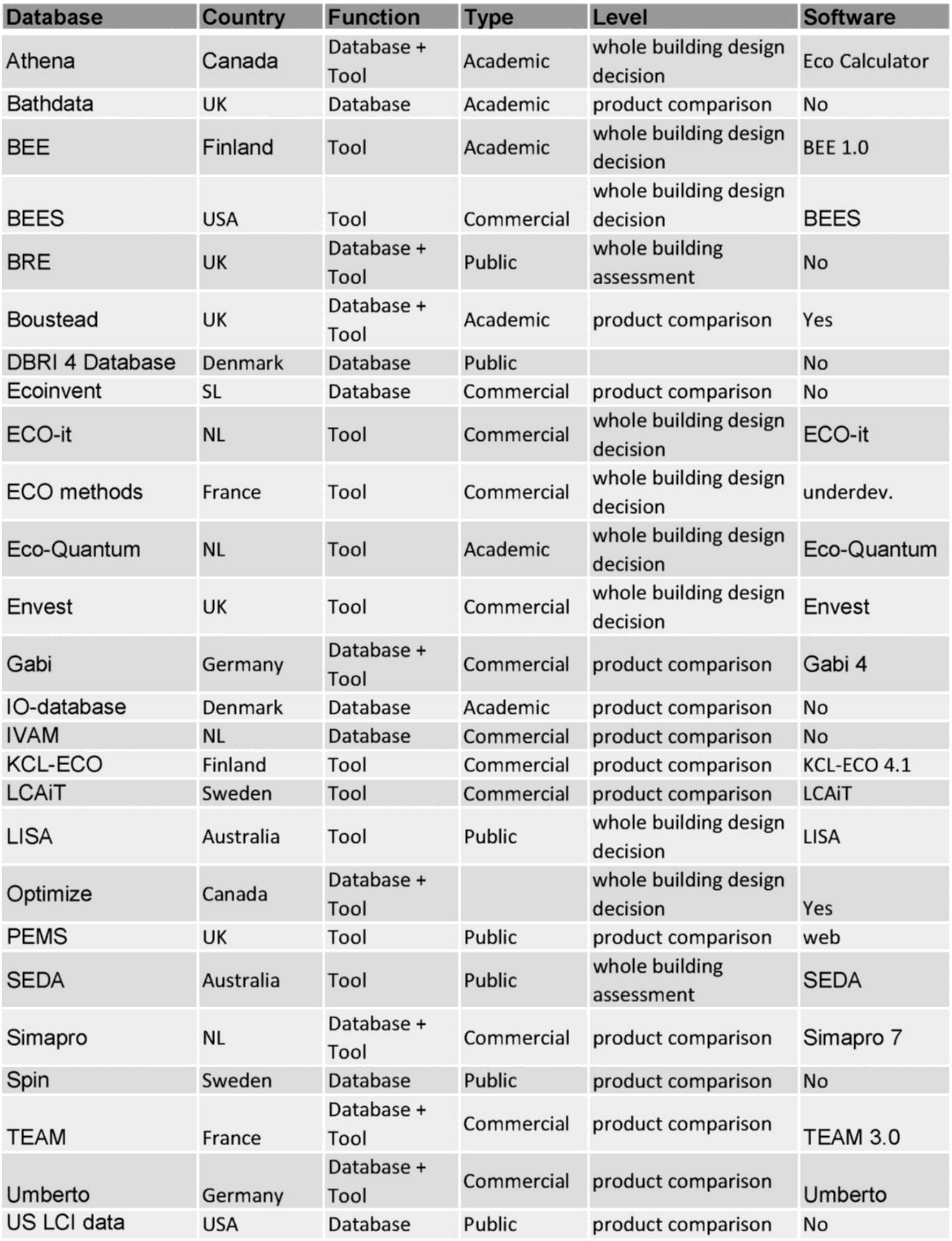
2.5. LCA Software and Databases

As a result of growing interest on life cycle assessment in last decade, several qualitative and quantitative assessment tools on LCA has been developed. Beside this database development is also crucial to perform an LCA study. Bribian et al. (2009) pointed out that it is recommended to use a database whose inventory of materials accords the reality of the area or region. Otherwise the outcome results should be considered as an approximation to the real environmental impacts.

Khasreen (2009) examined and classified general LCA databases and softwares according to country, function, type and level. Three types of database and tool determined as being for academic, public or commercial purposes. Whole building design decision and product comparison are two levels in examination. Is is seen that UK and NL are leading countries in developing LCA tools and databases. All tools and databases originated in Europe, America and Australia.

These data base shows generally national or continental properties. Each software uses its own database composition. While some of them contain only one database, some of them include different databases together.

Table 2.6. Databases and Tools of Life Cycle Assessment
(by Author, Source; Khasreen 2009)

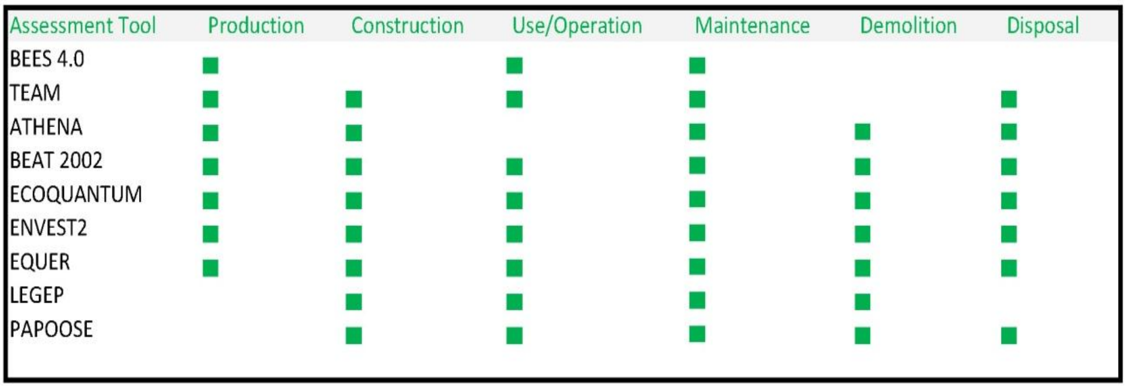


Database	Country	Function	Type	Level	Software
Athena	Canada	Database + Tool	Academic	whole building design decision	Eco Calculator
Bathdata	UK	Database	Academic	product comparison	No
BEE	Finland	Tool	Academic	whole building design decision	BEE 1.0
BEES	USA	Tool	Commercial	whole building design decision	BEES
BRE	UK	Database + Tool	Public	whole building assessment	No
Boustead	UK	Database + Tool	Academic	product comparison	Yes
DBRI 4 Database	Denmark	Database	Public		No
Ecoinvent	SL	Database	Commercial	product comparison	No
ECO-it	NL	Tool	Commercial	whole building design decision	ECO-it
ECO methods	France	Tool	Commercial	whole building design decision	underdev.
Eco-Quantum	NL	Tool	Academic	whole building design decision	Eco-Quantum
Envest	UK	Tool	Commercial	whole building design decision	Envest
Gabi	Germany	Database + Tool	Commercial	product comparison	Gabi 4
IO-database	Denmark	Database	Academic	product comparison	No
IVAM	NL	Database	Commercial	product comparison	No
KCL-ECO	Finland	Tool	Commercial	product comparison	KCL-ECO 4.1
LCAiT	Sweden	Tool	Commercial	product comparison	LCAiT
LISA	Australia	Tool	Public	whole building design decision	LISA
Optimize	Canada	Database + Tool		whole building design decision	Yes
PEMS	UK	Tool	Public	product comparison	web
SEDA	Australia	Tool	Public	whole building assessment	SEDA
Simapro	NL	Database + Tool	Commercial	product comparison	Simapro 7
Spin	Sweden	Database	Public	product comparison	No
TEAM	France	Database + Tool	Commercial	product comparison	TEAM 3.0
Umberto	Germany	Database + Tool	Commercial	product comparison	Umberto
US LCI data	USA	Database	Public	product comparison	No

For example Simapro software uses Simapro databases including different libraries as Dutch input-output database, Ecoinvent, ELCD, EU-DK input-output databases, USA ınput-output database and USLCI database. This variety provides a broad range product assessment.

If we look closely to the LCA tools specialized for whole building design decision, It is seen that BEES, TEAM, Athena, BEAT, Ecoquantum, Envest, EQUER, LEGEP and Papoose are the most common WPC LCA tools. Most of these tools are blackbox tools in which user is not allow to shape its own system boundaries and choosing different databases. Because these are generally developed for a specific aim. Table 2.7 shows the scope on life cycle phases of the whole building life cycle assessment tools. While BEES covers production, use and maintenance, TEAM includes production, construction, use, maintenance and disposal. BEAT, Ecoquantum, Envest and Equer evaluates all life cycle phases. While LEGEP excludes production and disposal, Papoose only excludes production phase.

Table 2.7. Building Life Cycle Assessment Tools and Their Scope on Life Cycle Phases
(by Author, Sourced; Haapio and Wiitaneimi 2008)



Assessment Tool	Production	Construction	Use/Operation	Maintenance	Demolition	Disposal
BEES 4.0	🟩		🟩	🟩		
TEAM	🟩	🟩	🟩	🟩		🟩
ATHENA	🟩	🟩		🟩	🟩	🟩
BEAT 2002	🟩	🟩	🟩	🟩	🟩	🟩
ECOQUANTUM	🟩	🟩	🟩	🟩	🟩	🟩
ENVEST2	🟩	🟩	🟩	🟩	🟩	🟩
EQUER	🟩	🟩	🟩	🟩	🟩	🟩
LEGEP		🟩	🟩	🟩	🟩	
PAPOOSE		🟩	🟩	🟩	🟩	🟩

Forberg and Malmberg (2004) compares the specific aims of these three tool as BEAT, Eco-quantum and BEE. They states that “BEAT 2000 and Eco-Quantum have the common primary goal of providing the building sector with tools to optimize new and refurbished buildings from an environmental point of view. The primary purpose of BEE 1.0 is to analyze entries to an architectural competition in Viikki, Finland. This can be compared with the primary purpose of ELP, which was to gain a tool to follow up and evaluate the environmental performance of a city district in Stockholm, Sweden”.

Haapio and Wiitaneimi (2008) indicate that these tools take different environmental issues into account by covering different life cycle phases. These tools are global, national and in some cases local. By choosing an appropriate database, a few national tools can be used in global scale. They also point out that these tool are developed for different purposes leading to different users, such as designers, architects, researchers, consultants, owners and authorities.

In this context tools like Simapro and Gabi, which are not developed for buildings specially, provides a flexible and comprehensive study potential for academic researchers and for the countries which have not a national tool and database for LCA studies. Therefore these tools have many users especially in research field.

CHAPTER 3

METHOD APPLICATION

3.1. Presentation of the Case Study

3.1.1. Selection of the Case Study

Izmir city has a large population growth rate of %39.99 which is clearly depending on internal migration towards to the western regions (İBB Report2008). This population growth brings about housing demand which is extending city boundaries. Many housing projects being developed on the urban periphery within the urban renewal or development projects. Housing delivery is mainly provided by real estate investment companies, metropolitan municipality and TOKİ (housing development administration of Turkey).

Selected Case; Olympic Houses is located on the southern development axis of the İzmir city. Uzundere Walley Urban Renewal project, Uzundere (TOKİ) Housing Development and Aktepe Emrez Urban Renewal and Development Project are other recent projects on this axis. Olympic Houses is the first housing project completed in t his development area.

It is important to find out the environmental impacts of a housing settlement built in last decade on the development axis of a fast growing western city in Turkey, to be able to make projection for future housing projects. There is no national code or regulation for holistic environmental impacts of dwellings from a life cycle perspective. Evaluation of the recently built housing stock will show the environmental results of current building-operating-dismantling techniques and combination of building regulations in Turkey.

Figure 3.1. Southern Development Axis of Izmir City
(Source: Izmir Metropolitan Municipality)

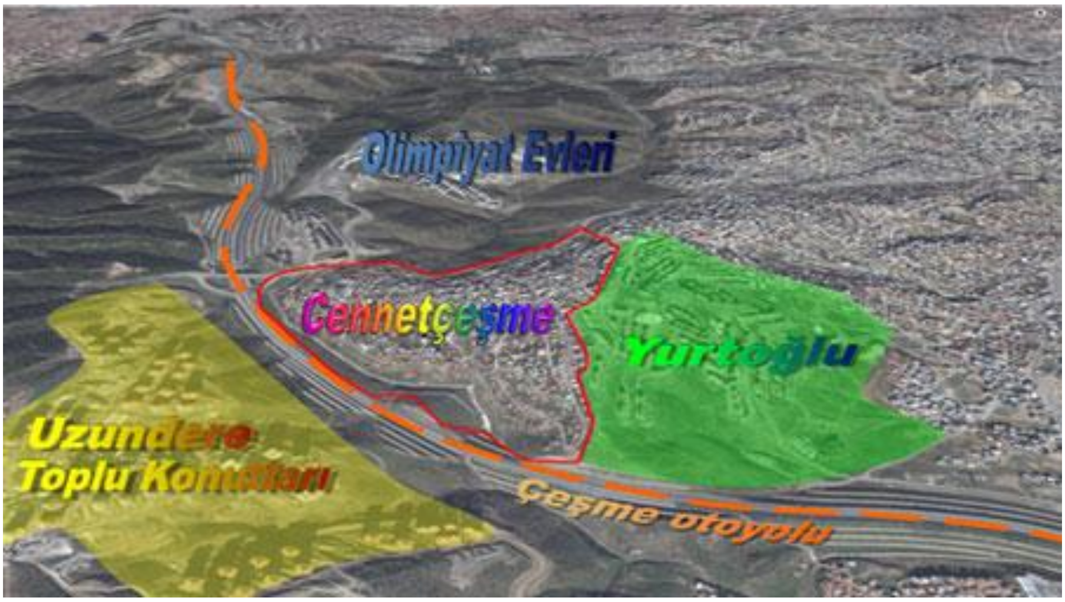


Figure 3.2. Recent Development Projects in the Southern Axis
(Source: Izmir Metropolitan Municipality)

3.1.2. Description of the Housing

Figure 3.3. General View of the Site

Olympic Houses is located in Izmir, on the edge of Çeşme-Aydın Highway, at 38 º 22’ 17’’ N and 27 º 04’ 55’’ E, an elevation between 205m and 140m from the sea level and the annual average temperatures are in winter 9.5^{o}C, spring 16.2^{o}C, summer 27.1^{o}C, autumn 18.7^{o}C (1975-2010 mgm.gov.tr).

Figure 3.4. Top View of the Site

Project developed by Metropolitan Municipality of İzmir which is also aimed to provide temporary housing for athletes during Universiade 2005. Construction period is between 2003-2005.

Main architectural characteristic of this housing settlement is accordance with topography. %81.25 of the total blocks are terraced types and others are apartment blocks.

Housing consists of 934 dwellings in 64 blocks. There are mainly 6 block types; 2 types for apartment blocks and 4 types for terraced blocks. 6 dwelling types are differentiated as A, B, C, D, E and F, according their floor area and plan typology. Distribution of the percentages of these types is 20.5% (192) for A types, 20.5% (192) for B types, 17% (158) for C types, 21.4% (200) for D types, 3.2% (30) for E types and 17.4% (162) for F types.

Table 3.1. Gross Areas of the Different Dwelling Types in the Housing Settlement (by Author)

	GROSS	TERRACE	COM.SPACE	TOTAL
A TYPE	148 M2	32 M2	30 M2	210 M2
B TYPE	122 M2	35 M2	30 M2	187 M2
C TYPE	105 M2	36 M2	30 M2	171 M2
D TYPE	66 M2	7 M2	30 M2	103 M2
E TYPE	122 M2	11 M2	20 M2	153 M2
F TYPE	70 M2	6 M2	24 M2	103 M2

Three types of dwellings are chosen from one apartment and two terraced blocks as representative cases according to their percentage, orientation and eligibility.

3.1.3. Description of the Dwelling

F Type Dwelling

This type of dwelling is situated in a 6 storey reinforced concrete apartment block which constitutes 18 identical flats. F type flat has a gross floor area of 70 m^2 with a living room, a kitchen, a bathroom, two bedrooms, an entrance/corridor area and plus a 6 m^2 balcony. All of the windows are facing to the east direction.

Figure 3.5. Typical Floor Plan of Block 06
(by Author, Source: Birok Architectural Office Archive)

3.2. Application of LCA

3.2.1. Goal Definition

The goal of this study is to estimate the life cycle environmental impacts of a typical dwelling unit built in last decade with standard construction techniques, in Turkey. Despite a growing number of LCA studies for construction sector have been conducted in the world, LCA studies in Turkey are very limited and neither considered the full life cycle from cradle to grave or the full range of impacts (Taygun 2005, Gültekin 2006, Esin 2007, Bozkurt 2007).

Results of the present study will pave the way to understand overall impacts of the recently built building stock with the aim of identifying hot spots and improvement opportunities along the construction sector. Also it will provide a research background and comparison opportunity for future studies. It is hoped that the results of this research will be useful for policy makers, stakeholders and architects.

3.2.2. Scope Definition

Table 3.2. System Description (by Author)

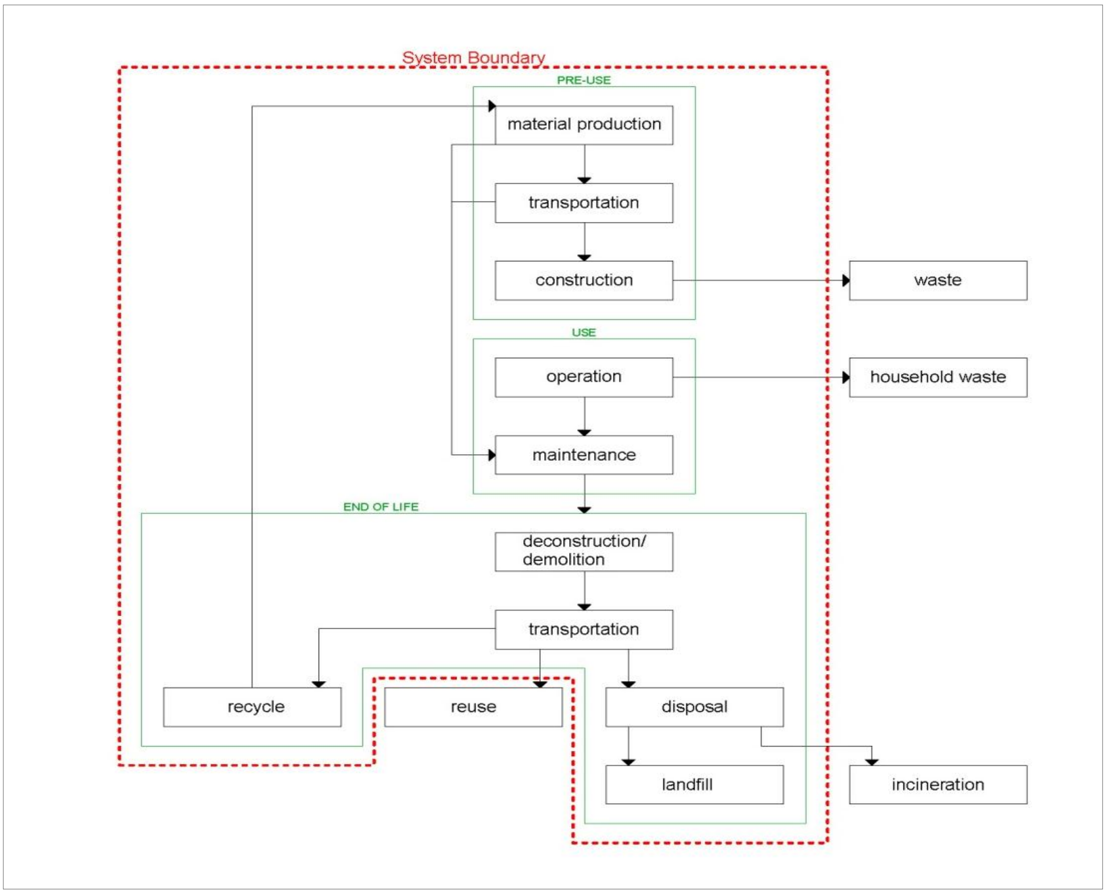
Building Features	
Total Elevation	22.90 m
Elevation, per Floor	3 m
Elevation, Ground Floor	4 m
No of Floors	7
No of Flats	18
No of Lifts, Stairs	1-1
No of Flats per Floor	3
Gross Area, Type F Flat	70 m^2
Gross Area+ Com. Areas, Type F Flat	103 m^2
Net Area, Type F Flat	57 m^2
Gross Area per Floor	308 m^2
Net Area per Floor	271 m^2
Total Net Area	1706 m^2

The LCA methodology follows the ISO 14040/44 standards. ILCD handbook is also used for further understanding. The LCA modeling is carried out in Simapro 7.3.2 software which is providing transparency and flexibility.

3.2.2.1. System Boundaries and Assumptions

The whole life cycle of the building is studied with a holistic approach. Building life cycle is processed in three main phases: pre-use, use and end-of-life. It is also shown in Table 3.3. Pre-use phase basically covers material production, transportation and construction which can also be called ‘’embodied’ impacts. Use phase includes operation and maintenance sub-phases. End-of-life phase consists of deconstruction/demolition, transportation, recycle and landfill. The system boundary excludes: urban planning and infrastructure, construction and operational waste, electrical wiring, plumbing, furniture and waste packaging.

Table 3.3. System Boundary (by Author)



3.2.2.2. Functional Unit

ISO 14040 defines the functional unit as measure of the function of the studied system. Human habitation service is the main function of a dwelling which is consistent to the size of living area and occupancy life span. Life span of a residential dwelling is a parameter which is difficult to standardize because of its dependence of many variables. Building life span assumptions are frequently seen between 40-80 years interval, in literature. Most of the authors (e.g Junilla 2004, Gervasio and Silva 2008, Glauman et al. 2008, Haynes 2010, Bribian et al. 2009) have assumed building life span of 50 years. Therefore life span for this study is also assumed as 50 years according to the literature data.

The adopted functional unit in the present case-study is “1m^2 usable floor area of a dwelling with a projected 50 years life span for two occupants.”

3.2.2.3. Impact Assessment Categories

CML 2001 version 2.05 (baseline) method elaborating on the problem oriented (mid-point) approach is chosen in performing LCA to provide a more transparent vision regarding to existing aggregated methods.

This method consists of ozone layer depletion (ODP), human toxicity (HT), freshwater aquatic ecotoxicity (FWAE), marine aquatic ecotoxicity (MAE), terrestrial ecotoxicty (TE), photochemical oxidation (PO), global warming 100a (GWP), acidification (A), abiotic depletion (AD) and eutrophication (E) impact categories.

3.2.2.4. Database

The choice of database is crucial for an LCA which has a direct influence on data quality. Although there is a growing interest on environmental issues in developing countries, there are a number of difficulties in conducting a building LCA. Lack of inventory data is the most important and costly aspect of it (Arena and Rosa 2003). In the case of Turkey also inventory data are not yet available in the required format. But Turkey is an important producer and exporter of construction materials in nearby geography[13]. Turkey Construction Sector View Report 2011 emphasizes that Turkey' construction industry will change the focus of 'production' to 'technology' to maintain the international competitiveness later on environmental issues[14]. While production does not strongly differ from developed countries, energy efficiency in processes can be still improved by %25 (TOBB, 2011).

In this context, regarding the average production technologies for primary construction materials in Europe are not very different from Turkey, the most comprehensive database for Europe; Ecoinvent 2.2, is chosen as the source of LCA inventory data. Since Turkey-specific inventory data is not available, the data from database is adapted as far as possible to reflect Turkey conditions, with respect to the Turkey energy mix.

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[13] Turkey's nearby geography: Eastern Europe countries, Russia, Northern Africa countries, neighboring countries. (According to Turkey Construction Materials View Report 2011.)

[14] Turkey's construction industry targets to increase exports to biggest importer countries such as Germany, France, Belgium, Netherlands, and Italy in Europe, and also UK, USA and China. Construction materials exported to these countries will have to meet the environmental product standards in these countries.

3.3. Life Cycle Phases

Life cycle phases are evaluated in three main phases as pre-use phase, use phase and end-of-life phase. These phases are also divided in sub-phases to provide detailed assessment.

3.3.1. Pre-Use Phase

In this study pre-use phase is evaluated in three sub-phases as material production, transportation to construction site and on-site construction. Pre-use phase has significance on the lifecycle of a building. In this phase environmental impacts can be minimized before a building has been built.

Case dwelling as described before is a flat in a 6 story block. It has $57m^2$ net usable area. Main building material is reinforced concrete. Detailed system description of dwelling for building components can be seen at Table 3.4. Determination and quantification of materials for construction which are crucial for this phase are provided from implementation project of the building, material specifications, construction guides and expert consultation.

With the aim of a detailed material quantification, building is divided into five main zones at first hand. As shown in Figure 3.6 these parts are; foundation, basement, ground floor, standard story and roof.

Table 3.4. Main Building materials and Components (by Author)

Building Elements	Main Building Materials and Components
Foundation (reinforced concrete)	Granulated mechanically stabilized fill
	Slab on grade wire mesh c25
	Reinforced concrete footings
	Fill with sand and gravel
	Block (crushed stone)
	Slab on grade with wire mesh c25
	Leveling concrete
	Screed
Basement	Columns
	Beams (0,55)
	Beams (1.17)
	Internal Walls
	Reinforced concrete ceiling slab-1
	Reinforced concrete ceiling slab-2
	Ceiling Slab Finishing’s for slab type A
	Ceiling Slab Finishing’s for slab type B
Ground Floor	Beams
	Columns
	Floor h:0.17
	Floor h:0.15
	Floor h:0.12
	Stair
	Parapet walls
	Walls
	Floor finishing
Standard Story	External walls
	Internal walls
	Beams
	Columns
	Floor h:0.17
	Floor h:0.15
	Floor h:0.12
	Stair
	Floor finishing
	Floor finishing (circulation area)
	External walls (circulation area)
	Parapet walls (circulation area)
	Windows
	Doors
Roof	Gravel(Æ16-22mm)
	XPS
	Waterproof-bitumen sealing
	Slope concrete %1
	Parapet walls
	Walls
	Columns
	Beams
	Slab

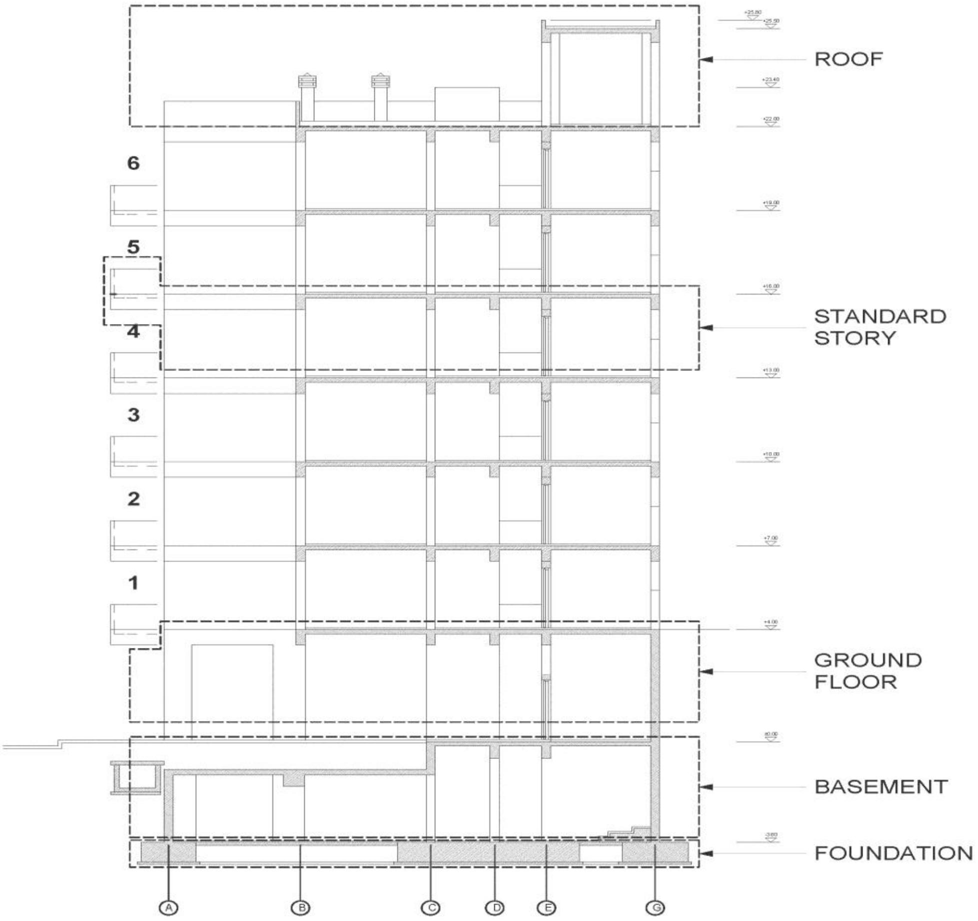


Figure 3.6. Zoning of the Case Block (by Author)

Table 3.5. Life Cycle Inventory Inputs: Pre-use Phase-Materials (by Author)

Life Cycle Inventory Inputs: pre-use phase-materials			
Components	Layers/materials		Mass (kg)/functional unit
External Walls	Acrylic paint		0,90
	Plaster (out)	Sand	160,96
		Cement	42,30
		Water	47,91
	Pumice block		84,19
	Plaster (in)	Sand	91,49
		Cement	11,95
		Water	12,86
		Lime Powder	6,30
	Alkyd paint		0,22
Internal Walls	Alkyd paint		0,10
	Plaster (in)	Sand	41,98
		Cement	5,43
		Water	5,90
		Lime Powder	2,85
	Brick		51,45
	Plaster (in)	Sand	41,98
		Cement	5,43
		Water	5,90
		Lime Powder	2,85
	Alkyd paint		0,10
Parapet Walls	Acrylic paint		0,03
	Plaster (out)	Sand	4,42
		Cement	0,80
		Water	1,44
	Reinforced concrete	Concrete	53,76
		Steel	26,21
	Plaster (out)	Sand	4,42
		Cement	0,80
		Water	1,44
	Acrylic paint		0,03
Floor Finishings	Wood Tile		9,26
	Ceramic Tile		9,01
	Adhesive Mortar		56,19
	Leveling Concrete/ceiling plaster	sand	193,23
		portland cement	36,16
		water	52,64
		powder lime	2,03
	Concrete		31,20
	Concrete Paving Blocks		24,89
	Gravel(12-16mm)		16,98
	xps		0,18
Structure	Concrete C25		3000,00
	Reinforcement steel		145,27
Foundation	Reinforced concrete footings	Concrete C25	367,20
		steel	16,85
	Fill with sand and gravel		168,25
	Block (crushed stone)		33,91
	Grobeton with wire mesh c25		24,87
	Leveling Concrete+Screed	sand	20,30
		portland cement	1,65
		water	4,59
Windows	Aluminium Frame		6,08
	Glass (double glazing)		2,40
Doors	Wood-aluminium		1,47
	Wood		3,72

Second step is to determine building components and related materials under these zones. Amount of materials for each zone and component are calculated considering entire zones and then these amounts are re-calculated for functional unit of the system.

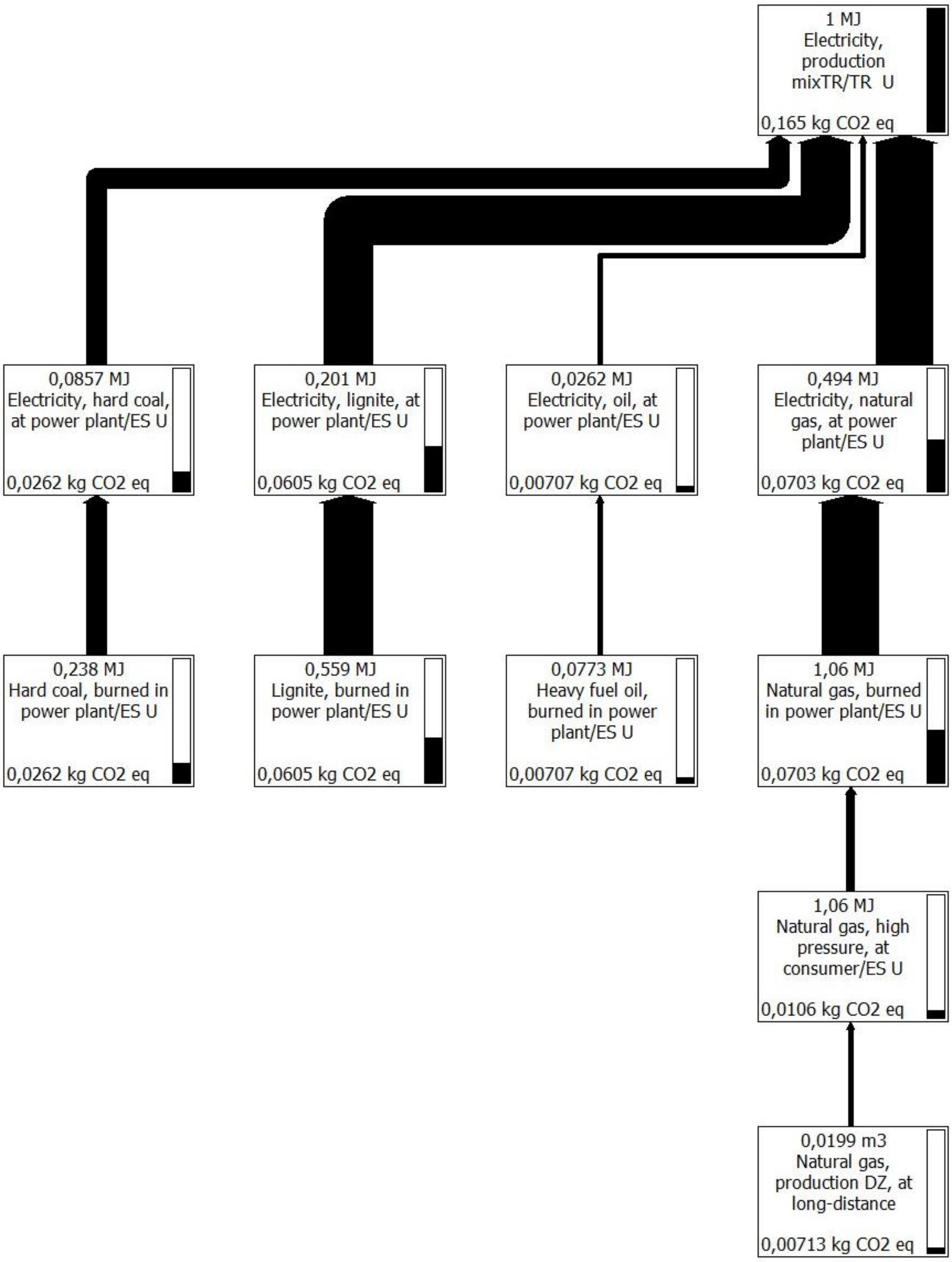
Table 3.6. Building Components Amount & Embodied CO_2 for functional unit (FU)

Components	**Mass (kg)/F.U.**	**Embodied CO_2 (kg CO_2 eq)/F.U.**
External Walls	459,08	64,9
Internal Walls	163,97	21,9
Parapet Walls	93,34	44,8
Floor Finishing	431,77	103
Structure	3145,27	526
Foundation	637,62	73,4
Windows	8,48	60,2
Doors	5,19	7,63

Material production is a cradle to gate stage covering raw material extraction, transport and manufacturing. The majority of embodied energy of materials occurs in this stage. Dwelling’s materials are quantified as kg and m^3 to be inventoried in Simapro 7.3. All materials data are chosen from construction materials section in Ecoinvent v 2.2 Database.

For the present, Ecoinvent is the most appropriate database for an LCA in Turkey by presenting Europe. To localize construction material data, electricity production data which is very determinative in energy consumption, are converted to Turkey’s electricity production mix. 1MJ of Turkey electricity supply corresponds to 0,136 CO_2 eq. According to Simapro hot spot results the major contributors are electricity from lignite and natural gas. For each country this electricity resources and respective shares differs and affects the environmental impacts of material production in this phase.

Table 3.7. Turkey’s Electricity Production Mix GWP Evaluation (by Author)



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3.3.1.1. Transportation to Construction Site

Transportation to construction site is another part of embodied energy of construction materials. No record can be obtained about material resources, except bims block, concrete and wooden floor materials. Transportation distance is assumed 50 km for all materials from production gate to construction site (Ortiz 2009, Cuellar 2012). All transportation is assumed to be by road using 16 t truck.

3.3.1.2. On-site Construction

The construction process of the building also requires energy and causes emissions, waste and noise (Szalay 2007). But in many LCA studies this phase is neglected based on its minimal effect in total environmental impacts of the building life cycle (Arena&Rosa, Bribian, Wallhagen, Trusty…) Deriving information for construction process from literature is limited. Pushkar (2008) stated that ‘’construction as a process is not static; it varies from building to building since each has its own function and different engineering characteristics’’ (Ortiz 2009). On-site construction data for this study are gathered by codes in implementation project referring construction guide of ministry of environment and urban planning. The energy data for construction machinery is calculated as electricity and oil. Primary construction works are determined as excavation and fill, compression, sand and gravel laying, cutting steel bars, concrete mixing, pumping and vibrating, vertical transfer of materials by mobile crane. Construction waste is not considered because of the lack of data and minimal share in overall impacts.

Table 3.8. Main Construction Works for FU (by Author)

Main Construction Works	Energy for FU
Excavation and Fill	220,15 MJ
Compression	0,220 MJ
Sand and gravel laying	1,26 MJ
Steel Bar Cutting	1,74 Kwh
Concrete mix-pump-vibration	9,51 MJ
Vertical Transport by Mobile Crane	157,64 MJ

3.3.2. Use Phase

The use phase comprises two main sub-phases: operation and maintenance. These phases will be examined in detail.

3.3.2.1. Operation Phase

The operation phase consists of total energy consumption of the dwelling during its lifetime. Heating, lighting, electrical appliances and domestic hot water supply are the major contributors to the dwellings operational energy consumption.

The case study dwelling is heated by district heating system via radiators. Energy source of the heating system is coal. Heating service is provided in December, January, February and March. Each dwelling has a heat cost allocator and consumption share can be calculated individually.

According to annual energy bills sum, the heating energy consumption for the case dwelling is 906 MJ. Considering the average life time of the building is 50 years, total heating energy consumption of the dwelling through its life time is calculated as 45309 MJ.

Case building is also modeled with Design Builder software and evaluated in Energy Plus program. Internal thermal comfort conditions of the dwelling are measured with hobos. Thermal comfort parameters evaluated are temperature and humidity. A meteorological station is also settled on the roof of the building and local climate conditions are measured. Model is calibrated according to these measured internal and external data and measured energy consumption. This calibrated model will be used for further research.

Electric consumption is sourced from 12 month electricity bills for a one year period between January 2011-2012. Yearly total electricity consumption of the dwelling is 2090 kWh. Consumption for each month can be detail seen in Table 3.9.

Table 3.9. Electricity Consumption per Month for Case Dwelling- January 2011-2012 (by Author)

January	216,00	kwh
February	145,00	kwh
March	137,00	kwh
April	167,00	kwh
May	185,00	kwh
June	195,00	kwh
July	162,00	kwh
August	165,00	kwh
September	188,00	kwh
October	158,00	kwh
November	169,00	kwh
December	203,00	kwh

3.3.2.2. Maintenance Phase

This phase includes replacement of materials and transportation. Periodic replacement of building elements depends on elements life span. Data for life span of the building elements derived from literature. While Ortiz determines life spans for windows, re-roofing, cabinets, PVC siding and painting, Cuellar defines replacement intervals for doors, carpets, ceramic tiles and laminated floor. Szalay (2007) compares life span data from four different sources (Steiger 1995, Adalberth 1997, Mithraratne 2001, Oswald 2003). Maintenance activities for this study are replacement of windows, repainting, replacement of ceramic tiles and doors. Main maintenance activities depends on technical ageing are considered. Data in this study are derived from these literature sources shown in Table 3.10. Numbers of replacements are based on the replacement intervals over the life span of the building.

Table 3.10. Maintenance Schedule Based on a 50 Years Life Span (by Author)

Building Elements	Typical Replacement Intervals (years)	Number of Replacements over 50 years
Aluminum Windows	25	1
Interior doors	20	2
Exterior doors	20	2
Ceramic floor tiles	20	2
Interior paint	10	4
Exterior paint	10	4

Table 3.11. Material Amounts in Maintenance Phase for Functional Unit (FU)

Building Elements	Kg /FU
Windows	6,08
Interior doors	7,54
Exterior doors	2,98
Ceramic floor tiles	18,02
Interior paint	1,66
Exterior paint	3,70

3.3.3. End-Of-Life Phase

End of life considers the demolition activities based on machine energy, transportation of dismantled building components to the final waste treatment site and waste management. There are three waste scenarios for the building materials which are landfill, recycle and incineration.

Land filling process includes environmental effects of the infrastructure, land use and land filled waste. There three different landfill types according to appropriate waste as inert landfill, residual landfill and sanitary landfill. Gervásio stated that building material wastes are usually inorganic and are treated to send inert landfill. Accordingly the landfill of building materials has a little or no emissions except land use and infrastructure.

Recycling process considers the infrastructure, recycling operation, end products and waste. This scenario can cause positive and negative values. Blengini (2010) pointed out that it is possible to spend more energy and cause more impacts through recycling process than energy and impacts saved as a consequence of avoided primary production. Blengini (2009) also stated that the ratio between net environmental gains of the demolition recycle chain and the from cradle to gate burdens of embodied materials is called recycling potential to determine the recycling whether eco-efficient.

Incineration process includes infrastructure, incineration operation, the energy generated and ashes. Transportation of residues and landfill are also included. Ortiz stated that incineration produces significant power and thermal energy owing to high calorific value of the construction materials waste. Non incinerable materials are sent to the landfill.

A number of uncertainties occur in implementation of the end-of –life scenarios due to long life time of the buildings and limited demolition energy data. Szalay (2007) suggested examining uncertainties due to long life time of the building under two options. First option is to apply today's situation concerning the percentage of waste scenario options based on current statistics. Second option is to define scenarios considering future situation and legislations.

It is clearly seen in literature that the majority of the WPC LCA studies including EOL uses statistical country specific data for the end-of-life phase (Cuellar, Ortiz, Szalay, Nemry, Dodoo…). Destination of the demolition waste statistics is an important input to determine appropriate waste scenario. Country specific reuse, recycle, landfill and incineration percentages of the waste for building materials should be known. Cuellar (2010) gives the percentages for UK in Table 3.12.

Table 3.12. Destination of demolition waste in the UK
(Source: Cuellar 2010)

Waste Type	Reused (%)	Recycled (%)	Landfill (%)	Total
Concrete, binders and aggregates	_	100	_	100
Brick	51	36	13	100
Gypsum	_	100	_	100
Ceramic tiles	57	7	36	100
Insulation	18	_	82	100
Inert	15	15	70	100
Timber	2	79	19	100
U-PVC	_	50	50	100

Another approach to obtaining end of life data is to measure a real case and use these data for future studies in this country. Blengini (2012) obtained specific measured data for demolition operations and aggregate recycling by studying a building life cycle demolished using the blasting technique.

End of life phase was in the system boundary of this study at preliminary plan. Building demolition energy, transport and waste treatment were the sub-stages of this phase. During later stages of the study, it's found that a database for building demolition energy in Turkey is not available. Also there is no literature on building demolition energy of multistory reinforced concrete buildings. Input data for demolition energy couldn't be achieved.

In Turkey there is no advanced legislation or strategy for building demolition wastes. Only legislation for building demolition waste is about 'Excavation Soil, Construction and Demolition Waste Control Regulation'. Waste recycling plants started to appear in the last few years. In Izmir there is eight active plants that half of them are separation-collection plants and the other half are recycling plants. But these plants are for only packaging wastes.

Izmir Metropolitan Municipality determines the building demolition waste storage areas. There are five demolition waste storages areas and the first demolition waste recycling plant planning continues.

In this study waste scenario was the inert landfill of the all of the construction waste materials. And these 5 landfill areas are in a 30 km radius from building site. Recycling impacts for glass, aluminum and steel components couldn't be calculated because of the lack of input data. Impact assessment according these inputs gives a share less than %1 and uncertainty is high. So the end of life phase is decided to be a cut off.

CHAPTER 4

DETAILED LCA RESULTS

4.1. General Results

Total life cycle environmental impact assessment of the studied dwelling for FU (1m2 usable area of the residential unit over a 50 years period) is shown in Figure 4.1 in ten impact categories. These categories are ozone layer depletion (ODP), photochemical oxidation (PO), eutrophication (E), terrestrial ecotoxicity (TE), acidification (A), abiotic depletion (AD), fresh water aquatic ecotoxicity (FWAE), human toxicity (HT), global warming potential (GWP) and marine aquatic ecotoxicity (MAE) which are the default midpoint indicators of CML 2001 method.

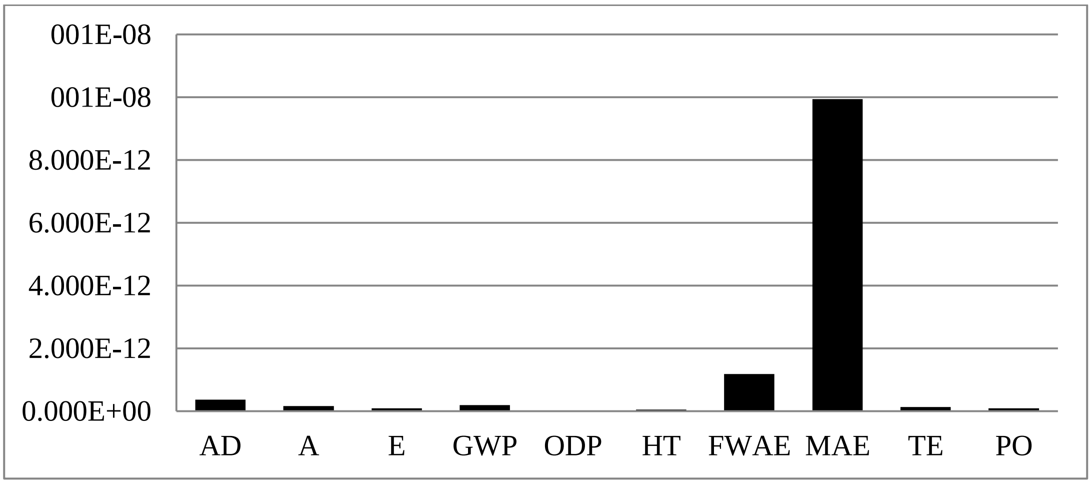

Figure 4.1. Total Environmental Impact Normalization of the Case Dwelling During Life cycle for FU (by Author)

Total normalized impact of the residential unit for FU, in all CML impact categories, is shown in Figure 4.1. The results demonstrate that this residential unit causes the most environmental impact in marine aquatic ecotoxicity (MAE) category (9.94E-09) refering to the impact of toxic substances emitted to marine aquatic ecosystems. Fresh water aquatic ecotoxicity (FWAE) appears as the second significant impact category (1.18E-09). It is clear that aquatic ecotoxicity is the most significant impact area for this case. Abiotic resource depletion (AD) is fallowing as the third important environmental impact category (3.73E-10).

The impact of an emitted gas is expressed in terms of its global warming potential (GWP) which is in fourth place for this residential unit as a considerable impact category (1.92E-10). During the 20th century, the average global temperature increased by about 0,6 °C due to the enhanced greenhouse effect which might cause a man change in climate patterns, the shift of vegetation zones and of the precipitation distribution, and the rise of the sea level due to the melting ice caps. Acidification potential (A) impact is the follow-up category (1.63E-10) referring to augmentation of the acidity of water and soil systems due to acid deposition from the atmosphere, mainly in the form of rain.

Other impact categories according to order of impact amount found as terrestrial ecotoxicity (TE) (1.34E-10), eutrophication potential (E) (9.82E-10), photochemical oxidation (PO) (8.90E-11), human toxicity (HT) (5.58E-11) and ozone layer depletion (ODP) (3.31E-13).

Although all CML environmental impact category results are given above, a detailed result analysis conducted for the common indicators recommended by CEN/TC 350 in order to provide a readable and comparable interpretation. These indicators are GWP, ODP, A, E and ADP. It is seen that toxicity indicators are excluded from this list.

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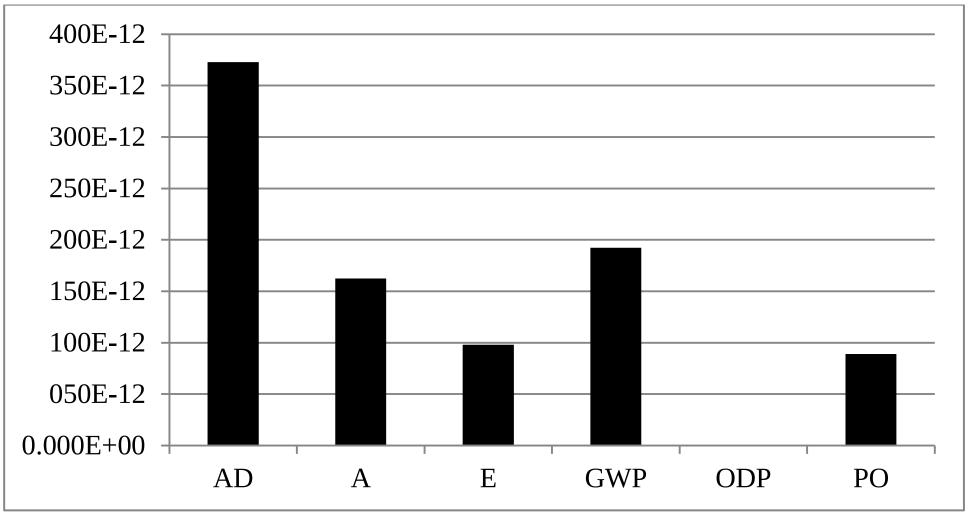


Table 4.2. Total Environmental Impact Normalization in Recommended Indicators for FU (by Author)

Environmental impact results distributed to all life cycle stages are examined for every single environmental impact categories given above. A general comparative assessment for these impact categories is also performed.

Global warming potential (GWP) normalization results of the life cycle stages for FU are shown in Figure 4.3. GWP results of life cycle phases clarify the relative relation to each other. Operation phase appears as the leading life cycle phase in GWP impact category with a share of 86 % of the total GWP impact. 6860 kg CO_2 eq/m^2 is generating by operation of the residential unit mainly due to the energy consumption for heating and electricity during useful life span. Building components is the second contributor of the GWP impact category which is responsible for 12 % of the total GWP by a 931 kg CO_2 eq/m^2. Contribution of maintenance (1.5 %), transportation (1%) and on-site construction (0.5 %) is negligible compared to the operation and building components results. Total GWP footprint of the case study for FU is 7983 kg CO_2 eq/m^2.

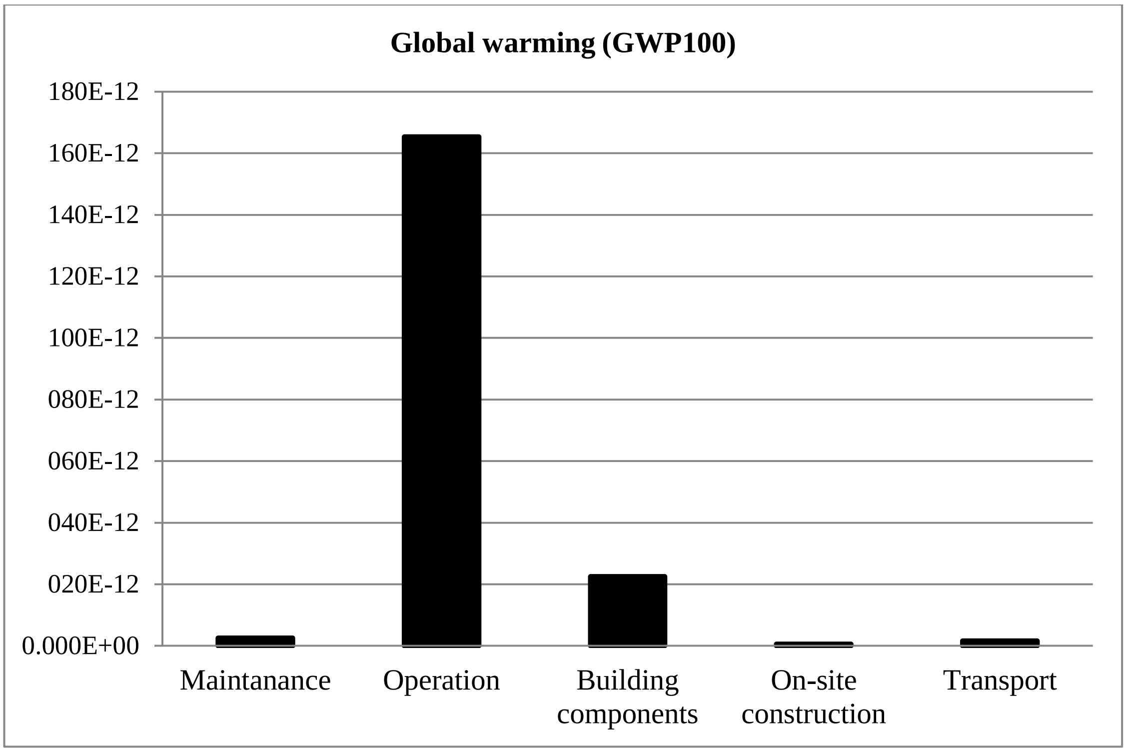


Figure 4.3. Global Warming Potential (GWP) Impact Normalization of the Life Cycle Phases for FU (by Author)

No other WPC LCA studies exists for housing sector in Turkey as mentioned before, so that a full comparison of the results is not possible. Instead, results of the current study are tried to be compared by other studies from literature with a limited scope. GWP as a most common environmental indicator can be compared with some other studies.

Ortiz et al. (2009) studied WPC LCA of a semi detached Spanish house with 160 m^2 usable area for 50 years life span. The study includes pre-use and use life cycle phases. The total GWP reported by Ortiz is 2340 kg CO_2 eq/m^2 per 50 years while in this study the total GWP is resulted 7983 kg CO_2 eq/m^2 per 50 years. Although there is a significant difference in total GWP results, both studies show a similar contribution to the GWP impact from different life cycle phases per unit area, with the use phase contributing around 90 % of the total GWP.

Cuellar et al. (2012) studied a typical UK brick house. The total GWP for UK house is estimated for 3500 kg CO_2 eq/m^2 per 50 years. With this study also, a similar contribution to the GWP impact from different life cycle phases per unit area with the use phase contributing around 90 % of the total GWP is found.

While we compared these results with this study, it is seen that GWP contribution of this study is more than these two comparable studies. This difference can be associated with different electricity production mix, energy resource and climate of the house location.

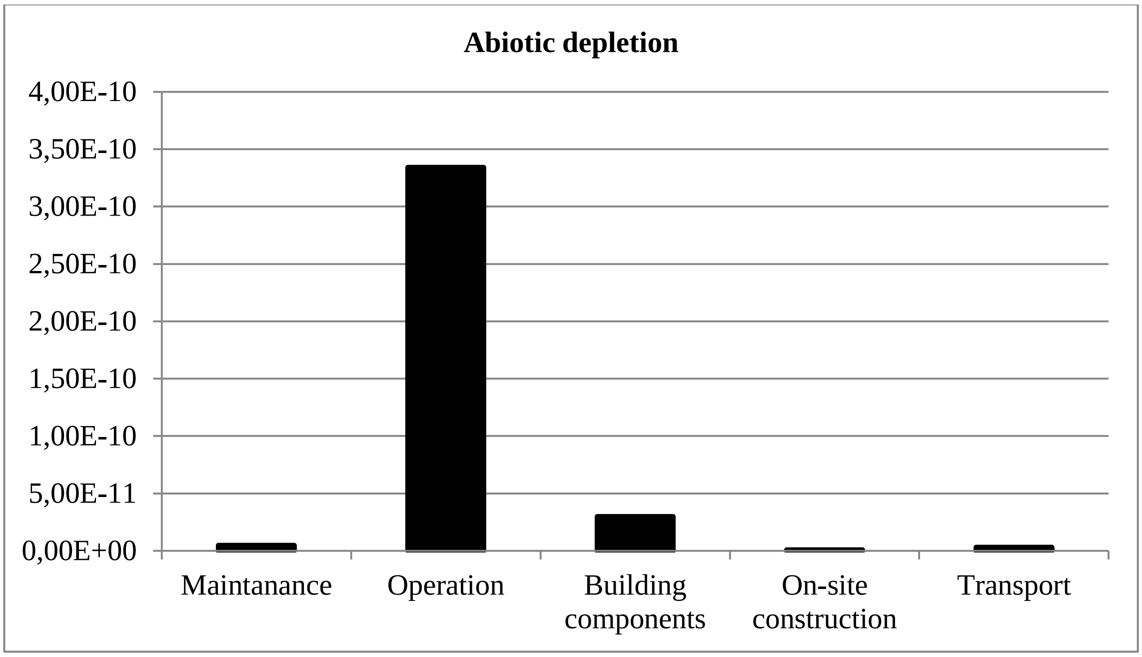
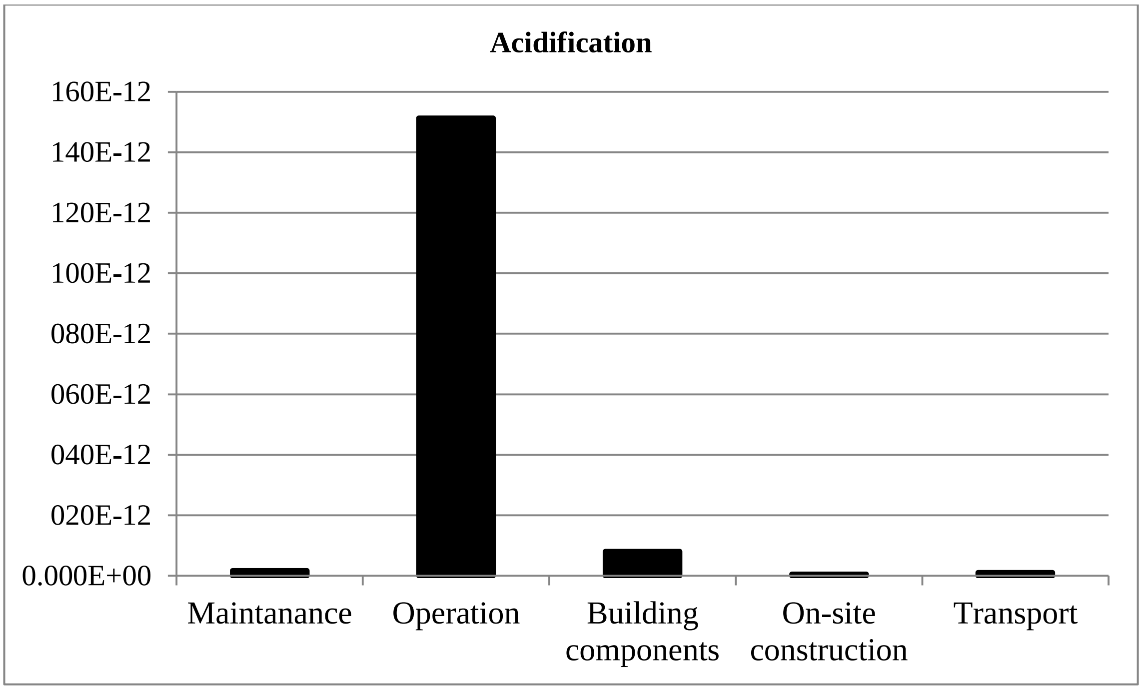


Figure 4.4. Abiotic Depletion (AD) Impact Normalization of the Life Cycle Phases for FU (by Author)

Abiotic resource depletion (AD) normalization results of the life cycle stages for FU are shown in Figure 4.4. Operation phase is also the largest contributor of the abiotic resource depletion with a share of 90 % of the total AD impact. 52.8 kg Sb eq/m^2 is generating by operation of the residential unit mainly due to the energy consumption.

Building components is responsible for 8 % of the total AD by a 4.6 kg Sb eq/m^2 . Contribution of maintenance, transportation and on-site construction is almost negligible compared to the operation and building components results with a total 2% share . Total AD footprint of the case study for FU is 58.3 kg Sb eq/m^2.



Figıre 4.5. Acidification (A) Impact Normalization of the Life Cycle Phases for FU (by Author)

Acidification potential (A) normalization results of the life cycle stages for FU are shown in Figure 4.5. Operation phase contributes 93% of the total in A impact category by generating 48.64 kg SO_2 eq/ m^2. Building components is the fallowing contributor of the A impact category which is responsible for 5 % of the total A by a 2.57 kg SO_2 eq/m^2 emission. Total acidification potential of the study is about 52.2 kg SO_2 eq/m^2 per 50 years.

The total acidification potential reported by Ortiz et al. (2009) is 18.5 kg SO_2 eq/m^2 per 50 years life span. More than 90% of this contribution occurs in use phase in Spanish house too. But Ortiz assumed electricity as the only source of energy which is differentiated from this study in this respect. In this case dominant energy source is the coal for heating system. This differentiation can be based on this beside other variables.

Cuellar et al. (2012) WPC LCA study of a typical UK brick house presents a result for total acidification potential (A) as 6.9 kg SO_2 eq/m^2 per 50 years which is approximately 9 times lower than this study.

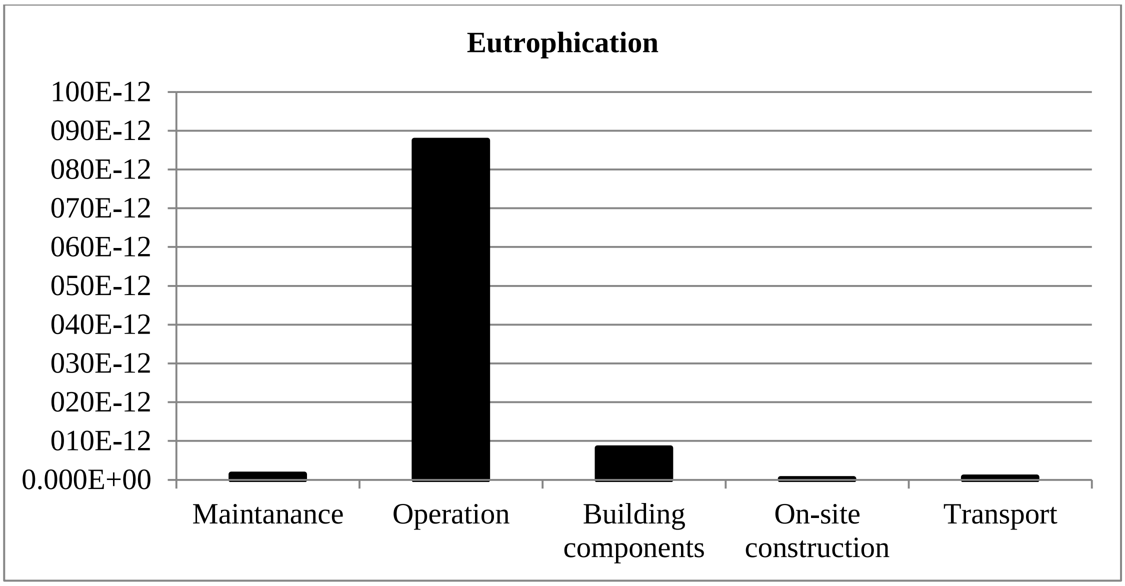


Figure 4.6. Eutrophication (E) Impact normalization of the Life Cycle Phases for FU (by Author)

Eutrophication potential (E) normalization results of the life cycle stages for FU are shown in Figure 4.6. Operation phase is the largest contributing life cycle phase in eutorphication (E) impact category with a share of 89 % of the total E impact. 12.9 kg PO_4 eq/m^2 is generating by operation of the residential unit. Building components is the second contributor of the eutrophication impact category which is responsible for 8 % of the total E by a 1.09 kg PO_4 eq/m^2. Total eutrophication footprint of the case study for FU is 12.98 kg PO_4 eq/m^2.

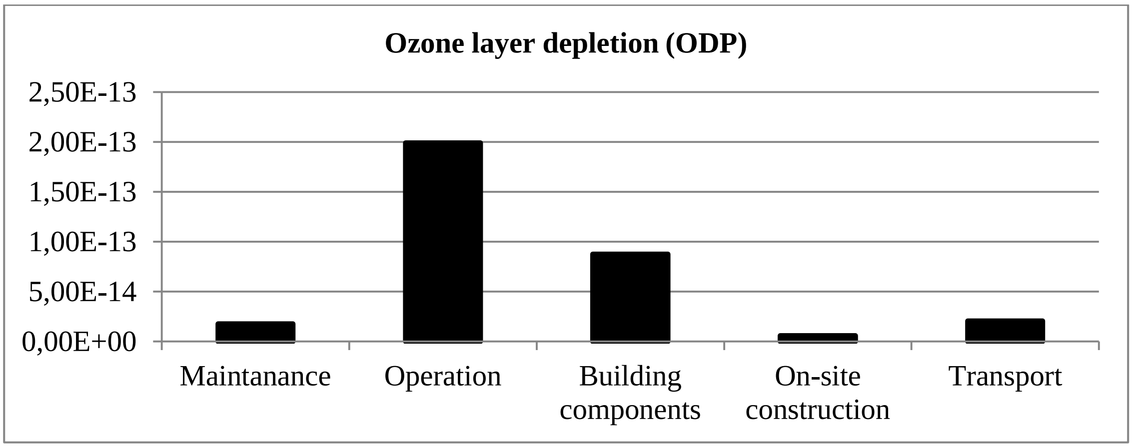


Figure 4.7. Ozone Layer Depletion (ODP) Impact Normalization of the Life cycle Phases for FU (by Author)

Ozone layer depletion (ODP) normalization results of the life cycle stages for FU are shown in Figure 4.7. Operation phase is the largest contributing life cycle phase in ozone layer depletion (ODP) impact category with a share of 60 % of the total ODP impact which is a lower percentage than above other impact categories. 1.03E-04 kg CFC-11 eq/m^2 is generating by operation of the residential unit. Building components is the second largets contributor of the ODP impact category with a significant percentage as 27 % of the total ODP by 4.51E-05 kg CFC-11 eq/m^2. Total ODP footprint of the case study for FU is 1.70E-04 kg CFC-11 eq/m^2. The depletion is mainly caused by CFCs which are used in aerosols, air conditioning, and refrigerators.

Ortiz et al. (2009) found a close result to this study as 1.17E-04 kg CFC-11 eq/m^2 per 50 years. But its system boundary covers also air cooling system differentiating from present study. While its operation phase responsible for more 80 % of the total ODP, in present study operation phase is about 60 % of the total. Turkey Electricity mix used in material production and using coal in heating system seems determinative according to ODP inventory data for process contribution of the present study.

When we compare the present study ODP results with the results of Cuellar et al. (2012) WPC LCA study of a typical UK brick house, it is seen that UK house ODP impact is higher with a factor approximately 60. The total ODP reported by Cuellar et al. (2012) is 9.90E-03 kg CFC-11 eq/m^2 per 50 years where the main contributor is in construction stage due to the use for insulation of expanded polystyrene produced using ozone depleting blowing agents such as HCFCs. This can be explaining the differentiation between two results regarding present case building does not have any insulation layer.

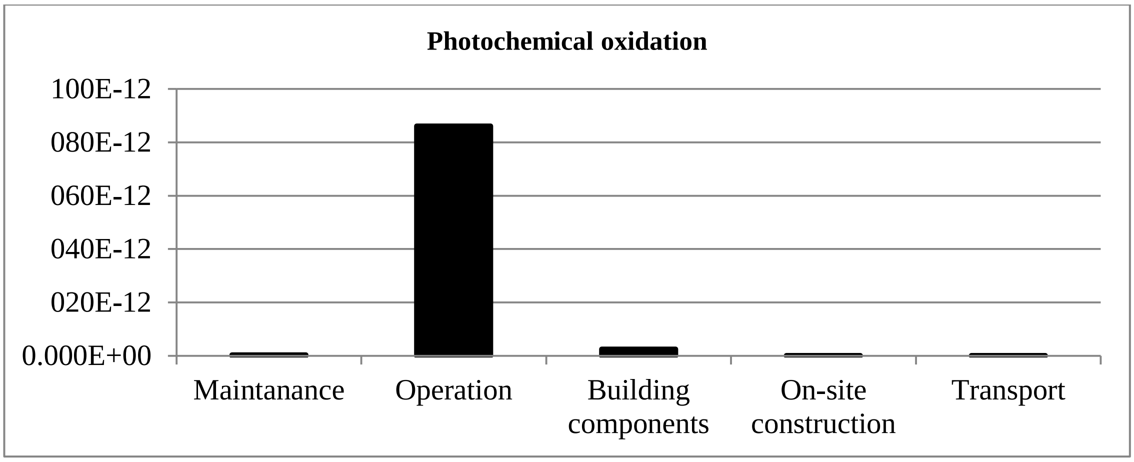
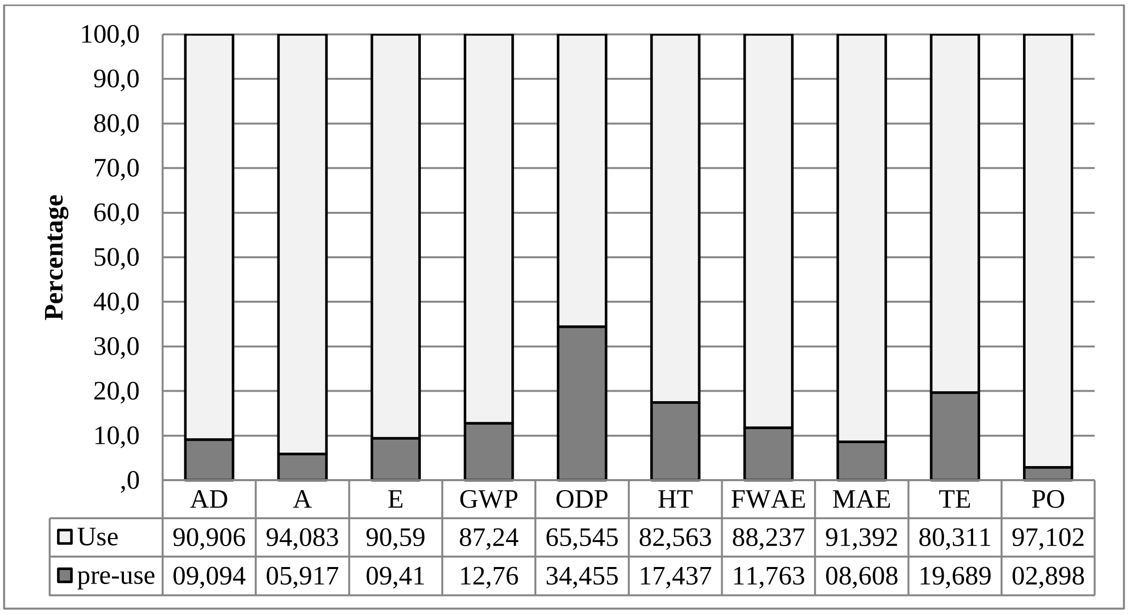


Figure 4.8. Photochemical Oxidation (PO) Impact Normalization of the Life cycle Phases for FU (by Author)

Photochemical oxidation (PO) normalization results of the life cycle stages for FU are shown in Figure 4.8. Operation phase is the largest contributing life cycle phase in photochemical oxidation (PO) impact category with a share of 97 % of the total and other life cycle phases contribution is negligible. Total photochemical oxidation footprint of the case study for FU is 8.55 kg C_2H_4 eq/m^2 while the Cuellar et al. (2012) is reported 99 kg C_2H_4 eq/m^2 .



	AD	A	E	GWP	ODP	HT	FWAE	MAE	TE	PO
□ Use	90,906	94,083	90,59	87,24	65,545	82,563	88,237	91,392	80,311	97,102
■ pre-use	09,094	05,917	09,41	12,76	34,455	17,437	11,763	08,608	19,689	02,898

Figure 4.9. Total Environmental Impact Distribution of the Case Dwelling During Whole Life Cycle (by Author)

According to the total environmental results use phase has the highest environmental impact in all categories. Use phase has the largest share for 97.1% in photochemical oxidation (PO) impact category and minimum share for 65,5 % in ozone layer depletion (ODP) impact category. Use phase place in interval 80.3-96.9 % of the total life cycle except 65.5 % ozone layer depletion (ODP). Total results for the other impact categories are; pre-use phase 9.41% and use phase 90.6 % for eutrophication impact category (E), pre-use phase 5.92 % and 94.1 % use phase for acidification (A) impact category, pre-use phase 9.09 % and use phase 90,9 % for abiotic depletion (AD), pre-use phase 11.8 % and use phase 88.2 % for fresh water aquatic ecotoxicity (FWAE), pre-use phase 17.4 % and use phase 82,6 for human toxicity (HT), pre-use phase 12.8 and use phase 87.2 % for global warming potential (GWP), pre-use phase 8.61 % and use phase 91.4 % for marine aquatic ecotoxicity (MAE).

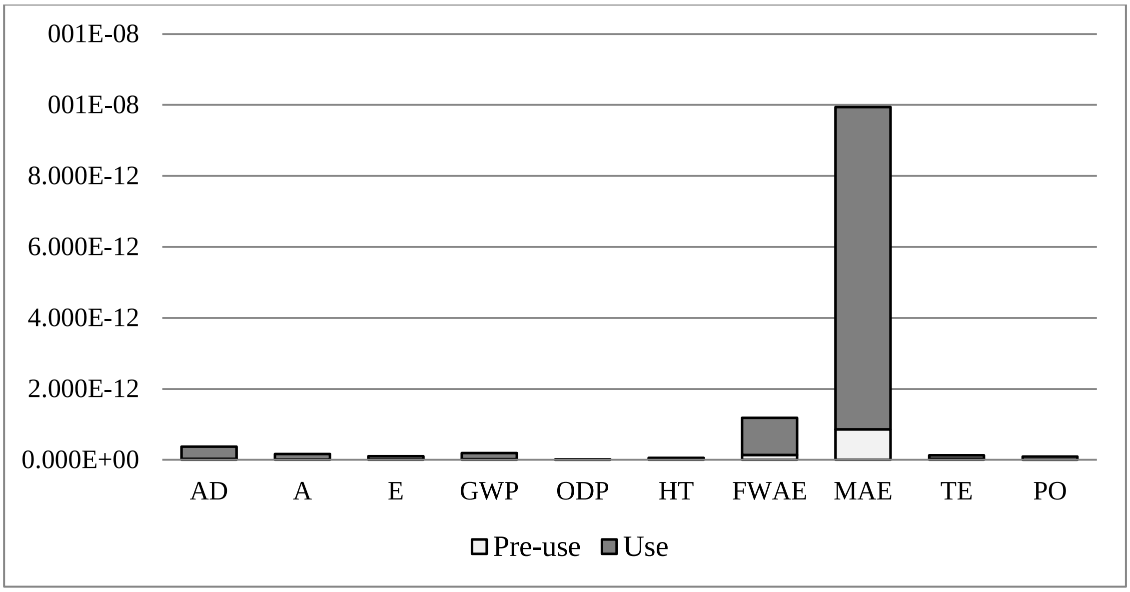


Figure 4.10. Total Environmental Impact Normalization of the Case Dwelling During Whole Life Cycle (by Author)

Total environmental impact values can be seen in Figure 4.9. and 4.10. Dwelling's highest total environmental impact occurs in marine aquatic ecotoxcity (MAE) impact category which accounts 9.94E-09 (5.1E6 kg 1.4-DB eq). Ozone layer depletion (ODP) impact has the lowest value for 3.31E-13 (0.00017 kg CFC-11 eq). The fallowing impact values from lowest to highest are; human toxicity impact category (HT) for 5.58E-11 (3.19E-3 kg 1.4-DB eq), photochemical oxidation (PO) for 8.9E-11 (8.56 kg C2H4-eq), eutrophication (E) for 9.82E-11 (13 kg PO4 eq), terrestrial ecotoxicity (TE) for 1.34E-10 (35.9 kg 1.4-DB eq), acidification (A) for 1.63E-10 (52.3 kg SO2 eq), global warming potential (GWP) for 1.92E-10 (7.99E3 kg CO2 eq), abiotic depletion (AD) for 3.73E-10 (58.4 kg Sb eq) and fresh water aquatic ecotoxicity (FWAE) for 1.18E-09 (2.41E3 1.4-DB eq).

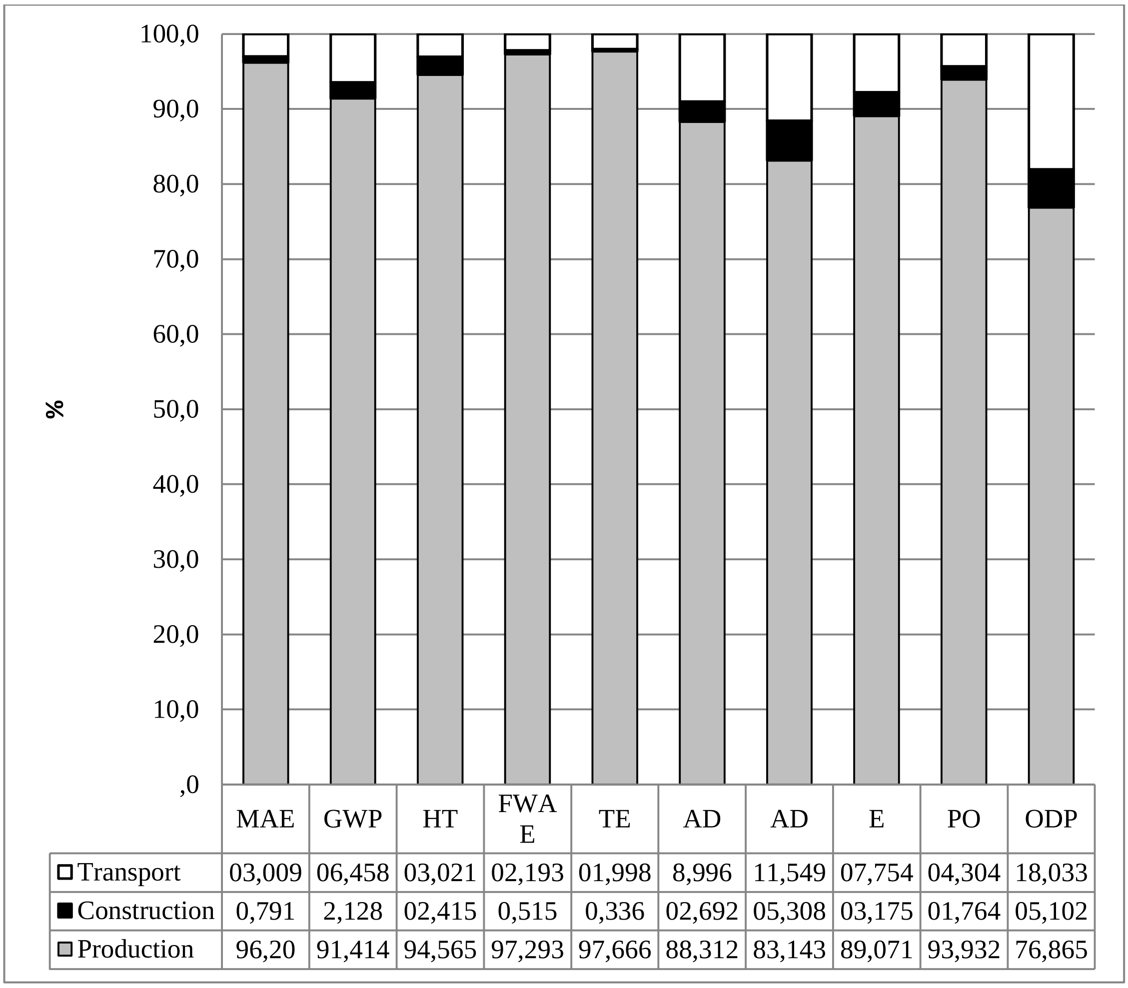
It is important to notice that general approach on choosing environmental indicators in previous studies is to use a determinate indicator set according the boundaries and aims of the study. In this present study all CML environmental indicators are examined in order to determine which indicators have the most significant environmental contribution and to serve a base indicator set according to order of load. It is found that marine aquatic ecotoxicity (MAE), fresh water aquatic ecotoxicity (FWAE), abiotic depletion (AD) and global warming potential (GWP) are the most significant indicators.

Iyer-Raniga and Wong (2012) conducted a whole building LCA study applied to eight residential heritage buildings in Australia. The results for total buildings life cycle concluded that photochemical oxidation (PO) loads were in an interval of 1.04-48 (kg C_2H_4/m^2) and eutrophication (E) loads were in 1.17-86.2 (kg PO_4/m^2) interval. In all cases use phase had the largest environmental impact share. Blengini (2009) studied LCA of a multi-storey residential building in Turin. It is found that use phase of the building excelled other life cycle phases of the building with a share of from 90.1 % to 95.2% depending on the indicator. Pre-use phase accounted for 6.2% to 11.5% and end-of-life which is the focus point of this study corresponds to a negative contribution as -0.2% to -2.6%. Matasci (2006) analyzed 21 buildings from 'German database' to evaluate life cycle environmental impacts. Results generated from this analysis showed that the use phase was the most environmentally impacting phase in almost all cases from 38% to 70% of the total impact. The refurbishment phase (which is not included in use phase in this study) was responsible for 16-40%. The construction phase was responsible for 11-25% of the total impacts and disposal for 2-6%. Importance of the refurbishment phase were outlined. Ortiz (2009) compared full building life cycle impacts of a Mediterranean Spanish house and a Colombian house. Acidification potential (A), global warming potential (GWP), Human toxicity (HT) and stratospheric ozone depletion (ODP) are the assessed CML indicators. It is clearly seen that operation phase has the highest environmental impact with a share for 77% to 93% in all categories, except human toxicity with a share for 75%. Maintenance which is evaluated as an independent life cycle phase fallows the operation phase impact share for 6% to 20% in total. End of life has the minimum share with a share for less than 1% in total as a result of the landfill scenario. The highest environmental impacts in Colombian house life cycle occurred in use phase parallel to Spanish house. Construction phase has a share for 9% to 31% in total.

It is found that use phase of the building overshadowed other life cycle phases of the building, pre-use and end of life are following by a decrease of share, as expected regarding results of the previous studies depending on the indicator.

4.1.1. Results of the Pre-use Phase

Environmental impact evaluation of the pre-use phase covers the material production, transportation and on-site construction sub-phases impacts in detail. Pre-use phase is responsible for the 2.09-34.5 % of the total environmental impacts of the dwelling.



	MAE	GWP	HT	FWAE	TE	AD	AD	E	PO	ODP
□ Transport	03,009	06,458	03,021	02,193	01,998	8,996	11,549	07,754	04,304	18,033
■ Construction	0,791	2,128	02,415	0,515	0,336	02,692	05,308	03,175	01,764	05,102
▨ Production	96,20	91,414	94,565	97,293	97,666	88,312	83,143	89,071	93,932	76,865

Figure 4.11. Environmental Impact Distribution of the Case Dwelling for Pre-use Phase (by Author)

Environmental impact distribution for pre-use is shown in Figure 4.11. Material production phase has the largest share in total environmental loads of the pre-use phase. The maximum share for the material production phase occurs in terrestrial ecotoxicity category (TE) that has a percentage for 97.7%. Minimum impact share for material production phase is in ozone layer depletion (ODP) category which is for 76.9%. Second largest contributor to environmental loads in share is transportation phase. Consequently, where material production share is maximum transportation share is minimum because of the on-site construction share is in very low level. Transportation phase has the largest impact share for 18 % in ozone layer depletion (ODP) impact category and lowest impact share for 2 % in terrestrial ecotoxicity (TE) impact category. On-site construction phase shows the minimum impact share for 0.3 % in terrestrial ecotoxicity (TE) impact category and the maximum impact share for 5.3 % in acidification (A) impact category.

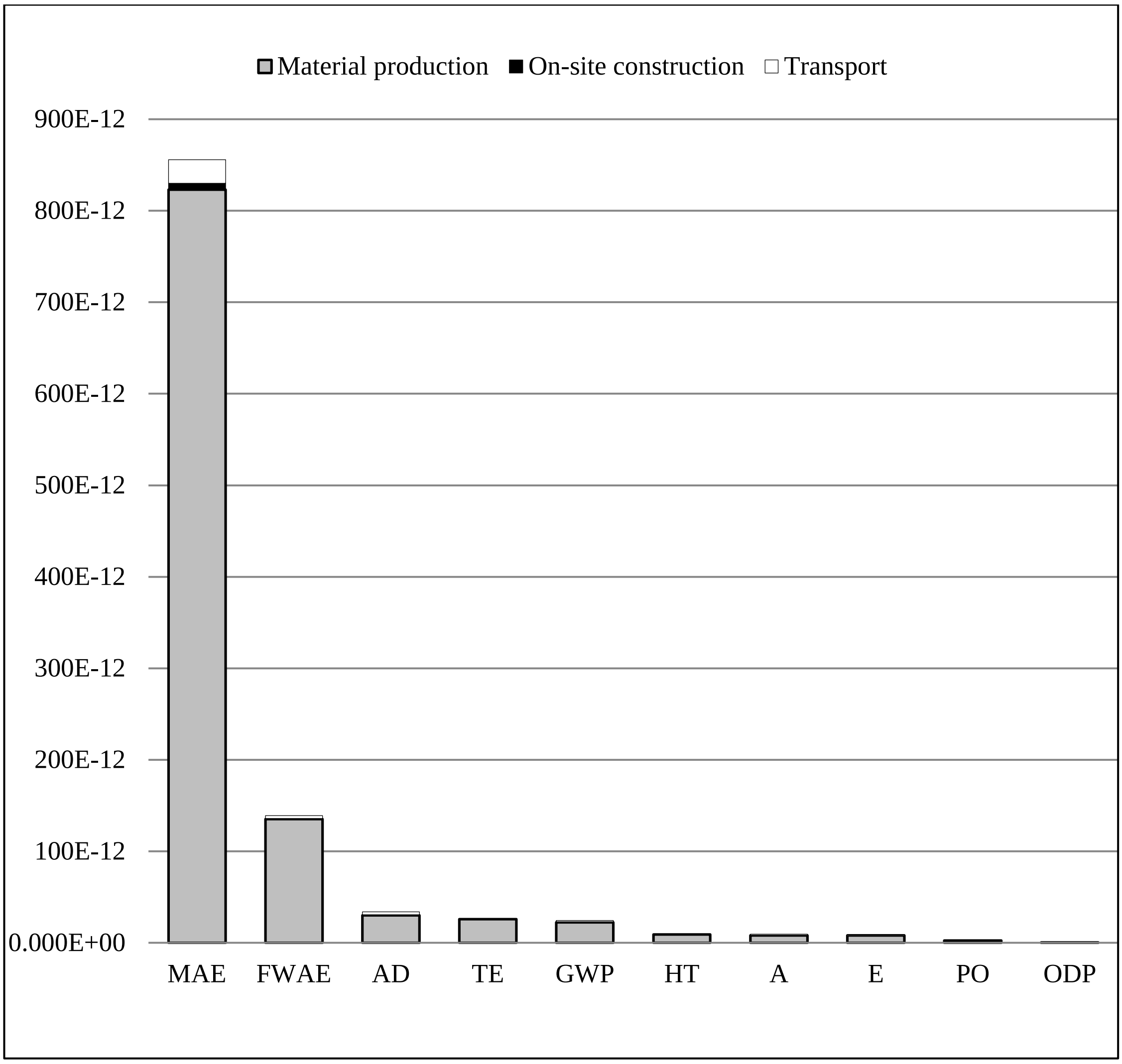


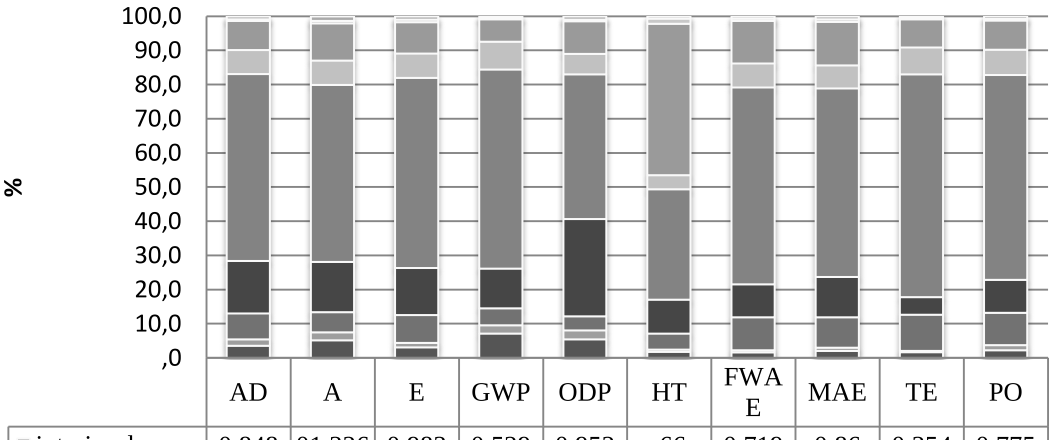
Figure 4.12. Total Environmental Impact Normalization of the Case Dwelling in Pre-use Phase (by Author)

Normalized environmental impact values for pre-use phase are given in Figure 4.12 for further understanding on this phase. The largest environmental impact contributor category is marine aquatic ecotoxicity (MAE) for pre-use phase with a total value of 8,56E-10 (4,39E-5 kg1,4-DB eq). The fallowing impact values from highest to lowest are; global warming potential (GWP) for 2,46E-11 (1,02E3 kg CO2eq), human toxicity (HT) for 9,74E-12 (556 kg 1,4 –DB eq), fresh water ecotoxicity (FWAE) for 1,39E-10 (284 kg 1,4-DB eq), terrestrial ecotoxicity (TE) for 2,63E-11 (7,07 kg C2H4 eq), abiotic depletion (AD) for 3,39E-11 (5,31 kg Sb eq), acidification (A) for 9,62E-12 (3,09 kg SO2 eq), eutrophication (E) 9,24E-12 (1,22 kg PO4 eq), photochemical oxidation (PO) for 2,58E-12 (0,248 kg C2H4 eq), ozone layer depletion (ODP) for 1,14E-13 (5,87E-5 CFC-11 eq).

4.1.1.1. Results of the Material Production Phase

Material production phase evaluates the cradle to gate environmental loads of the building components and materials. The case building examined in nine building components which are; external, internal and parapet walls, floor finishing, structure, foundation, windows, internal and external doors.

Figure 4.13 clarifies the details of the production phase environmental load distribution for impact categories. It is clearly found that structure is the most environmentally destructive part of the building in all impact categories except human toxicity (HT). Windows have the heaviest impact on human toxicity (HT) category with a share of 44%, although it has an average impact on other categories. Structure's share in total loads is in an interval 32.3 % - 65.2 %. Its lowest share is in human toxicity (HT) and the highest share in terrestrial ecotoxicity (TE).



	AD	A	E	GWP	ODP	HT	FWAE	MAE	TE	PO
■ interior doors	0,848	01,326	0,983	0,529	0,952	,66	0,719	0,86	0,354	0,775
■ exterior doors	0,477	0,802	0,718	0,353	0,498	01,504	0,675	0,735	0,57	0,473
■ windows	08,536	10,817	09,253	06,545	09,571	44,336	12,42	12,751	08,163	08,531
■ foundation	07,023	07,122	07,089	08,128	05,956	04,159	06,992	06,81	07,897	07,411
■ structure	54,698	51,827	55,616	58,291	42,403	32,291	57,648	55,117	65,246	59,955
■ floor finishings	15,404	14,735	13,787	11,613	28,4	09,946	09,681	11,842	05,123	09,662
■ parapet walls	07,604	05,895	08,144	05,026	04,122	04,626	9,653	08,848	10,594	09,485
■ internal walls	01,848	02,349	01,282	02,397	02,668	0,653	0,614	0,931	0,385	01,417
■ external walls	3,561	05,127	03,128	07,119	05,431	01,826	01,599	02,107	01,668	2,289

Figure 4.13. Environmental Impact Distribution of the Case Dwelling for Production Phase (by Author)

Exterior and interior doors have the minimum environmental load share in total. They are almost negligible components. External pumice block walls shows the largest impact share in global warming potential (GWP) category by 7.12 % and minimum share in fresh water aquatic ecotoxicity (FWAE) by 1.6 %. Reinforced concrete parapet walls has the maximum share of 10.6 % in terrestrial ecotoxicity category and the minimum share of 4.12 % ozone layer depletion (ODP). Floor finishing impacts the ozone layer depletion (ODP) by a share of 28.4 % and the terrestrial ecotoxicity (TE) by a share of 5.12 %. Foundation has its highest impact share in global warming potential (GWP) category with a 8.13 % share and the lowest in ozone layer depletion (ODP) category with a 5.96 % share.

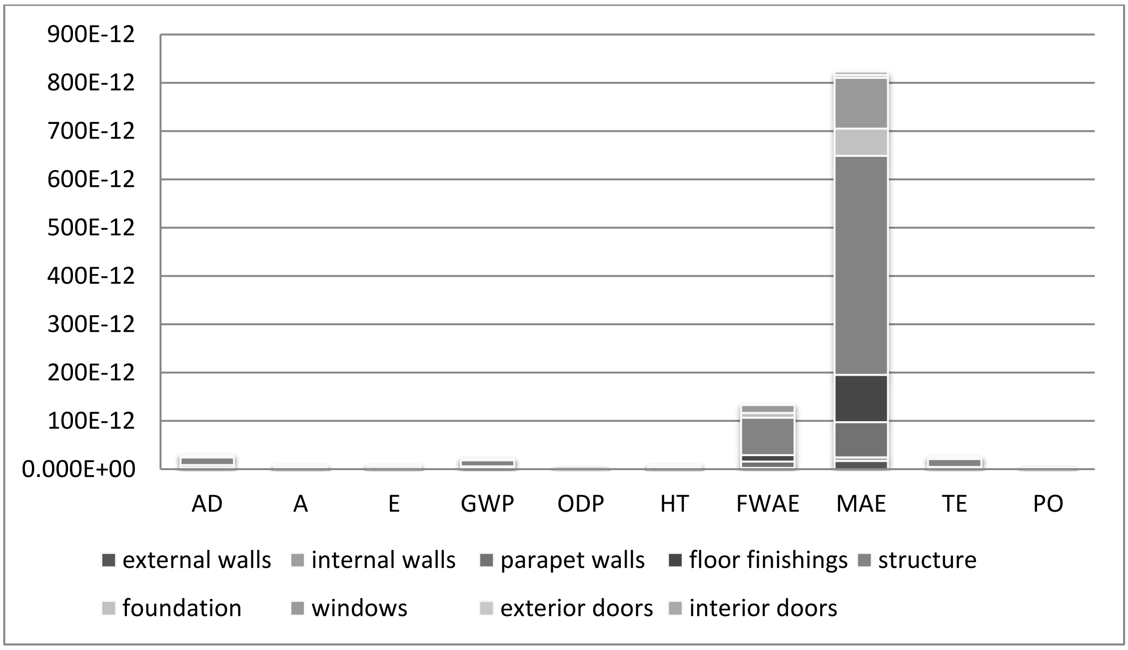


Figure 4.14. Total Environmental Impact Normalization of the Case Dwelling for Production Phase (by Author)

Figure 4.15 demonstrates total normalized environmental impacts occurring for each building component which provide a clear understanding on environmental impact graduation of the building components for 1m^2 of the usable area (FU) in material production phase. According to these results structure has the largest total environmental impact (56%). Windows follows as the second largest contributor in total environmental impact graduation of the building components (13%) and floor finishings group appears as the third one (11%).

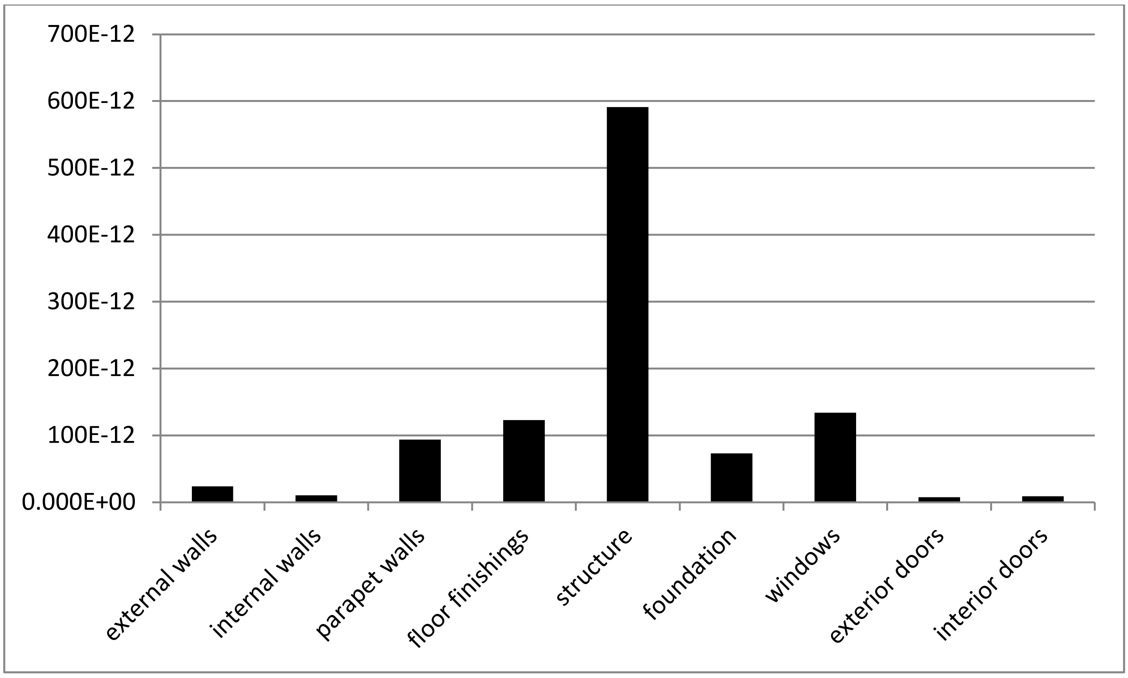


Figure 4.15. Total Environmental Impact Normalization of the Building Components for Material Production Phase (by Author)

Structural system is composed of steel and concrete. Structural steel has an impact share on structure components' total environmental loads between 40%-90%. Except GWP and ODP categories, steel is the dominant material versus concrete in environmental load share of structure in all impact categories. According to the normalized environmental loads, steel' environmental impact is heavier than concrete in total.

Aluminum windows total environmental load is very significant regarding to its minimal share in mass amount of total building components for 1m^2 usable are. Windows mainly consist of aluminum frame and double glazing panel. Aluminum frame has a heavy environmental impact in all impact categories while impact of glass is minimum.

Floor finishings as a group of materials is the third largest contributor of the total environmental impact share in building components. Adhesive mortar found as the dominant material of the floor finishings in this aspect.

Marine aquatic ecotoxicity has again maximum environmental load value in total material production phase environmental impact for 8.23E-10 (4,22E5 kg 1,4-DB eq). Fresh water aquatic ecotoxicity (FWAE) follows as second important impact area by a value of 1.35E-10 (276 kg 1,4-DB eq). Abiotic depletion (AD) has a value of 2.99E-11 (4.69 kg Sb eq). The other contributors from highest to lowest are; terrestrial ecotoxicity (TE) for 2.57E-11 (6.9 kg 1.4-DB eq), global warming potential (GWP) for 2.25E-11 (932 kg CO2 eq), human toxicity (HT) for 9.21E-12 (526 kg 1.4-DB eq), eutrophication (E) for 8.23E-12 (1.09 kg PO4 eq), acidification (A) for 8E-12 (2.57 kg SO2 eq), photochemical oxidation (PO) for 2.42E-12 (0.233 kg C2H4 eq) and ozone layer depletion (ODP) for 8.75E-14 (4.51E-5 kg CFC-11).

4.1.1.2. Results of the On-site Construction Phase

On-site construction is the least environmental impact in pre-use phase as estimated in this study. Although detailed data were not available for this stage, information gathered from consultants, on-site photos and energy calculated with the construction guide of ministry of environment and urban planning. According to pre-use phase results on-site construction has the minimum share in terrestrial ecotoxicity (TE) phase with 2 % and maximum share in acidification (A) with 5.31 %.

According to detailed results of on-site construction phase, mobile crane has the largest share. This result is mostly related to estimation of all materials are vertically transferred with crane. Energy consumed in crane is responsible for 73.2 % of the ozone layer depletion (ODP) with the maximum share and 44.5 % of the fresh water aquatic ecotoxicity (FWAE) with the minimum share.

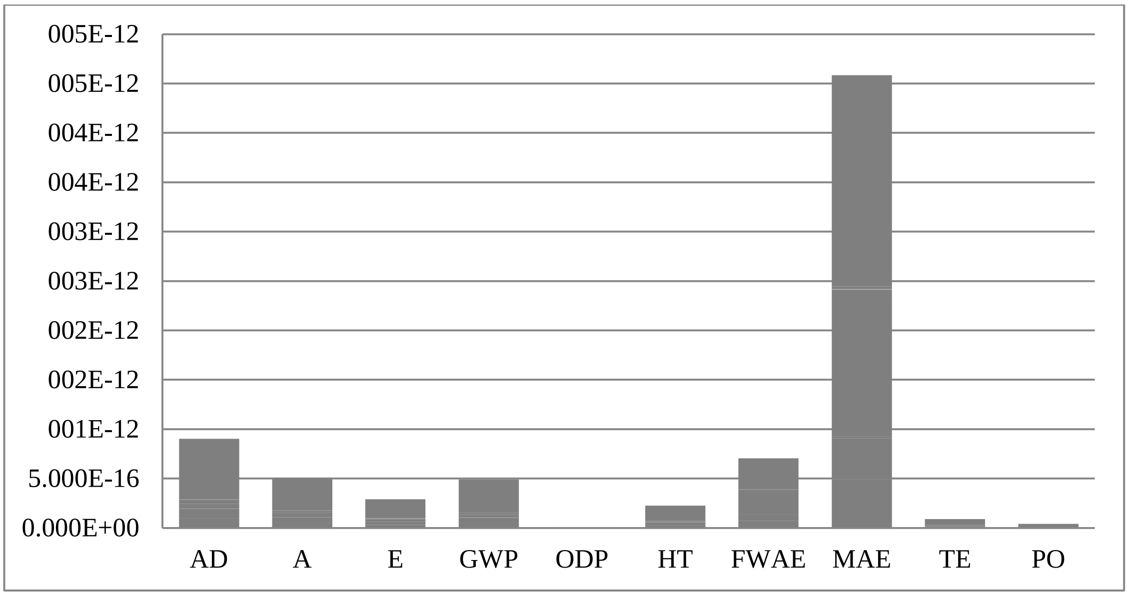
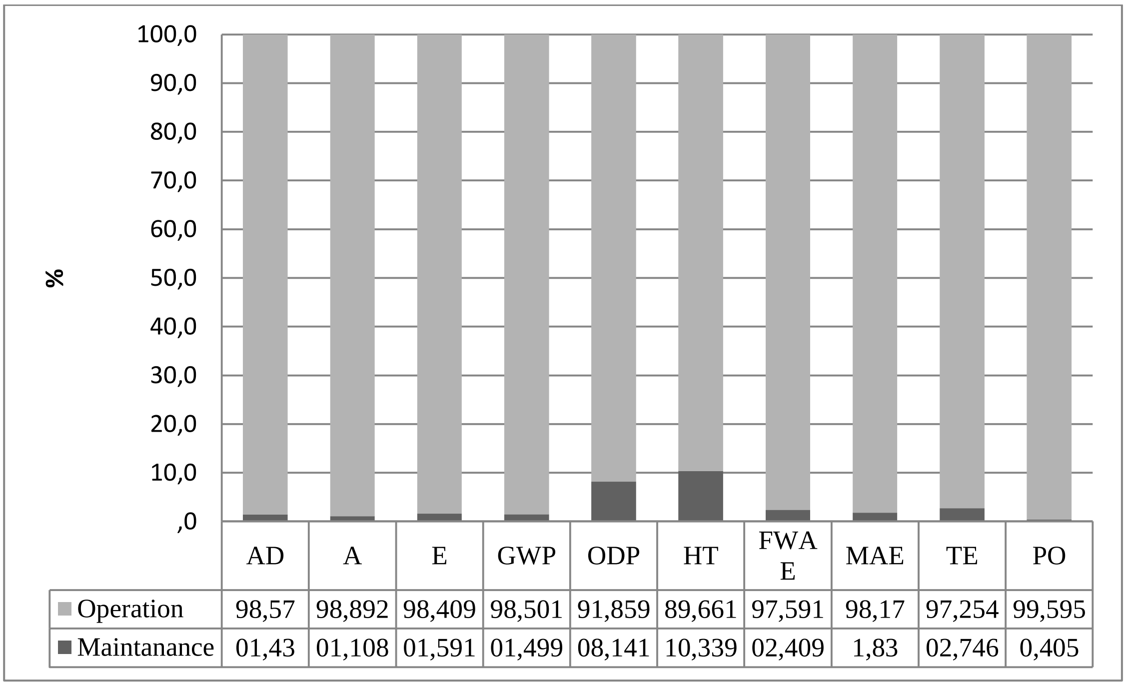


Figure 4.16. Total Environmental Impact Normalization of the Case Dwelling for On-site Construction Phase (by Author)

Marine aquatic ecotoxicity (MAE) is the largest contributed impact category for the environmental loads in this phase.

4.1.2. Results of the Use Phase

Use phase is the most significant phase in building life cycle with the highest load share between 65.5 %-97.1 %. Long during time of this phase as 50 years life span of the building increases its environmental impacts. Use phase consists of operation and maintenance sub-phases. Detailed examination of the environmental load share of the use phase is given in Figure 4.17.



	AD	A	E	GWP	ODP	HT	FWAE	MAE	TE	PO
■ Operation	98,57	98,892	98,409	98,501	91,859	89,661	97,591	98,17	97,254	99,595
■ Maintanance	01,43	01,108	01,591	01,499	08,141	10,339	02,409	1,83	02,746	0,405

Figure 4.17. Environmental Impact Distribution of the Case Dwelling for Use Phase (by Author)

Operation phase that is mainly consists of energy, has the maximum environmental load share with an 89.7 %-99.6 % value interval. Impact share of maintenance phase is almost negligible except ozone layer depletion (ODP) share of 8.14 % and human toxicity (HT) share of 10.3 %.

According to normalized values, the largest total impact on environment occurs in marine aquatic ecotoxicity (MAE) with a value of 9.08E-9 (4.66E6 kg 1,4-DB eq). Fresh water aquatic ecotoxicity (FWAE) is in second row with a value of 1.04E-9 (2.13E3 kg 1,4-DB eq). Following normalized values through minimum are; abiotic depletion (AD) for 3.39E-10 (53 kg Sb eq), global warming potential (GWP) for 1.68E-10 (6.97E3 kg CO2 eq), acidification (A) for 1.53E-10 (49.2 kg SO2 eq), terrestrial ecotoxicity (TE) for 1.07E-10 (28.8 kg 1,4-DB eq), eutrophication (E) for 8.89E-11 (11.8 kg PO4 eq), photochemical oxidation (PO) for 8.65E-11 (8.31 kg C2H4 eq) and ozone layer depletion (ODP) for 2.17E-13 (0.000112 kg CFC-11 eq).

Global warming potential (GWP) is the fourth most contributed category which is significantly related to energy consumption. Approximately 98.5 % of the global warming potential in use phase occurs in operation phase. Regarding GWP in operation phase it is also important to indicate that the use of heating system and electrical appliances are the most important household activities.

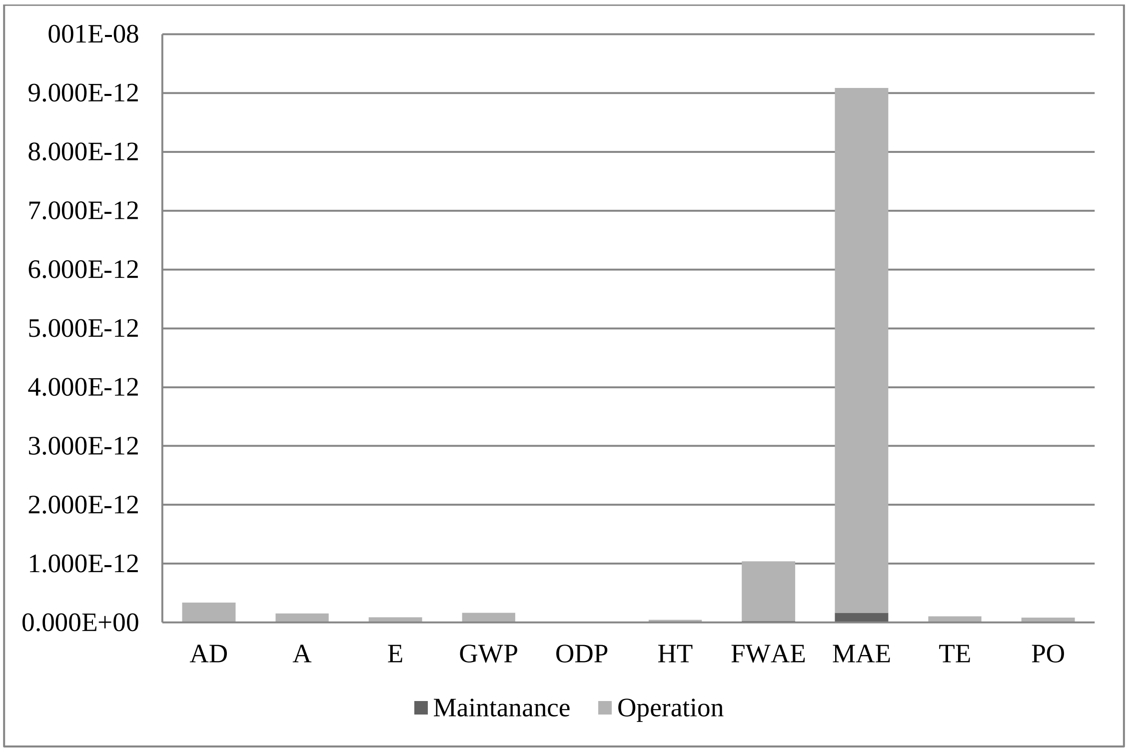
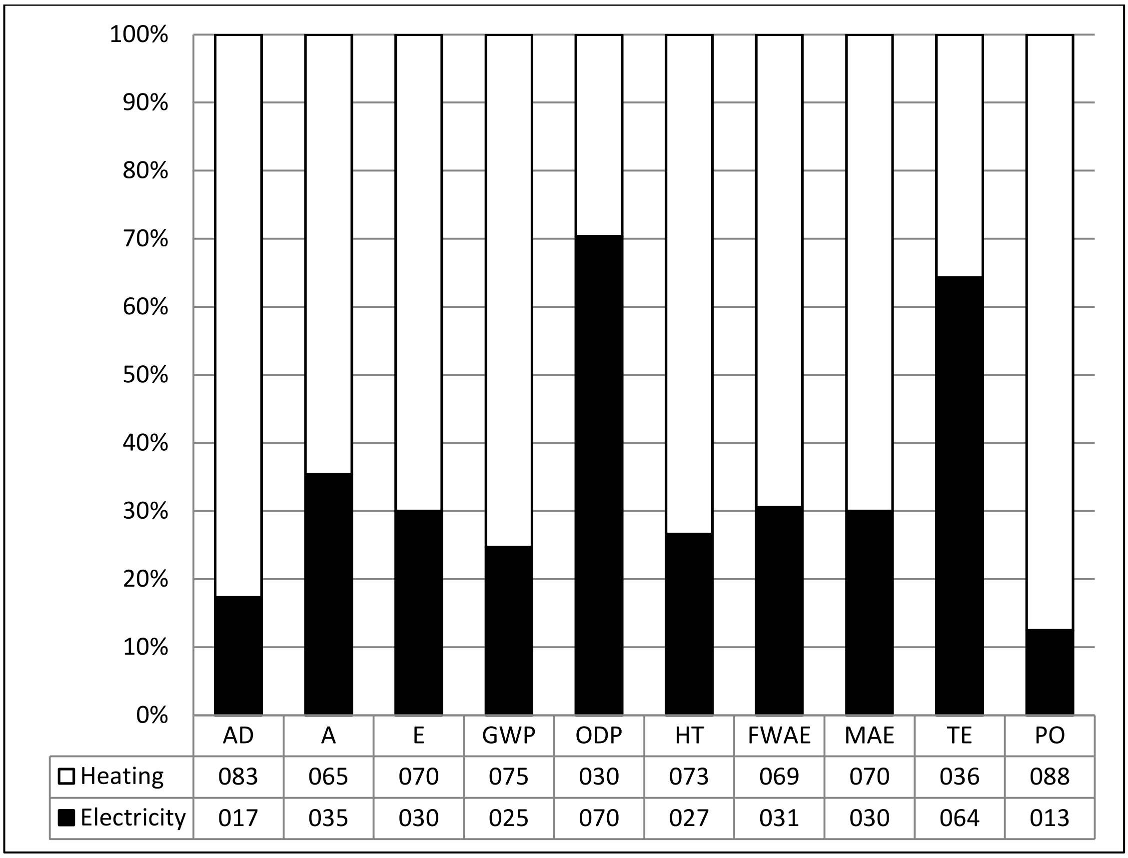


Figure 4.18. Total Environmental Impact Normalization of the Case Dwelling Use Phase (by Author)

4.1.2.1. Results of the Operation Phase

Environmental impacts of operation phase are based on energy consumption related to dwelling heating system and user related electrical energy consumption for lighting and electrical appliances. Figure 4.19 shows the load characteristics of the operation phase in detail.

Heating energy consumption has the largest contribution despite it is operating just four months approximately. Energy resources as coal have a heavy environmental load. Heating energy from coal has a share between 29.8 % (ODP)-91.7 % (PO). Electricity consumption load distribution places in an interval between 8.27 % (PO)-70.2 % (ODP).



	AD	A	E	GWP	ODP	HT	FWAE	MAE	TE	PO
☐ Heating	083	065	070	075	030	073	069	070	036	088
■ Electricity	017	035	030	025	070	027	031	030	064	013

Figure 4.19. Environmental Impact Distribution of the Case Dwelling for Operation Phase (by Author)

The greatest impact occurs in marine aquatic ecotoxicity (MAE) as same as previous phases with a value of 8.92E-09 (4.57E-6 kg 1.4-DB eq). Fresh water aquatic ecotoxicity (FWAE) and abiotic depletion (AD) categories follows with result as 1.02E-09 (2076 kg kg 1.4-DB eq) and 3.34E-10 (52.29 kg Sb eq). Following normalized values through minimum are; global warming potential (GWP) for 1.65E-10, acidification (A) for 1.51E-10 (48.64 kg SO_2 eq), terrestrial ecotoxicty (TE) for 1.04E-10 (28.03 kg 1.4-DB eq), eutrophication (E) for 8.75E-11 (11,57 kg PO_4 eq), photochemical oxidation (PO) for 8.61E-11 (8.28 kg C_2H_4 eq), human toxicity (HT) for 4.13E-11 (2362 kg 1.4-DB eq) and ozone layer depletion (ODP) for 1.9E-13 (1E-04 kg CFC-11 eq).

Operation phase is responsible for 76.6 % of the total life cycle impact in GWP results. While 15 % of this share comes from electricity from grid, 70.1% is from heating energy from coal. 6862 kg CO2 eq impact occurs for 1m2 of this dwelling.

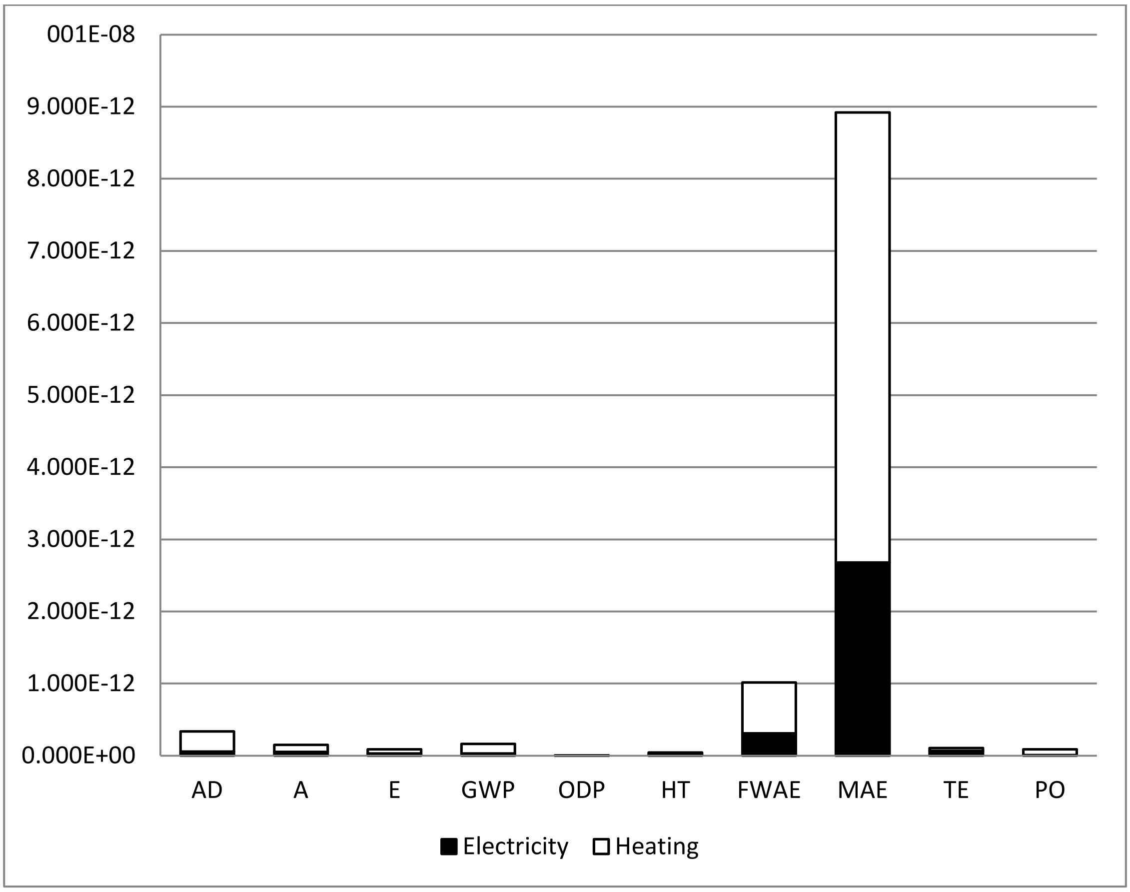


Figure 4.20. Total Environmental Impact Normalization of the Case Dwelling for Operation Phase (by Author)

4.1.2.2. Results of the Maintenance Phase

Maintenance phase has a low share in total environmental impact occurs in operation phase which is almost negligible (2%). Impacts of this phase mostly depend on materials. Chart 4.20. demonstrates the total environmental impact occurs in maintenance phase for each building components. According to the total results, aluminum window frame has the largest impact (61%) while ceramic tile found as the second contributor (10%). Inner doors have a share for 9% making it the third largest impacting building component. Impact of transportation of the materials appears insignificant with its minimum impact share.

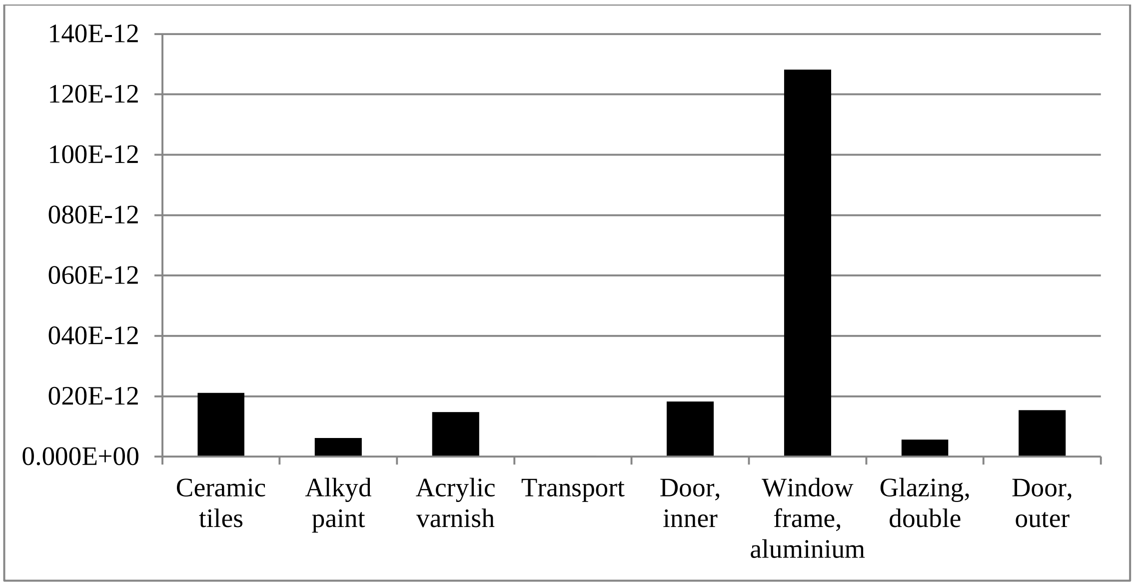


Figure 4.21. Total Environmental Impact Normalization of the Building Components for Maintenance Phase (by Author)

Figure 4.21 shows the detailed load distribution of the maintenance phase. Window frame highest impact occurs in human toxicity (HT) category with a share of 84.6%, while its lowest impact occurs in ozone layer depletion (ODP) as 44.2%. Ceramic tiles has the minimum impact share in human toxicity (HT) with a share of 3% and the maximum impact share in ozone layer depletion (ODP) with a share of 8.7%. Inner doors creates highest impact share in acidification potential (A) category for 13% and lowest impact share in human toxicity (HT) category for 3%.

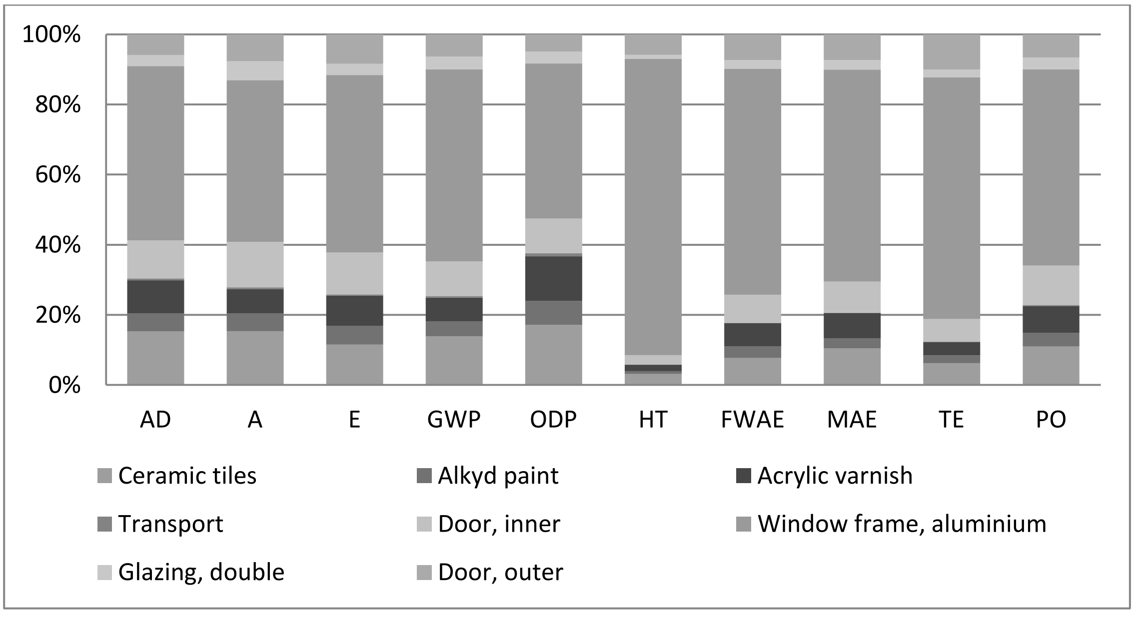


Figure 4.22. Environmental Impact Distribution of the Case Dwelling for Maintenance Phase (by Author)

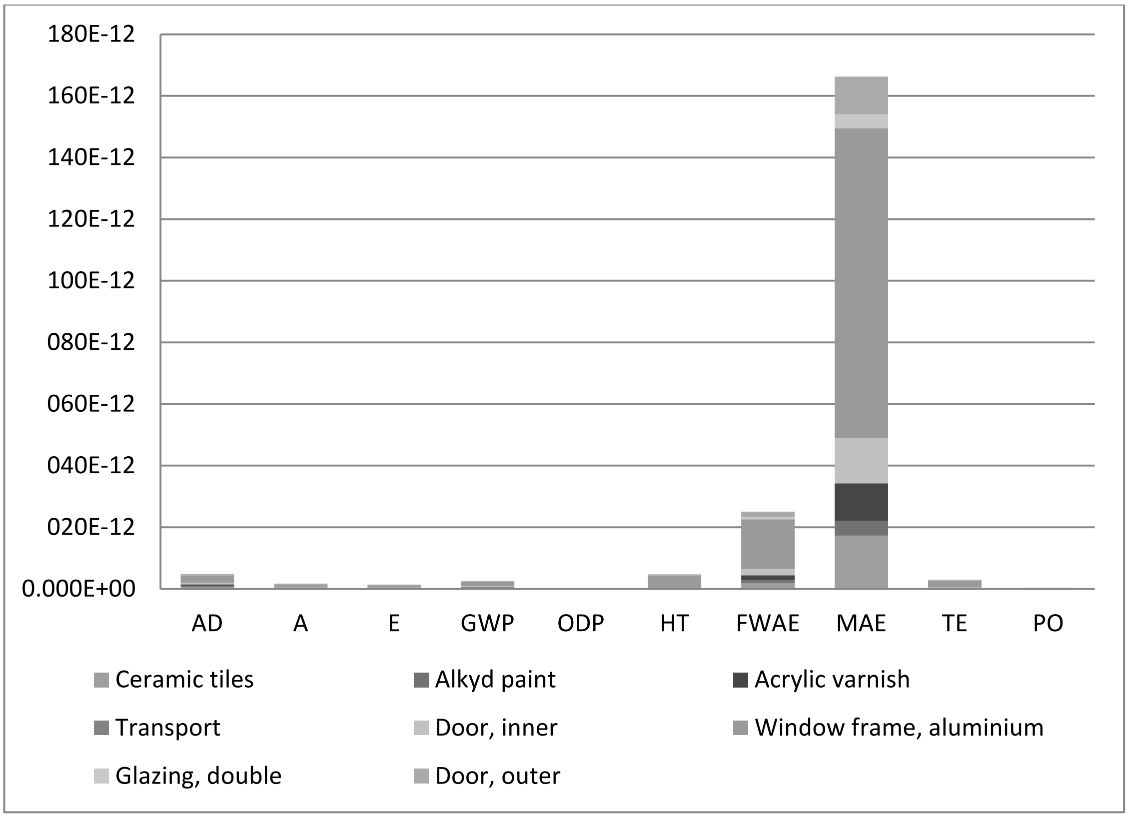


Figure 4.23. Total Environmental Impact Normalization of the Case Dwelling for Maintenance Phase (by Author)

CHAPTER 5

CONCLUSION

The application of LCA methodology into residential dwellings should be an essential task for achieving sustainability precepts in the building sector. Today many northern countries integrated the LCA in their national building codes. Besides, the simplified LCA methodologies are still developing to catalyze this integration to support the decision makers in building sector and policy making. Yet, the LCA is not a well-known strategy in Turkish building sector, utilized in decision-making for the optimization of sustainability indicators in a holistic approach.

The adaptation of sustainability assessment tools into building design requires a process over time for southern countries like Turkey. In general, environmental precautions are perceived in the construction industry as a factor for additional cost, and therefore, for reducing monetary profits. Melchert (2007, p.894) states that "the construction sector in developing world rather reactive, usually adopting crisis-oriented management approaches, seeking to comply with legislations, but not go beyond them." Yet, southern countries have also the significant advantage of being still under construction. The conceptualization of correct environmental prescriptions for the construction industry is of key importance to contribute its long-term environmental sustainability.

The present research studied in detail the life cycle environmental impact assessment of a multistory residential building in Izmir. The LCA results serve to successfully determine environmentally critical phases, components and materials. Yet, the results of this study are case specific, i.e. limited to only one sampling. In order to obtain generalized results for multistory buildings in Turkey, the expanded research should be carried out on a number of building cases.

This thesis ascertained the environmental impacts occurred during the life cycle of a multi-storey residential building, constructed in Turkey in the last 10 years. It analyzed the life phases, building components and operational processes which have the heaviest impact on the environment. The main outcome of this study indicated that the use phase has the highest environmental burden in the life cycle of multistory residential building. Accordingly, the major improvement opportunity should be related to reduce the environmental impacts of use phase, mainly depending on energy consumption. It is responsible for 66-97% of the total impacts of the 1 m^2 dwelling during whole life cycle, while the pre-use phase is 3-34%. The end-of-life phase is accounted for less than 1%, i.e. the minimal contribution for all environmental impacts, thus it is assumed to be out of the consideration of this thesis.

A brief overview of the results for all life cycle phases, according to normalized total environmental impact results, clarifies that the operation phase is generating 89.2% of the total impacts while material production phase is responsible for 8.7%, maintenance phase for 1.7%, transport for 0.3% and on-site construction phase is negligible in total impacts.

The results indicate that the operation phase, as one of two sub-phases of the use phase, has the largest environmental load in overall impacts. 92-99% of the impacts of use phase occur in building operation stage. The impact of maintenance phase, as the second sub-phase, is minimal with approximately 1-8%.

The pre-use phase has lower impact than the use phase, yet no negligible one. The material production is the largest contributor of this phase. While the impact of on-site construction is minor, the impact of transportation is nearly insignificant.

By this thesis, the highest environmental impact categories are determined, and a set of top priority environmental indicators through CML methodology is find out for future research in the field of building LCA in Turkey. The marine aquatic ecotoxicity (MAE), referring to impacts of toxic substances on marine ecosystem, determined as the most significant impact category which accounts 5.1E6 kg 1.4-DB eq in total. The fresh water ecotoxicity (FWAE) is the second most contributed impact category with a value for 2.41E3 1.4-DB eq. The abiotic depletion (AD) within the third place is responsible of a impact value for 58.4 kg Sb eq. The global warming potential (GWP) comes after accounting with 7.99E3 kg CO_2 eq. The acidification (A) is accounts totally for 52.2 kg SO_2 eq. These five presented categories have the most influential ones among total ten CML categories of environmental impact.

The direct comparison of LCA study results of this building with previous reviewed ones is rather complicated, because of the differences in their functional units. It is noticeable that two top priority indicators of this study, namely MAE and FWAE referring to aquatic ecotoxicity, are not common indicators in the literature. Therefore the indicators of GWP, A, ODP and PO are compared with Ortiz (2009) and Cuellar (2012)'s WPC LCA studies which are similar with the present study in terms of functional unit, general aims and environmental indicators. It is concluded that the total GWP result of present study (7983 kg CO_2 eq/m^2 per 50 years) is bigger than both two studies (Ortiz: 2340 kg CO_2 eq/m^2 per 50 years, Cuellar: 3500 kg CO_2 eq/m^2 per 50 years), while the load distributions in life phases are similar. The acidification potential of present study represents considerably higher values than (52.2 kg SO_2 eq/m^2 per 50 years) the other ones (Ortiz: 18.5 kg SO_2 eq/m^2 per 50 years, Cuellar: 6.9 kg SO_2 eq/m^2 per 50 years). The total ODP result of present study (1.70E-04 kg CFC-11 eq/m^2 per 50 years) is slightly higher than the study of Ortiz (1.17 kg CFC-11 eq/m^2 per 50 years), and lower than the study of Cuellar (9.90E-03 kg CFC-11 eq/m^2 per 50 years).

The building operation, as the sub-phase of use phase, is the biggest source of GWP among all phases with a result of 1.65E-10 (6.86E3 CO_2 kg eq). The district heating fueled with coal is the heaviest stage of operation phase accounting for 30-83% in this phase. The electricity consumption shows the largest load share in ODP with 70%.

The study also presents that for 50 years of building life span, the significant amount of material related contribution also occurred via the production of building materials and components. The building structural system, windows and floor finishing have the highest environmental load. While the structural system is responsible for 56% of the total environmental impact in material production phase, windows and floor finishing share 13% and 11%, respectively. The structural system causes the maximum environmental impact on TE with 65%, PO with 60% and GWP with 58%. The aluminum windows as the second largest contributed building component have the maximum share for 44% in HT.

In terms of building materials, the steel used in the structural system is the material with the highest environmental impact in total with 39% load share in the material production phase. The concrete and aluminum with 14.5 and 12.4% shares are the second and third most contributed materials to the total environmental impact occurred in material production phase.

Another significant result of this study is the determination of limitations of LCA applications in Turkey’s conditions. The most significant limitation in the case of Turkey is the data limitation because of lack of national inventory database for building materials and components. Localization of the data for a complete building LCA requires case-specific material and components inventory data which is very hard to obtain because of need for a long period of time due to the absence of an official data center and lack of data sharing by the manufacturers. Therefore a practical integrated building LCA needs a national database to provide high certainty in impact results. Another important limitation for WPC LCA appeared in the ability to include all life cycle phases. The end of life phase kept out of the system boundary due to accessibility for a reliable and accountable data on demolition energy and waste scenario. The only possible way to take into account the impact of landfill, at the moment, is by the average European data.

Few Words for the Future Work:

This thesis underpins the necessity of a broad-based WPC LCA research applied on the larger building sample groups from different climatic regions and common building typologies to identify environmental impacts of residential stock of Turkey, as the primary future work. Secondly, a comparative building LCA base model to analyze improvement options is found worthwhile for future research.

For obtaining a comparable and reliable LCA model especially for operation sub-phase, one year simultaneous measurements on indoor thermal comfort conditions of residential unit and local climatic conditions of housing settlement area should be carried out. In this thesis, even if on-site measurements are executed in order to develop and evaluate retrofitting options by simulating variable scenarios on materials and energy sources, this is left for a future study because of time limitation. The author believes that the building energy performance should be evaluated depending on various building component combinations in order to determine best environmental solution.

There is also a potential research area on the specification of environmental impacts of architectural decisions. The selected mass-housing area consists of different housing types such as terraced flats and apartment blocks. A LCA comparison between these architectural types may draw attention to the importance of decision process in early design stage.

Lastly, the end of life phase for buildings in Turkey appears as a particular research area due to develop a reliable scenario. The period begins with the recent Urban Transformation Law by 2012 may serve an opportunity to obtain the measured data on demolition energy and the statistical data on management of demolition wastes.

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