COMPARING ENVIRONMENTAL IMPACTS OF FOUR BUILDING ENVELOPE CONFIGURATIONS USING e-Tool LCA

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ABSTRACT

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Environmental degradation and exhaustion of nonrenewable resources are the unavoidable results of the era we live in. Fortunately, awareness regarding these impacts has increased and so has actions aiming to reduce the related environmental impacts. Building construction industry is one of the important contributors and one of the major consumers of natural resources. Building material selection plays an important role in sustainable building design. Reducing environmental impacts of building materials especially in material production stage is one of the significant steps towards mitigating these impacts.

This study focuses on evaluating four different building envelopes according to conventional construction techniques in Turkey on the basis of their environmental impacts. Erdoğan Akdağ Center for Research and Education as a case study is located in Yozgat, Turkey was selected and eTool LCA software was used to calculate the environmental impacts of four building envelopes according to six indicators, namely: global-warming-potential, fossil fuels consumption, fresh water consumption, ozone layer depletion and acidification.

Furthermore, the information related to case study building and data required for three stages of LCA are used to quantify these environmental impacts. It was seen that AAC is the most environmentally friendly material in comparison to concrete and brick.

Keywords: Environmental Impacts, Life Cycle Assessment, eTool LCA, Building Envelope.

ÖZ

eTool LCA KULLANARAK DÖRT FARKLI BINA KABUK TIPININ ÇEVRESEL ETKİLERININ KARŞILAŞTIRILMASI

Fazli, Torkan
Yüksek Lisans, Yapı Bilimleri, Mimarlık Bölümü
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Çevresel bozulma ve yenilenemeyen kaynakların tükenmesi yaşadığımız çağın kaçınılmaz sonuç ve sorunudur. Neyse ki, bu etkiler konusunda farkındalık arttı ve bu etkileri azaltmayı amaçlayan çalışmalar yapılmaya başladı. Yapı inşaat sektörü bu çevresel etkilerde önemli katkısı olan ve doğal kaynakların büyük tüketicilerinden biridir. Yapı malzemesi seçimi, sürdürülebilir bina tasarımında önemli bir rol oynar. Özellikle malzeme üretimi aşamasında yapı malzemelerinin çevresel etkilerinin azaltılması, bu etkilerin azaltılması yönünde önemli adımlardan biridir.

Bu çalışmada, çevresel etkilerin temelinde Türkiye'den geleneksel yapım tekniğine ile dört farklı bina kabuğu değerlendirilmesi üzerinde durulmaktadır. Erdoğan Akdağ Araştırma ve Eğitim Merkezi (Türkiye,Yozgat) bir çalışma alanı olarak seçildi. eTool LCA yazılımı, dört bina kılfları çevresel etkilerinin altı göstergelerine göre (Küresel ısınma potansiyeli, fosil yakıtların tüketimi, su tüketimi, ozon tabakasının incelmesi, asit yağmurlarının ve insan toksisite) hesaplamak için kullanıldı.

Ayrıca, çalışmas alanı olarak seçilen bina ve Yaşam Döngüsü Değerlendirmesinin (LCA) üç aşamaları için gerekli veri ile ilgili bilgiler bu çevresel etkileri ölçmek için kullanıldı. Sonuçlar gazbetonun beton ve tuğlaya göre daha çevre dostu bir malzeme olduğunu gösterdı.

Anahtar Kelimeler: Çevresel Etkileri, Yaşam Döngüsü Değerlendirmesi, eTool LCA, Bina Kabuğu

To My Beloved Family

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LIST OF ABBREVIATIONS

AAC: Autoclaved Aerated Concrete

AKG: Name of AAC producer firm

ATHENA: EcoCalculator for Assemblies North America

BEAT: Biomass Environmental Assessment Tool

BEES: Building for Environmental and Economic Sustainability

BRE: Building Research Establishment

BREEAM: Building Research Establishment Environmental Assessment Method

DALY: Disability Adjusted Life Year

ENVEST: Environmental Impact Assessment and Whole Life Cost

EU: European Union

GHG: Greenhouse Gases

HVAC: Heating, Ventilation and Air Conditioning

IEA: International Energy Agency

ISO: International Organization for Standardization

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LEED: Leadership in Energy and Environmental Design

OECD: Organization for Economic Cooperation and Development

RCC: Reinforced Cement Concrete

TEAM:	Tools for Environmental Analysis and Management
TS:	Turkish Standards
TÜBİTAK:	Türkiye Bilimsel ve Teknolojik Araştırma Kurumu
UK:	United Kingdom
USGBC:	US Green Building Council
UNEP:	United Nations Environment Programme
XPS:	Extrude Polystyrene

CHAPTER 1

INTRODUCTION

This study is about the environmental impacts of different building envelope types. In this chapter are presented the argument, objectives, procedure and the disposition of the study.

1.1 Argument

Large amount of energy and natural resources are consumed in building construction sector and in recent years rapid urbanization, growth of industrialization and increasing living qualities have raised this amount of consumptions. Building construction industry increases greenhouse gases emissions and therefore causing serious threats for natural environment. Another consequent and important issue is excessive consumption of non-renewable energy resources, a crucial concern for future energy needs. A great variety of materials are used for constructing buildings. Selection of building materials should be in a way that satisfies the users' requirements and comfort along with being energy efficient and environmentally friendly. During the production of materials, significant amount of energy is consumed that results in greenhouse gas emissions and adverse environmental impacts. Recently awareness for choosing the materials with less environmental impacts and limited demand for natural resources has increased in construction industry.

For a long time, the energy consumptions during the manufacturing of building materials, transporting the materials to construction site, building erection and maintenance of the building (embodied energy) was neglected and attention was only paid to the energy consumptions during the building’s operation phase. In recent years, the building with energy efficiency in operation phase which are constructed with materials that need high energy amounts to be produced, are not considered as sustainable buildings. This has resulted in more concentration on energy consumptions of materials and building construction, transport and maintenance phases.

With the motivation arisen by these changes in prioritizing the energy consumed in different phases of building construction, and also with the aim of verifying environmental impacts of alternative materials, this study focuses on evaluating environmental impacts of AAC as a building construction material in comparison to brick and hollow concrete blocks as conventional construction techniques used in Turkey. Since external walls and roof as the building envelope are the major parts of the whole building, this study carries out the comparison of mentioned materials in terms of different building envelope designs.

1.2 Objective

The scope of this study is assessing environmental impacts of conventional building materials with specific attention paid to constructions made of AAC. In other words the main aim of this thesis is quantifying the environmental impacts of case study building envelope regarding to different masonry wall types and roof structures to compare different building envelope designs in terms of environmental impacts and also in order to figure out the least and most environmentally friendly types.

1.3 Procedure

This research concentrates on evaluating various building envelopes by estimating environmental impacts of different walls and roof systems with a particular attention paid to AAC in comparison to other materials. This is carried out on Erdoğan Akdağ Center, located in Yozgat, Turkey. In order to calculate environmental impacts of materials, LCA software, called eTool LCA, is used. The methodology of this study is based on feeding the required inputs into the eTool LCA and interpreting the outputs.

The input data for eTool LCA is obtained as follows: first of all the case study building in terms of the required data and information is defined. The next step is optimizing the case study building envelope and designing two alternative building envelopes that satisfy thermal insulation requirement according to TS 825 (2008). Therefore required material thicknesses for walls and roofs are determined. The next required data for software inputs are the lifetime of the case study materials and transport distances from the plants to construction site. Finally, generated data from eTool LCA in the form of graphs and tables are summarized and the comparable results are discussed in terms of environmental impacts of case study materials.

1.4 Disposition

In the first chapter the argument and objectives of the study is described and afterward, the procedure of the study is summarized.

The second chapter concentrates on literature review on the study area. This chapter covers the concept of sustainable development, brief information about case study materials and the impact of emissions on environment. Furthermore, the issues related to life cycle assessment such operational and embodied energy and analysis methods and available simulation and analysis software are discussed.

In the third chapter the material and method of the study is described. In the material part the case study building and the utilized software are clarified and in the method section required input data for analyzing case study materials in the LCA software are identified.

In the fourth chapter the results and discussions are presented. In this chapter, environmental impacts calculations of different building design types are depicted and according to graphs and measurements that are reported by the software, these different building designs are compared.

In the fifth chapter by summarizing the study and results, the conclusion of the study is described

Finally Appendix A presents the interfaces of eTool LCA software in the form of figures and Appendix B presents the distances between factories and case study building location according to the gathering data from materials association in Turkey.

CHAPTER 2

LITERATURE REVIEW

This chapter covers concepts and definitions of sustainable development, performance of case study materials, life cycle assessment and life cycle assessment tools in order to evaluate and analyze the environmental impacts of construction materials.

2.1 Buildings and Sustainable Development

According to Berardi (2013), the 1970s were the starting point for the energy efficient development. The publication “The Limits to Growth” by the Meadows, Randers and Meadows (1972) was the first theoretical framework of this notion. Berardi (2013) continues his investigation in sustainable development history by stating that the UN Conference resulting in the Cocoyoc Declaration on the Human Environment was the first main international conference to discuss sustainability. The result of this conference was founding of the United Nations Environment Programme (UNEP) which discussed the concept of sustainable development by considering future generation and long term view.

The most well-known early definition by the Brundtland Commission (WCED, 1987), states that “sustainable development is a development which meets the needs of the present without compromising the ability of future generations to meet their own needs”. Ramesh, Prakash and Shukla (2010) describe sustainable development as development which result in low environmental impacts, and have social and economical advantages. Berardi (2013) also defines the concept of sustainable development for buildings as “a healthy facility designed and built in a cradle-to-grave resource-efficient manner, using ecological principles, social equity, and life-cycle quality value, and which promotes a sense of sustainable community". The author summarizes that the best way is using a long term procedure instead of rigid condition in categorical way to evaluate the sustainability.

Sustainable building should increase requirement for safe building, market, flexibility, economic and value. Also it should reduce the environmental impacts, limited natural resource use and improve the human comfort and occupants' convenience for the whole life cycle. Moreover, sustainability should preserve cultural values, increase social justice and aesthetics improvements. (Berardi, 2013 Gustavsson and Joelsson, 2010)

As Asif, Muneer and Kelley (2007) claim, buildings use 30-40% of primary energy worldwide and 40-50% of greenhouse gas emissions are resulted from consumption of this amount of primary energy. Also Organization for Economic Cooperation and Development (OECD), states that the residential and commercial buildings consume 30% of primary energy consumed in OECD countries. This percent of energy consumption is almost the same in Turkey. According to TUBITAK report (2003) in Turkey 40% of primary energy consumption is by buildings where building materials sector is only 10% of country's industry. Consequently sustainable development in the world is one of the important issues related to building construction. In order to accomplish sustainability, Asif et al. (2007) state that multi-disciplinary procedure is required for covering aspects such as energy conservation, reuse and recycling of materials, better use of materials counting water and emissions control. The authors consider life cycle energy analysis of buildings as a method to examine and develop methods and strategies to achieve reduction in primary energy use of the buildings as well as controlling emissions.

Crawford (2011) in the book "Life Cycle Assessment in the Built Environment" categorized strategies that can reduce the environmental impacts of the buildings and constructions when considered during the design process (Table 2.1). The aim of Environmental Design is minimizing demands with negative impact from nature and minimizing outputs with negative impact to nature. Ramesh et al. (2010), propose using renewable energies instead of fossil fuels that can reduce environmental impacts severely.

Table 2.1 Environmental design principles relevant to the built environment (Source: Crawford 2011)

Strategy	Environmental Benefits
Use resources more efficiency	• Preservation of non-renewable resources • Sustainable consumption of renewable resources • Reduced waste production
Minimize non-renewable resource use	• Preservation of non-renewable resources • Minimized emissions from energy production
Minimize pollutant releases	• Maximized water, air and soil quality • Preservation of ecosystems
Design of disassembly	• Preservation of natural resources • Maximized resource value • Reduced waste production
Minimize waste production	• Minimized low-value land activities (i.e. landfill) • Minimized soil and water contamination • Maximized resource value
Design for recyclability	• Preservation of natural resources • Maximized resource value • Reduced waste production
Design for durability	• Reduced demand for raw materials, energy, water • Preservation of non-renewable resources • Reduced waste production
Design for adaptive reuse	• Preservation of natural resources • Reduced demand for raw materials, energy, water • Maximized resource value • Reduced waste production

As Ekincioglu, Gurgun, Engin, Tarhan and Kumbaracibasi (2013) mention, the efficient usage of limited resources and environmentally friendly building constructions is very important. Generally, in the U.S. and the EU “Sustainability” principles are considered in the construction industry. Several certificate systems exist to organize the standards of sustainable construction. Ekincioglu, et al. (2013) state that BREEAM (Building Research Establishment Environmental Assessment Method), the British system, that Building Research Establishment (BRE) has developed and LEED (Leadership in Energy and Environmental Design), the American system, that is developed by U.S. Green Building Council (USGBC) are two famous certification systems. Some other certification systems in different countries such as Japan, Australia and Canada are used. In Turkey recognition and evaluation of environmental performance of the buildings and construction materials has also been started, such that till September 2013, 68 buildings have been certified, 37 rated by LEED and 31 by BREEAM.

2.2 Environmental and Structural Performance of Case Study Materials

As noted by Kotaji, Schuurmans and Edwards (2003) Construction sector have significant negative impacts on environment in two main ways; environmental deterioration and excessive resource extraction. These effects increase the demand for environmentally friendly building materials. On the other hand, increasing structural performance of building material plays an important role to reach the goal of sustainability in building design by extending building life which causes minimizing the requirement for building material and preserving initial embodied energy as well (Kneer and Maclise, 2008). Therefore, it is essential to understand the environmental and structural performance of construction materials which are shown in the following sections.

2.2.1 Concrete

Gambhir (2004) states that, concrete has the highest rate of usage among man-made construction materials all over the world and is the most utilized substance after water. Neville (2008) define concrete in the broadest way as a product made from reaction between hydraulic cement and water which named as cementing medium. To describe concrete in a clear and simple way, as noted by Gambhir (2004), concrete consists of appropriate proportions of mixing cementitious materials, aggregates, water and sometime admixtures. This mixture is hardened by pouring in specific forms and curing. As mentioned by author, hardening procedure is a reaction between water and cement which takes a long time; as a result concrete become stronger day by day. Hardened concrete can be mentioned as a man-made stone that fine aggregates fill the holes of coarse aggregates and cement fill the holes of fine aggregates.

Gambhir (2004) explains concrete ingredients in detail as below:

Cement: At present Portland cement is the most utilized cementitious ingredient that consists of calcium, aluminum, iron and oxygen.

Aggregate: Aggregates are materials existing in nature such as sand, crushed stone and gravel. Nowadays it is tried to use recycled and artificial products instead of natural resources.

Chemical Admixtures: These ingredients are added to the mix in order to accelerate curing time, reduce water requirement and increase the durability of production.

Supplementary Cementitious Materials: These materials such as natural pozzolans, ground granulated blast-furnace slag, fly ash and silica fume are called mineral additives, which are added to mixture through hydraulic or pozzolanic activity.

Water: As mentioned by Schwartz (2000), mixing water with cement makes a paste. Water is the key component to make stone like materials from loose mixtures.

The book by Berge (2009) about the ecology of building materials categorizes concrete mixes based on their properties and areas of use as shown in Table 2.2.

Table 2.2 Concrete mixes, their properties and areas of use (Source: Berge 2009)

Type	Mixtures, part by volume	Properties	Areas of use
Lime sandstone	Lime 1; Quartz sand 9	Durable, sensitive to moisture/frost	Internal and external structures, cladding, moisture buffering
Lime concretes	Lime 1; Sand 2-4; Aggregate 4-6	Elastic, sensitive to moisture/frost	Internal structures, moisture buffering
Lime pozzolana concretes	Lime/pozzolana 3; Sand 1; Aggregate 2	Medium strength, elastic, resistant to moisture/frost	Internal and external structures
Gypsum concretes	Gypsum 1; Sand 1; Aggregate 2	Sensitive to moisture/frost	Internal structures, moisture buffering
Portland concretes	Cement 1; Sand 3-6; Aggregate 3-5	Strong, durable, not particularly elastic, resistant to moisture/frost	Internal and external structures, foundations
Portland-pozzolana concretes	Cement/pozzolana 1; Sand 3; Aggregate 3	Strong, durable, little to moderate elasticity, resistant to moisture/frost	Internal and external structures, foundations
Sulphur concretes	Sulphur 1; Sand/Aggregate 3	Waterproof but still sensitive to frost	Internal and external structures, foundations

As mention by Hornbostel and Hornbostel (1980) concrete is produced in various forms such as plain, reinforced and prestressed concrete depending on the role and the use of material in the construction. Concrete is used for foundation, footing, walls and roofs, piling, floors, retaining walls and structural members.

As noted by Gambhir (2004) concrete is tough in compression but brittle in tension, so that if tension is unavoidable, reinforced cement concrete (RCC) that is strengthened by steel bars or fiber reinforced concrete that is consisted of short distributed fibers should be used. Moreover, ingredients of concrete, their proportions, compaction method and controls during the production are important for its properties, such as strength and durability.

Prefabricated concrete components are another way of utilizing concrete in construction sector which is found in different types of block, decking, beams, columns, roofing, flooring tile, girders, artificial stone, and so on (Hornbostel and Hornbostel, 1980). In Figure 2.1 some examples of prefabricated concrete constructions are shown. According to Berge (2009), prefabricated concrete systems are cast in factories in shuttering or prefabricated as blocks or larger units. The author states that most of the time prefabricated concretes designed for use with steel reinforcement. In the following section some types of prefabricated concrete is mentioned.

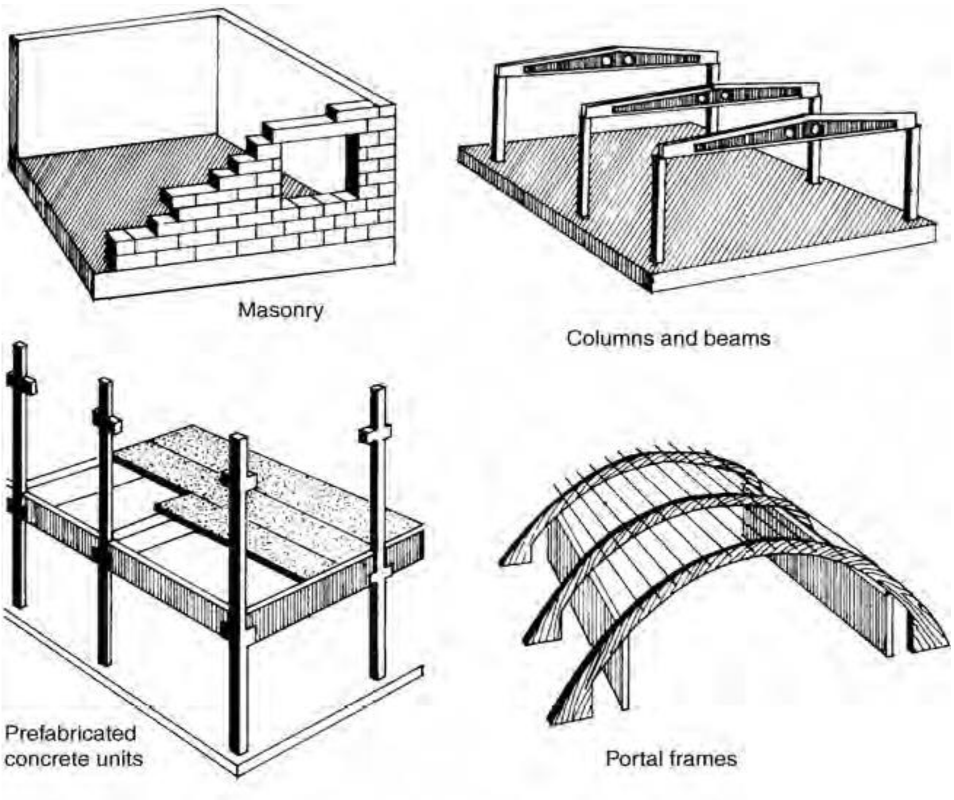


Figure 2.1 Prefabricated concrete construction systems (source: Berge 2009)

According to Hornbostel and Hornbostel (1980), concrete blocks are made of Portland cement, water, blended cements and some other aggregates such as crushed stone, sand, volcanic cinders (pozzolan), expanded slag, expanded shale or clay, coal cinder, gravel, air-cooled slag. The authors also divide concrete blocks into three types: solid loadbearing, hollow loadbearing and hollow non-loadbearing. Solid concrete blocks are called concrete bricks and hollow ones are called concrete blocks, cinder blocks or generally hollow blocks. As depicted in Table 2.3, according to their density concrete units are produced in three classes: lightweight units, medium weight units and normal weight units (Mamlouk and Zaniewski, 1999)

Table 2.3 Weight Classifications and Related Densities

(Source: Mamlouk and Zaniewski, 1999)

Weight Classification	**Denstiy (Kg/m^3)**
Light Weight	1680
Medium Weight	1680-2000
Normal Weight	2000

Gambhir (2004) names some of the general advantages of concrete and concrete blocks as well as disadvantages of concrete as below:

Advantages of Concrete:

- Concrete is more economic compared with other construction materials
- High compressive strength is one of the important properties of concrete
- Concrete is durable when prepared properly as it resists corrosive and erosion and freezing
- Concrete can easily made in any form or shape according to requirements
- Because of high compressive strength and in combination with steel bars it can be used in various types of structural systems and applications

- Concrete can be used for cracks repairs by filled into cracks via guniting process
- Concrete is fire resistance
- Concrete require limited maintenance and care.
- Hollow concrete blocks have low thermal and sound conductivity

Disadvantages of concrete:

- Concrete is brittle in tension and it is required to reinforce by steel bars or fibers
- Temperature changes have effects on concrete by expanding causing cracks. Therefore, expansion joints must design in order to avoid deformations.
- Concrete is not impenetrable to moisture and can cause efflorescence.
- Alkali and sulphate attacks can result in decomposition and decay of concrete.
- The conventional cement used in concrete production has a high density of 2400 kg/ m_3 that increase the structures dead load.

Concrete production is complex and has negative environmental impacts as a consequence of releasing pollutants such as carbon dioxide, carbon monoxide, heavy metals, Nitrogen oxides, organic hydrocarbons, sulphur dioxide and alkaline wastewater (Berge, 2009). In addition, the largest consumer of natural supplies such as gravel, sand, crushed rock and water is concrete industry. Almost 7 per cent of world's carbon dioxide (CO_2) emissions are related to Portland cement. According to Reddy (2009) clinker which is used in the manufacturing of cement releases 0.9 tons of CO_2 per ton of clinker. Besides, Portland cement burns at high temperature ($1450^o C$) that result in use of high amount of fossil fuels (Gambhir, 2004). As mentioned by Berge (2009) the amount of global warming potential (GWP) obtain by concrete production is 65 g/kg.

It is hard, time and money consuming and sort of useless to recycle in situ concrete. The only usages of this concrete are as an aggregate or as landfill after crushing process. Prefabricated concretes like blocks and slabs have a higher chance of recycling by using mechanical fixings or mortar joints that make disassembling possible (Berge, 2009).

2.2.2 Autoclaved Aerated Concrete

Autoclaved Aerated Concrete is a result of 100 years old systematic development. AAC which is used nowadays was developed in Scandinavia approximately 30 to 40 years ago and was used as wall, floor and roof panels (Dubral, 1992).

Aroni (1993) defines AAC as a lightweight cellular material which is the result of chemical reaction between calcareous powder which is usually lime and/or cement and siliceous materials which are sand and/or slag and pulverized fuel ash (PFA).The cellular structure can be formed either by a chemical process resulting in aeration or by creating gaps of pure air in the slurry by mechanical means. Afterwards, the mixtures set and the required cellular structure are produced.

Figure 2.2 shows the AAC production process in which the fine powder of Portland cement, quarts sand, lime and gypsum are mix with water and aluminum powder as an aerated factor. Then, the produced slurry substance pours in the steel molds and required products are obtained by cutting the mass. In the case of reinforced AAC production before pouring mix, rust proofing steel mesh fits to casting cars (released online at www.akg-gazbeton.com).

Dubral (1992) divides AAC materials into two different types according to their area of use in residential and nonresidential buildings as below:

- **Non-reinforced AAC:** This type of AAC blocks are used for basement and foundation walls, loadbearing internal and external walls, for partition walls, filler walls and linings.
- **Reinforced AAC:** Roof and floor slabs, lintels, wall panels, loadbearing or non-loadbearing, beams and columns are examples of reinforced AAC.

Narayanan and Ramamurthy (2000) argue that AAC can be produced in different densities by varying the compositions in order to area of uses. AAC with 350 kg/ m^3 density or more is used in load bearing constructions. Also, AACs with low density are proper for thermal insulation purposes. As stated by authors, changes in ranges of density are occurred by chemical reactions that adjust the pore volume in AAC products. Pore volume in the AAC product is responsible for some properties like strength, shrinkage, permeability and diffusivity.

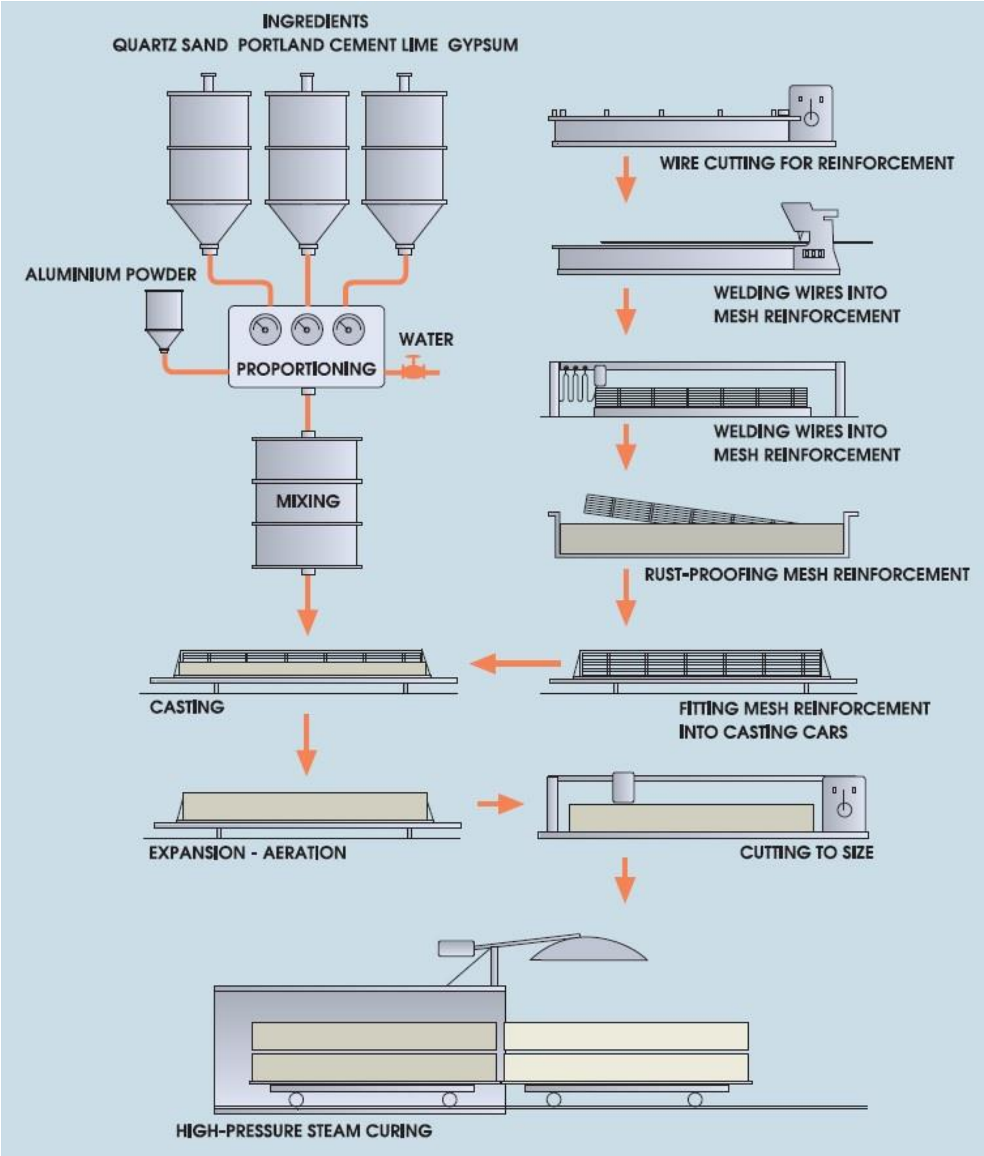


Figure 2.2 Autoclaved Aerated Concrete Production Process

(Source: http://www.akg-gazbeton.com)

Low weight, thermal insulation, fire resistant and sound insulation are some properties of AAC; besides it is easily drilled, shaped and sawed (Dubral 1992, Allen and Iano, 2009). On the other hand, AAC is very susceptible to deteriorations caused by moisture because of its high capacity for water absorption therefore AAC cannot be used as a finishing material. Furthermore, AAC is not widely produced, so it is difficult for many consumers to obtain it locally and consequently would cause more transportation cost and using gas resources (Narayanan and Ramamurthy

2000). Additionally, since AAC is not as strong as cement concrete, it can only be used for low rise constructions as load bearing structure (Allen and Iano, 2009).

AAC is not nearly as strong as normal density concrete, but it is sufficiently strong to serve as load bearing walls, floors, and roofs in low rise constructions. AAC, compared to other construction materials has low consumption of natural resources that cause conservation in raw materials. As a result, gas emissions such as CO_2, NO_x and CO that are because of the steam generation during AAC production are low. Besides, some industrials wastes such as slags and fly ash can be used in AAC production. The whole energy consumption during AAC production procedure is 2010 MJ/t or 1005MJ/m^3 at a density of 500 kg/m^3 which is 2 or 3 times lower than other construction materials, like burnt bricks (Aroni 1993, Allen and Iano 2009).

2.2.3 Brick

Hornbostel and Hornbostel (1980) define brick as rectangular, small building unit block made of inorganic, nonmetallic substances of minerals and hardened in various ways and produce in solid or cored shapes. Brick types are divided into three main categories:

Adobe Brick: Hornbostel and Hornbostel (1980) state that the word Adobe's origin is the Arab word Atob that means sun-dried brick. Adobe brick is composed of "calcareous, sandy clay or any alluvial desert clay with good plastic properties". The authors state that, this composition dries by letting it stand for a day and creates a homogeneous mass. In order to prevent shrinkage cracks, straw or agricultural fibers are added during the curing process. The whole combination is mixed, placed in the molds and letting it stand for two weeks to create a hard and homogeneous mass. Adobe brick making process has not change with time.

Burnt Brick: Berge (2009) describes this kind of brick as a hydrated silicate of alumina (Al_2O_3, $2SiO_2$ and $2H_2O$) and consists of different amounts of iron, sodium, calcium, titanium, magnesium, potassium and sulfur. Clay product fire at high temperatures to have high compressive strength and low absorption material. During firing process vitrification occurs when the temperature is high enough to close all pores and fuse the ingredients, accordingly the mass become impenetrable and it turns to ceramic materials.

Sand-lime Brick: Sand-lime is made from a mixture of sand and lime. This type is hardened with age and is a good acid, frost and fire resistant. Furthermore sand-lime brick can be washed without any efflorescence occurrence (Hornbostel and Hornbostel 1980)

Allen and Iano (2009) describe three major methods of brick forming: Soft mud process, dry-press process and stiff mud process. The oldest method is soft mud process that moist clay with 20-30% water pressed into simple casts by hand or machines. The dry-press process is used in areas that during drying step clays shrink extremely. In this process, the clay is mixed with water not more than 10% and pressed into casts at high pressure by machines. The authors also mention that nowadays the widely used method is stiff mud process in which clay with 12 to 15% water pass through the vacuuming step to remove the pores of air and also pass through the rectangular die to form a rectangular column and then cutting wires are used to slice it into bricks. After molding process the bricks are dried for 1 or 2 days in dryer kiln with low temperature and so far they are ready for the last transformation process named firing or burning (Allen and Iano, 2009). The firing temperature varies between $900^{o}C$ and $1200^{o}C$ for brick production which results in different colors such as brown, dark red, purple, etc. (Mamlouk and Zaniewski, 1999).

Berge (2009) divided bricks that are used in structures into solid bricks, cellular bricks and perforated bricks. In order to decrease the thermal conductivity various light ingredients are added. Cellular and perforated bricks are also produced in the form of large blocks. Perforated blocks and bricks used worldwide and use less clay compared with other types. As mentioned by author, bricks with more than 40% perforation and bricks with 20% perforation have the same strength, though the first option requires additional mortar that smaller holes can solve the problem.

Berge (2009) states some advantages and disadvantages of brick uses and production in his book. The author argues that brick repairs and replaces with new bricks easier compared with other construction materials. Also brick is one of the durable materials in constructions even more durable than concrete. In addition, bricks have high resistance for chemical attacks except for most corrosive acids. Furthermore, bricks require low maintenance and have a very long lifespan. On the other hand brick is brittle in stretching and must be used in a situation that compressive strength is needed. Bricks are heavy and sometimes need to go through long distances that cause climate gas emissions and pollution.

Koroneos and Dompros (2007) claim that brick production industry consume large amount of natural resources that result in negative environmental impacts. Also energy consumption during the fired brick manufacturing which causes pollution and greenhouse gas emissions is so high. One of the large negative environmental impacts of brick production is sulphur dioxide emissions that adding lime to the clay can filter or reduce amount of emissions (Koroneos and Dompros 2007 and Berge 2009). According to investigation by Koroneos and Dompros (2007) on brick production, most of greenhouse gas emissions and negative environmental impacts of energy use are occurred during consumption of petroleum coke, diesel and use of large amount of electricity. As discussed by the authors, CO_2 has the biggest percentage of emissions among all releases emissions to the atmosphere by brick production such as NO_x and SO_2. Moreover, acidification has the highest rate as compared with other environmental impacts.

Berge (2009) proposes some ways to reduce the energy consumptions during brick manufacturing. Large amounts of oil-based energy are used to obtain required low temperature in order to dry the unfired bricks before firing procedure. Thereby recovered waste heat from kilns and solar energy could be proper replacements. Furthermore, in recent years in most countries only well-fired bricks are used, while unfired and low-fired alternatives could be used instead of well-fired brick for rendered nonloadbearing walls and internal walls.

2.3 Impacts of Emissions on Environment

Crawford (2011) defines anthropogenic emissions as the greenhouse gases resulted by human activity. Human activities with highest ranks of producing greenhouse gases are burning of fossil fuels, clearing of land and forests, certain farming practices (such as the use of fertilizers), industrial processes and decomposition. In 2004, reporting by Parry (2007), consumption of fossil fuel was the largest reason of global anthropogenic greenhouse gas emissions, as Figure 2.3 shows.

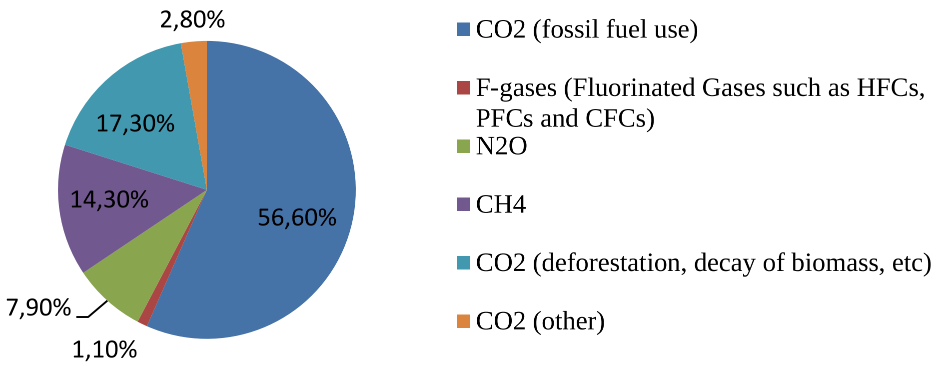


Figure 2.3 Global anthropogenic greenhouse gas emissions (Source: Parry 2007)

According to Crawford (2011), energy is a critic necessity of current human life, a vital need for most of industrial processes and transportation systems, lightning and warming building systems and other amenities. Figure 2.4 shows the total global greenhouse gas emissions by sectors for 2004. As seen, 25.9% of global greenhouse gas emissions are result of the work of the power stations to produce energy for human civilization. According to Parry (2007), rise in the temperature, which seems to be resulted by escalation in anthropogenic greenhouse gases in the atmosphere, happens in a rate that can change Earth’s physiological and biological processes significantly. It is also stated that air temperature and incidents like rise in sea levels, extreme flooding and droughts, the rise in frequency and intensity of extreme weather events and also increased incidence of disease are closely and complexly related to anthropogenic emissions.

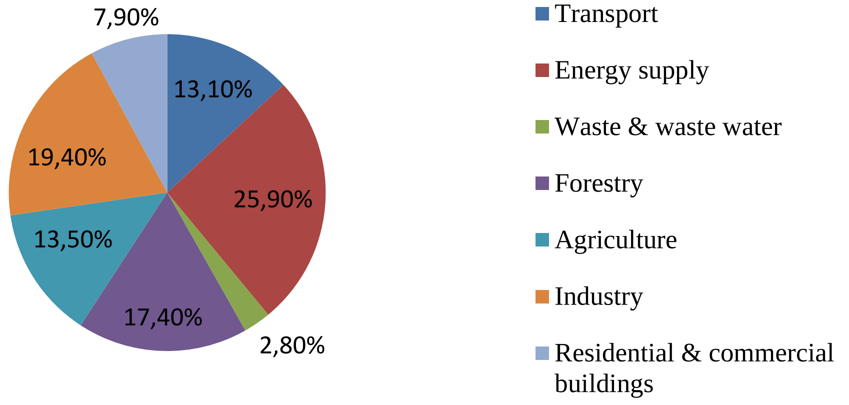


Figure 2.4 Global Greenhouse Gas Emissions by Sectors (Source: Parry 2007)

According to Dimoudi and Tompa (2008), Yan, Shen, Fan and Wang (2010) and Asif et al. (2007), the construction industry, to be more precise, manufacturing and transporting of building materials, and installing and constructing of buildings, as one of the main factors of socio-economic development is a dominant consumer of energy and natural resources in all countries. Building construction industry, which produces 40-50% of greenhouse gases (GHG) and agents of acid rain worldwide, uses 40% of the materials of the global economy. Each material in the construction industry needs various processes and also transportation in order to be used. The energy used for all these activities is essential for progress of human life, but on the other hand their side effects contain risks that affect the quality survival of the biosphere, Hammond (2000) states.

As Shukla, Tiwari and Sodha (2009) state, technologies and materials for the building construction should be chosen in a way that they effect the environment in the least rates possible while satisfying the needs of consumer. Designers all around the world try to lessen the impact of the process of building construction on the environment; impacts like emission of greenhouse gases, e.g. CO_2.

To ascertain global carbon footprint, Beattie, Bunning, Stewart, Newman and Anda (2012) categorize the sources of CO_2-e (CO_2 Equivalent) emissions in urban development and construction stage of buildings. OECD defines CO_2 equivalent as a measurement for comparing different greenhouse gases emissions regarding to their global warming potential by expressing amounts of gases in terms of the amount of CO_2 that would create the same amount of global warming potential. The categorized sources of CO_2-e emissions in urban development by Beattie, et al. (2012) is illustrated as below:

- Material: The CO_2-e emissions caused by extraction of raw materials and production of assemblies used in buildings and variations of the cases when the material is regional or recycled as well;

- Construction: The CO_2-e emissions caused during buildings demolishing and preparing the sites for construction and also the construction process. To be more precise, the emissions that happen by fuels, water and power transportation to site, variations with different procedures and site waste management;

- Operational: The CO_2-e emissions caused by building or development processes from electrical power and natural gas that vary between different building types with different source types;

- Transport: The CO_2-e emissions caused by transport fuels used by residents of the area that vary by different urban and designs;

- Water: The CO_2-e emissions caused during the full water cycle containing emissions linked to distributed or centralized water infrastructures; and

- Waste: The CO_2-e emissions caused by solid waste generated and its different scenarios like re-use and recycle materials.

2.4 Life Cycle Assessment of Buildings

Definition of life cycle assessment is discussed widely in technical and academic literature. Asif et al. (2007) describe life cycle assessment as below:

> "Life Cycle Assessment is a process evaluating the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the

> environment (to assess the impact of those energy and materials used and releases to the environment) and to identify and evaluate opportunities to affect environmental improvements”.

In another but similar point of view, Keeler and Burke (2009) define life cycle assessment as following:

> “A holistic and comprehensive way to evaluate the full environmental burden of a material, building assembly, system, or service over its full life cycle, from extraction of raw material, through manufacture, packaging, transport, operation, cleaning, repair, and maintenance, to disposal, recycling, or disassembly and reuse”.

Keeler and Burke (2009) mention that LCA is about the methods of characterizing, quantifying and analyzing environmental impacts and presenting the outcomes so that they will be useful for builders and designers. Similarly, Scheuer, Keoleian and Reppe (2003) state that, in LCA on one side extraction, production, transportation and construction and on the other side deconstruction and disposal of products and services, which they call upstream and downstream flows of processes respectively, are listed and then based on rates of usage of energy and production of waste, their impacts are computed.

As mentioned by Crawford (2011), elements of a built environment like buildings can age decades and sometimes hundreds of years. Over their life time, these systems see various life cycle stages as depicted in Figure 2.5, from producing raw materials for their construction to their eventual demolition and disposal.

As mentioned by Crawford (2011) environmental impacts happen during various stages of the life cycle of built environment which are extraction of raw materials, producing building materials, the construction procedure, operation stage, maintenance and recurring. Using natural resources like energy and water are result in production of gas emissions and wastes and these environmental impacts significantly depend on factors like methods of production, origin of natural resources and types of fuel that are being used during the whole process.

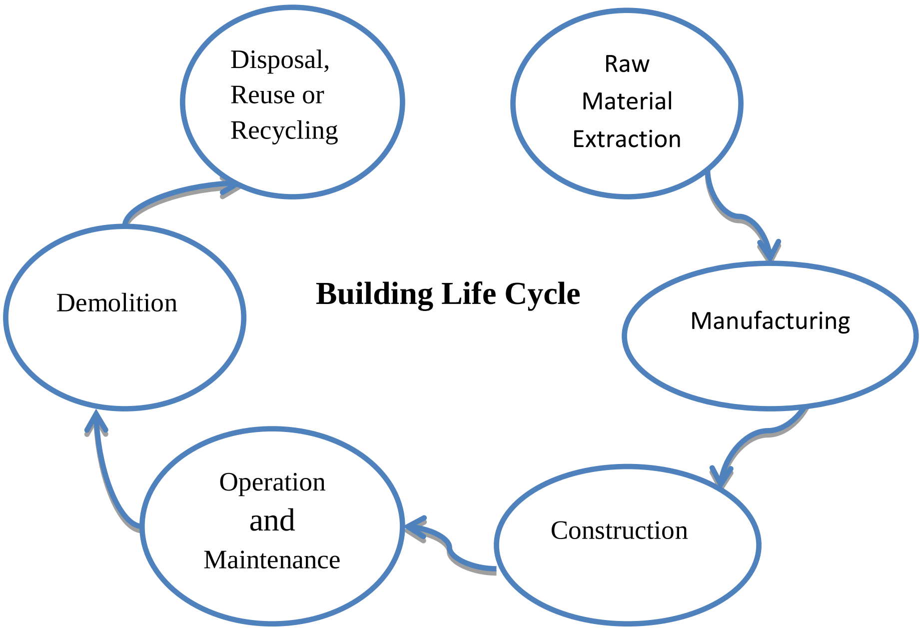


Figure 2.5 Stages involved in the building life cycle (Source: Crawford 2011)

The International Organization for Standardization (ISO) is the world's largest producer and manager of standards related to climate changes, cosmetics, and so on (ISO 14040, 2006). This International Standard states necessary concepts and also the structure for providing and representing LCA studies; it also contains information about minimum rate of requirements. According to ISO 14040 (2006), LCA is defined as a method of evaluating the environmental characteristics and possible impacts of a product, by listing of relevant inputs and outputs of a product system, analyzing the possible environmental impacts of those inputs and outputs and interpreting the results of these two steps considering the aim of the study.

According to ISO standardization guidelines (2006), LCA procedure consists of following phases: "Goal and scope definition of LCA, Inventory analysis (LCI), Impact assessment (LCIA), Interpretation of results, and Reporting and critical review". These steps are as following:

1- **Goal and scope definition:** According to Crawford (2011), this phase has the significant role of determining the direction of the study and defining the study boundaries. Generally the main goal of an LCA study is to select the process or product that has the least negative environmental impacts or develops new processes and products that result in fewer effects on environment. Also, the scope phase considers the boundaries for the LCA including the assumptions or shortcomings of the study and mentioning the inputs and outputs of the system.

2- **Life Cycle Inventory Analysis:** Keeler and Burke (2009) state that the second step is to collect information about the environmental impacts of the product system. Any data with any kind of attributes and impacts are gathered. Flows, both for inputs (e.g. use of natural resources) and outputs (e.g. emissions) are verified. Afterwards as mentioned in ISO International Standard 14040 (2006) quantifying the inputs and outputs of the product or process over its life cycle is done.

3- **Impact Assessment:** Crawford (2011) states that in this phase LCI findings are translated into numerical forms to show the effects of the product or process on environment. Bare and Gloria (2005) make it clear that impact assessment stage create a relation between inventory analysis and interpretation phases by giving metric values of inventory step. Without impact assessment, "releasing a pound of mercury to the environment would look just like releasing a pound of sand", stated by the authors. In other words, ISO International Standard 14040 (2006) notes that the impact assessment step considers the results of the life cycle inventory analysis and assess the importance of possible environmental effects.

4- **Interpretation:** ISO International Standard 14040 (2006) defines life cycle interpretation as a phase of life cycle assessment at which conclusions and recommendations are developed considering the results of the inventory analysis or the impact assessment, or both of them, in combination with goal and scope stage.

5- **Reporting and critical review:** According to ISO 14040 (2006), results and conclusion of LCA should be presented for audiences in proper form, also all the inputs, methods, limitations and assumptions related to the study should be mentioned. Besides, critical review plays an important role by considering whether LCA could satisfy requirements for method, interpretation and reporting.

Ramesh et al. (2010) explain life cycle energy analysis as a method that considers all energy inputs to a building during its life cycle. The system boundaries of this analysis as shown in Figure 2.6 include the energy use of the following stages: manufacture, use, and demolition. Manufacture stage consists of production and transportation of building materials and installations used in construction and restoration of the buildings. Operation stage includes all processes about the utilization of the buildings, over its lifetime such as preserving comfort condition in buildings, water usage and powering instruments. Demolition stage consists of raze of the building and transportation of demounted materials. In the next sections these three stages of life cycle energy analysis is described.

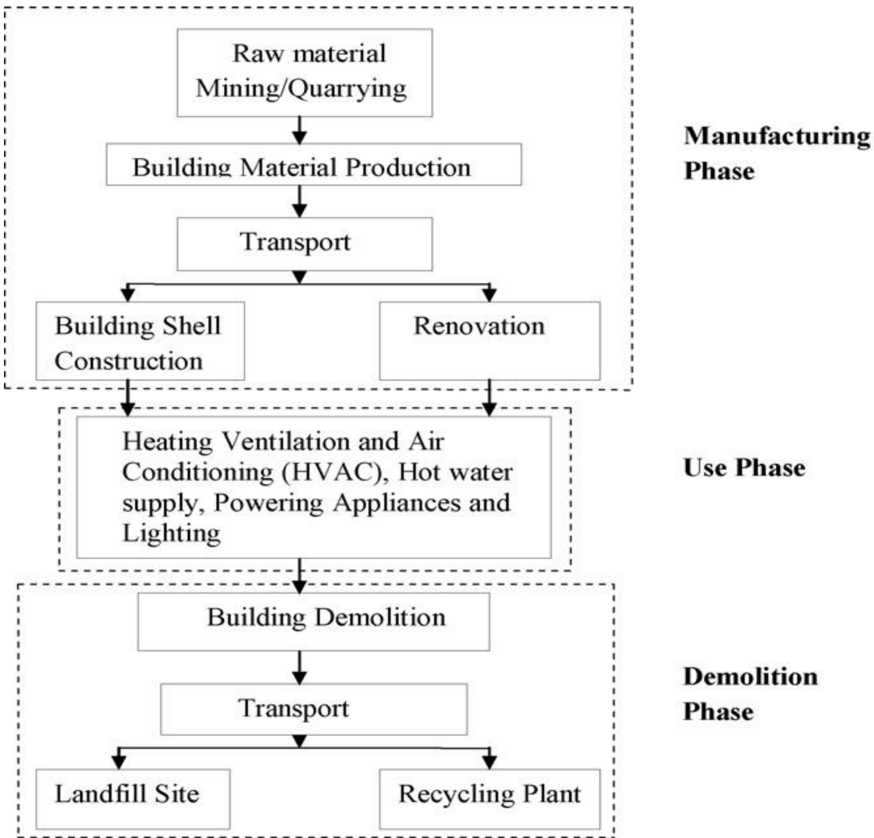


Figure 2.6 System boundaries for life cycle energy analysis

(Source: Ramesh et al. 2010)

2.4.1 Operational Energy

As Ramesh et al. (2010) note, operational energy is the energy necessary for preserving buildings in comfort conditions. It consists of the energy needed for HVAC (heating, ventilation and air conditioning), providing hot water, lighting and operating devices. Also as mentioned by authors, operational energy depends on the required comfort zone, devices' runtimes and weather conditions. Ramesh et al. (2010) state buildings' operation energy as:

$$OE = E_{OA}\,L_b$$

Where OE = operating energy in the life span of the building; E_{OA} = annual operating energy; L_b = life span of the building.

In researches conducted by Scheuer et al. (2003) and Thormark (2002), it is claimed that operational stage of a building is responsible for the most of the energy consumption in the building's life cycle distribution and related environmental effects. Precisely, operation phase is responsible for more than 83% of listed environmental burdens, other than waste generation.

Scheuer et al. (2003) also state that most of the burdens can be corrected and new opportunities are explored for future developments by improving initial design. It is the initial design of a building that defines the starting point from which the building will begin its operational life despite the fact that designers do not decide what happens to a building after it is constructed. Some of the factors that can be mentioned in initial design to optimize the operation energy phase are high performances building envelops and devices and considering renovations in design basis.

2.4.2 Embodied Energy

Ramesh et al. (2010), Reddy and Jagadish (2003) and Langston and Langston (2008) define embodied energy as the energy that is used in raw materials extraction, materials production processes, transportation to the factory and building site, technical installations, and energy consumed for assembling the materials. Cabeza, Barreneche, Miró, Morera, Bartolí and Inés Fernández (2013) assert that in life cycle analyses most concentration was on operating energy until now but nowadays concentration is moving toward embodied energy in building materials because of recent developments in energy efficient devices as well as insulation materials.

In order to determine the magnitude of embodied energy, Hammond and Jones (2008) point out that, an accounting technic is necessary to calculate all the energy inputs over the material supply chain or life cycle. Holtzhausen (2007) states that Mega Joules (MJ) or Giga Joules (GJ) per unit of weight (Kilogram or tonne) or area (square meter) is the units of energy. Calculating embodied energy is a complex process with different data sources. For example geographical location of factories and methods of materials production processes and methods are some of the few factors that have significant effect on materials' embodied energy.

Holtzhausen (2007) states that the amount of energy used in the producing building materials are closely related to CO_2 emissions. Precisely, for one GJ of embodied energy an average amount of 0.098 tonnes of CO_2 are emitted. According to Reddy and Jagadish (2003), using energy efficient or alternative building materials such as lime, adobe and cow dung can decrease embodied energy of a building.

A study carried out by Thormark (2006) showed that 40% of the whole energy necessary for a building with 50 years life span was its embodied energy but material substitution can reduce this amount to 17%. The author emphasize that material producing procedure, efficiency of production, accessibility of raw materials in region, and the amount of material used in construction are the factors that embodied energy of construction materials depends on.

Ramesh et al. (2010) divide embodied energy in to initial embodied energy and recurring embodied energy.

-Initial embodied energy

According to Holtzhausen (2007) initial embodied energy is non-renewable energy used through the extraction of raw materials to the construction of the building. As an example to clarify the concept the author considers a steel window frame; it will always contain the initial embodied energy that is consumed in mining, melting and transportation of raw material and manufacturing and transport of the window. Origin and type of materials and the nature of the building are the factors that initial embodied energy depend on. Ramesh et al. (2010) express initial embodied energy as:

$$EE_i = \sum m_i M_i + E_C$$

EE_i = initial embodied energy of the building; m_i = quantity of building material (i); M_i = energy content of material (i) per unit quantity; E_C = energy used at site for erection/construction of the building.

As Atkinson, Hobbs, West and Edwards (1996) mention, it is obtain that 70% of the total energy used in building construction and about 20% of the total energy requirement for UK industry is consumed as initial embodied energy. Yohanis and Norton (2002) indicate that, the initial embodied energy increases from zero to a maximum during the construction phase as shown in Figure 2.7. Since the building is not occupied during the construction phase operation energy is zero. During the operation stage because of maintenance, repairing and refurbishment necessities like replacement of lamps, repainting, re-carpeting, etc. embodied energy is increased.

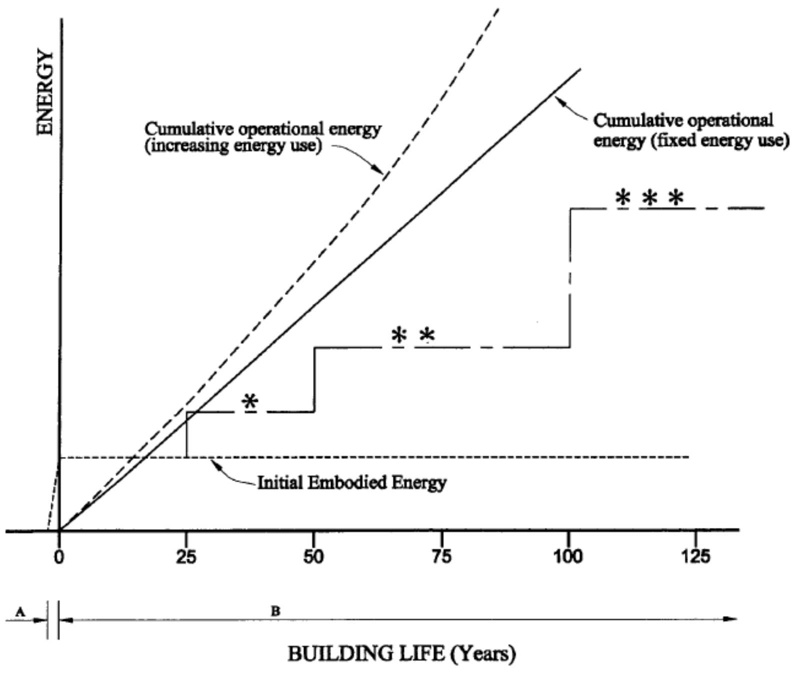


Figure 2.7 Operational and embodied energy as a function of building life
* Initial embodied energy plus recurring embodied energy over 25 years *, 50 years**, and 100 years***. A, Construction Phase; B, Operation Phase
(Source: Yohanis and Norton 2002)

-Recurring embodied energy

Holtzhausen (2007) defines recurring embodied energy as a non-renewable energy used to restore, maintain, refurbish, repair, or replace materials and components at the building's lifetime. Considering the window frame again, one can see that the window frame is not preserved from rust and it should be replaced, or painted during its life span. Persistence and preservation of building materials and components installed in the building, and the life span of the building are the factors that recurring embodied energy depend on.

In other words, Ramesh et al. (2010) state that, some of the different materials used in a building will have a shorter lifetime than the building itself and so they should be fixed or replaced. Moreover regular maintenances are inevitable incidents in a building lifetime. The total energy which will be consumed for performing all these actions should be calculated. Recurring embodied energy can be expressed as:

$$EE_r = \sum m_i \, M_i \, [(L_b / L_{mi}) - 1]$$

EE_r = recurring embodied energy of the building; L_b = life span of the building; L_{mi} = life span of the material (i)

Demolition Energy:

As Ramesh et al. (2010) state, when a buildings life span is over, specified energy is consumed to demolish the building, remove the waste from sites and/or move them to recycling plants. Yohanis and Norton (2002) claim that, this part is very hard to evaluate because it is not easy to predict the building's useful life, the energy implications of materials and components which can be re-use or recycled later and demolition methods.

Ramesh et al. (2010) express demolition energy as:

$$DE = E_D + E_T$$

DE = demolition energy; E_D = energy incurred for destruction of the building; E_T = energy used for transporting the waste materials

In some articles demolition energy is mentioned as a part of embodied energy but in some is not a part of embodied energy. For instance, Yohanis and Norton (2002), Chen, Burnett, and Chau (2001) and Dixit, Fernández-Solís, Lavy and Culp (2010) indicate demolition as a part of embodied energy, while Cole and Kernan (1996), Treloar (1997), Ramesh et al (2010), Hammond and Jones (2008) and Reddy and Jagadish (2003) do not mention it as part of embodied energy.

According to Ramesh et al. (2010) however embodied energy comprises just 10-20% of the life cycle energy, minimizing amount of embodied energy should not relinquish. One of the solutions for embodied energy reduction is using energy efficient construction materials.

Numbers of researchers have provided some estimated about the embodied energy of popular materials used in constructions. The investigation by Reddy and Jagadish (2003) on alternative building materials in India shows that soil-cement block is one of the most energy efficient materials. The energy consumed during soil-cement manufacturing is approximately 25% amount of energy consumed during burnt clay brick manufacturing. Also concrete blocks are more energy efficient than burnt clay bricks. Shukla et al. (2009) assert that adobe brick house has about 50% of energy content of conventional concrete house.

Also, according to the work by Yohanis and Norton (2002) on the embodied energy of wall construction systems of generic single story home, steel wall structures has the maximum amount of embodied energy and Clay bricks are the next material with high embodied energy in category and the structures made of concrete blocks are in the third rank and the most energy efficient wall structure is related to timber walls.

Hammond and Jones (2008) in their investigation about material's embodied energy and carbon, state that among different types of concrete production, general concrete that is used in construction of buildings under three stories, precast concrete, autoclaved aerated concrete and fibre-reinforced concrete respectively have 0.95 Mj/Kg, 2 Mj/Kg, 3.5 Mj/Kg, 7.75 Mj/Kg amount of embodied energy. Also the authors summarize different materials contribution to embodied energy and show the breakdown of embodied energy and carbon in Figure 2.8. It can be concluded that brick and concrete have the most embodied energy and embodied carbon among other alternative construction materials.

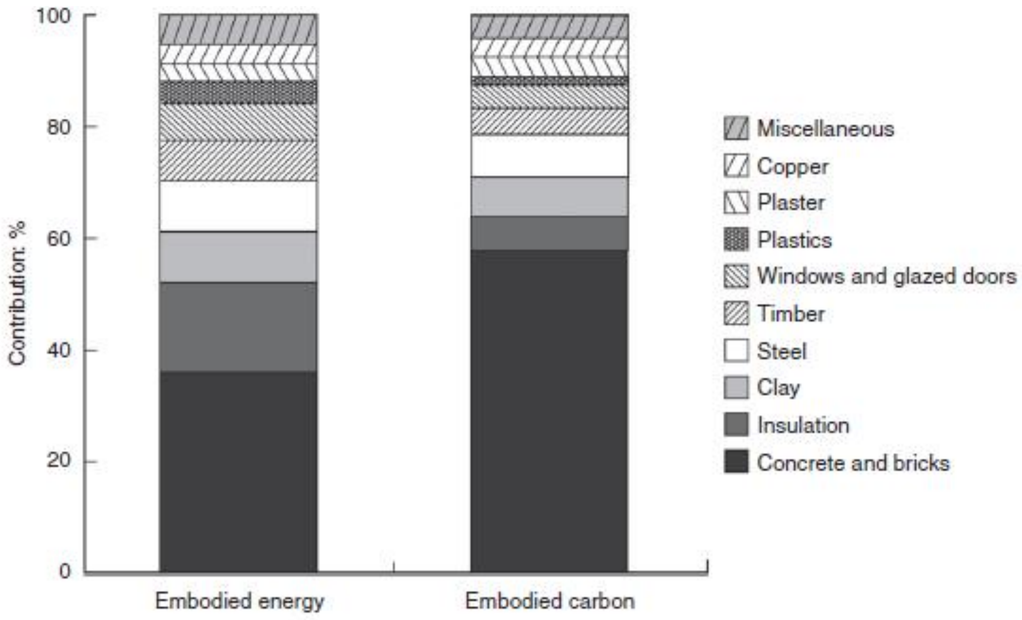


Figure 2.8 Breakdown of embodied energy and carbon by material

(Source: Hammond and Jones 2008)

2.5 Embodied Energy Analysis Methods

As mentioned by Treloar (1997), the energy that is needed for all activities in order to support a process is referred as embodied energy and is divided to direct and indirect types of energy. Direct energy is the energy consumes on site during the erection of the building and energy buys by construction firms and indirect energy is the energy consumed to manufacture inputs of the products and goods. Treloar (1997) obtains embodied energy values by three methods name as Input Output Analysis, Process Analysis and Hybrid Analysis.

2.5.1 Input Output Analysis

Input-output analysis as a top-down economic technique is commenced by Leontief in 1960's. Crawford (2011) states that this technique uses input-output tables that are the matrices of sector based monetary deals and also average tariffs. Therefore this method has an economic system boundary. All the required products and services by sectors are considered in these tables. In this method the energy sold to the sector is account as monetary value and multiply by average national tariffs to calculate the amount of direct energy of the specified sector (Crawford, 2011). Indirect energy calculation is important for embodied energy analysis. Treloar (1997) use "embodied energy paths" term to explain the process of following the energy input upstream for calculating indirect energy amount.

Crawford (2011) claims that any type of environmental data such as energy, raw material and water consumption, greenhouse gas emissions like CO_2 and waste productions can be integrated into input output tables. According to Treloar (1997) although this method has advantages like being representative of the domestic average case and covering the entire system boundary, this method can be inaccurate because of tariffs, scale and homogeneity of sectors.

2.5.2 Process Analysis

As Crawford (2011) describe, process analysis is a method that uses a combination of product, process and location–specific data to count the amount of environmental impacts of different sectors. Process analysis method uses actual measured data for every singular product and process. Individual procedures can be shown in a process flow diagram to identify required data for all processes. Figure 2.9 depicted a process flow diagram for production of concrete.

Treloar (1997) defines process analysis as an embodied energy analysis method that uses all sources of data except input-output tables. The author explains this analysis method in three steps. First, calculation of all direct energy is needed for main process, and also the outputs of the process in the determined period of time. Second, accounting the inputs of other products as an indirect energy that are needed for the procedure and the last step is recognizing energy embodied in each product in the main process. One of the shortcomings of this method is that focus on details and the system boundary are not complete.

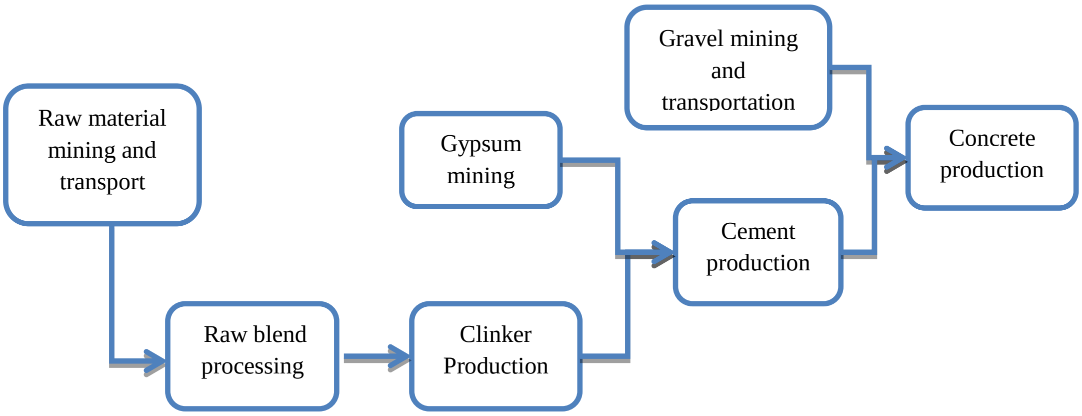


Figure 2.9 a process flow diagram for concrete production (Source: Crawford 2011)

Process analysis is more reliable than input-output analysis though this method is incomplete and it can be time consuming. The incompleteness of this analysis is referred to presence of product systems by a limited boundary and elimination of other components outside the defined boundary (Crawford 2011 and Treloar 1997).

2.5.3 Hybrid Analysis

Hybrid analysis is the combination of input-output analysis and process analysis. At the first step, input-output tables are used to identify direct energy inputs and in the next step process analysis is used to define indirect energy inputs. Hybrid method tries to use the advantages of both techniques and reduce the probable shortcomings related to both analysis methods. However, since hybrid technique is based on process analysis data, this method also has limitations (Crawford 2011 and Treloar 1997).

2.6 LCA Limitations

Following issues are considered to be limitations of LCA by ISO International Standard 14040 (2006).

- Choices and assumptions in LCA (e.g. selection of data sources, system boundary setting and impact categories) may be done without considering the whole picture and subjectively.
- Inventory analysis and environmental impact assessments are based on assumptions that may not include all potential applications and impacts.
- LCA studies may be improper for local applications when they consider only global and regional issues.
- Availability and quality of relevant data limit the reliability and accuracy of LCA studies.
- Ambiguity in impact assessment procedure that is caused by shortages temporal and spatial dimensions in the inventory data.

2.7 LCA Tools

As noted by Crawley and Aho (1999), the building industry was obliged to concentrate on how buildings were designed, built and operated because of increasing market demand for environmentally friendly products and services. Haapio and Viitaniemi (2008) state that different types of tools are found for a whole building or building components and each tool include different phases of life cycle and environmental impacts. The authors state that environmental assessment tools are designed for global, national and local cases. Databases of some national tools can be changed to be used as global tools. Research, consulting, decision making and maintenance are some of the reasons of developing these tools and each of them is used by different entities like researchers, designers, consultants, architects, tenants, owners and authorities.

Different environmental measures such as issues related to economic or health and comfort are defined for the needs of relevant interest groups. Building Research Establishment Environmental Assessment Method (BREEAM) was the first tool that satisfies assessing to a wide range of environmental considerations (Crawley and Aho, 1999). BREEAM was established in 1990 in the UK and was the first available environmental assessment tool for buildings (Grace, 2000). Haapio and Viitaniemi (2008) state that there are two popular classification systems for the environmental assessment tools. The classifications developed by the ATHENA Institute (Trusty, 2009) and IEA Annex 31(2004). ATHENA classification system is shown in Table 2.4 and IEA Annex 31 classification is shown in Table 2.5 (IEA Annex 31, 2004).

Table 2.4 ATHENA Classification System (Source: Haapio and Viitaniemi 2008

Athena Classification	**Description**	**Examples of Assessment Tools**
Level1	product comparison tools and information sources	BEES 3.0 and TEAM™
Level 2	whole building design or decision support tools	ATHENA™, BEAT 2002,
Level 3	whole building assessment frameworks or systems	BREEAM, EcoEffect,

Table 2.5 IEA Annex 31 classification
(Source: IEA Annex 3 2004 and Haapio and Viitaniemi 2008)

IEA Annex 31 classification	**Assessment Tools**
Energy Modeling software	
Environmental LCA Tools for Buildings and Building Stocks	BEES 3.0 and TEAM™ ATHENA™, BEAT 2002,
Environmental Assessment Frameworks and Rating Systems	BREEAM, EcoProfile,
Environmental Guidelines or Checklists for Design and Management of Buildings	
Environmental Product Declarations, Catalogues, Reference Information, Certifications and Labels	

As mentioned by Haapio and Viitaniemi (2008), increasing role of the tools motivates categorizing them that helps to see similarities and the differences of these tools and this information can be used in the development and improvement of the tools. The authors categorize the building environmental assessment tools as below:

- **Types of the assessed building**

As mentioned by Haapio and Viitaniemi (2008), building environmental assessment tools can evaluate different types of buildings like existing buildings, new buildings, buildings under refurbishment as well as building products and components.

- **Users**

Building environmental assessment tools are designed to be used for different intentions like commercial and research as well as decision making and maintenance by different types of users like researchers, professionals (architects, engineers, and constructors), investors/ building owners, consultants, residents, producers of building products, facility managers and authorities (Haapio and Viitaniemi 2008).

- **Life cycle phases**

In order to enable the comparison of the building environmental assessment tools, Haapio and Viitaniemi (2008) consider the building life, from "cradle to grave" in different stages:

- Production of materials and components
- Construction
- Use/operation of the building
- Maintenance
- Demolition
- Disposal (recycling, landfill, incineration for energy recovery etc.).

The environmental assessment tools concentrate on different stages of the building's life cycle. Table 2.6 shows the phases of the life cycle for selected softwares.

- **Result forms**

Graphs, tables, grades, certificates, and reports, of which graphs and tables are most used, are different method for presenting the results of the environmental assessment of a building. Types of reports that are provided to present the results are also different between tools. Not all the tools have grades and certificates. For instance, BREEAM uses pass, good, very good, excellent grades and LEED uses silver, gold and platinum grades (Haapio and Viitaniemi, 2008)

Table 2.6 Phases of the life cycle (Source: Haapio and Viitaniemi 2008)

ATHENA Classification	Assessment tool	Production	Construction	Use/operation	Maintenance	Demolition	Disposal
1	BEES 4.0	■		■	■		■
	TEAM™	■	■	■	■		■
2	ATHENA™	■	■		■	■	■
	BEAT2002	■	■	■	■	■	■
	Eco_ Quantum	■	■	■	■	■	■
	Envest 2	■	■	■	■	■	■
	EQUER	■	■	■	■	■	■
	LEGEP®		■	■	■	■	
	PAPOOSE	■		■	■	■	■
3	BREEAM	■	■	■	■		■
	EcoEffect	■	■	■	■	■	■
	EcoProfile			■	■		
	ESCALE	■	■	■	■		
	LEED®	■	■	■	■	■	■

- **Databases**

Haapio and Viitaniemi (2008), claim that different types and amounts of data are necessary for each building environmental assessment tool. Moreover, each tool uses only one database and sometimes a combination of databases. Oekoinventare (ETHZ), DEAM™ and ATHENA™ are some of the popular databases that are being used by some tools (Table 2.7).

Table 2.7 Databases of the tools (source: Haapio and Viitaniemi 2008)

ATHENA classification	Assessment tool	Database
1	BEES 4.0	Generic data and brand specific
	TEAM™	DEAM Starter Kit
2	ATHENA™	ATHENA Institute
	BEAT 2002	Collected by DBUR (Danish Building and Urban Research)
	BeCost	Environmental profiles of building materials produced in Finland
	Eco-Quantum	A compilation of a number of publicly available generic data sources such as BUWAL, APME and ETH and data from LCA's conducted by IVAM
	Envest 2	UK based data on service life, exposure factor, energy and water consumption benchmarks, LCA data for material and Ecopoints.
	EQUER	Product data bases of Swiss and German origin, Oekoinventare (ETHZ) on building materials
	LEGEP®	SIRADOS, ECOINVENT, GEMIS, the Baustoff Ökoinventare, and LEGEP database
3	BREEAM	Green Guide
	EcoEffect	Accompanied by a database for energy and materials
	EcoProfile	No database included

2.7.1 eTool Life Cycle Assessment Software

Beattie et al. (2012) states that eTool (released online at www.etool.net.au) is a suitable tool for computing embodied and operating energy and related CO_2-e emissions of buildings and small civil works. eTool LCA which according to Haynes and Bruce (2010) is a result of a two and a half years work developed in Western Australia.

eTool LCA employs a lifecycle analysis and calculates a building's lifespan, initial embodied energy of materials , maintenance and transport during construction and key aspects of operational energy but not energy related to end-of-life aspects like demolition or recycling of materials (Beattie et al, 2012).

eTool LCA, with the aim of estimating impacts, is precise enough to compare various design options and allows reporting of numerous impacts (Byrne 2012). The environmental impacts that are reported in eTool LCA are global-warming-potential, fossil fuels consumption, fresh water consumption, costs, land transformation and use, ozone layer depletion, acidification and human toxicity (released online at http://etool.net.au/).

Beattie et al. (2012) review eTool LCA to evaluate how it takes each source of CO_2 -e emissions into account in the framework:

- **CO_2-e Emissions used in Materials:** Beattie et al. (2012) state that, eTool provides the options to select details of the materials of construction like foundations, floors, walls, roof, finish and fittings and service infrastructure can be selected from the database. User can enter lifespan of every component and this makes it possible to calculate the recurring energy over the design life of the building. eTool collects and reports energy and carbon emissions related to initial and recurring materials separately.

- **CO_2-e Emissions in the Construction Process:** eTool calculates CO_2-e emissions from materials transportation to place of production and finally to distribution place and delivery to site during the construction process. The option to enter the hours of equipment use and its depot location to calculate transport and operational energy use is also provided (Beattie et al. 2012)

- **Operational Energy:** Beattie et al. (2012) continue that data related to gas supplies, electricity demand for thermal comfort, lightening, water heating, refrigeration and appliances are available and can be entered to measure the loads on supply systems. Also operation energy option can be used for renewable energy systems like photovoltaic systems.

• **Transport Fuels:** Carbon emissions related to fuels transportation during the occupancy phase are not considered Beattie et al. (2012).

• **CO_2-e Emissions in the Water Cycle:** Energy consumption and CO_2-e emissions related to water supply and sewerage treatment are computed. Moreover, with materials and assembly components of the tool, materials and construction processes for simple water supply and sewerage infrastructure can be evaluated (Beattie et al. 2012).

• **Solid Waste:** Materials and assembly components of the tool assesses the energy in emissions related to construction of simple waste treatment facilities but carbon emissions from solid waste are not calculated (Beattie et al. 2012).

As mentioned in previous section, Haapio and Viitaniemi (2008) state that LCA software concentrate on different stages of the building's life cycle and their boundaries are not similar with each other. The system boundary of eTool LCA for analysis is depicted in Figure 2.10.

eTool LCA Databases

- Building Materials LCI: The default materials LCI database, Australasian specific dataset, was developed by Life Cycle Strategies. Before public release of this data, carbon and energy figures mostly were obtained from the Inventory of Carbon and Energy published by Bath University (Hammond and Jones, 2008). Though it is an excellent source of information it is limited to quantization of energy and carbon associated with materials production. (released online at http://etool.net.au/).

- Transport and Stationary Energy Sources: Australian National Greenhouse and Energy Reporting Technical Guidelines (2011-2012) which only quantifies energy and carbon of fuel consumption is the current (August 2012) source for carbon impact related to energy (released online at http://etool.net.au/).

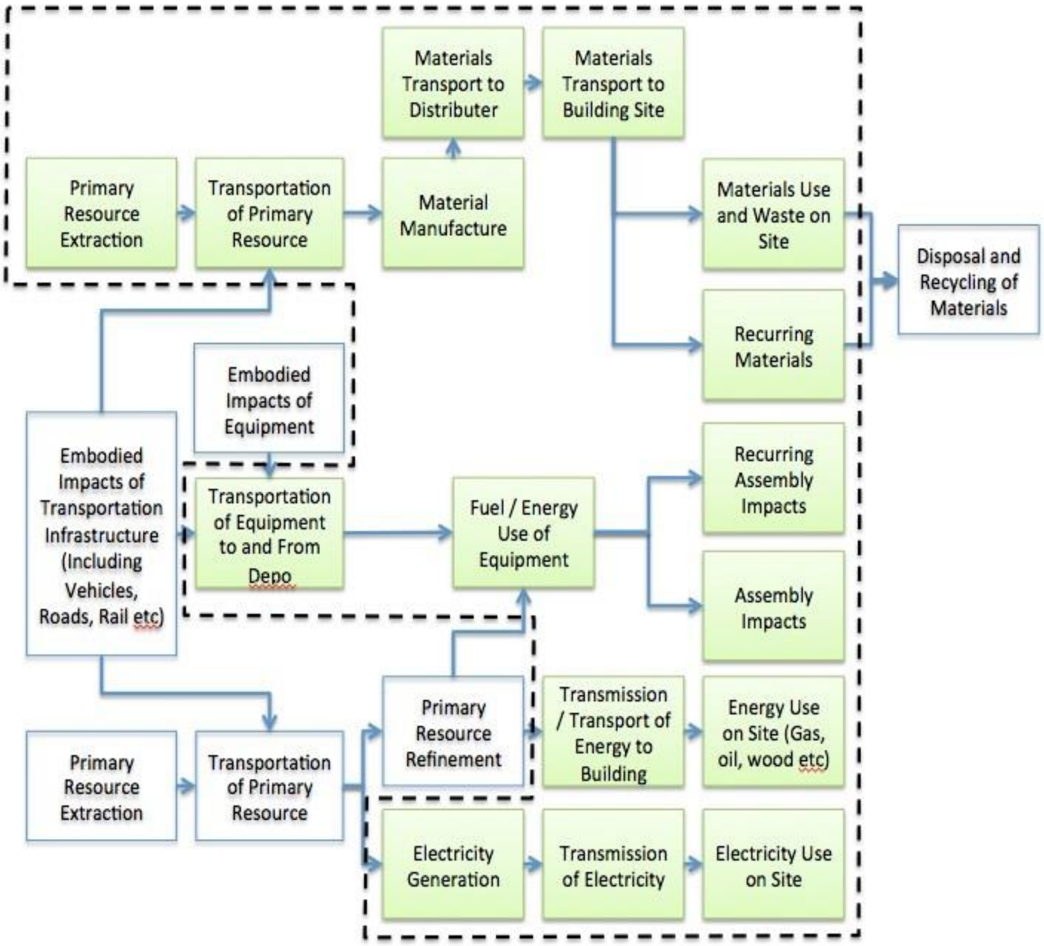


Figure 2.10 System Boundary of LCA (Source: Byrne 2012)

-Distribution grid energy consumption: Based on the location of the grid this data is obtained from a variety of documents. Australian Bureau of Agriculture and Resource Economics and National Greenhouse and Energy Reporting Technical Guidelines are the major sources of electricity and distributed gas data sets in Australia (released online at http://etool.net.au/).

-Transport Energy Consumption: "Waste Tyres, a National Approach", the Australian Department of Environment publication is currently used for eTool LCA's transport coefficients. (released online at http://etool.net.au/)

2.7.2 LCA Tools Limitations

As Haapio and Viitaniemi (2008) state, most of the time LCA tools include uncertainties in analyses, calculations and interpretations of outcomes. Two kinds of errors, random errors and systematic errors usually occur during assessments. Random errors do not have serious impacts on results since negative and positive errors neutralize each other. But systematic errors are effective since measuring tools or methods cause the errors. The authors point out that some of these systematic errors can occur because of errors in database values and this probability may increase if the database is editable. Furthermore, the collection method of the data is mentioned as a reason of errors and the last but not least, products and processes develop rapidly and these cause changes in environmental impacts and therefore change in assessments outcomes.

CHAPTER 3

MATERIALS AND METHODS

This chapter presents the materials used for research and the methodology of the research in two sections. The section on material describes the Erdoğan Akdağ Center as a case study building and the eTool LCA software which is used for environmental impacts calculation. The methodology section consists of software simulation, data processing and data evaluation.

3.1 Materials

In this study a building, located in Yozgat, Turkey is selected in order to carry out the research on two different types of building envelope designs compared with base case building envelope. Furthermore, eTool LCA as a simulation program is explained.

3.1.1 Case Study Building

Erdoğan Akdağ Center for Research and Education (EACRE) was chosen as the case study building because it is part of the Kerkenes Eco-Center (Figure 3.1) where research related to sustainable buildings and renewable resources is being conducted for the past decade. The Ecocenter is located in Shahmuratli village, in the Yozgat province of Turkey and houses 9 different buildings of different materials. The reason to select this particular building is that it is built of AAC as the main construction material and the aim was to see its impact on the environment also. The EACRE is a single story building with a storage area under the projected terrace in front of the building (this space has not been considered in the evaluations). The building has a meeting room, an office room, a kitchen, a pantry, two WCs, one shower room and an entrance corridor. It is constructed with reinforced concrete columns and beams; reinforced AAC roofing (Figure 3.2). The e walls and ceiling are AAC blocks with 25cm thickness and AAC panels with 25cm thickness respectively and also the roof has a timber structure. The list of case study materials is shown in Table 3.1 (Elias-Ozkan, Summers, Karaguzel and Taner, 2008). The case study building has a total floor area of 93.73 m^2 and usable area of 77.7 m^2. Figures 3.3-3.6 show EACRE during and after construction phase.

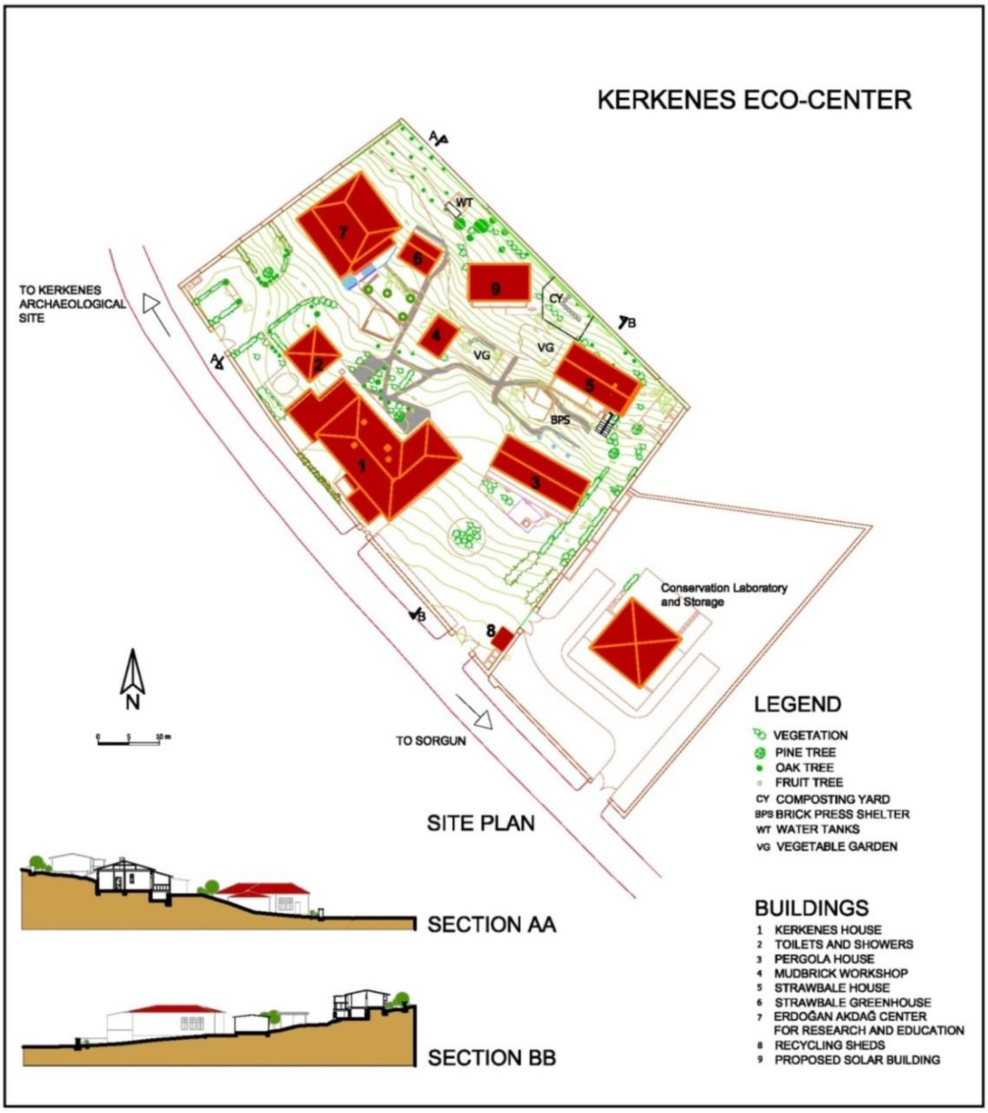


Figure 3.1 Kerkenes Eco-Center plan

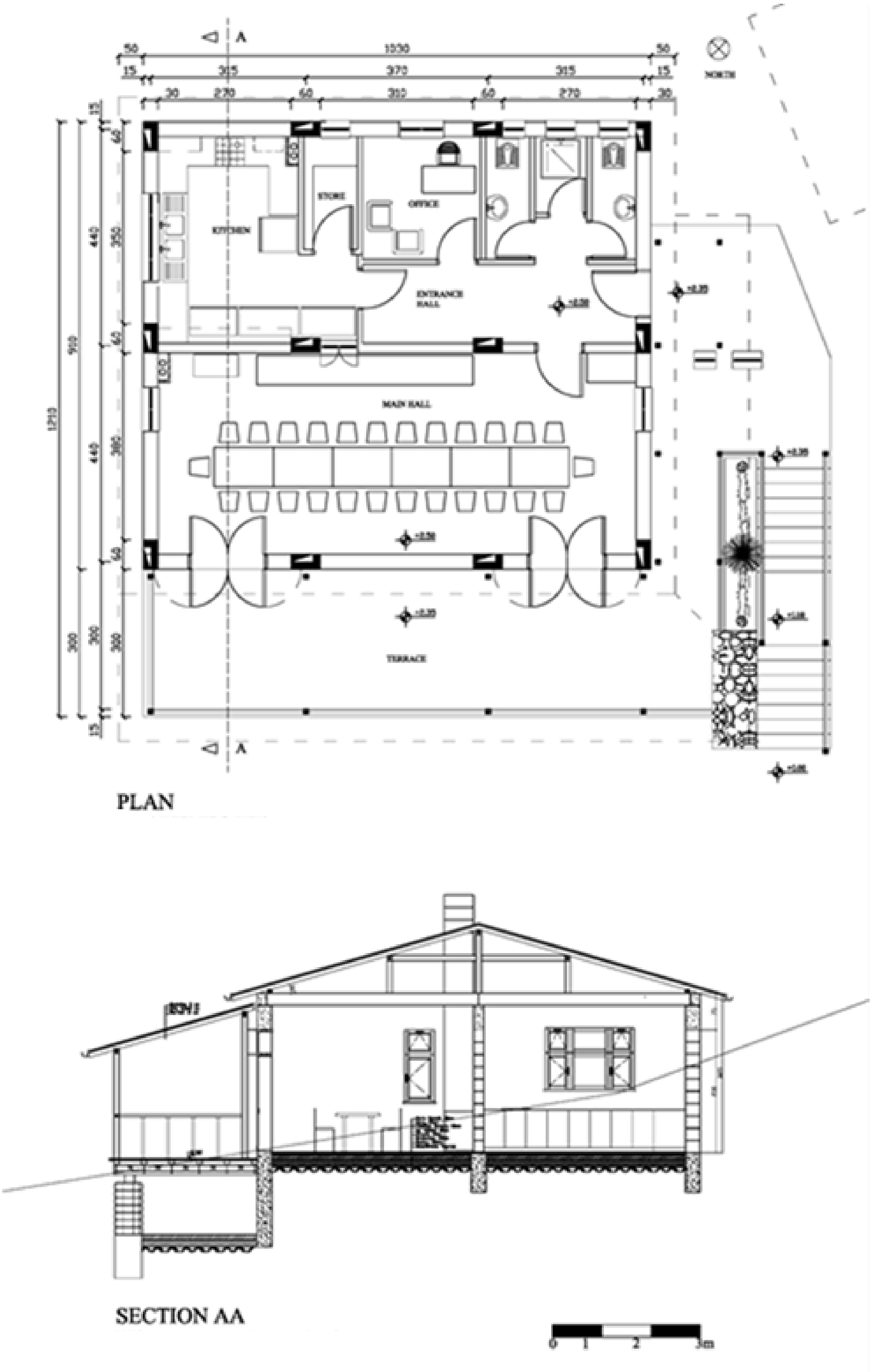


Figure 3.2 Erdoğan Akdağ Center, plan and section

Table 3.1 Physical and thermal properties of base case building

Used Material	Density (Kg/m^3)	Thickness (mm)	Thermal Transmission (U-Value) (W/m^2K)
Floor			
Compacted Earth	1300	300	0.98
Blockage	2300	150	
Grobeton	2300	100	
Water Proof	1100	10	
Insulation	15	20	
Levelling Concrete	2100	50	
Mortar	1650	20	
Mosaic	> 2600	20	
External Walls			
Cement Plaster	2000	25	0.567
AAC Blocks (600×250×250)	500	250	
Cement Plaster	2000	25	
Roof Slab			
AAC Panel (6000×600×250)	500	250	0.56
Cement Plaster	2000	25	
Roof			
Roofing Tile	1000	4	2.62
Water Proof	1100	10	
Timber	720	25	

Figure 3.3 Erdoğan Akdağ Center - construction phase

Figure 3.4 Erdoğan Akdağ Center - construction phase

Figure 3.5 Erdoğan Akdağ Center – south view

3.2.2 eTool Life Cycle Assessment Software

In this research in order to calculate environmental impacts of different materials used in conventional buildings in Turkey, eTool LCA is used. eTool LCA is a free access software and unlike most of LCA software, eTool LCA is user friendly and does not require training courses and also include all case study materials. General description of eTool LCA is mentioned in section 2.6.1. According to ATHENA classification eTool LCA can listed in level 1 of this classification and provides assessment of various aspects of buildings like a building's lifespan and their environmental impacts during construction and operating phases. However, this software does not provide calculation of end of life aspects like recycling and demolition of materials. Therefore this software satisfies four of the six sources of CO_2-e emissions. In general, eTool LCA focuses on quantifying the environmental impacts of the building and compares these impacts with other alternatives design options and benchmarks, and use various databases (see section 2.6.1). It should be mention that the last access to this software was at November 30th 2013. The following steps briefly explain how this software functions.

Step 1: eTool LCA is a web based software that needs registration to log in-to the program. Under "My eTool" tab the project and its features can be defined by entering general information related to project such as project name, project category, country, province and occupancy.

Step 2: In the "Projects" section the case study buildings are identified by mentioning their name, density, and construction type, and design quality, number of occupants and location of the building.

Step 3: In the next step the design criteria can be defined by entering general descriptions like building area, conditioned area and number of stories, dwellings, bedrooms and bathrooms which are required for environmental impacts calculation.

Step 4: In the "Design" section "Categories" tab assembly input, materials input and operational input options can be selected from a list. In order to calculate building envelopes' environmental impacts and related environmental impacts, material input section which is consisted of external finishes, floor, internal finishes, roof and walls and also assembly inputs should be filled. These inputs can be selected from the software's default templates for every part of building construction, or can be filled by selecting the specific material and its properties manually with information like material type, quantity, life time, and distance from factory to construction site.

Step 5: In the last step, in the "Design" section "Reports" tab, reports for different design options can be generated. For each single design or its comparison with other design options and benchmarks, a total of seven types of reports can be provided. Reports that are shown in this research are as follows:

- Life Cycle Assessment report on:
    - Global-Warming-Potential
    - Fossil Fuels
    - Fresh Water Consumption
    - Ozone Layer Depletion
    - Acidification

3.2 Method

In this study evaluation of different building envelopes is done in terms of environmental impacts calculation. What come next are the components that are established in order to categorize eTool LCA inputs to calculate environmental impacts of each type of building envelope configuration. The first step is defining case study building with different types of envelope materials. In the next steps software inputs are determined in three sections: cradle to gate stage, transportation of material to construction site and recurring stage.

In this study the assembly section is neglected because of two reasons: first reason is that there is not sufficient data related to the building erection phase to confirm the type and hours of power tools used. Besides most of the building construction was done manually therefore machinery equipment and power tools were used rarely which required negligible amount of energy consumption compared with other stages.

3.2.1 Defining Case Study Building

The first step of environmental impacts estimations in this research is describing Erdoğan Akdağ Center for Research and Education as the case study. In this procedure, EACRE is explained in terms of the building's name, its location (Sahmuratli village, Yozgat, Turkey) and project occupancy (which is assumed to be 5 people). Additionally, project type and building density is required for this process. Although the EACRE in Kerkenes Eco-Center is used for village, archeological and ecological activities, project type should be selected as a community building, because of the limited categories in eTool LCA it has been mentioned as residential building. As mentioned in section 3.1.1 since the building has a concrete frame and load bearing elements are reinforced concrete, "Concrete, Poured in Situ" is selected for construction type. Also, since the building is located in rural area and it is not built for a specific purpose, very low suburb redevelopment potential (Rural) and low design quality (Spec built) are chosen respectively.

In this study, building envelope components such as exterior walls, roof and floor are verified. In the section about designing the building with different materials for building envelope, fully enclosed building area (93.73 m^2) and conditioned Area (42.86 m^2) are defined. In addition, the number of stories (1), dwellings (1), work stations and bedrooms (2) and bathrooms (3) are set.

3.2.2 Cradle to Gate Stage

eTool LCA calculates embodied energy ($MJ/Dwelling$) and embodied carbon ($KgCO_2/Dwelling$) and other environmental impacts of building materials by using the databases. In this section two alternative exterior walls and roof slab materials are chosen to be applied to the base-model in order to calculate their environmental impacts. In other words, along with base case building, modified cases are assigned that have the same properties with base case building except for the exterior walls and roof slabs. AAC blocks and panels in external walls and roof slab are substituted with two alternative design options, design option A (hollow brick block walls and concrete slab roof) and design option B (hollow concrete block walls and a slab of concrete beams and hollow in-filling brick blocks for roof slab). Physical and thermal properties of as-built case study are mentioned in Table 3.1.

According to the Turkish Standards regarding thermal insulation in buildings (TS825, 2008), Turkey is divided into four thermal regions and Yozgat is located in the fourth region, which has the harshest climate (Figure 3.7). Therefore alternative building envelopes in this study have to satisfy the requirements mentioned in the Thermal Regulations Document for this region.

According to TS825 maximum heat transmission value, U Value, is 0.4 $W/m^2 K$ for external walls, 0.25 $W/m^2 K$ for roof slab structure and 0.4 $W/m^2 K$ for floor.

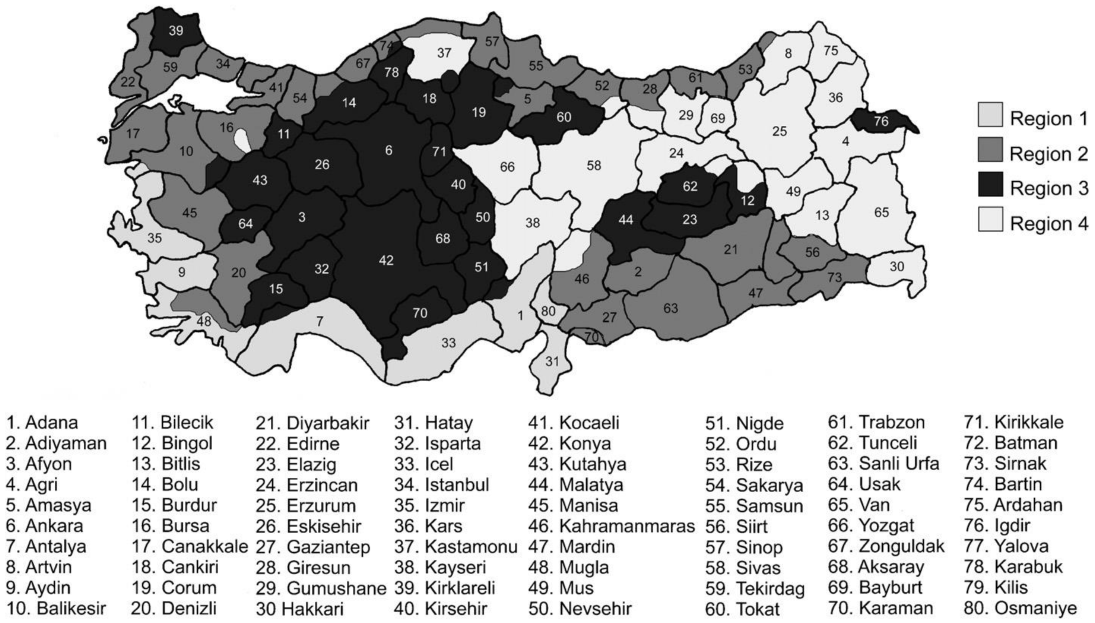


Figure 3.6 Climate regions of Turkey and cities
(Source: Sisman, Kahya, Aras and Aras, 2007)

Since the base case building does not satisfy thermal insulation requirements according to TS 825, the base case building is optimized with two configurations. The first configuration is done by using thermal insulation material in building envelope as shown in Table 3.2 and the second configuration is done by using thermal insulation material in building envelope except external walls. In this building envelope type the external walls optimized in order to satisfy thermal insulation requirement by increasing the thickness of AAC blocks (Table 3.3). Also, the alternative walls and roofs with different materials are designed in specific thicknesses to satisfy required U value for region 4. Alternative exterior walls and roof slab constructions according to Turkish Standards are shown in Table 3.4 and Table 3.5. It is necessary to mention that because of the differences of the eTool LCA database and the exact data for Turkey, data for the most similar materials are selected as eTool LCA inputs.

Table 3.2 Physical and thermal properties of option A

Used Material	Density (Kg/m^3)	Thickness (mm)	Thermal Transmission (U-Value) (W/m^2K)
External Walls			
Cement Plaster	2000	25	0.4
AAC Blocks	500	370	
Cement Plaster	2000	25	
Roof Slab			
AAC Panel (6000×600×250)	500	250	0.25
Insulation (XPS)	15	70	
Cement Plaster	2000	25	
Floor			
Compacted Earth	1300	300	0.354
Blockage	2300	150	
Grobeton	2300	100	
Water Insulation	1100	10	
Insulation (XPS)	15	70	
Levelling Concrete	2100	50	
Mortar	1650	20	
Mosaic	> 2600	20	

For the next building envelope configurations the floor details are all the same as optimized case A, which is shown in Table 3.2.

Table 3.3 Physical and thermal properties of option B

Used Material	Density (Kg/m^3)	Thickness (mm)	Thermal Transmission (U-Value) (W/m^2K)
External Walls			
Cement Plaster	2000	25	0.362
AAC Blocks (600×250×250)	500	250	
Insulation (XPS)	15	30	
Cement Plaster	2000	25	
Roof Slab			
AAC Panel (6000×600×250)	500	250	0.25
Insulation (XPS)	15	70	
Cement Plaster	2000	25	

Table 3.4 Physical and thermal properties of option C

Used Material	Density (Kg/m^3)	Thickness (mm)	Heat Transmission (U-Value) (W/m^2K)
Exterior Walls			
Cement Plaster	2000	25	0.366
Hollow Brick (190×135×190)	600	190	
Thermal Insulation (XPS)	> 25	60	
Cement Plaster	2000	25	
Roof Slab			
Thermal Insulation (XPS)	> 25	110	0.25
Reinforced Concrete	2400	120	
Cement Plaster	2000	25	

Table 3.5 Physical and thermal properties of option D

Used Material	Density (Kg/m^3)	Thickness (mm)	Thermal Transmission (U-Value) (W/m^2K)
Exterior Walls			
Cement Plaster	2000	25	0.365
Hollow Concrete (390×150×190)	< 1800	190	
Thermal Insulation (XPS)	> 25	60	
Cement Plaster	2000	25	
Roof Slab			
Thermal Insulation (XPS)	> 25	110	0.24
Hollow Bricks (200×400×250)	600	250	
Reinforced Concrete	2400	250	
Cement Plaster	2000	25	

Figures 3.7 - 3.10 show the simplified detail of building envelope configurations which are evaluated in this thesis.

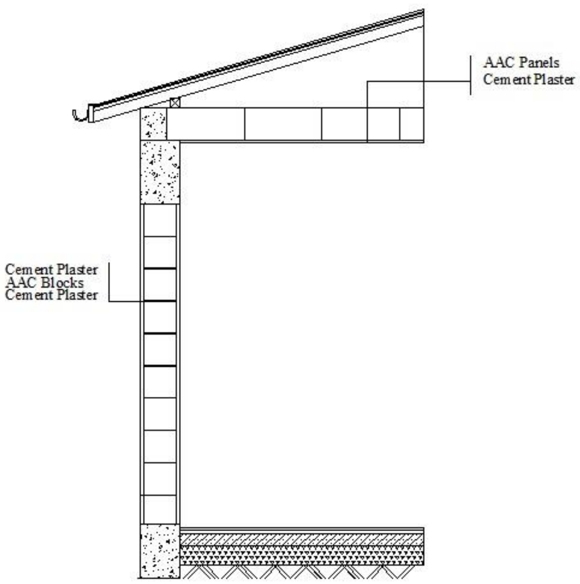


Figure 3.7 Building envelope details of base case (walls are 25cm thick) and Option A (walls are 37cm thick)

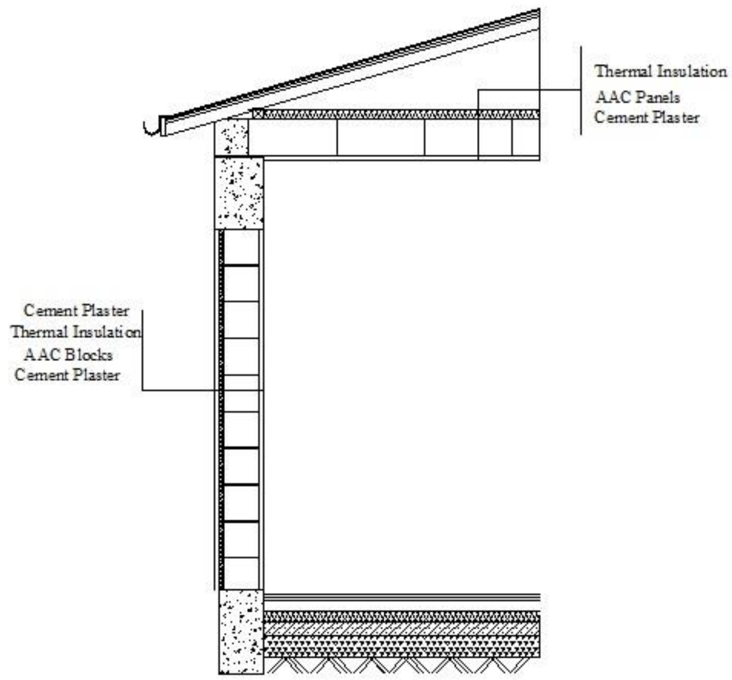


Figure 3.8 Building envelope details of Option B

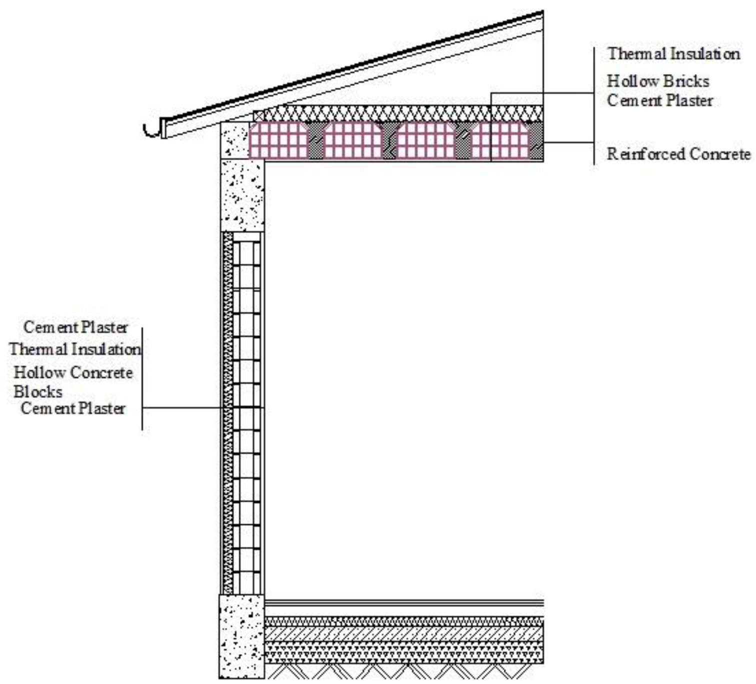


Figure 3.9 Building envelope details of Option C

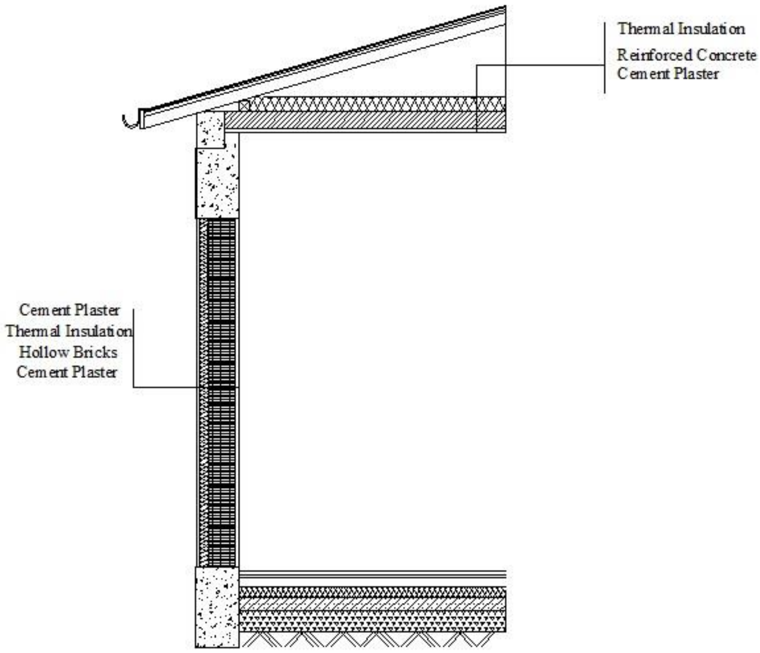


Figure 3.10 Building envelope details of Option D

Material volume or weight and in some cases the area is required for accurate calculations. Table 3.6 shows the Area and volume of different parts of the EACRE. In order to calculate materials' volume, occupied area by each material is multiplied by the thickness of the material. Tables 3.7-11 depict necessary data required as an input for cradle to gate impacts estimations.

Table 3.6 Data used to determine the software inputs

Area (m^2)	
Fully Enclosed	93.73
External Masonry Walls	61.75
Roof	130.6
Internal Roof Slab finish	82.45
Windows	7.5
External Doors	9.75
Internal finish of the building envelope	91.95
External finish of the building envelope	104.3
Volume (m^3)	
Columns	4.5
Beams	5.64

Table 3.7 eTool inputs for cradle to gate environmental impacts estimations-base case

Materials Input	Thickness (mm)	Material Quantity
Walls		
AAC Block	250	15.44 m^3
Portland Cement joints	250	228.5 Kg
Reinforced Concrete Column	300	5.4 m^3
Reinforced Concrete Beams	300	10.095 m^3
Windows	300	7.5 m^2
Doors	300	0.0945 m^3
Roof Slab		
Reinforced AAC Panel	250	23.43 m^3
Roof		
Timber Cover	25	3.265 m^3
Water Insulation	10	1.0306 m^3
Roof Covering (Onduline)	4	0.5224 m^3
Floor		
Blockage	150	14.06 m^3
Grobeton	100	9.373 m^3
Water Insulation	10	0.9373 m^3
Thermal Insulation (XPS)	20	1.8746 m^3
Levelling Concrete	50	4.6865 m^3
Internal Finish		
Wall- Cement Mortar	25	2.3 m^3
Wall- Plaster	-	91.95 m^2
Ceiling- Cement Mortar	25	1.9425 m^3
Ceiling- Plaster	-	77.7 m^2
Floor- Cement Mortar	20	1.554 m^3
Floor- Mosaic	20	1.554 m^3
External Finish		
Wall- Cement Mortar	25	2.6075 m^3
Wall- Plaster	-	104.3 m^2

Table 3.8 eTool inputs for cradle to gate environmental impacts estimations – Option A

Materials Input	Thickness (mm)	Material Quantity
Walls		
AAC Block	370	22.85 m^3
Portland Cement joints	370	338.18 Kg
Reinforced Concrete Column	300	5.4 m^3
Reinforced Concrete Beams	300	10.095 m^3
Windows	300	7.5 m^2
Doors	300	0.0945 m^3
Roof Slab		
Reinforced AAC Panel	610	57.1753 m^3
Roof		
Timber Cover	25	3.265 m^3
Water Insulation	10	1.0306 m^3
Roof Covering (Onduline)	4	0.5224 m^3
Floor		
Blockage	150	14.06 m^3
Grobeton	100	9.373 m^3
Water Insulation	10	0.9373 m^3
Thermal Insulation (XPS)	70	6.5611 m^3
Levelling Concrete	50	4.6865 m^3
Internal Finish		
Wall- Cement Mortar	25	2.3 m^3
Wall- Plaster	-	91.95 m^2
Ceiling- Cement Mortar	25	1.9425 m^3
Ceiling- Plaster	-	77.7 m^2
Floor- Cement Mortar	20	1.554 m^3
Floor- Mosaic	20	1.554 m^3
External Finish		
Wall- Cement Mortar	25	2.6075 m^3
Wall- Plaster	-	104.3 m^2

Table 3.9 eTool inputs for cradle to gate environmental impacts estimations – Option B

Materials Input	**Thickness (mm)**	**Material Quantity**
Walls		
AAC Block	250	15.44 m^3
Portland Cement joints	250	228.5 Kg
Thermal Insulation (XPS)	30	3.129 m^3
Reinforced Concrete Column	300	5.4 m^3
Reinforced Concrete Beams	300	10.095 m^3
Windows	300	7.5 m^2
Doors	300	0.0945 m^3
Roof Slab		
Reinforced AAC Panel	250	23.43 m^3
Thermal Insulation (XPS)	70	6.56 m^3
Roof		
Timber Cover	25	3.265 m^3
Water Insulation	10	1.0306 m^3
Roof Covering (Onduline)	4	0.5224 m^3
Floor		
Blockage	150	14.06 m^3
Grobeton	100	9.373 m^3
Water Insulation	10	0.9373 m^3
Thermal Insulation (XPS)	70	6.5611 m^3
Levelling Concrete	50	4.6865 m^3
Internal Finish		
Wall- Cement Mortar	25	2.3 m^3
Wall- Plaster	-	91.95 m^2
Ceiling- Cement Mortar	25	1.9425 m^3
Ceiling- Plaster	-	77.7 m^2
Floor- Cement Mortar	20	1.554 m^3
Floor- Mosaic	20	1.554 m^3
External Finish		
Wall- Cement Mortar	25	2.6075 m^3
Wall- Plaster	-	104.3 m^2

Table 3.10 eTool inputs for cradle to gate environmental impacts estimations-

Option C

Materials Input	Thickness (mm)	Material Quantity
Walls		
Hollow Bricks	190	10.232 m^3
Mortar Joints	190	1.501 m^3
Thermal Insulation (XPS)	60	6.258 m^3
Reinforced Concrete Column	300	5.4 m^3
Reinforced Concrete Beams	300	10.095 m^3
Windows	300	7.5 m^2
Doors	300	0.0945 m^3
Roof Slab		
Reinforced Concrete Slab	120	11.2476 m^3
Thermal Insulation (XPS)	110	10.3103 m^3
Roof		
Timber Cover	25	3.265 m^3
Water Insulation	10	1.0306 m^3
Roof Covering (Onduline)	4	0.5224 m^3
Floor		
Blockage	150	14.06 m^3
Grobeton	100	9.373 m^3
Water Insulation	10	0.9373 m^3
Thermal Insulation (XPS)	70	6.5611 m^3
Levelling Concrete	50	4.6865 m^3
Internal Finish		
Wall- Cement Mortar	25	2.3 m^3
Wall- Plaster	-	91.95 m^2
Ceiling- Cement Mortar	25	1.9425 m^3
Ceiling- Plaster	-	77.7 m^2
Floor- Cement Mortar	20	1.554 m^3
Floor- Mosaic	20	1.554 m^3
External Finish		
Wall- Cement Mortar	25	2.6075 m^3
Wall- Plaster	-	104.3 m^2

Table 3.11 eTool inputs for cradle to gate environmental impacts estimations-
Option D

Materials Input	Thickness (mm)	Material Quantity
Walls		
Hollow Concrete Block	190	10.98 m^3
Mortar Joints	190	0.75 m^3
Thermal Insulation (XPS)	60	6.258 m^3
Reinforced Concrete Column	300	5.4 m^3
Reinforced Concrete Beams	300	10.095 m^3
Windows	300	7.5 m^2
Doors	300	0.0945 m^3
Roof Slab		
Hollow bricks	250	18.76 m^3
Reinforced Concrete	250	2.344 m^3
Thermal Insulation (XPS)	110	10.3103 m^3
Roof		
Timber Cover	25	3.265 m^3
Water Insulation	10	1.0306 m^3
Roof Covering (Onduline)	4	0.5224 m^3
Floor		
Blockage	150	14.06 m^3
Grobeton	100	9.373 m^3
Water Insulation	10	0.9373 m^3
Thermal Insulation (XPS)	70	6.5611 m^3
Levelling Concrete	50	4.6865 m^3
Internal Finish		
Wall- Cement Mortar	25	2.3 m^3
Wall- Plaster	-	91.95 m^2
Ceiling- Cement Mortar	25	1.9425 m^3
Ceiling- Plaster	-	77.7 m^2
Floor- Cement Mortar	30	2.331 m^3
Floor- Mosaic	20	1.554 m^3
External Finish		
Wall- Cement Mortar	25	2.6075 m^3
Wall- Plaster	-	104.3 m^2

3.2.3 Transportation of material to construction site

eTool LCA, calculates environmental impacts of transportation stage by using transport method, transport distance and materials weight. Building materials need to get transported from the factories and other resources to the construction site. In order to estimate the proximate distances between factories and construction site, the location of the factories in Turkey are determined. The list of factories for each specific production is provided from the material's Industrial Association and the closest factory to the case study site is selected and is shown in Table 3.12. The distances between factories and construction site are determined by means of Google Map directions. Furthermore, distances between factories and case study building site is assumed to be the distances between city center of the factories and center of the Shamuratli village.

Table 3.12 eTool inputs for transport distances of case study materials

Material Type	City	Distance (Km)
AAC Blocks and Panels	Kirikkale	172
Hollow Bricks	Yozgat	51
Hollow Concrete Blocks	Kayseri	163
Concrete	Kirsehir	146
Steel Rebar	Sivas	200
Cement	Yozgat	51
Plaster	Ankara	242
Fine Joint Adhesive	Kirikkale	172
Thermal Insulation (XPS)	Mersin	446
Water Insulation	Gaziantep	518
Roof Covering	Sakarya	563

eTool LCA categorized methods of transportation in 6 main groups named as Light Commercial, Rigid Truck, Articulated Truck, Rail, Sea and Air. Since highways are the most common way to transport freights, and articulated trucks are used for large amounts of materials, light commercial and rigid trucks are used in this study. Additionally based on materials weight and volume one of these two methods are selected. In Tables 3.13-14 eTool LCA inputs and method of transport for each material is depicted.

Table 3.13 eTool LCA inputs to calculate environmental impacts of transportation stage for base case

Materials Input	**Transportation Type**	**Transport Distances (Km)**
Walls		
AAC Block	Rigid Truck	172
Concrete (Columns and Beams)	Rigid Truck	200
Steel Rebar (Columns and Beams)	Rigid Truck	200
Windows	Light Commercial	51
Doors	Light Commercial	51
Roof		
Reinforced AAC Panel	Rigid Truck	172
Water Insulation	Light Commercial	518
Roof Covering	Rigid Truck	563
Floor		
Blockage	-	-
Grobeton	Rigid Truck	146
Water Insulation	Light Commercial	518
Thermal Insulation (XPS)	Light Commercial	446
Levelling Concrete	Rigid Truck	146
Internal Finish		
Wall- Cement Mortar	Light Commercial	51
Wall- Plaster	Light Commercial	242
Ceiling- Cement Mortar	Light Commercial	51
Ceiling- Plaster	Light Commercial	242
Floor- Cement Mortar	Light Commercial	51
Floor- Mosaic	Light Commercial	51
External Finish		
Wall- Cement Mortar	Light Commercial	51
Wall- Plaster	Light Commercial	242

Table 3. 14 eTool LCA inputs to calculate environmental impacts of transportation stage for option A and B

Materials Input	Transportation Type	Transport Distances (Km)
Walls		
AAC Block	Rigid Truck	172
Thermal Insulation (XPS)	Light Commercial	446
Concrete (Columns and Beams)	Rigid Truck	200
Steel Rebar (Columns and Beams)	Rigid Truck	200
Windows	Light Commercial	51
Doors	Light Commercial	51
Roof		
Reinforced AAC Panel	Rigid Truck	172
Thermal Insulation (XPS)	Light Commercial	446
Water Insulation	Light Commercial	518
Roof Covering	Rigid Truck	563
Floor		
Blockage	**-**	-
Grobeton	Rigid Truck	146
Water Insulation	Light Commercial	518
Thermal Insulation (XPS)	Light Commercial	446
Levelling Concrete	Rigid Truck	146
Internal Finish		
Wall- Cement Mortar	Light Commercial	51
Wall- Plaster	Light Commercial	242
Ceiling- Cement Mortar	Light Commercial	51
Ceiling- Plaster	Light Commercial	242
Floor- Cement Mortar	Light Commercial	51
Floor- Mosaic	Light Commercial	51
External Finish		
Wall- Cement Mortar	Light Commercial	51
Wall- Plaster	Light Commercial	242

Table 3.15 eTool LCA inputs to calculate environmental impacts of transportation stage for option C

Materials Input	Transport Type	Transport Distances (Km)
Walls		
Hollow Concrete Block	Rigid Truck	163
Thermal Insulation (XPS)	Light Commercial	446
Windows	Light Commercial	51
Doors	Light Commercial	51
Concrete (Columns and Beams)	Rigid Truck	146
Steel Rebar (Columns and Beams)	Rigid Truck	200
Roof		
Hollow bricks	Rigid Truck	51
Concrete	Rigid Truck	146
Steel Rebar	Rigid Truck	200
Thermal Insulation (XPS)	Light Commercial	446
Water Insulation	Light Commercial	518
Roof Covering	Rigid Truck	563
Floor		
Blockage	-	-
Grobeton	Rigid Truck	146
Water Insulation	Light Commercial	518
Thermal Insulation (XPS)	Light Commercial	446
Levelling Concrete	Rigid Truck	146
Internal Finish		
Wall- Cement Mortar	Light Commercial	51
Wall- Plaster	Light Commercial	242
Ceiling- Cement Mortar	Light Commercial	51
Ceiling- Plaster	Light Commercial	242
Floor- Cement Mortar	Light Commercial	51
Floor- Mosaic	Light Commercial	51
External Finish		
Wall- Cement Mortar	Light Commercial	51
Wall- Plaster	Light Commercial	242

Table 3.16 eTool LCA inputs to calculate environmental impacts of transportation stage for Option D

Materials Input	Transport Type	Transport Distances (Km)
Walls		
Hollow Bricks	Rigid Truck	51
Thermal Insulation (XPS)	Light Commercial	446
Windows	Light Commercial	51
Doors	Light Commercial	51
Concrete (Columns and Beams)	Rigid Truck	146
Steel Rebar (Columns and Beams)	Rigid Truck	200
Roof		
Hollow Concrete Blocks	Rigid Truck	163
Concrete	Rigid Truck	146
Steel Rebar	Rigid Truck	200
Thermal Insulation (XPS)	Light Commercial	446
Water Insulation	Light Commercial	518
Roof Covering	Rigid Truck	563
Floor		
Blockage	-	-
Grobeton	Rigid Truck	146
Water Insulation	Light Commercial	518
Thermal Insulation (XPS)	Light Commercial	446
Levelling Concrete	Rigid Truck	146
Internal Finish		
Wall- Cement Mortar	Light Commercial	51
Wall- Plaster	Light Commercial	242
Ceiling- Cement Mortar	Light Commercial	51
Ceiling- Plaster	Light Commercial	242
Floor- Cement Mortar	Light Commercial	51
Floor- Mosaic	Light Commercial	51
External Finish		
Wall- Cement Mortar	Light Commercial	51
Wall- Plaster	Light Commercial	242

3.2.4 Recurring Stage

Recurring stage is related to maintenance and replacement of building materials; while the churn rate, which is the number of times the material is replaced during the building's life span is required for calculating environmental impacts of recurring stage (Haynes, 2010). eTool LCA also calculates amounts of environmental impacts of transportations related to recurring stage. In this study all materials' life spans are taken from eTool LCA software’s library section. In Table 3.15 building materials life time is depicted.

Table 3.17 Materials life span

Materials Input	**Life Span (Years)**
AAC	200
Hollow Concrete Blocks	200
Hollow Bricks	175
Concrete	200
General Timber	50
Blockage	150
Thermal Insulation (XPS)	75
Water Insulation	75
Mosaic	100
Cement Mortar	150
Plaster	50
Onduline	20

CHAPTER 4

RESULTS AND DISCUSSION

This chapter consists of two main sections. In the first section, data generated by eTool LCA are depicted in tabular form. The second section discusses and compares the environmental impacts of base case building compared with other four design options, which their details are provided in the previous chapter.

4.1 Results

The required information related to case study building and the simulation program is mentioned in materials section and the inputs of the LCA software are presented in the method section. This section is subdivided into four sections that are consisted of the outputs of the LCA software for four different design options which are referred to as follows:

- Base case: existing building (using AAC blocks for exterior walls and reinforced AAC panels for roof slab)
- Option A (AAC as main envelope material, without insulation, according to TS 825)
- Option B (AAC as main envelope material, with insulation according to TS 825)
- Option C (hollow bricks for exterior walls and a concrete slab roof with insulation according to TS 825)
- Option D (hollow concrete blocks for exterior walls and slab of concrete beams and hollow in-filling brick blocks for roof slab with insulation according to TS 825).

In each subsection total estimations are presented in six forms considering six different indicators such as global-warming-potential, fossil fuels consumption, fresh water consumption, acidification, and ozone layer depletion. Afterwards, breakdowns of impacts by building envelope components are depicted regarding the environmental impact indicators in tabular forms. In this study cradle to gate, transportation to site and maintenance phases are considered to evaluate the environmental impacts of the defined building envelopes. Therefore amounts of environmental impacts are shown in materials production, transport and recurring stages separately. Materials production stage is consisted of primary resources extraction, transportation of primary resources, and materials manufacture, transport stage is consisted of materials transport to distributer and materials transport to building site and at the end recurring stage is referred to materials maintenance. According to eTool LCA calculation the design life for case study building is 85 years while the maximum durability is 150 years. However, the buildings' design life is mentioned as expected life span.

4.1.1 Base Case Building

As mentioned in previous chapter, in this study EARCE with its original building envelope materials is selected as the base case building. The environmental impacts related to six environmental indicators such as global-warming-potential, fossil fuels, fresh water consumption, acidification and ozone layer depletion of the single dwelling are calculated and are depicted in Table 4.1. These amounts include the recurring estimations over a life span of 85 years for the base case building.

eTool LCA displays amounts of environmental impacts related to the building envelope components for various design options separately. In Table 4.2 a breakdown of the total environmental impacts estimations by building envelope components of the base case are presented. Furthermore, eTool LCA depicts the amounts of environmental impacts referred to building life cycle stages. In this study, evaluations are done in manufacturing stage as well as transportation of products to the site. Also recurring stage values are calculated for each environmental impact. In Table 4.3 estimations of environmental impacts of base case building according to life cycle stages are shown.

Table 4.1 Summary of environmental impacts for Base case

Environmental Impacts	**Estimation per Dwelling**
Global-Warming-Potential	77,242 ($KgCO_2e$)
Fossil Fuels Consumption	1,117,726 (MJ)
Fresh Water Consumption	519 (kL)
Ozone Layer Depletion	2,410 ($mg\ CFC_{11}e$)
Acidification	8,300 ($Kg\ SO_2e$)

Table 4.2 Breakdown of environmental impacts by building envelope components for Base case

Environmental Impacts	**Roof**	**Walls**
GWP ($KgCO_2e$)	24,883	15,899
Fossil Fuels Consumption (MJ)	463,228	185,908
Fresh Water Consumption (kL)	37	92
Ozone Layer Depletion ($mg\ CFC_{11}e$)	60	145
Acidification ($Kg\ SO_2e$)	4,334	165

Table 4.3 Summary of environmental impacts by life cycle stages for Base case

Environmental Impacts	**Materials Production**	**Transport**	**Recurring**
GWP ($KgCO_2e$)	47,850	9,437	19,955
Fossil Fuels Consumption (MJ)	580,463	144,492	392,771
Fresh Water Consumption (kL)	504	1	14
Ozone Layer Depletion($mg\ CFC_{11}e$)	2,326	2	82
Acidification ($Kg\ SO_2e$)	188	55	8,057

4.1.2 Option A

In order to satisfy thermal insulation requirements according to TS 825 regulations, the other building envelope configuration is done by using thermal insulation materials in building envelope except the external walls. Therefore the external walls optimized by increasing the thickness of AAC materials. In Table 4.4 the evaluation of total environmental impacts of option A is shown. Also, in Tables 4.5 and 4.6 the summary of these evaluations are presented by construction areas and life cycle stages respectively.

Table 4.4 Summary of environmental impacts for Option A

Environmental Impacts	Estimation per Dwelling
Global-Warming-Potential	81,449 ($KgCO_2e$)
Fossil Fuels Consumption	1,195,445 (MJ)
Fresh Water Consumption	533 (kL)
Ozone Layer Depletion	2,466 ($mg\ CFC_{11}e$)
Acidification	8,406 ($Kg\ SO_2e$)

Table 4.5 Breakdown of environmental impacts by building envelope component for Option A

Environmental Impacts	Roof	Walls
GWP ($KgCO_2e$)	26,089	18,038
Fossil Fuels Consumption (MJ)	493,444	211,827
Fresh Water Consumption (kL)	38	103
Ozone Layer Depletion ($mg\ CFC_{11}e$)	82	164
Acidification ($Kg\ SO_2e$)	4,391	174

Table 4.6 Summary of environmental impacts by life cycle stages for Option A

Environmental Impacts	Materials Production	Transport	Recurring
GWP ($KgCO_2e$)	49,968	10,489	20,992
Fossil Fuels Consumption (MJ)	616,179	160,594	418,672
Fresh Water Consumption (kL)	517	1	15
Ozone Layer Depletion($mg\ CFC_{11}e$)	2,364	2	100
Acidification ($Kg\ SO_2e$)	194	61	8,151

4.1.3 Option B

As stated in previous chapter, the EARCE building as a base case does not satisfy thermal insulation requirements according to TS 825 regulations. Therefore, the building envelope is optimized for compliance. In Table 4.7 the evaluation of total environmental impacts such as global-warming-potential, fossil fuels, fresh water consumption, acidification, and ozone layer depletion of option B is shown. Furthermore, in Tables 4.8 and 4.9 the summary of these evaluations are presented by construction areas and life cycle stages respectively. These calculations include the recurring estimations over a life span of 85 years for the optimized case building.

Table 4.7 Summary of environmental impacts for Option B

Environmental Impacts	Estimation per Dwelling
Global-Warming-Potential	79,885 ($KgCO_2e$)
Fossil Fuels Consumption	1,183,939 (MJ)
Fresh Water Consumption	521 (kL)
Ozone Layer Depletion	2,458 ($mg\ CFC_{11}e$)
Acidification	8,424 ($Kg\ SO_2e$)

Table 4.8 Breakdown of environmental impacts by building envelope component for Option B

Environmental Impacts	Roof	Walls
GWP ($KgCO_2e$)	26,089	16,474
Fossil Fuels Consumption (MJ)	493,444	200,321
Fresh Water Consumption (kL)	38	93
Ozone Layer Depletion ($mg\ CFC_{11}e$)	82	155
Acidification ($Kg\ SO_2e$)	4391	192

Table 4.9 Summary of environmental impacts by life cycle stages for Option B

Environmental Impacts	Materials Production	Transport	Recurring
GWP ($KgCO_2e$)	49,092	9,513	21,280
Fossil Fuels Consumption (MJ)	612,408	145,653	425,878
Fresh Water Consumption (kL)	505	1	15
Ozone Layer Depletion ($mg\ CFC_{11}e$)	2,350	2	106
Acidification ($Kg\ SO_2e$)	192	56	8,176

4.1.4 Option C

This design option is the same as the base case building but with different exterior walls and roof slab materials. Hollow brick blocks are used instead of AAC blocks in exterior walls and the AAC panels are replaced with concrete slab for roof slab construction. In Tables 4.10-4.12 the summary of environmental impacts in the six above mentioned indicators are depicted. It should be noted that these amounts include the recurring estimations over a life span of 85 years for the option C.

Table 4.10 Summary of environmental impacts details for option C

Environmental Impacts	Estimation per Dwelling
Global-Warming-Potential	85,466 ($KgCO_2e$)
Fossil Fuels Consumption	1,263,428 (MJ)
Fresh Water Consumption	878 (kL)
Ozone Layer Depletion	2,535 ($mg\ CFC_{11}e$)
Acidification	8,493 ($Kg\ SO_2e$)

Table 4.11 Breakdown of environmental impacts by building envelope components for option C

Environmental Impacts	Roof	Walls
GWP ($KgCO_2e$)	29,071	19,073
Fossil Fuels Consumption (MJ)	551,892	221,361
Fresh Water Consumption (kL)	83	404
Ozone Layer Depletion ($mg\ CFC_{11}e$)	161	154
Acidification ($Kg\ SO_2e$)	4,435	217

Table 4.12 Summary of environmental impacts by life cycle stages for option C

Environmental Impacts	Materials Production	Transport	Recurring
GWP ($KgCO_2e$)	53,817	9,734	21,915
Fossil Fuels Consumption (MJ)	672,656	149,039	441,733
Fresh Water Consumption (kL)	862	1	15
Ozone Layer Depletion ($mg\ CFC_{11}e$)	2,416	2	117
Acidification ($Kg\ SO_2e$)	203	57	8,233

4.1.5 Option D

The second design option is also same as base case, but in this case hollow concrete blocks are used for exterior walls and slab of concrete beams and hollow in-filling brick blocks is used for roof slab construction. In Tables 4.13-4.15 the summary of environmental impacts in the same six indicators such as global-warming-potential, fossil fuels, fresh water consumption, acidification, and ozone layer depletion are depicted. These amounts include the recurring estimations over a life span of 85 years for option D.

Table 4.13 Summary of environmental impacts details for option D

Environmental Impacts	Estimation per Dwelling
Global-Warming-Potential	80,780 ($KgCO_2e$)
Fossil Fuels Consumption	1,198,338 (MJ)
Fresh Water Consumption	1,084 (kL)
Ozone Layer Depletion	2,467 ($mg\ CFC_{11}e$)
Acidification	8,475 ($Kg\ SO_2e$)

Table 4.14 Breakdown of environmental impacts by building envelope components for option D

Environmental Impacts	Roof	Walls
GWP ($KgCO_2e$)	30,434	18,959
Fossil Fuels Consumption (MJ)	543,731	226,370
Fresh Water Consumption (kL)	620	124
Ozone Layer Depletion ($mg\ CFC_{11}e$)	118	191
Acidification ($Kg\ SO_2e$)	4,434	219

Table 4.15 Summary of environmental impacts by life cycle stages for design D

Environmental Impacts	Materials Production	Transport	Recurring
GWP ($KgCO_2e$)	51,116	7,749	21,915
Fossil Fuels Consumption (MJ)	637,959	118,646	441,733
Fresh Water Consumption (kL)	1,068	1	15
Ozone Layer Depletion ($mg\ CFC_{11}e$)	2,348	2	117
Acidification ($Kg\ SO_2e$)	197	45	8,233

4.2 Discussion

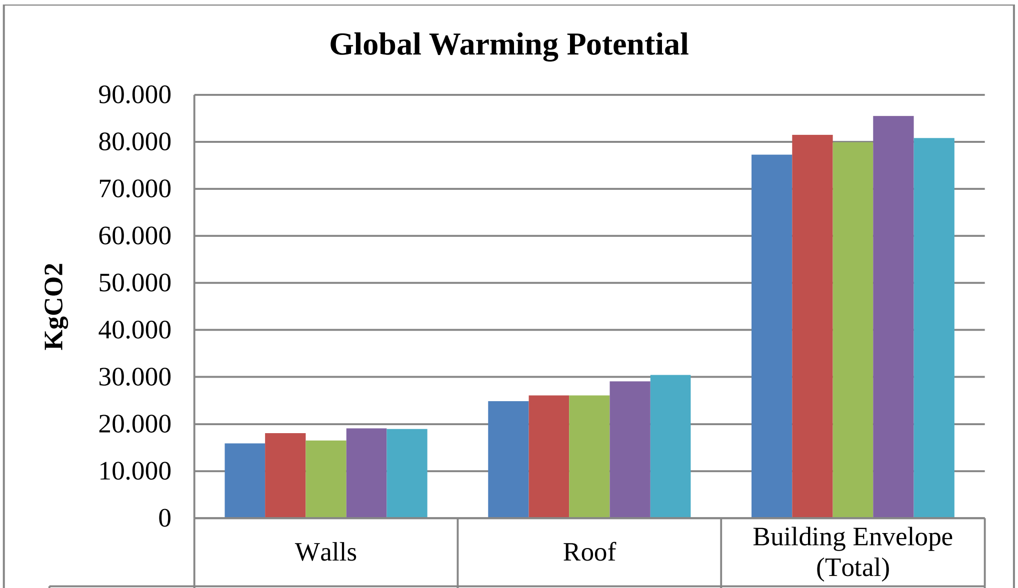
The environmental impacts of five building envelope design options are mentioned in previous section. The comparisons of these impacts are discussed and presented in two subsections. At first the comparisons are done according to total amount of environmental impacts (global-warming-potential, fossil fuels, fresh water consumption, acidification, and ozone layer depletion) for each building envelope configuration which is consisted of floor, exterior walls and roof and also in terms of construction area related to each option are presented and then the comparisons in terms of options' life cycle stages are stated.

4.2.1 Comparisons of Case Studies According to Environmental Impacts

In chapter 3 the case study building as a base case, the option A according to thermal insulation requirements and without insulation in exterior walls and two alternative building envelope configurations were described. Also in the result section the measurements of environmental impacts were presented. In this section comparison of case studies are shown in the form of charts in order to compare two alternative design options with optimized options. Since the alternative design options are also designed according to TS 825 regulation, these two options are compared with optimized cases with respect to the impacts due the different materials.

As depicted in Figure 4.1 from the point of view of global-warming-potential, option C has the maximum impact compared with other options. In other words, option A, C and D have 2%, 7% and 1.1% more global-warming-potential impact than option B respectively. Therefore, option B is the most energy efficient in terms of global-warming-potential impacts.

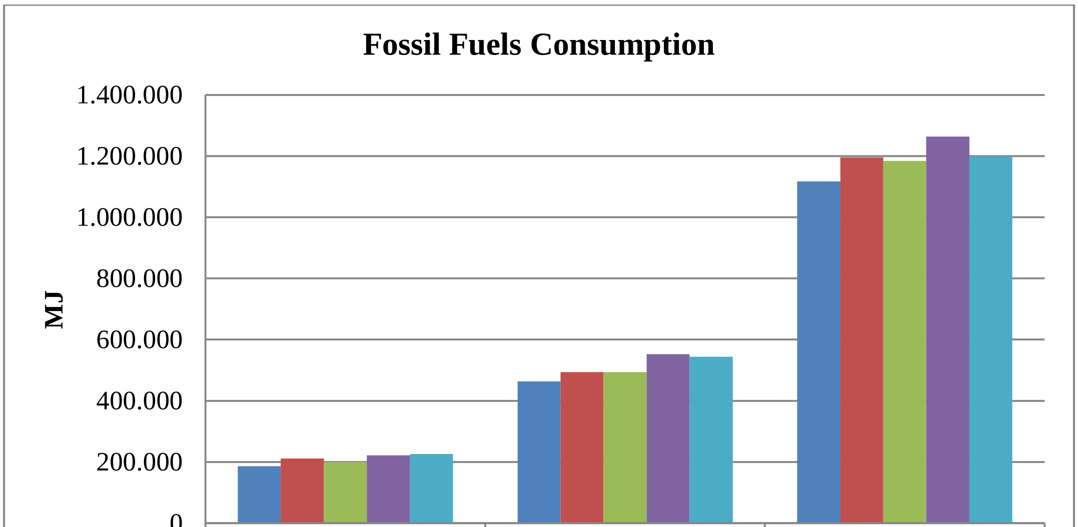
One of the objectives of this research is to compare building envelopes with various design options using different materials to one with AAC as the main building material. The base case is composed of AAC blocks in exterior walls and AAC panels in the roof slab. Therefore, main comparison is done among roof slabs and exterior walls of case studies. According to Figure 4.1, among the exterior walls options, option C has the maximum global-warming-potential impact and among the roof slab options, option D has the maximum global-warming-potential impact. To be precise, the concrete slab roof has less global-warming-potential impact than slab of concrete beams and hollow in-filling brick blocks. Also, AAC block walls with insulation have the minimum impact and walls with hollow brick blocks have the maximum impact. Consequently, concrete slab roof has 11.4% more global-warming-potential impact than roof with AAC panels and slab of concrete beams and hollow in-filling brick blocks has 16.6% more global-warming-potential impact than AAC panels. Also hollow brick block walls have 5.7% more global-warming-potential impact than AAC block walls without insulation and 15.8% more global warming potential impact that AAC block walls with insulation and hollow concrete block walls have 5.1% more global-warming-potential impact than AAC block walls in option A and 15.1% more global-warming-potential impact than AAC block walls in option B.



	Walls	Roof	Building Envelope (Total)
Base Case	15.899	24.883	77.242
Option A	18.038	26.089	81.449
Option B	16.474	26.089	79.885
Option C	19.073	29.071	85.466
Option D	18.959	30.434	80.780

Figure 4.1 Comparison of 4 case study design options according to global-warming-potential

Figure 4.2 shows the amount of fossil fuels consumption for building envelope configurations. According to this chart option C has the maximum impact compared with other options. Furthermore, options C and D have 6.7% and 1.2% more fossil fuels consumption than option B respectively and 5.7% and 0.2% more fossil fuels consumption than option A. According to Figure 4.2, among the exterior walls configurations, option D has the maximum fossil fuels consumption. Also, the roofs with AAC panels have the minimum fossil fuels consumption and the roof with slab of concrete beams and hollow in-filling brick blocks has the maximum impact. Also, AAC block walls with insulation have the minimum impact and hollow concrete block walls have the maximum impact. In other words, AAC block walls with insulation have 5.4%, 9.5% and 11.8% less fossil fuel consumption than AAC block walls without insulation, hollow brick block and hollow concrete block walls respectively. Also the roof with AAC panels has 10.6%, 10.69.1% less fossil fuel consumption than concrete slab roof and slab of concrete beams and hollow in-filling brick blocks one respectively.

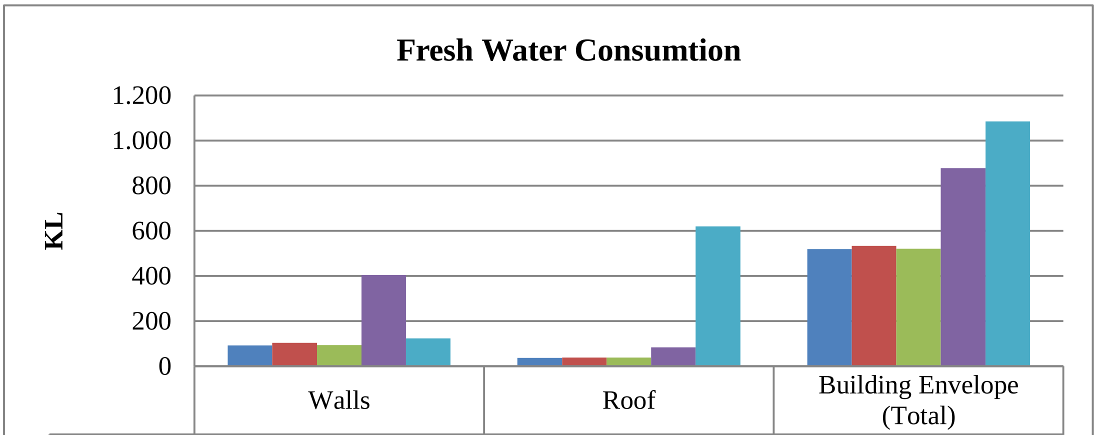


	Walls	Roof	Building Envelope (Total)
Base Case	185.908	463.228	1.117.726
Option A	211.827	493.444	1.195.445
Option B	200.321	493.444	1.183.939
Option C	221.361	551.892	1.263.428
Option D	226.370	543.731	1.198.338

Figure 4.2 Comparison of 4 case study design options according to fossil fuels consumption

In Figure 4.3 the comparison of case studies in terms of fresh water consumption is presented. According to the chart the option D has the maximum impact compared with other options. Therefore, using AAC products in walls and roof construction decrease amount of fresh water consumption significantly.

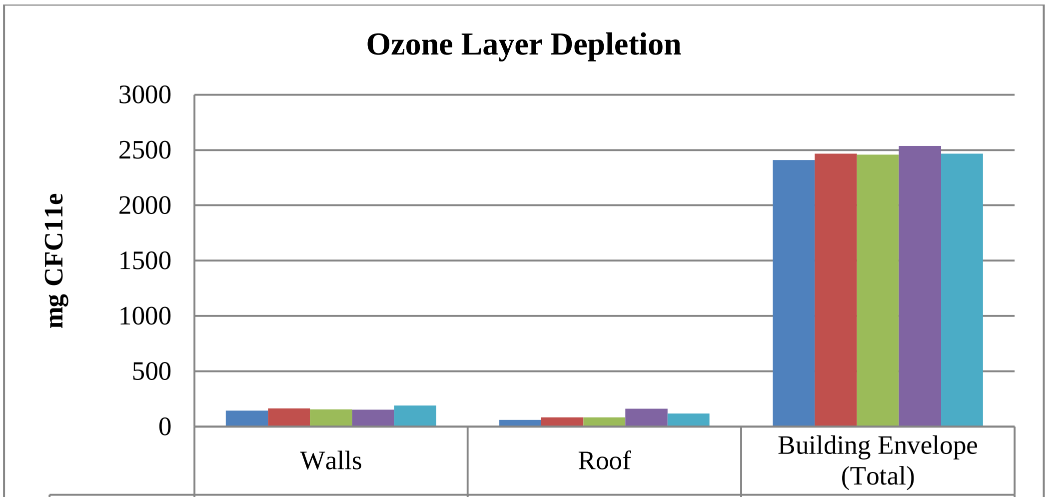
As depicted in Figure 4.3 fresh water consumption in exterior walls of option C is significantly more than other options and also fresh water consumption in roof of option D is more than the others. In other words, AAC Panel roof has the minimum amount of fresh water consumption and slab of concrete beams and hollow in-filling brick blocks for roof has the maximum impact. In other words, AAC block walls with insulation have 77% and 25% less fresh water consumption than hollow brick block and hollow concrete block walls respectively and AAC block walls without insulation have 74.5% and 16.9% less fresh water consumption than hollow brick block and hollow concrete block walls respectively. Also, AAC panel roof has 54.2% and 93.9% less fresh water consumption than concrete slab and slab of concrete beams and hollow in-filling brick blocks respectively.



	Walls	Roof	Building Envelope (Total)
Base Case	92	37	519
Option A	103	38	533
Option B	93	38	521
Option C	404	83	878
Option D	124	620	1084

Figure 4.3 Comparison of 4 case study design options according to fresh water consumption

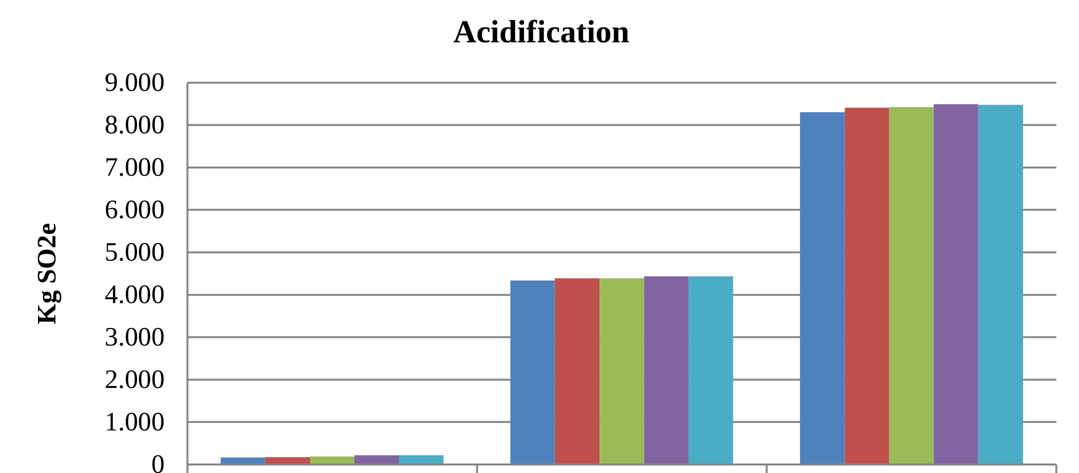
In the comparison of case studies in terms of ozone layer depletion impact, as shown in Figure 4.4 the option C has the maximum impact compared with other options. As depicted in Figure 4.4 hollow concrete block walls and the concrete slab roof have the maximum impact and brick walls and AAC roof have the minimum impacts. In other words, brick walls in option C have 6.1% and 0.65% and 19.4% less ozone layer depletion impact than AAC blocks without insulation, AAC blocks with insulation and hollow concrete block walls respectively. Also, AAC panel roof has 49.1% and 30.5% less ozone layer depletion than concrete slab and slab of concrete beams and hollow in-filling brick blocks respectively.



	Walls	Roof	Building Envelope (Total)
Base Case	145	60	2.410
Option A	164	82	2.466
Option B	155	82	2.458
Option C	154	161	2.535
Option D	191	118	2.467

Figure 4.4 Comparison of 4 case study design options according to ozone layer depletion

Figure 4.5 refers to acidification impact, and as presented the amounts for building envelope configurations are pretty close to each other and option C has the maximum impact compared with other options. Also as depicted in Figure 4.5, concrete block walls have the most amount of acidification impact and roof with AAC walls and roof are the most environmentally friendly option in terms of acidification impact compared with other options.



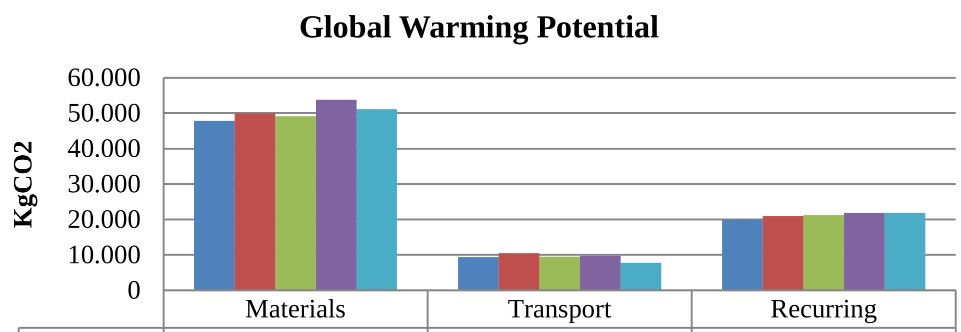
	Walls	Roof	Building Envelope (Total)
Base Case	165	4334	8300
Option A	174	4391	8406
Option B	192	4391	8424
Option C	217	4435	8493
Option D	219	4434	8475

Figure 4.5 Comparison of 4 case study design options according to acidification

4.2.2 Comparisons of Life Cycle Stages According to Environmental Impacts

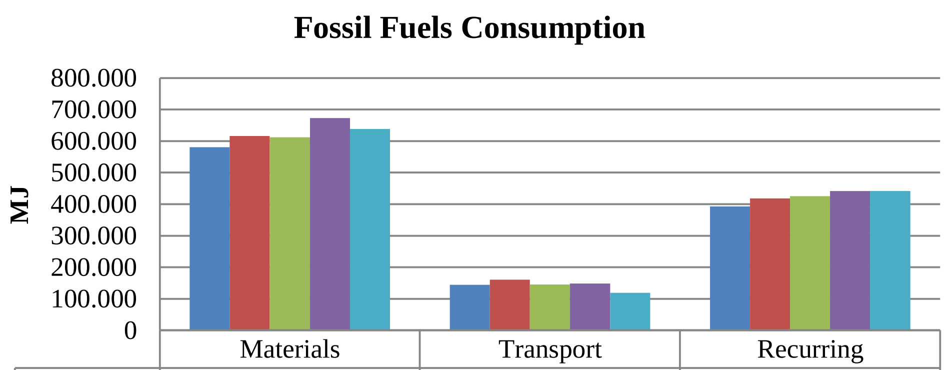
According to charts depicted in this section it is obvious that the raw materials extraction and productions' manufacturing stage plays the dominant role among life cycle stages considered in this study in terms of all environmental impacts.

As shown in Figures 4.6 and 4.7, the option C produces the maximum amounts of global-warming-potential, fossil fuels in materials production stage. In other words, the option B has 1.7%, 8.8% and 4% less global-warming-potential impact than options A, C and D in materials production stage respectively. In transport stage, the option D has the minimum amounts of global-warming-potential and fossil fuels compared with other alternatives. Also, the option B has 0.6%, 9% and 4% less fossil fuels consumption than options A, C and D in materials production stage respectively. In transportation stage the option D and in recurring stage the option A have the minimum environmental impacts in terms of global warming potential and fossil fuels.



	Materials	Transport	Recurring
Base Case	47.850	9.437	19.955
Option A	49.968	10.489	20.992
Option B	49.092	9.513	21.280
Option C	53.817	9.734	21.915
Option D	51.116	7749	21915

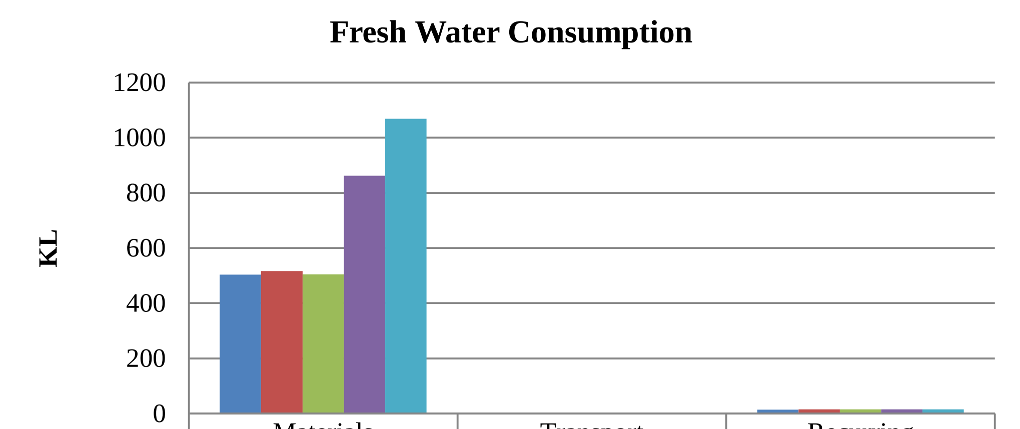
Figure 4.6 Comparisons of life cycle stages according to global-warming-potential



	Materials	Transport	Recurring
Base Case	580.463	144.492	392.771
Option A	616.179	160.594	418.672
Option B	612.408	145.653	425.878
Option C	672.656	149.039	441.733
Option D	637.959	118.646	441.733

Figure 4.7 Comparisons of life cycle stages according to fossil fuels consumption

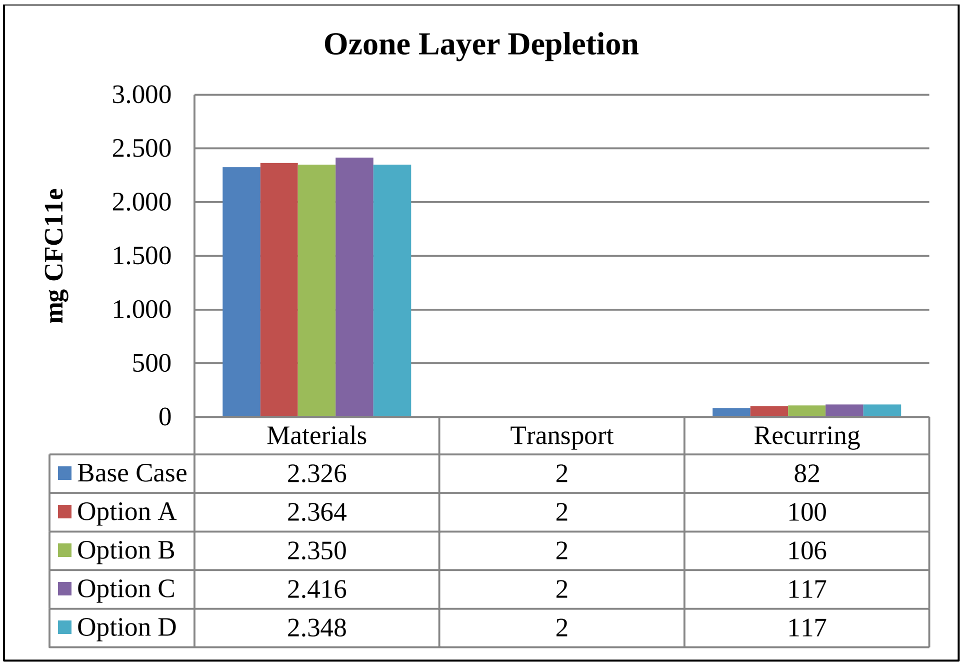
In Figures 4.8-4.10 the comparisons of life cycle stages according to fresh water consumption, ozone layer depletion and acidification are presented. According to the charts it is clear that the amounts of these impacts are quite close to each other in transport and recurring stages, and even in some cases the amounts of the impacts are the same. However, in materials stage as shown in Figure 4.8, in terms of fresh water consumption, option D is the most water consumer and option B is the most environmentally friendly one and the amount of fresh water consumed during transport and recurring stages are negligible and are the same for all configurations.



	Materials	Transport	Recurring
Base Case	504	1	14
Option A	517	1	15
Option B	505	1	15
Option C	862	1	15
Option D	1.068	1	15

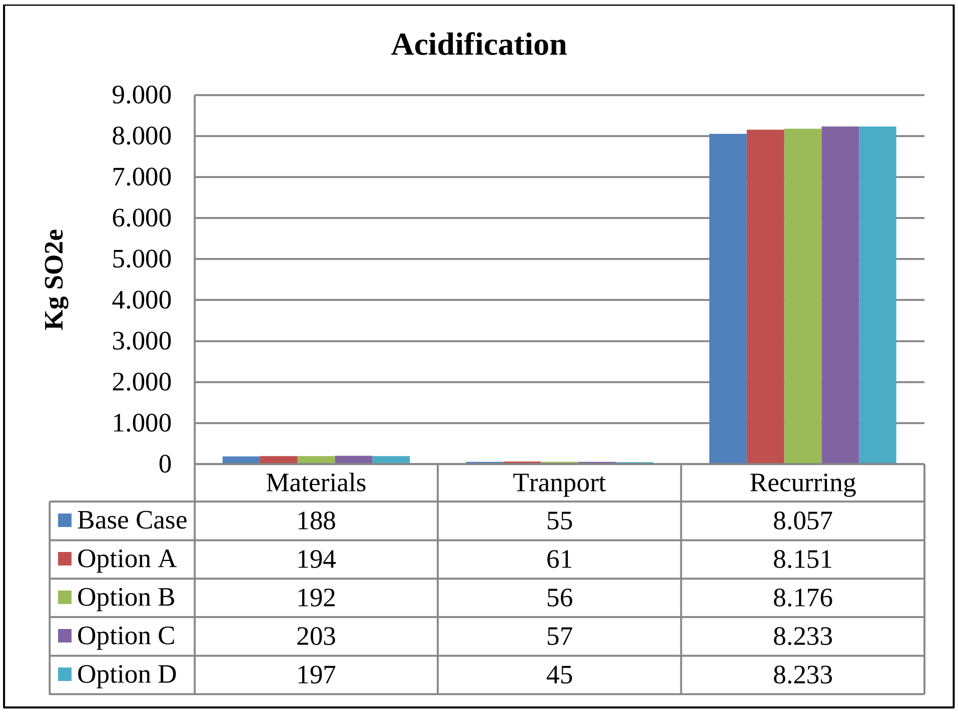
Figure 4.8 Comparisons of life cycle stages according to fresh water consumption

In Figures 4.9 and 4.10, in material stage the option C has the most amounts of impacts and option B has the least amount of impacts in terms of ozone layer depletion and acidification. Also, in recurring stage, option C and D have the maximum environmental impacts and option A has the minimum amount in both ozone layer depletion and acidification impacts. According to all charts in this section option D has the minimum and option A has the maximum environmental impacts in transport stage in comparison to other configurations in terms of all mentioned impacts.



	Materials	Transport	Recurring
Base Case	2.326	2	82
Option A	2.364	2	100
Option B	2.350	2	106
Option C	2.416	2	117
Option D	2.348	2	117

Figure 4.9 Comparisons of life cycle stages according to ozone layer depletion



	Materials	Tranport	Recurring
Base Case	188	55	8.057
Option A	194	61	8.151
Option B	192	56	8.176
Option C	203	57	8.233
Option D	197	45	8.233

Figure 4.10 Comparisons of life cycle stages according to acidification

CHAPTER 5

CONCLUSION

In this thesis, environmental impacts of four different building envelope types that are common in Turkey was analyzed, considering cradle to site boundary and maintenance stage. At first, required data as software inputs was generated and numerical amounts of various environmental impacts of each building envelope type were presented and finally these impacts were compared and discussed in order to recognize the more and less environmentally friendly building envelope types according to six environmental impacts indicators.

Nowadays, because of natural resources depletion and greenhouse gases emissions effects, selection of material alternatives with less environmental impacts has become significantly obvious. According to this thesis it can be concluded that, since contribution of building envelope is significant, it has an important role in reducing amounts of energy and other environmental impacts of buildings. Hence, choosing building envelope materials wisely can mitigate environmental degradations.

According to this study, by evaluating the building envelope configurations which are designed in order to satisfy TS825 requirements, it can be concluded that the building envelope configurations with AAC walls and roof slab are the most environmentally friendly types and it is recognized that using thermal insulation material in AAC construction made the building envelope more energy efficient compared to the one without insulation. On the other hand the configuration with brick walls and concrete slab roof is the most harmful type in terms of environmental impacts except fresh water consumption.

To be precise, the best performing wall system in terms of environmental impacts is the AAC wall and the next one could be the concrete wall system and among the roof systems the AAC roof slab has the best performance and the concrete slab roof is the second environmentally friendly roof system.

Considering six environmental impacts indicators in this thesis, reducing amounts of these impacts could be occur by various solutions. For instance, renewable resources like solar and wind energies can be used instead of fossil fuels and nonrenewable ones during material production process in order to reduce emissions of greenhouse gases which are responsible for global warming. Also reducing acidification potential by decreasing fossil fuel equivalents combustion and reducing fresh water consumption in materials production can assist to have environmentally friendly and sustainable buildings.

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APPENDIX A

eTool LCA INTERFACES

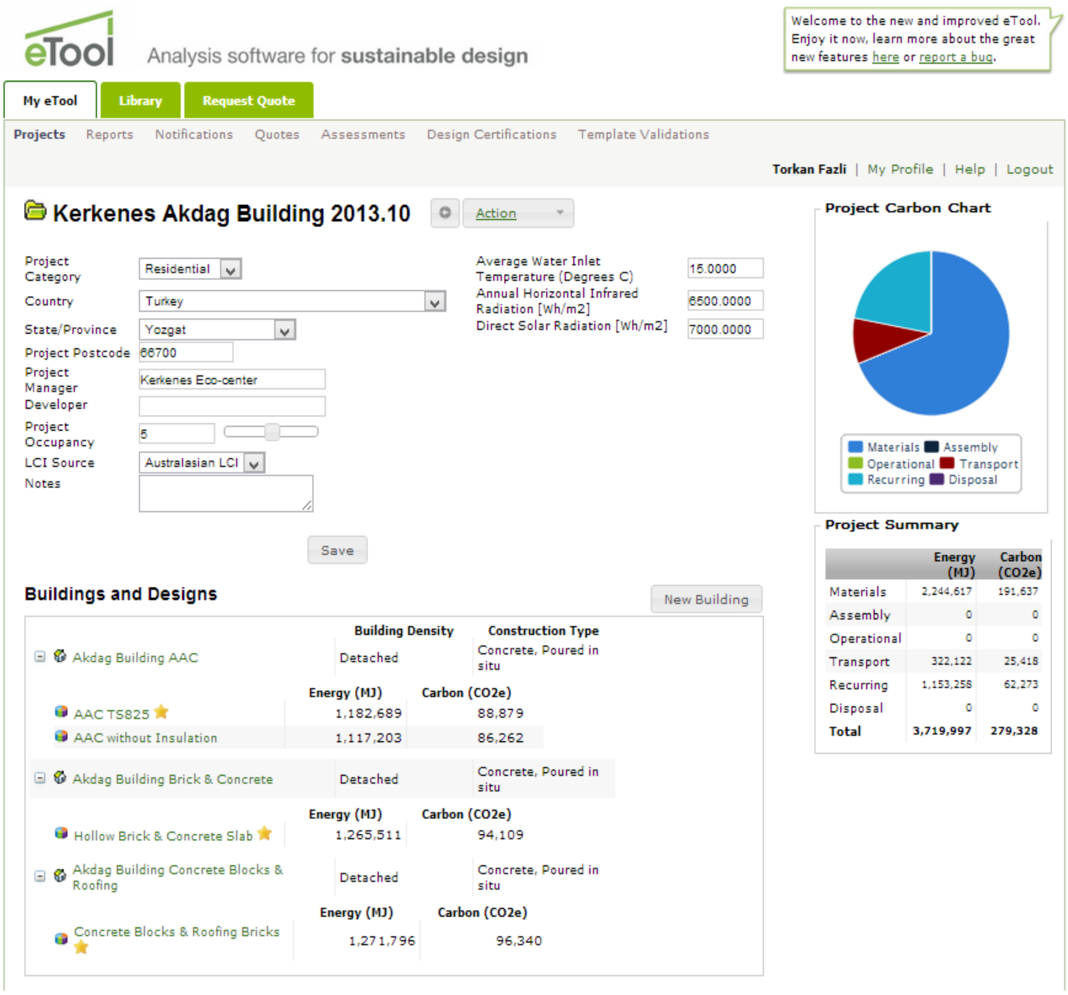

Figure A.1 eTool LCA interface of case study building and four designs

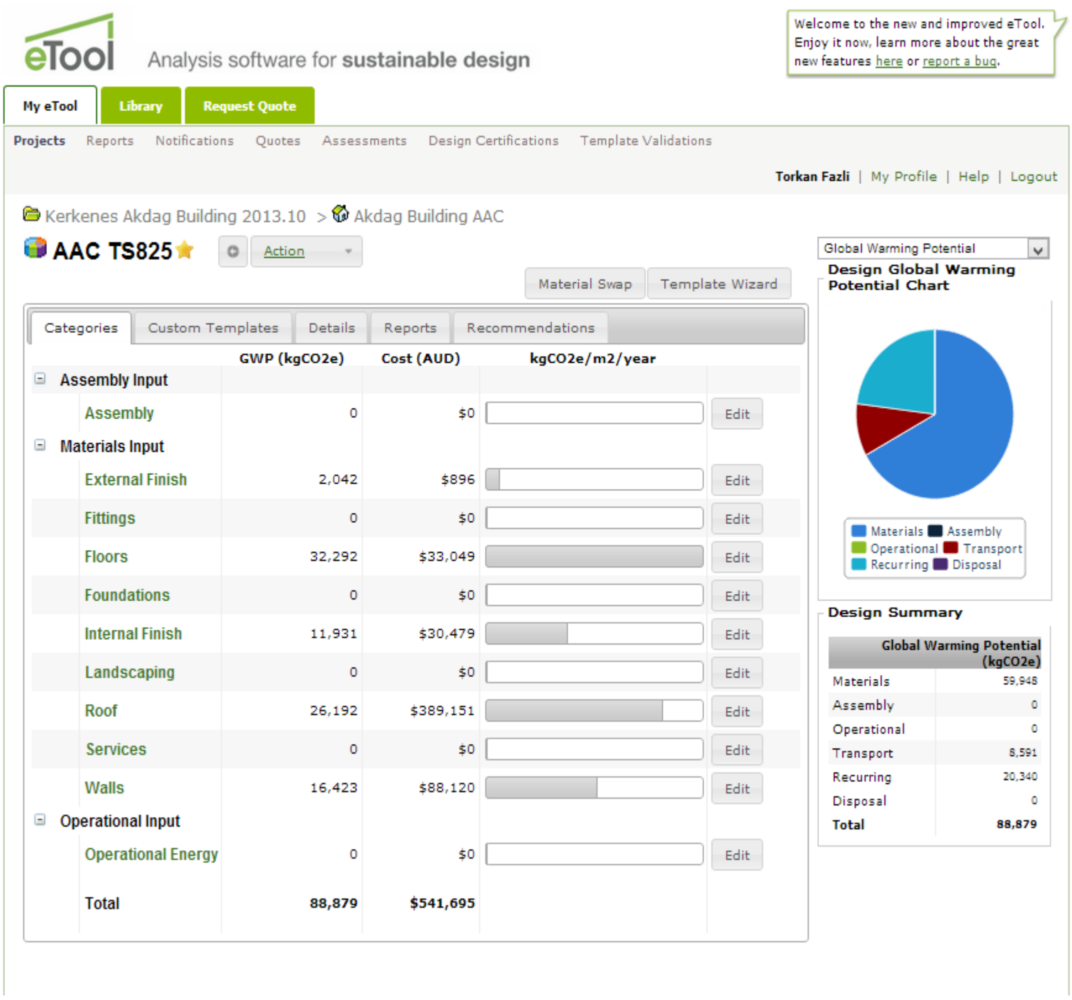

Figure A.2 eTool LCA interface for input categories

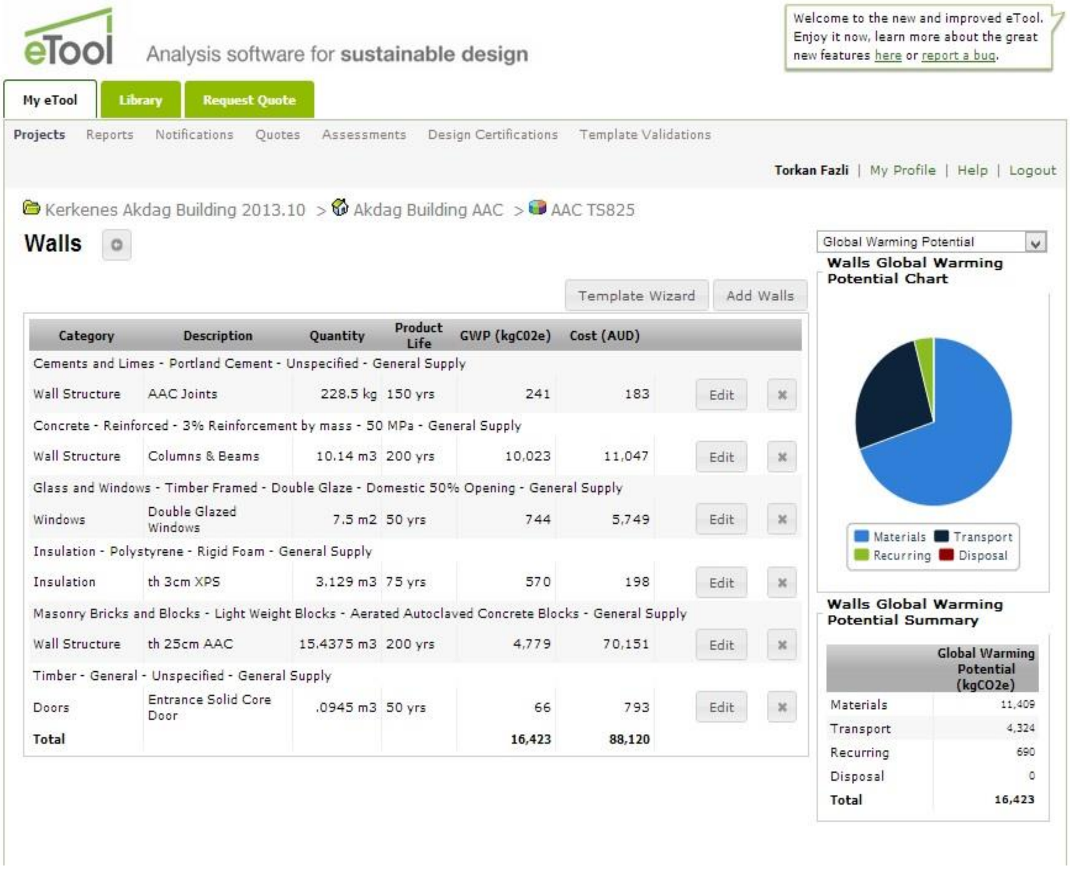

Figure A.3 eTool LCA interfac for building evelope components input

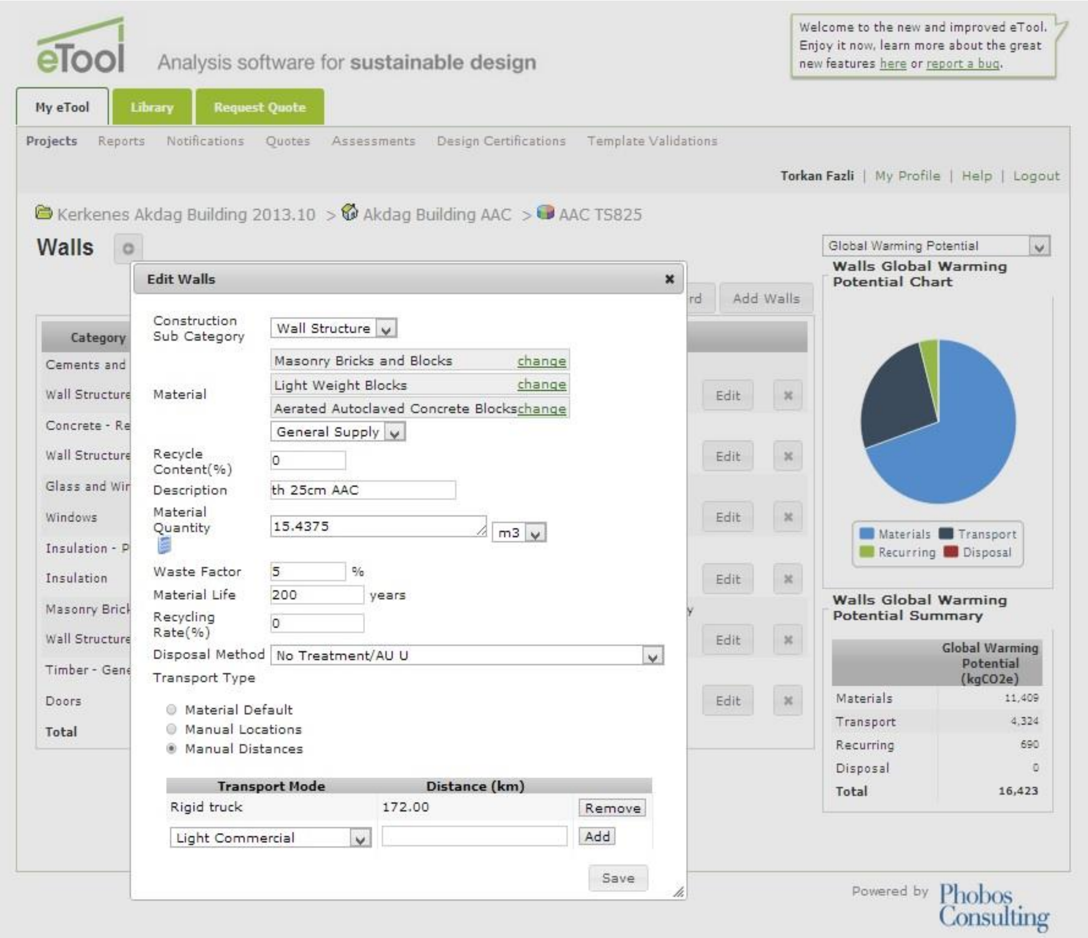

Figure A.4 eTool LCA interface for material detail

APPENDIX B

DISTANCES BETWEEN FACTORIES AND SHAHMURATLI VILLAGE

Table B.1 Distances between AAC factories and Shahmuratli village

AAC Factories In Turkey	Cities	Distances From Sahmuratli Village (Km)
AKG Gazbeton	İzmir	845
AKG Gazbeton	Kirkkale	172
AKG Gazbeton	Çorlu	913
YTONG	Gaziantep	518
YTONG	Pendik	664
YTONG	Bilecik	569
YTONG	Tekirdağ	840
YTONG	Antalya	704
NUH Yapi	Kocaeli	592
Nearest Factories' Distances		**172**

Table B.2 Distances between brick factories and Shahmuratli village

Brick Factories In Yozgat Province, Turkey	Distances From Sahmuratli Village (Km)
Coşkun Toprak	**51**
Yozgat Tuğla	51

Table B.3 Distances between concrete factories and Shahmuratli village

Concrete Factories In Central Anatolia, Turkey	Cities	Distances From Sahmuratli Village (Km)
Votorantim	Kirkkale	172
Votorantim	Kırşehir	146
Votorantim	Nevşehir	193
Çimsa Çimento	Nevşehir	193
Votorantim	Kayseri	163
Çimsa Çimento	Kayseri	163
Nearest Factories' Distances		**146**

Table B.4 Distances between plaster factories and Shahmuratli village

Plaster Factories In Turkey	**Cities**	**Distances From Sahmuratli Village (Km)**
Atışkan	Eskişehir	491
Doğanar	Ankara	242
LaFarge Dalsan	Ankara	242
ABS Alçı ve Blok	Ankara	242
Knauf	Ankara	242
Rigips Türkiye	Ankara	242
AllAlçı Türkiye	Anakra	242
AllAlçı Türkiye	Batman	767
Nearest Factories' Distances		**242**

Table B.5 Distance between concrete block production factories and Shahmuratli village

Concrete Blocks Factories In Turkey	**Cities**	**Distances From Sahmuratli Village (Km)**
Acerler Bims	Nevşehir	193
AGTBims	Nevşehir	193
Bintas	Kayseri	163
EuroBims	Kayseri	163
Yalapbims	Nevşehir	193
Probims	Nevşehir	193
Nearest Factories' Distances		**163**

Table B.6 Distances between XPS factories and Shahmuratli village

XPS Factories In Turkey	**Cities**	**Distances From Sahmuratli Village (Km)**
Megaboard	Elazığ	538
Ecofoam	Bursa	713
Btm	Izmir	845
Wallboard	Gaziantep	518
Styrofoam	Istanbul	695
Teknopanel	Mersin	446
Ode-isipan	Istanbul	695
Yalteks board	Kocaeli	592
BASF	Ataşehir	673
Nearest Factories' Distances		**446**

Table B.7 Distances between bitumen factories and Shamuratli village

Water Insulation, Bitumen, Factories In Turkey	Cities	Distances From Sahmuratli Village (Km)
Btm	Izmir	845
Ode-isipan	Tekirdağ	840
Onduline	Istanbul	695
Standartizolasyon	Istanbul	695
Stoper	Kocaeli	592
Focusmembran	Sakarya	556
Focusmembran	Gaziantep	518
Yalteks	Kocaeli	592
Nearest Factories' Distances		**518**

Table B.8 Distances between steel factories and Shahmuratli village

Steel Rebar Factories In Turkey	Cities	Distances From Sahmuratli Village (Km)
Yesilyurt	Sumsun	301
Yazici	İskenderun	561
Sidemir	Sivas	200
Sider Demir	Izmir	845
Kroman Celik	Kocaeli	592
Kardemir	Karabuk	464
Kaptan Demir Celik	Tekirdağ	840
İçdaş	Çanakkale	982
Ekinciler	İskenderun	561
Ege Celik	Izmir	845
Nearest Factories Distances		**200**