LIFE CYCLE ASSESSMENT OF MASONRY WALL TYPES USING SIMULATION TECHNIQUE

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ABSTRACT

LIFE CYCLE ASSESSMENT OF MASONRY WALL TYPES USING SIMULATION TECHNIQUE

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This is the report of a Life Cycle Assessment (LCA) study on some masonry wall types. As the starting point, literature on masonry materials, techniques and possible end-of-life scenarios were examined that are needed for the formulation of a LCA study. Prevalent masonry types were detected as fired clay brick, AAC block, natural stone, mud brick as well as prevalent end-of-life cases as landfill, reuse and recycling. Additionally, an overview of the literature on Environmental Impact Assessment (EIA) was presented in order to detect a framework for the structure of a LCA study. After the collection of all needed information, several possible life cycle scenarios were formulated in a realistic manner for each stated masonry type. Obtained information was applied to a LCA evaluation software product named SimaPro life cycle inventory software (PRé Consultants, 2012). By means of the software product, general scores of environmental impact for all alternatives were obtained. Besides analyzing and comparing the scores, basic reasons behind the results were discussed in terms of similarity and difference.

The results reveal that when the requirements shaping the wall are clearly described, the most and the least environmental friendly wall types are detectable. During the study two main scopes, such as commonly used wall thicknesses and thicknesses for thermal insulation were described and several types of walls with life cycle alternatives were labeled as the most or the least harmful to nature.

To conclude, although it is not reasonable to point out one type of masonry as the least harmful one for any cases, the conditions of each case detect the most and the least harmful type of masonry walls. Nevertheless, the relatively low environmental impact of mud brick masonry is striking. Therefore the environmental friendly aspect of mud brick masonry is underlined –one more time- by the results of this study.

Keywords: Masonry wall type, Life cycle assessment (LCA)

ÖZ

BENZETİM TEKNİĞİ İLE KÂGİR DUVAR ÇEŞİTLERİNİN YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ

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Bu doküman, bazı kâgir duvar çeşitlerine dair yapılmış bir Yaşam Döngüsü Değerlendirme (YDD) çalışmasının raporudur. Başlangıç noktası olarak, çalışmanın oluşturulması için gereken kâgir duvar malzemeleri, teknikleri ve olası yaşam sonu senaryoları ile ilgili kaynaklar incelenmiştir. Yaygın olan kâgir çeşitleri pişmiş kil tuğla, gaz beton blok, doğal taş ve kerpiç tuğla olarak belirlenirken yaygın olan yaşam sonu uygulamaları da atık gömme, yeniden kullanım ve geri dönüşüm olarak tanımlanmıştır. Ek olarak, YDD için bir omurga oluşturmak üzere Çevresel Etki Değerlendirmesi başlığı incelenmiş ve sunulmuştur. Gereken bilgilerin toplanmasından sonra, belirtilen kâgir çeşitleri için olası yaşam senaryoları gerçekçi bir yaklaşımla hazırlanmıştır. Hazırlanan bilgi, bir YDD yazılımı olan SimaPro’ ya (PRé Danışmanlık, 2012) aktarılmıştır. Bu yazılım ürünü aracılığı ile tanımlanmış alternatiflerin çevresel etki puanları elde edilmiştir. Sonuç puanlarının analizi ve karşılaştırılmasının yanı sıra, sonuçlara yol açan sebepler de benzerlik ve farklılık açılarından tartışılmıştır.

Sonuçlara göre, duvarı şekillendiren gerekler tam olarak tanımlandığında doğaya en az ve en çok zararlı duvar çeşidinin belirlenmesi mümkündür. Çalışma sırasında iki temel kapsam, yaygın kullanılan duvar kalınlıkları ve ısı yalıtım değerine göre duvar kalınlıları tanımlanmış ve duvar çeşitleri yaşam sonu alternatiflerine göre en az ve en çok zararlı olarak etiketlenmiştir.

Sonuç olarak, her ne kadar her koşulda geçerli olacak şekilde tek bir kâgir duvar türünü en az zararlı olarak işaret etmek mümkün olmasa da, her durumun kapsamı en az ve en çok zararlı türleri belirlemektedir. Yine de kerpiç kâgir’ in tanımlanan kapsamlar için diğer kâgir türlerine kıyasla oldukça düşük çevresel etkisi dikkat çekicidir. Bu yüzden, bu çalışmanın sonuçları kerpiç kâgir çeşidinin çevre dostu özelliğinin altını –bir kez daha- çizmiştir.

Anahtar Kelimeler: Kâgir duvar çeşitleri, Yaşam döngüsü değerlendirmesi (YDD)

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Thanks to

My family

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AAC	:	Autoclaved Aerated Concrete
AKG	:	Name of AAC producer firm
ATHENA	:	EcoCalculator for Assemblies North America
ASTM	:	American Society of Testing and Materials
AUB	:	Arbeitsgemeinschaft Umweltvertragliches Bauproduct (Association for Environmentally friendly building)
B.C.	:	Before Christ
BEES	:	Building for Environmental and Economic Sustainability
BREEAM	:	Building Research Establishment Environmental Assessment Method
CML	:	Chain Management by Life Cycle Assessment
DALY	:	Disability Adjusted Life Year
EN	:	European Norms
ENVEST	:	Environmental Impact Assessment and Whole Life Cost
EIA	:	Environmental Impact Assessment
EPS	:	Environmental Priorities System
EPS	:	Expanded Polystyrene
IEE	:	Initial Environmental Examination
IPCC	:	Intergovernmental Panel on Climate Change
ISO	:	International Organization for Standardization
LCA	:	Life Cycle Assessment
LCI	:	Life Cycle Inventory
LEED	:	Leadership in Energy and Environmental Design
TEAM	:	Tools for Environmental Analysis and Management
TRACI	:	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts

TS	:	Turkish Standards
TUKDER	:	Tuğla ve Kiremit Sanayicileri Derneği (Brick and Tile Manufacturers Association)
WHO	:	World Health Organization
XPS	:	Extrude Polystyrene
YDD	:	Yaşam Döngüsü Değerlendirme (Life Cycle Assessment)

CHAPTER 1

INTRODUCTION

This chapter contains the overview of the argument, objectives, procedure and the disposition of the study.

1.1 Argument

There are many alternative products that meet a demand. The alternatives are diversified according to the discrete aspects and needs of the product. With respect to the built environment, many products are being used to produce buildings that house the various needs of human beings. Each product has different requirements in terms of raw material, equipment and energy. One basic component of the building is its envelope system, which consists of its roof, walls, windows and floors. Walls, which are either load-bearing or infill make up at least 2/3 of the envelope, hence their impact carries a lot of weight in the overall impact of a building. For example, in order to produce the structural system of a building, we use moulds. The mould types that are designed in order to satisfy the main requirement i.e. hold the liquid concrete until it stiffens, have additional unique properties. The common types of moulds are made up of wood or steel both of which has some advantageous and disadvantages. The wooden ones are convenient to obtain as well as to shape while steel ones are good in terms of speedy construction. Similarly, all types of products have several impacts on the environment while meeting the demand. For instance, the production of wooden and steel moulds is different in terms of the auxiliary material taken from nature. Additionally, the energy and tools required for the forming of moulds again differ according to material type. Right after the production of moulds, their durability differs which results in different consumption amounts. Lastly, the disposal method is also varied from material to material.

The basic aspects of lifecycle mentioned here results in different resultant negative impacts on nature e.g. the disposal method of steel is by far complicated in comparison to the decay of wood. When all these aspects are regarded, the impacts of the mould types can be documented and the relative impact levels can be compared with the help of some comparative assumptions. For instance, although the needs may be fewer for the production of a wooden mould compared to a steel one, its total impact may be relatively higher owing to the shorter useful lifetime that obliges the use of much wood for a mentioned period of time. This example points out to the importance of each stage in terms of life cycle assessment (LCA) studies. The example stated here, is more or less the same for any product. For instance masonry wall types that are discussed in this thesis are the design alternatives to meet the need to shelter; and similarly, all alternatives have different impacts on nature. In order to evaluate the impact levels and to detect the environmental friendlier ones, all phases of life cycle should be analyzed i.e. the parameters used to define the needs during production, useful lifetime requirements and end-of-life alternatives should be analyzed. Similarly, if all phases of the masonry wall are analyzed, the level of its environmental impact could be identified and compared to other walls.

In this perspective this study argues that, the environmental impact levels of 1 m^2 masonry walls (solid clay brick, hollow clay brick, AAC block, stone block and mud brick) with several thicknesses are comparable with the help of LCA software, SimaPro.

1.2 Objectives

Primary objectives:

- Comparison of main masonry wall types in terms of environmental impact levels considering the parameters of human health, ecosystem quality and resources
- Detection of the most and the least environmental friendly walls

Secondary objectives:

- Collection of information on historical and modern masonry from related published sources
- Detection of useful lifetime periods and possible life cycle scenarios from literature review and referring to available building practices in Turkey

- Presentation of environmental impact assessment (EIA) and related software in order to detect the most appropriate tool for the formulation of life cycle assessment (LCA) of some masonry walls

1.3 Procedure

First of all, available information on masonry construction types including historical and modern samples was collected. Among these wall types, main ones i.e. solid clay brick, hollow clay brick, AAC block, stone block and stone block masonry were selected and presented in a detailed manner. Additionally, sources on EIA and LCA were analyzed and summarized to structure the LCA for selected masonry walls. The wall thicknesses were determined according to two criteria: thickness used in conventional wall construction in Turkey and thickness meeting the thermal resistance property as required by TS 825 (2008). Thereafter, possible end-of-life scenario alternatives such as landfill, reuse and recycling were formulated. Useful lifetime periods of walls were obtained from similar studies in addition to the estimated values according to the registered historical buildings in the selected cities (see Tab. A.1.1). With the help of LCA software, SimaPro; cumulated information was analyzed and the results were obtained. The environmental impact levels of selected walls were presented in terms of human health, ecosystem quality and resources. Referring to the comparisons the impact levels were ranked. Thus, the most and the least environmental friendly wall types are determined. Lastly the results were discussed according to similarity and difference criteria.

1.4 Disposition

This report contains five chapters and two appendices.

Chapter 1 contains the introduction of the report on argument, objectives, procedure and disposition.

Literature review part, namely, Chapter 2 contains information on masonry materials, techniques and possible end-of-life scenarios in addition to EIA.

In Chapter 3, the material and method of the study is described. The material is the information on the properties of prevalent masonry wall types while the method is the evaluation of possible life cycle scenarios with the help of a LCA evaluation tool, SimaPro.

Chapter 4 focuses on the results and discussion part of the research. In this respect, the score results of prepared scenarios are compared and the reasons behind the score ranks are discussed.

Chapter 5 contains the conclusion of the report that overviews the study to generalize the interpretations for further studies.

Appendix 1 contains the table indicating sample buildings selected for the estimation of lifetime periods of walls while Appendix 2 presents the figures indicating interface of the SimaPro software.

CHAPTER 2

LITERATURE SURVEY

A total of about 100 sources are covered in this survey. Obtained information is presented under three titles i.e. masonry construction, end-of-life scenarios for masonry and environmental impact assessment. Under the first title, materials and techniques are summarized while under the second recovery and recycling of masonry is analyzed and lastly environmental impact assessment is presented in several perspectives.

2.1 Masonry construction

The first examples of masonry have been presented in many publications (Kömürcüoğlu, 1962; Besserat, 1977; Smith *et al.,* 1979 and Beall, 1987) similar to the development process (Smith *et al.,* 1979; Beall, 1987; Hendry, 2001 and Lyons, 2007).

According to Beall (1987) one of the first needs of human beings was to shelter and so they used available materials which were basically reed, mud and stone. The author exemplifies the issue with the remains of walls at Jericho (8^{th} millennium B.C.), temples at Ur (3^{rd} millennium B.C.) and tombs at Mycenae (14^{th} century B.C.). The author states that, the first stone building technique was rock carving to create space for living besides using ready monolithic blocks to shelter, later on the invention of specialized tools and techniques helped the evolution of masonry in terms of converting existing building technique from monolith block to articulated units. Therefore, the author declares masonry as a revolutionary step since it is a novel method to span long distances which was previously satisfied only by the use of single block of either stone or timber. In addition to the statements of Beall (1987) Besserat (1977), who is a specialist on the use of clay in Anatolia, states that mud brick has a long history starting from 7500 - 6800 B.C. In addition, the paper by Smith *et al.* (1979) underlines the critical dates in brick development as the common use of fired brick around 1500 B.C. and later sun dried brick use together with fired brick around 300-200 B.C. in the construction of The Great Wall of China.

Hendry (2001) states that there were not remarkable changes in masonry techniques and materials until the industrial revolution. However, the author entitles the industrial revolution as a turning point since the rapid growth of iron, steel and concrete reduced the demand for masonry to a point that it was regarded only as a facing, infill and fireproofing material. Smith, *et al*. (1979) explain the changing conditions of masonry from a different perspective. The authors state that modern architecture tends to make lighter buildings that had three impacts on masonry. First, the conversion of load bearing masonry into infill of framework, second the development of hollow units and lastly the conversion of stone from main building material into almost entirely a facing material. Yet Beall (1987) points out that especially after 1920s masonry has been highlighted especially while searching alternatives to solve economic problems. The author also states that, new studies appeared on materials and techniques that widened the masonry world in terms of new materials, techniques, details, binders, and accessories. Thus, Beall (1987) underlines the influence of masonry on history of architecture as follows:

> "The history of man is the history of his architecture, and the history of architecture is the history of masonry" (Beall, 1987: 1).

2.1.1 Masonry Materials

Although there are many types of masonry material in the market, fundamentally all of them fall into one category of clay product, cementitious masonry unit or natural stone (Beall, 1987). These are described in more detail below:

(i) Clay Products

The material presented here includes the information on historical examples besides basic properties on modern clay products (Kömürcüoğlu, 1962; Besserat, 1977; Smith *et al*., 1979; Beall, 1987; Beall, 2001; Gürfidan, 2006; Lyons 2007; Bown, 2009; Chel & Tiwari, 2009; Sen *et al*., 2010; Işıklar brick catalog, 2012 and Kilsan brick catalog, 2012).

- Mud brick: Besserat (1977) states that clay products have several development stages which start with primitive mud brick unit. The author claims that mud brick was dated back to 7500-6800 B.C. in Aşıklıhöyük, Çayönü and Hacılar. In addition to historical examples, Kömürcüoğlu (1962) points out that mud brick is still one of the most preferred materials especially in rural settlements owing to its positive aspects. Referring to the same document although the ratios depend on the properties of local material, basically the mixture of mud brick contains clay, aggregate (sand gravel mix) and plant fibers that are blended with water. Besides the convenience of material, mud brick construction also has very low maintenance and operational needs that makes it one of the most environmental friendly construction types (Kömürcüoğlu, 1962).

In addition to the traditional techniques of mud brick, there are also recent studies to develop the properties of mud brick. Acun & Gürdal (2003) summarize the development stages of mud brick and attract attention to the addition of gypsum in the mixture of mud. The authors state that gypsum added brick i.e. Alker offers several improvements especially in terms of structural aspects and endurance towards humidity. Besides gypsum addition, Binici *et al*. (2010) remind us the new versions of mud brick with use of textile and plastic fibers to better the quality.

- Fired clay brick: According to Lyons (2007) proper mixture of clay moulded into blocks and processed by heat is called fired brick. The process was defined as follows:

> "Clay as a raw material is most valued for its ceramic characteristics. When subjected to high firing temperatures in a kiln, the silicates in clay melt, fusing the particles to a density that approaches vitrification. The resulting strength and weather resistance make brick, tile, and terra cotta among the most durable of building materials" (Beall, 1987: 30).

Many types of product are widespread in the construction material market owing to the above mentioned process. Although there are many alternatives, building brick and facing brick are the two main types according to the classification of ASTM C62 (1987). Referring to the same source, unit produced for structural purpose or for infill is named building brick (common brick) while the unit for exposed areas where appearance is a priority is called facing brick. In addition, Beall (1987 and 2001) points out other types with three categories as hollow brick, glass block and special purpose brick. The author attracts attention to the standards of hollow brick as follows:

> "One of the traditional distinctions made between different clay masonry products is based on the definition of brick as solid (core area of less than 25%) and clay tile as hollow (more than 25% cored area). However, during the 1970s, new standards were developed for hollow brick with a greater core area than that previously permitted for brick, but less than that allowed for tile" (Beall, 1987: 43).

Although at first glance it is similar to the hollow unit, there is one more type named structural clay tile (Beall; 1987 and 2001). Referring to the same documents, the main difference of this type is the location of cells, either horizontal or vertical, in addition to the solid void ratio. Additionally, the author presents the sub categories as facing tile that has physical properties of ordinary brick with a finer finishing, ceramic glazed facing tile that has clear or color glazed finishing and screen tile used for shading in several patterns. One other product presented in the same document is decorative cladding that is called ceramic veneer (terra cotta).

(ii) Cementitious Masonry Units

According to Beall (1987 and 2001) the main difference of cementitious material compared to clay product is consolidation by means of chemical reaction instead of ceramic fusion. However, the author attracts attention to the similarities in terms of area of use and unit dimensions as well as the nomenclature; i.e. 40-50% coring is termed hollow and up to 25% core is called solid unit. The author gives the main classification and basic properties as follows:

- **Concrete brick:** The main contents are Portland cement and aggregate. Fine and coarse aggregate can be composed of lightweight sand and gravel materials thus concrete unit can be lightweight.
- **Sand lime brick:** Main content is silica with the addition of hydrated lime. The mixture is steam cured in high-pressure autoclaves.
- **Gypsum block:** Main content is gypsum with the addition of vegetable fibers in some cases.

- Cast stone: Main content is stone chips with the addition of cement binders.

- Cellular concrete Block: Main ingredients are sand, lime and aluminum powder.

- Concrete block: The difference compared to concrete brick is the availability of hollow versions.

(iii) Natural Stone

According to Beall (1987 and 2001) natural stone is described as follows:

> "All stone is made up of one or more minerals of specific crystalline structure and definable chemical makeup" (Beall, 1987: 77).

He classifies natural stone into three categories as follows:

- Igneous rock: The cooled version of molten volcanic mixture e.g. granite which is widely used in building.

- Sedimentary rock: Formation of unified minerals which have been affected by weather in a long period of time. Thus, this type is weaker than igneous rock. Sandstone, shale and limestone which are widely used types in building.

- Metamorphic rock: This type of stone is highly modified by the heat and the pressure. Marble, quartzite, slate are the commonly used types in building.

2.1.2 Masonry Techniques

Owing to the meaningful classification of related sources, the material here is classified into two groups as masonry with mortar and masonry without mortar, namely, mortarless masonry. The scope contains historical and recent examples (Lloyd*,* 1958; Martin, 1967; Sowden, 1990; Bingöl, 2004 and Adam, 2005).

(i) Masonry with mortar

- History and development of the technique: Besserat (1977) states that, widespread wall construction technique was mud brick with mud mortar in Aşıklıhöyük around 7000 B.C. where the 65.5 cm wall was formed by two layers of mud brick. The author also states that although the walls were a single layer of greenish clay bricks, they were about 72 cm thick in total in Hacılar around 7000 B.C. One other commonly used technique in the Roman period (see Fig. 2.1 and Fig. 2.2) reported by Adam (2005) was as follows:

> "Whether the walls have the outside appearance of being built of stone or brick, the internal construction is made up of rubble, i.e. stones of all shapes and sizes, debris from stone cutting or fragments of broken tile and bricks bonded with mortar, contained between the two carefully dressed facings. These facings thus serve as the permanent framework for the material that forms the body of the wall and functions as the supporting elements forming the visible surfaces have so often been removed without affecting the condition of the building" (Adam, 2005: 76).

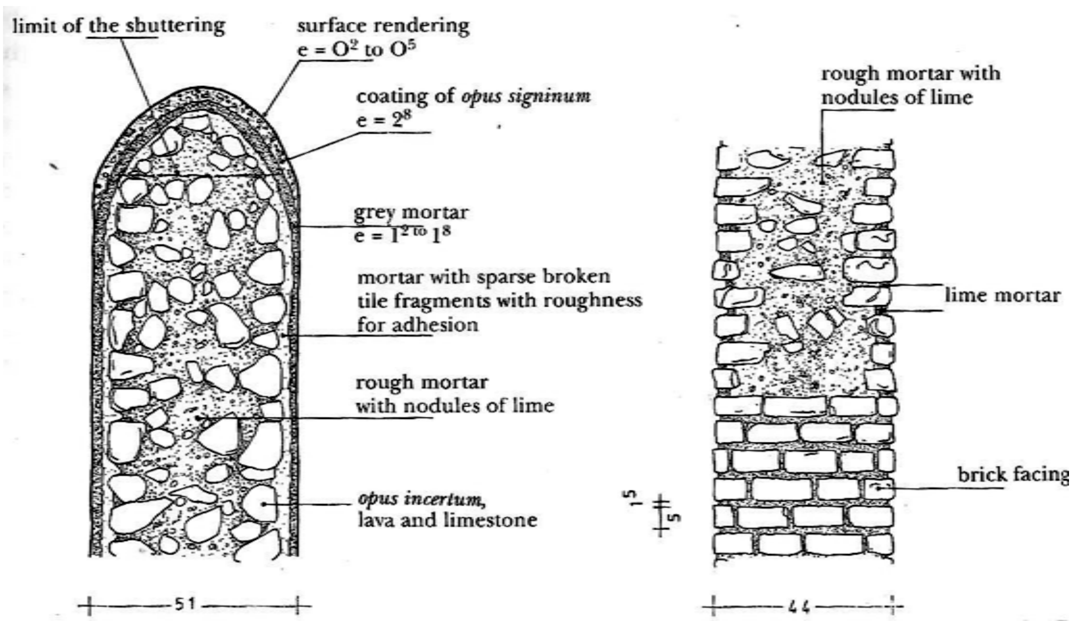

Figure 2.1 Masonry wall section in ancient Roman period (Adam, 2005: 77)

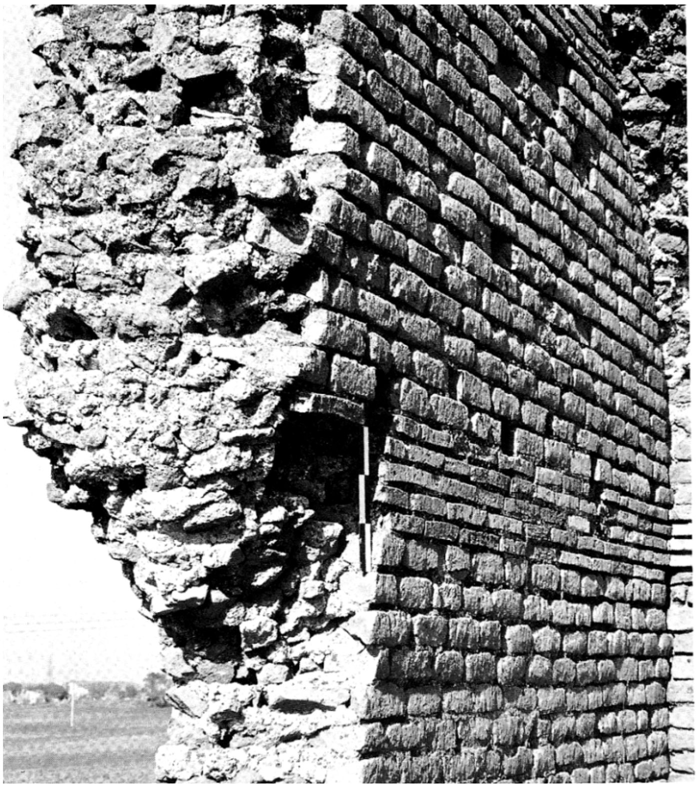

Figure 2.2 Masonry wall in ancient Roman period (Adam, 2005: 78)

This technique was also widespread in Byzantine, Turkish Principalities and Ottoman architecture (Mango, 1978; Bakırer, 1990; Goodwin, 1971 and Kolay, 2002). Additionally, masonry was widely used in Gothic architecture and during Renaissance period (Özen, 2006). On the other hand, Beall (1987) states that there is a shift from empirical design of masonry to theoretical design in more recent times (Fig 2.3). Hence, the theoretical design information is documented as follows:

> "Structurally, modern masonry may be divided into load bearing, non-load bearing and veneer construction. Walls may be single or multi-wythe design. They may also be solid masonry, solid walls of hollow units, or cavity walls. Finally, masonry may be reinforced, partially reinforced, or plain, and either empirically or analytically designed" (Beall, 1987: 7).

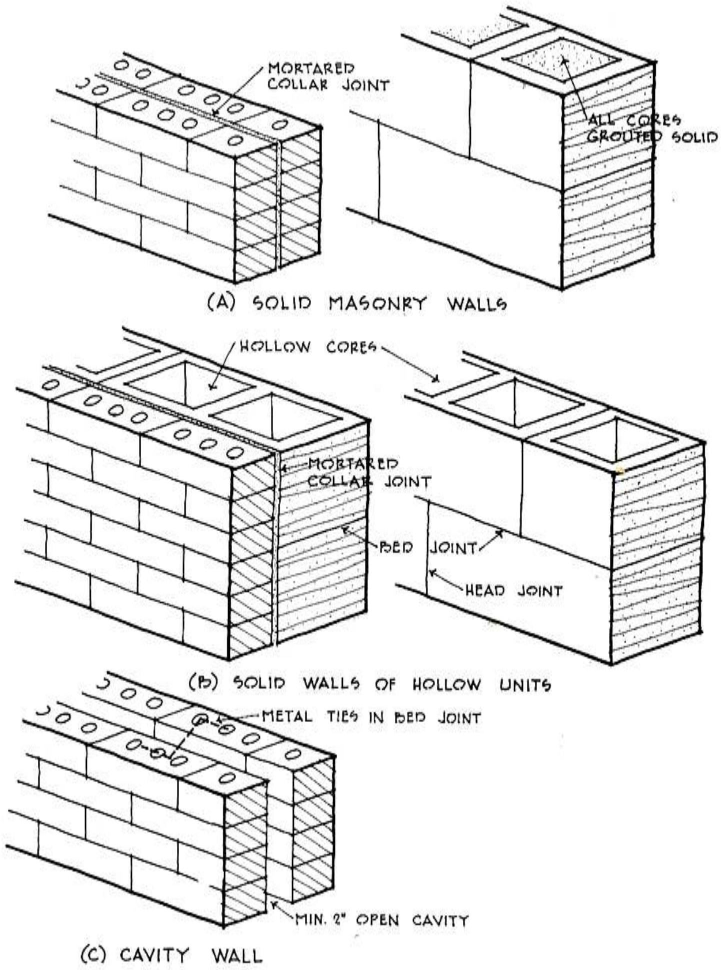

Figure 2.3 Modern masonry wall types and nomination (Beall, 1987: 7)

- Development of mortar: A look at the history of masonry reveals that mortar has a development process similar to the masonry unit. Besserat (1977) states that mud mortar is the first type used around 7500 B.C. and it contained burned gypsum and sand in construction of Giza Pyramid around 27th century B.C. The author points out the difference of mortar used during the Greek and Roman period's builders was the addition of lime or crushed volcanic aggregate.

Among all innovations, the development of Portland cement mortar is regarded as a breaking point. According to Beall (1987) Portland cement is an outcome of experiments to eliminate the disadvantages of previous mixtures of mortar. He classifies modern mortar into two groups as Portland cement lime mortar and masonry cement mortar: while the former mostly contains lime and sand besides Portland cement, the latter is a special kind of mortar used only for connecting masonry units. The author states that, one type of masonry cement mortar is not appropriate for all cases. Similarly, ASTM C270 (1987) presents eight different types as presented below:

- **Type M:** Highly durable type owing to high strength of the mixture.
- **Type S:** Tensile bond is quite strong owing to cement and lime addition.
- **Type N:** Medium strength mortar especially suitable for masonry veneer and interior wall.
- **Type O:** Low strength type because of high lime ratio in the mixture. It is suitable for non-load-bearing wall.
- **Type K:** Since it has very low compressive and tensile strength, it is suitable only for non-load-bearing interior partitions.
- **Refractory:** Special mortar for fire places.
- **Chemical Resistant:** Formed in order to meet special functional needs such as sulfur mortar, silicate and epoxy resin mortar.
- **Extra high strength:** Developed in order to bond prefabricated masonry panels.

In addition to the main types, Beall (1987) reminds of the appearance of new classes with the aid of technological developments such as synthetic adhesive mortar that is applied only a thin layer with the help of chalking gun.

- Bond types: Relevant works (Smith *et al*., 1979 and Beall, 1987) reveal that although there are many bond types, typical ones are illustrated in following Figures 2.4, 2.5 and 2.6 with the addition of application detail examples in Figure 2.7.

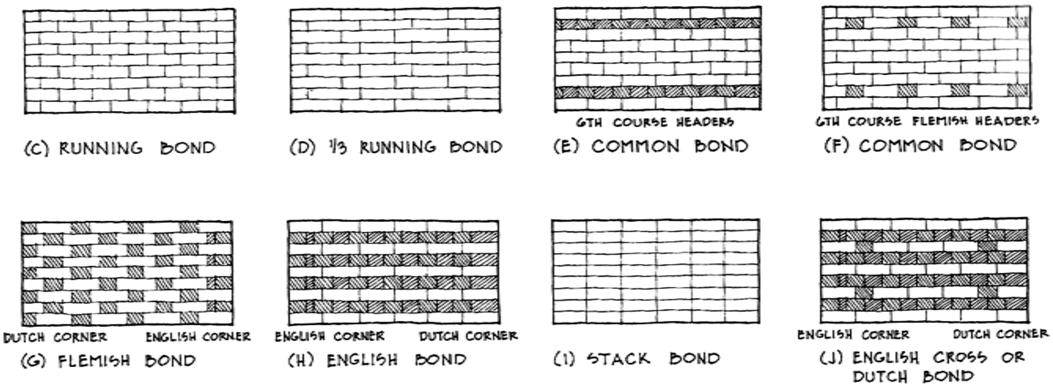

Figure 2.4 Brick masonry patterns (Beall, 1987: 358)

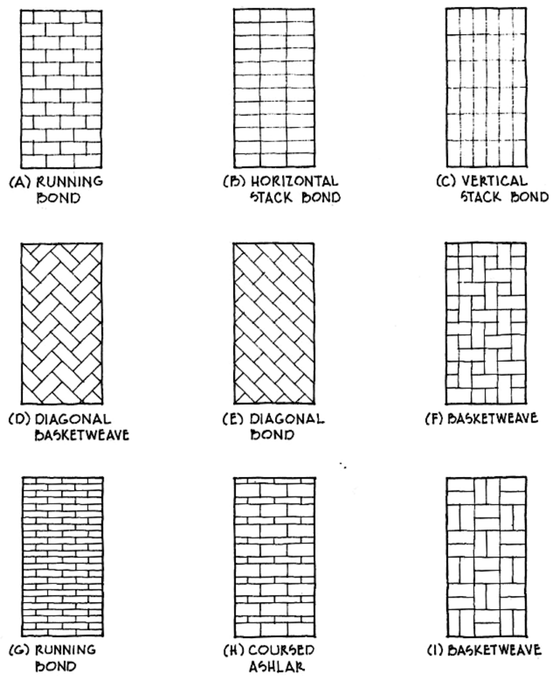

Figure 2.5 Concrete masonry patterns (Beall, 1987: 359)

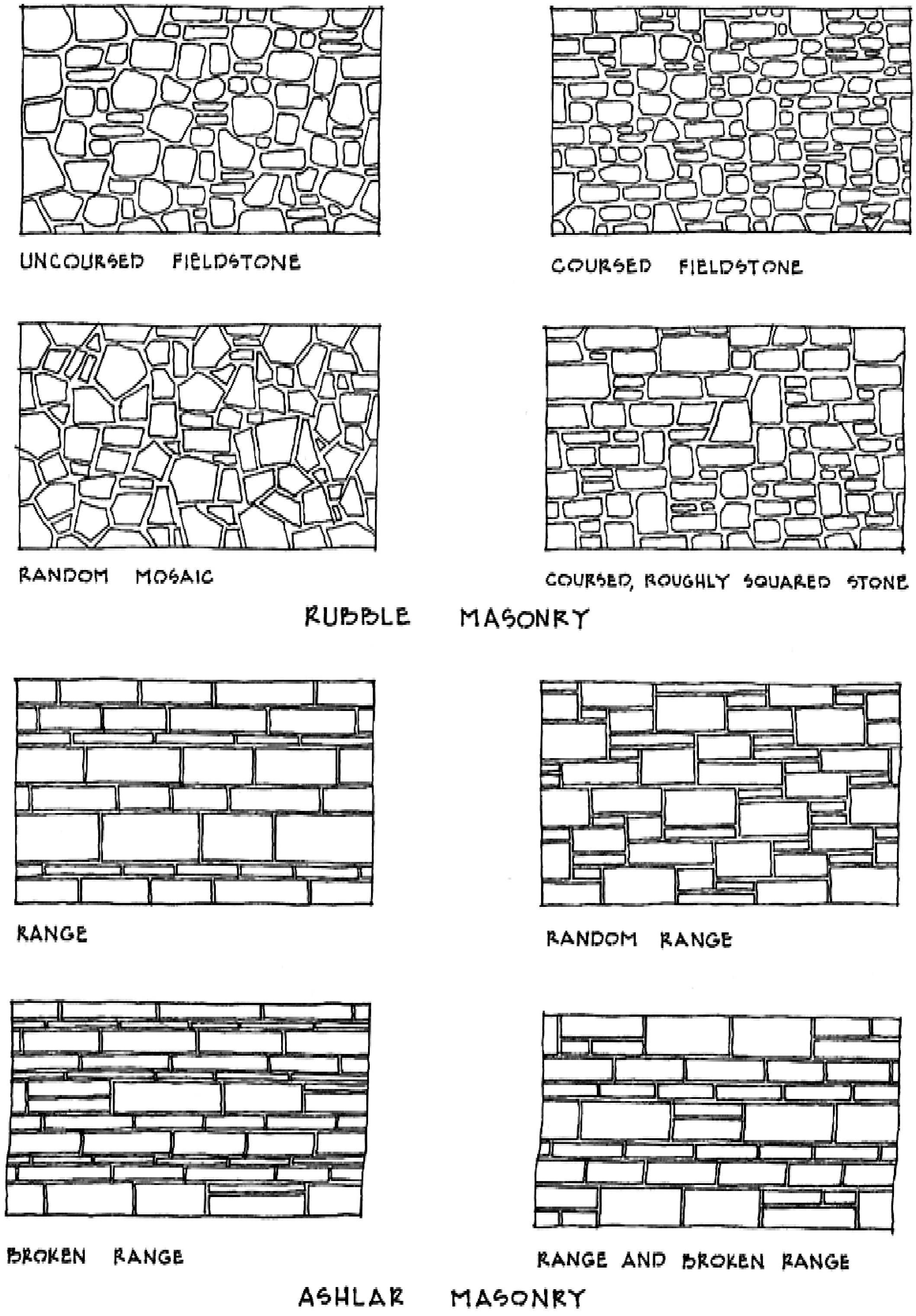

Figure 2.6 Stone masonry patterns (Beall, 1987: 85)

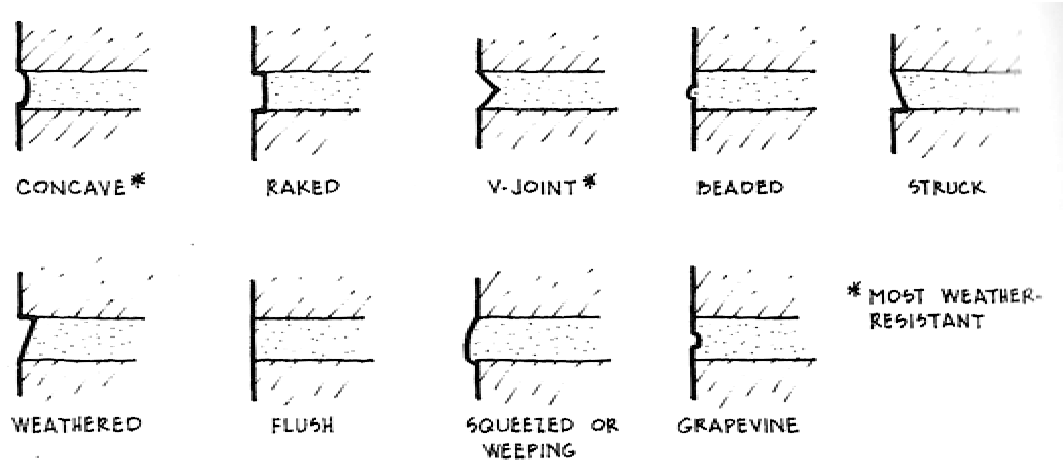

Figure 2.7 Mortar joint details (Beall, 1987: 359)

(ii) Mortarless Masonry

Referring to the related sources, mortarless masonry can be classified into four groups (Martin, 1967; Sowden, 1990; Beall, 2001; National Concrete Masonry Association, 2003; Bingöl, 2004; Adam, 2005 and Santos, 2007). Various types of masonry techniques can be classified broadly under the following groups which are described in detail in the following sections.

(a) Dry stacked masonry
(b) Interlocking dry stacked masonry
(c) Interlocking dry stacked masonry with binding material
(d) Dry stacked masonry with bolts

(a) Dry stacked masonry

Several kinds of stone were used in masonry throughout history (Şengün, *et al.*, 2009; Daloğlu & Emir, 2010; and Sancak *et al.*, 2010). Additionally, many methods were applied to ensure the stability of the wall, one of which is dry stacking. For instance, according to Bulgurlu (1999) the walls of Perge Towers were built without binders (see Fig. 2.8).

Figure 2.8 Perge Towers
(http://www.antalyamuzesi.gov.tr/tr/perge-orenyeri, last access 08.02.2012)

In addition to the historical examples, Sowden (1990) attracts attention to the common use of this kind of bonding for retaining walls of highways in recent years (Fig. 2.9).

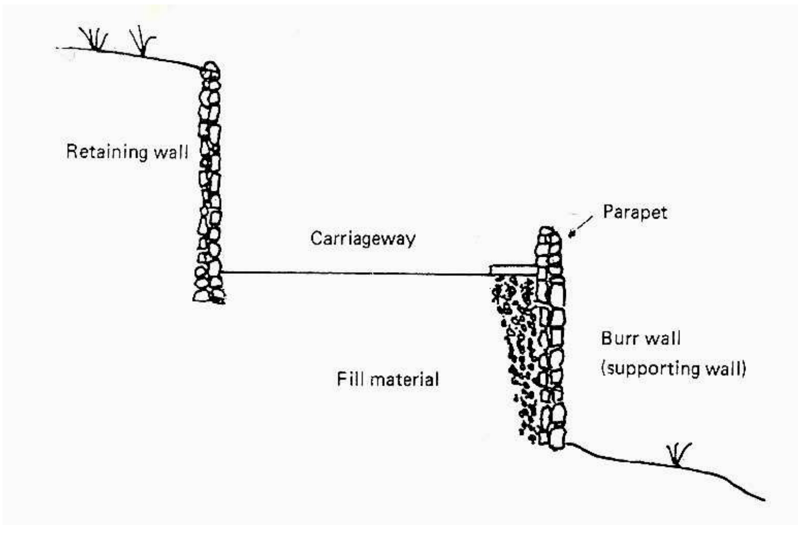

Figure 2.9 Dry stacked retaining wall (Sowden, 1990: 350)

(b) Interlocking dry stacked masonry

Bingöl (2004) states that there is an alternative method of dry stacked masonry which is based on the geometrical unity of components as illustrated in Figure 2.10 below.

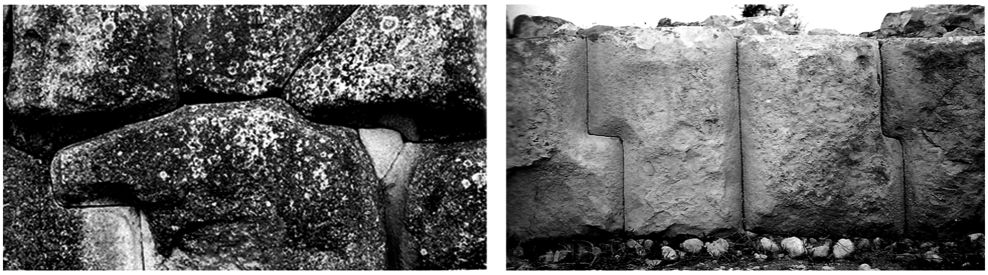

Figure 2.10 Wall details in Alacahöyük City entrance (Bingöl, 2004: 52 and 53)

In addition, Stefaneu, *et al*. (2010) remind us that interaction of the units was crucial for the stability of the stone walls in historical constructions. The authors describe the point as follows:

> "Observing ancient masonry structures, one could claim that the interlocking of the building blocks was an essential characteristic and a desired feature. Take for instance the masonry wall depicted in Figure 2.11 from the civilization of Incas, the interlocking of the building blocks is apparent" (Stefaneu *et al*., 2010).

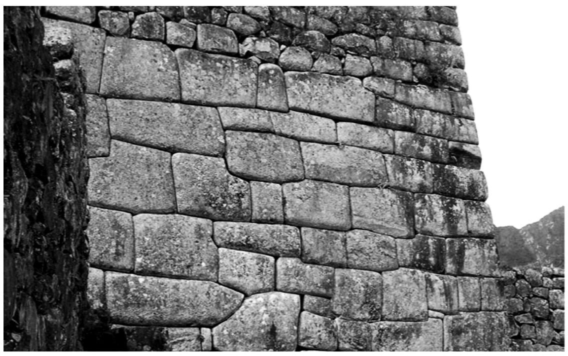

Figure 2.11 Historical masonry wall (Stefaneu *et al*., 2010: 1523)

Besides the historical uses, relevant studies reveal that the derivation of this kind is also widely used in recent times (Thanoon *et al.,* 2004; Thanoon *et al.,* 2007 and Deepak, 2010). Thus, there are many kinds of masonry units in the market which are designed according to the interlocking principle (Fig. 2.12) since it has several advantages such as speeding up the construction and reducing the labor requirement.

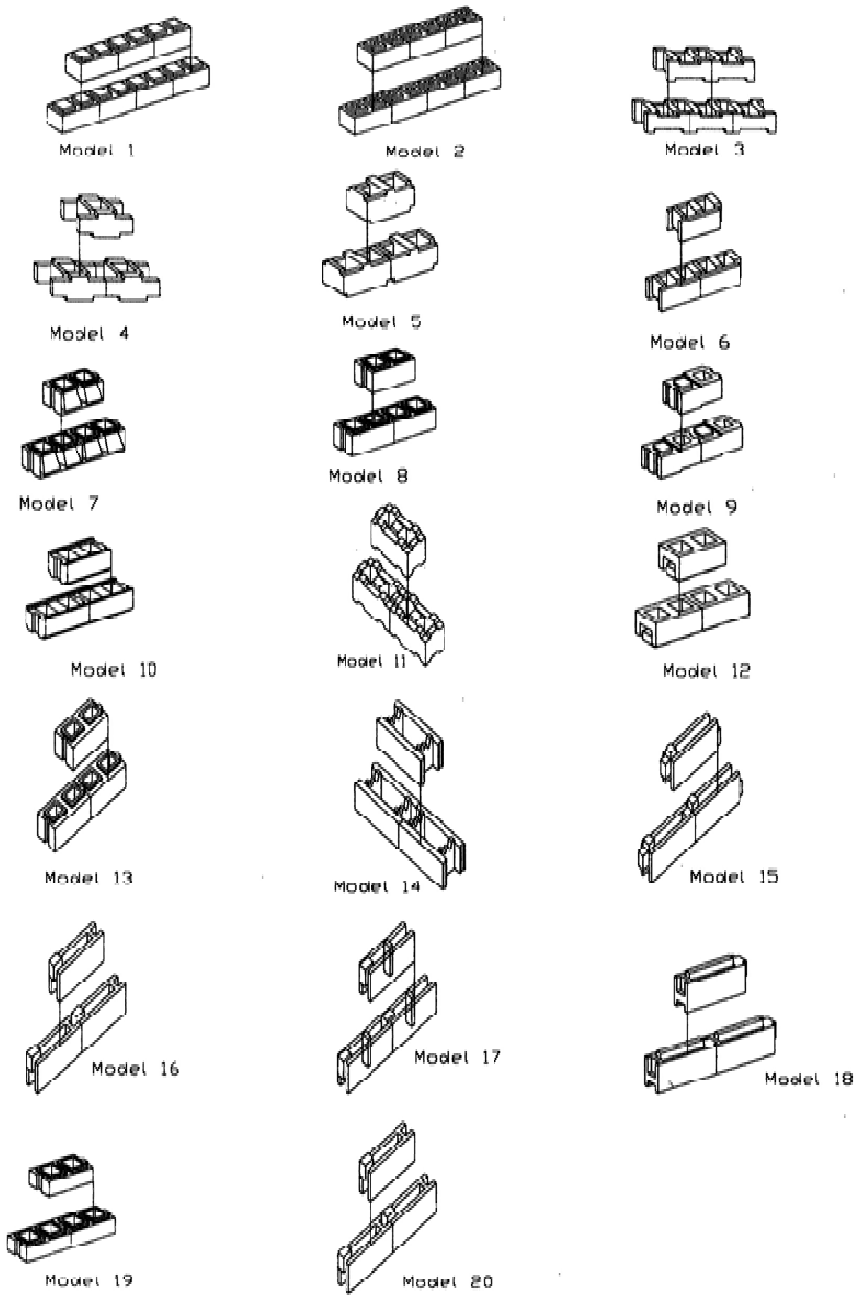

Figure 2.12 Interlocking hollow block types (Thanoon *et al*., 2004: 449)

(c) Interlocking dry stacked masonry with binding material

There are also interlocking techniques with additional binders such as partial mortar and surface bonder as illustrated in Figures 2.13 and 2.14 below (National Concrete Masonry Association, 2003 and Thanoon *et al*., 2004)

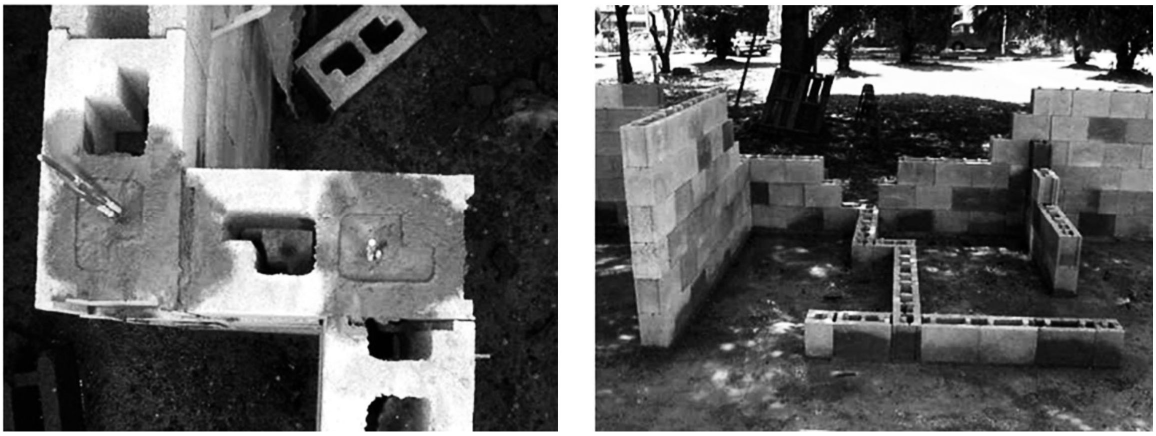

Figure 2.13 Use of partial mortar (Thanoon *et al*., 2004: 453)

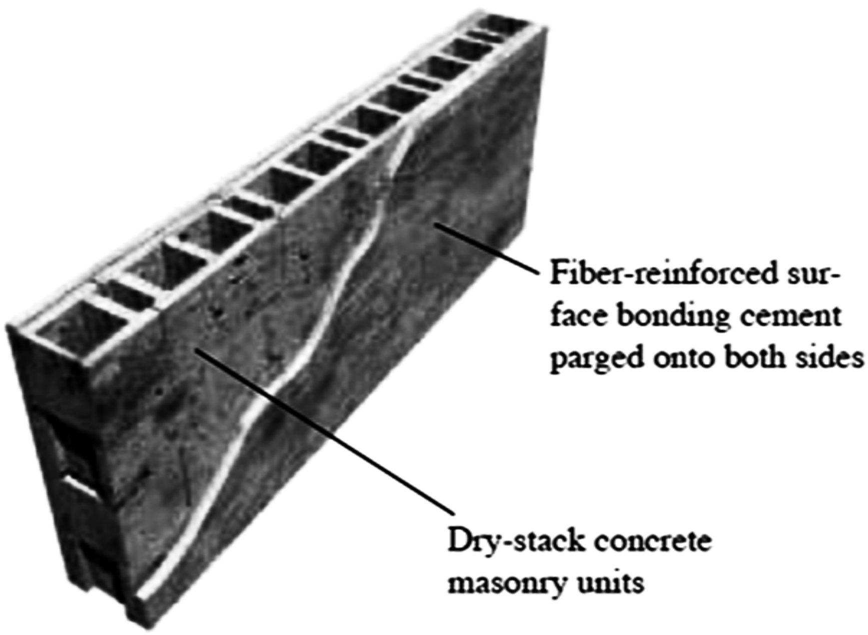

Figure 2.14 Use of surface bonder (National Concrete Masonry Association, 2003: 2)

(c) Dry stacked masonry with bolts

According to Lloyd (1958) stone masonry had innovative and attracting details in ancient Greece with the aid of the good supply of stone quarries. Martin (1967) supports the statement of Lloyd (1958) as follows:

> "The setting up and assembly of blocks was a specially important operation in ancient architecture which rejected the use of mortar or plaster, except in the case of country buildings made of rubble, and only relied on accurate joints or links in the form of metal bolts and seals. It resorted to the piling up of courses which were held in place by gravity alone. There was no need to have resource to buttresses except occasionally to break vertical facings which were too massive or subjected to the outward thrust of terraces above. It was enough to prevent blocks from slipping over one another or gaps from appearing between the carefully calculated joints. This was the function of metal seals and bands which seem to have had limited powers of resistance in comparison with the massive weights they had to support" (Martin, 1967: 48).

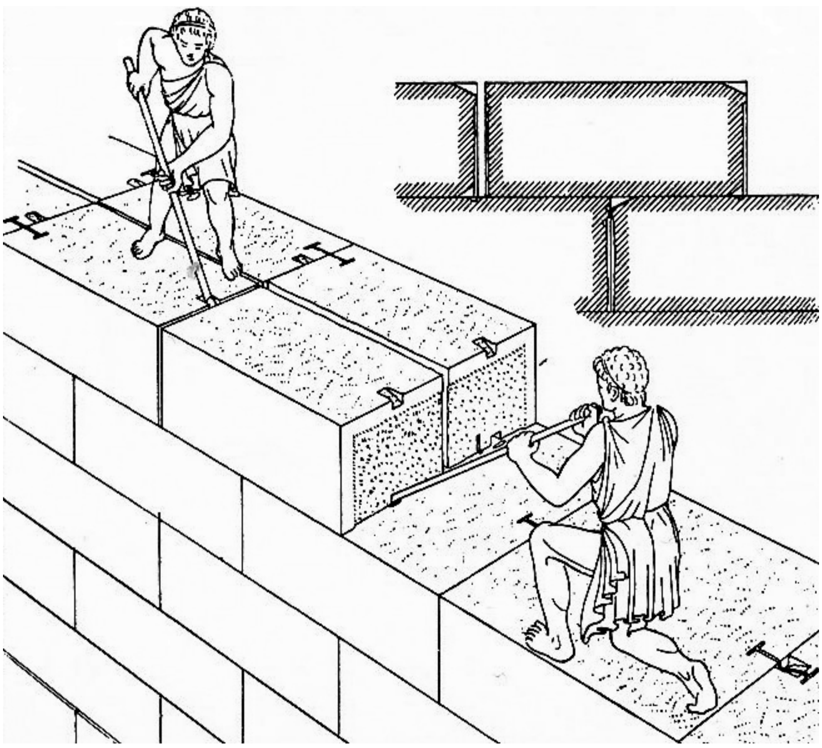

Figure 2.15 Construction with connectors (Martin, 1967: 50)

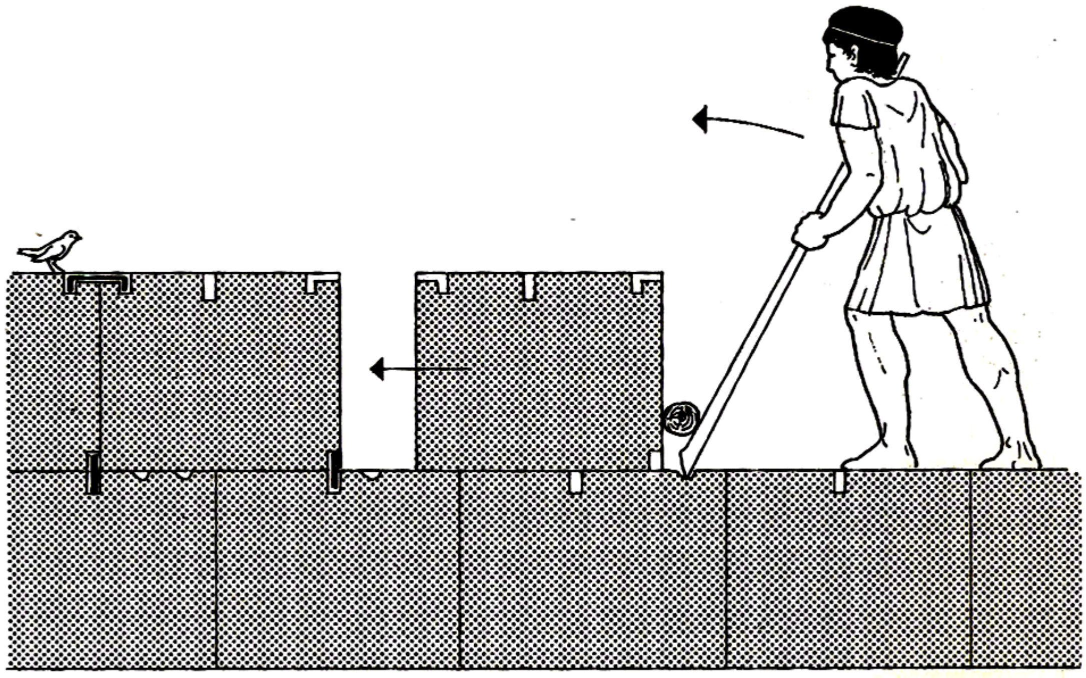

Figure 2.16 Use of bolts (Adam, 2005: 53)

Besides clarifying the innovative aspect of the construction type, Martin (1967) also defines the details of the technique as follows:

> "Once the course was complete its upper surface was hewn and polished to receive the next. Then, cavities were chiseled out for bolts and plugs. The pegs and tenons of wood, bronze and iron were finally coated with molten lead which filled any gaps and prevented the infiltration of water. For time it was imperative to prevent oxidization, which could split the marble. This was encountered in the course of the early restorations of the buildings on the Acropolis at Athens when, after some unfortunate experiments, it was found necessary to have resource to the methods of the original builders" (Martin, 1967: 49).

Referring to the report of Bingöl (2004) bolts used for horizontal fixing are called clamps while bolts for vertical connection are called dowels. The author states that there are wooden, iron, bronze, lead and lead coated examples of both clamps and dowels. Although there are several types of clamps and dowels, widely used clamp types are illustrated in Figure 2.17 and remains of dowels are indicated in Figure 2.18.

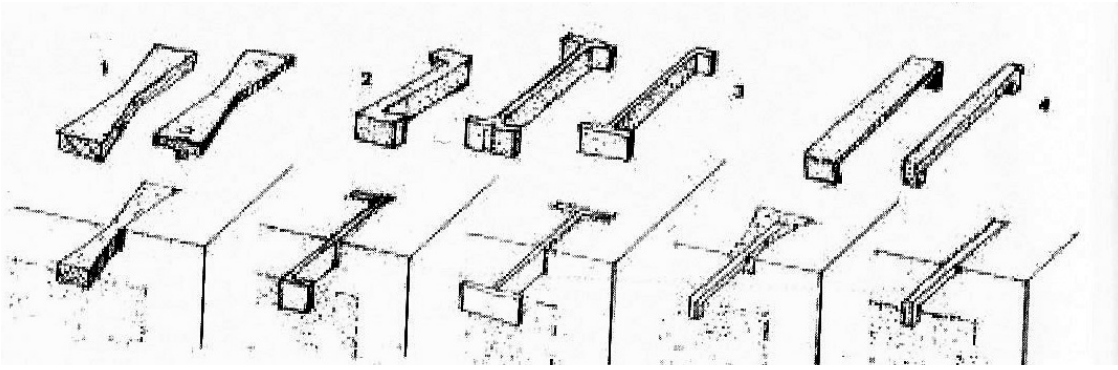

Figure 2.17 Clamp types (Bingöl, 2004: 100)

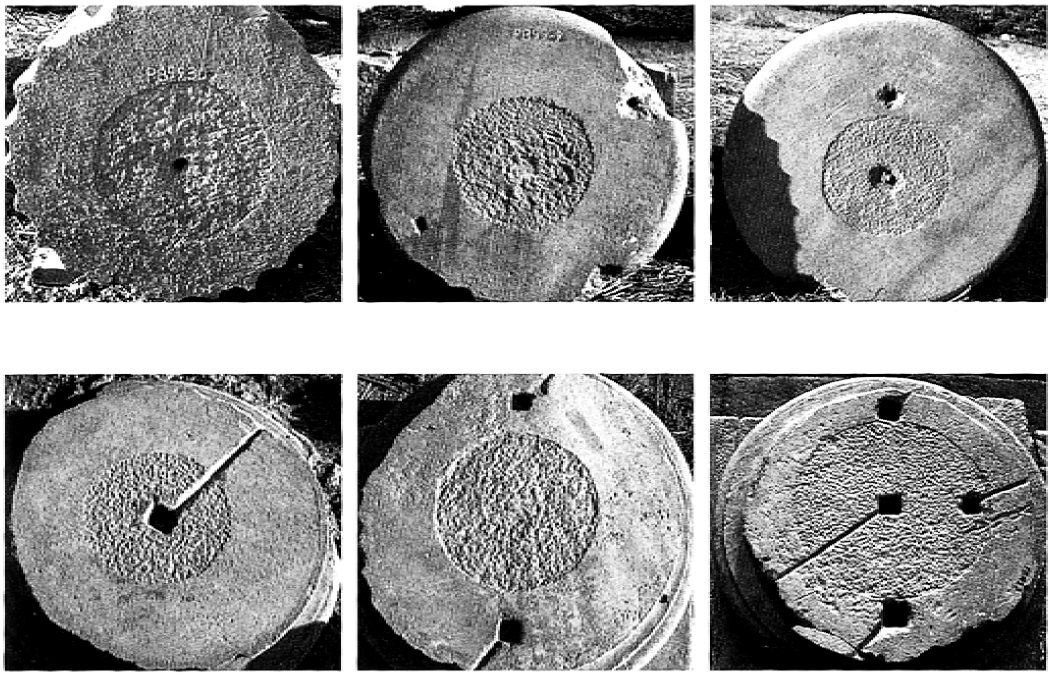

Figure 2.18 Dowel houses (Bingöl, 2004: 97)

In contrast to the historical prevalence, this masonry technique has very few examples in recent times. Among the mere examples, Santos (2007) presents a dry technique with special clips in stainless steel referring to the applications in Belgium and Netherlands (see Fig. 2.19).

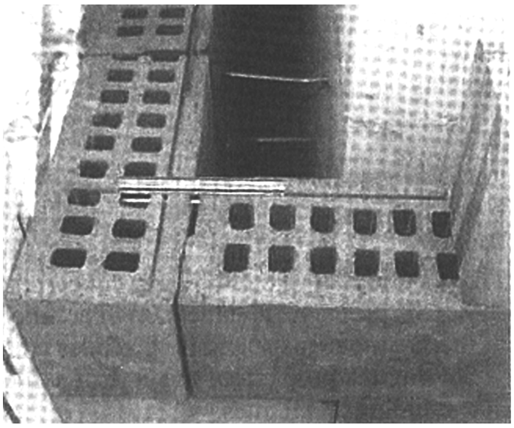

Figure 2.19 Use of special clips (Santos, 2007: 12)

In addition to the example presented by Santos (2007), Beall (1987) introduces the use of similar metal connectors for cladding as illustrated in Figure 2.20 below.

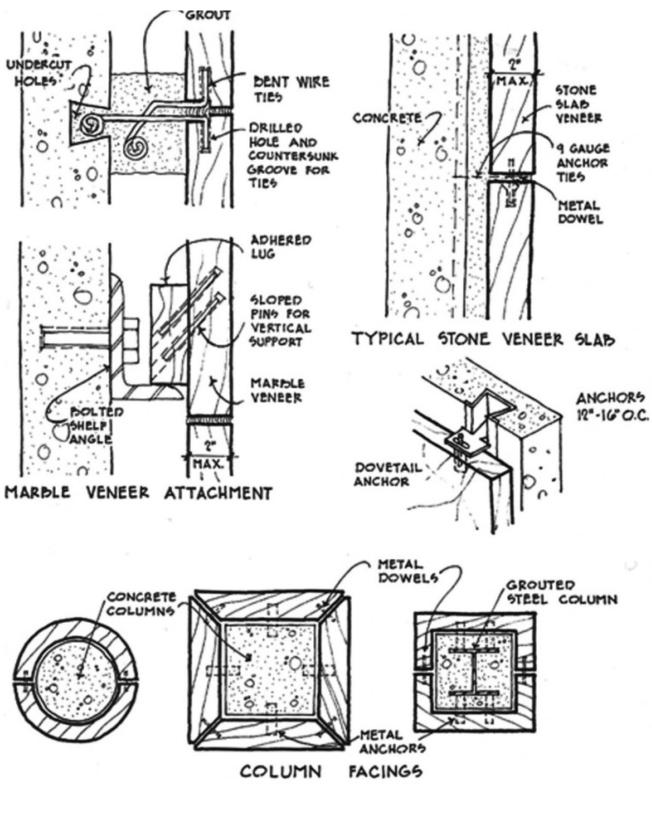

Figure 2.20 Use of metal connectors (Beall, 1987: 185)

2.2 End-of-life scenarios for masonry

Waste production has been a growing problem all around the world. According to Guy & Shell (2002) around 30% of annual waste production is construction debris in the United States. According to the report by Ozkan & Düzgüneş (2002) the scene is more or less same for the other countries including Turkey. There are several studies in order to tackle with waste problem in many disciplines including architecture. In terms of masonry, the alternative suggestions on end-of-life scenarios are categorized into two main groups as described below.

2.2.1 Recovery of masonry walls

Existing sources mainly fall into two categories as historical reuse examples (Demiriz, 1970; Öney, 1970; Tanyeli & Tanyeli, 1989 and Bakırer, 2009) and unit recovery studies (Thormark, 2001; Guy & Shell, 2002; Dijk *et al*., 2002 and Mulder *et al*., 2007).

Demiriz (1970), Öney (1970), Tanyeli (1989) and Bakırer (2009) state that since stone masonry was very common in history, readymade units were always very valuable. Thus, the disassembly of masonry remains for reuse was widespread. The authors remind us that several stone masonry buildings contain units recovered from other constructions. The main evidence of this statement was clarified with decorations belonging to previous cultures as illustrated in Figure 2.21 below.

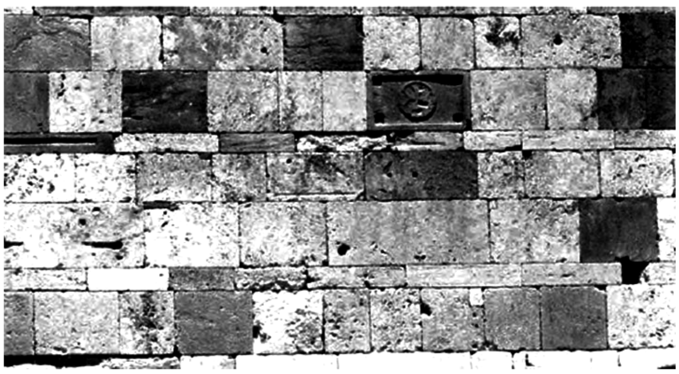

Figure 2.21 Reused stones in Zazadin Han (Önge, 2004: 73)

Besides the historical information on recovery and reuse of masonry, there are several studies in recent years. For instance, According to Dijk *et al*. (2002) and Rathmann (?) masonry is regarded as waste during the demolition although it still has potential usability which is described as follows:

> "When architecture is demolished, the spatial continuum may be broken, but the materials continuum need not be. Just as the saprophyte reduces dead organisms to their simpler elements within natural systems, the demolition contractor might reduce a building to its simpler elements. The necessary shift that must take place for this analogy to hold true is from destructive demolition to conservative disassembly" (Rathmann, ?: 64).

According to Guy & Shell (2002) the basic aspect of unit recovery is the design of joint with the probability of deconstruction. For instance mortar should allow separation in the end-of-life phase although it was strong enough for adhesion during the useful lifetime.

Additionally the authors draw attention to the different disassembling potentials of mechanical and chemical joints i.e. anchors versus glue based sealants. In order to prepare a guide for the prediction of reliable recovery rates, Thormark (2001) introduces a framework as illustrated in Table 2.1 where several questions are asked and each wall gains a score according to answers that refers to its relative recoverability ratio of reusable units.

Table 2.1 Framework to detect the ratio of reusable material (Thormark, 2001: 70)

Goal for the disassembly	Assessed parameter	Assessment	Score
Reuse	Risks in the working environment	Big	1
		Small	2
		None	3
	Time requirement	Long	1
		Medium	2
		Short	3
	Tools / equipment	Advanced	1
		Simple	2
		Manual	3
	Access to joints	Very little	1
		Acceptable	2
		Good	3
	Damage to the material caused by disassembly	Very much	1
		Acceptable	2
		Very little	3
Material recycling	Relevant parameters		
Combustion	Relevant parameters		

In addition to manual disassembly examples, Mulder *et al*. (2007) note that thermal process is a way to disassemble fired clay masonry units. The authors state that, the particles recovered from masonry with the help of heat treatment can be used as aggregate in concrete. A similar study by Dijk *et al*. (2002) asserts a three step process as illustrated in Figure 2.23. The first step of the experiment is thermal process that results in recovery of whole brick. Second step is separation of stony rubble from mortar. Third step is use of clay brick pieces in new brick production line. The authors add that although the convenient heat level differs according to type of unit and mortar used, the results of experiments reveal that, the best temperature is around 540 °C for cement based mortars. Other results are illustrated in Table 2.1.

Figure 2.22 Masonry debris during demolition (Dijk *et al*., 2002: 1422)

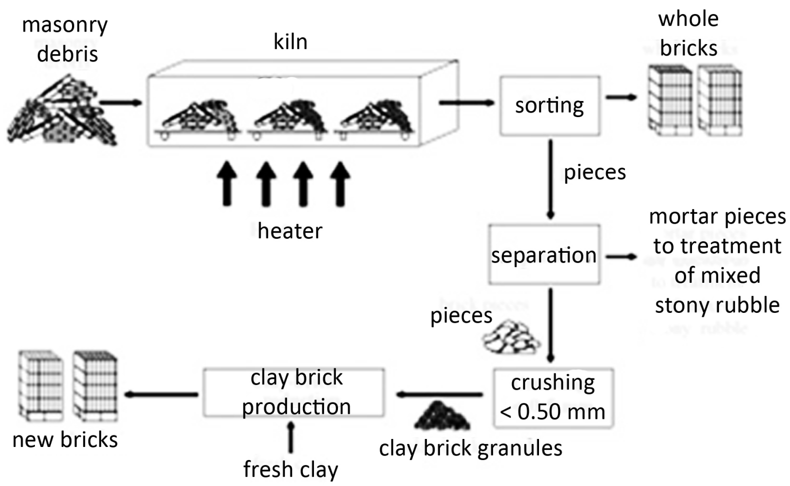

Figure 2.23 Heat treatment recovery of masonry (Mulder *et al*., 2007: 1411)

Table 2.2 Recovery with heat treatment details (Dijk *et al.,* 2002: 1418)

Experiment	Heating Time	Max temperature / time	Cooling time	Sample	Results
1	0:30	600 / 2:00	Non forced	softmud clay brick red + Portland cement mortar	clay bricks are cracked into 2 pieces, with a size of a half brick
				hand molded clay brick + lime mortar	lots of cracks in the bricks
				plastered masonry	bricks are broken into two pieces, the cracks on the mortar brick interface can be seen clearly
2	0:30	400 / 1:00	Non forced	softmud clay brick red + Portland cement mortar	no visible cracks, brick recovery is not successful even with mechanical force
				hand molded clay brick + lime mortar	cracks are visible on brick mortar interface, bricks can be recovered after a soft hit with a hammer
				plastered masonry	cracks on brick mortar interface
3	2:00	600 / 1:00	Non forced	softmud clay brick red + Portland cement mortar	masonry part falls apart, the bricks are totally cracked
				hand molded clay brick + lime mortar	idem
				plastered masonry	idem
4	2:00	500 / 2:00	Non forced	softmud clay brick red + Portland cement mortar	the brick can not be recovered
				hand molded clay brick + lime mortar	the brick mortar interface is cracked, bricks are recovered
				plastered masonry	the brick mortar interface is cracked, bricks are recovered
Gas heated kiln					
5	2:00	540 / 1:00	Non forced	softmud clay brick red + Portland cement mortar	brick mortar interface is cracked, some bricks are broken into 2 , some pieces of mortar are still stuck to the brick
				hand molded clay brick + Portland cement mortar	same result, some bricks are recovered
6	2:00	540 / 1:00	Non forced	softmud clay brick red + Portland cement mortar	cracks on brick mortar interface, recovered
				hand molded clay brick red + Portland cement mortar	cracks on brick mortar interface, recovered
Electric kiln					
7	2:00	540 / 1:00	Non forced	softmud clay brick red + Portland cement mortar	bricks are totally cracked

Dijk *et al*. (2002) summarize the results of experiment as about 45% recovery of units in reusable form and quality provided that care is taken during the dismantling process which is a key to high recovery rate. In the cases where recovery is not possible, other option can be recycling as described in the following part.

2.2.2 Recycling of masonry walls

Related studies discuss the concern in terms of recycling of clay products (Demir & Orhan, 2003) cementitious units (Tam *et al*., 2007) and natural stone (Calkins, 2009). Thus, there is at least one way to recycle all masonry material types. For instance, Demir & Orhan (2003) state the recycling option for clay brick can be summarized as follows:

> "A mixture of up to 30% waste brick additives can be used in brick production. Usage of waste material in the raw mixture minimizes the physical damage that may occur during brick production. The reuse of waste-brick material in brick production provides an economical contribution and also helps protect the environment" (Demir & Orhan, 2003).

Tam, *et al*. (2007) have experimental studies on recovering aggregate from cementitious masonry debris. The authors remind us that the most important disadvantage of recycled aggregate is the partial mortar remains on the surface of aggregate which causes low adhesion. In order to remove the remains from the aggregate, the authors attract attention to the importance of the pre-soaking process which is illustrated in Figure 2.24. The authors indicate that when recovered aggregate stays in several acidic solutions such as: hydrochloric acid (HCl), sulfuric acid (H2SO4) and phosphoric acid (H3PO4); the separation of clean aggregate is by far easier.

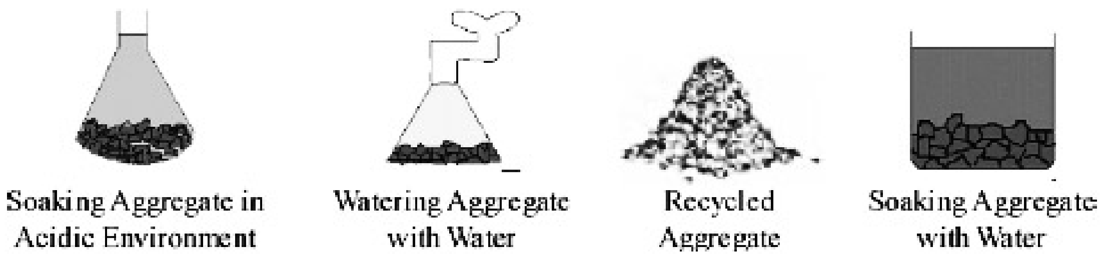

Figure 2.24 Production of recycled aggregate (Tam, *et al.,* 2007: 1411)

In terms of recycling of stone based material, Calkins (2009) attracts attention to the reuse of stone chips in the production of cement mixed materials. In terms of AAC units, Evcin *et al.* (2006) state that recycling is possible up to about 5% recycled content ratio. Lastly, although sources on mud brick recycling were not available it is known that traditionally mud brick debris is used again and again for the production of new mud brick mixture.

2.3 Environmental impact assessment (EIA)

According to Cashmore (2004) environmental impact assessment (EIA) is a tool used to identify and evaluate the possible environmental impacts of actions. The instrument is the arbiter of environmental issues on all stages of action starting from decision making phase.

2.3.1 History, development and basic features

Lawrence (2004) state that EIA is an interdisciplinary concept encompassing natural and social aspects, Although there were some impact assessment studies especially on social concerns dated back to 17th century, EIA originated in 1969 in the United States. Cashmore (2004) thinks of this existence as an outcome of rapid changes arising from industrial revolution.The author also points out that the draft of EIA has been enacted into a law in the United States one year later. In addition, the law has been promulgated by 100 other countries during the next 15 years which has also been the main concern for sustainability studies (Sadler, 1996). Referring to cited sources, EIA concept has been highly developed, diversified and detailed from 1969 onward. Lawrence (2004) states that although there are many EIA methods, most of them overlap in terms of both the basic mission and the process as using checklists, matrices, networks and models (see Tab. 2.3).

Referring to overlap of methods, Anjaneyulu & Manickam (2007) describe the main features of the concept of EIA of any action or production in three groups as follows:

- Identifying short and long term effects
- Reducing negative impacts up to lowest possible level
- Monitoring the implementation and effectiveness

Table 2.3 EIA types (Lawrence, 2004: 231)

Impact assessment	What is assessed?
ecological	potential ecosystem impacts
social (SIA)	consequences on people and on how people and communities interact with their surroundings
economic	impacts on how people make a living, on material well-being, and on economic activities
strategic environmental (SEA)	environmental impacts of a policy, plan or program and its alternatives, generally within policy sectors
cumulative effects (CEA)	impacts of an action when combined with other past, present and reasonably foreseeable future human activities
technology (TA)	effects on society from new or modified technology
human health impact (HIA)	human health impacts of a proposed action
sustainability appraisal or SA	extent to which action contributes to or undermines ecological and societal sustainability
life cycle (LCA)	environmental effects of products, processes, systems and services during their life cycles
integrated environmental (IEA)	the ecological, economic, social and institutional effects of societal activities and government policy, across policy sectors

Lawrence (2004) states that, the environmental concerns must come into play with the first planning stage in order to complete the tasks stated above. Therefore the author points out to the importance of environmental analysis in all phases of the project. Other researchers have also emphasized the importance of the processes used in EIA e.g. Anjaneyulu & Manickam (2007) attract attention to the process of evaluation and classifies it into two main phases as follows:

(i) Initial Environmental Examination (IEE): This is a preparatory phase where an assessable project is analyzed in order to detect which assessment method is appropriate for the case. Since it is preparatory work, the authors overview the stage as the initial negative impact determination against restrictions such as time limitation, data and budget inadequacy.

(ii) Full scale environmental impact assessment (EIA): According to Anjaneyulu & Manickam (2007) this category is the main component of the assessment which is classified into four groups as follows:

(a) Scope definition: The main mission of this group is to specify the scale of impacts within the scope of time. The affected boundary is stated as either the natural environment such as air, water and soil or manmade one as economic and social environment. In addition, main required information is described as determination of important and less important issues, concerns and regulatory requirements.

(b) Identification: The required information of this phase is description of existing environmental system, determination of the components of the project and statement of the boundary modified by the project.

(c) Prediction: The mission of this phase is the speculation on the major changes due to environmental impact, probability, quantity and scale that may occur.

(d) Evaluation and analysis: The tasks of this phase are detecting the least harmful alternative, interpreting the impacts and clarifying the final statement.

2.3.2 Life cycle assessment (LCA)

Tukker (1999) describes life cycle assessment (LCA) as detailed version of EIA. The basic definition of LCA supports this statement as follows:

> "Life cycle assessment is a technique for assessing the environmental aspects associated with a product over its life cycle.
> - Analysis of the contribution of the life cycle stages to the overall environmental load, usually with the aim to prioritize improvements on products or processes.
> - Comparison between products for internal communications" (Goedkoop *et al.*, 2008: 1).

Like the similarity of definitions, the steps of the LCA bring to mind the process of EIA. The description of the process of LCA is mentioned below:

(i) Goal and scope definition: According to the report by Goedkoop *et al.* (2008), since life cycle study is a model of real case, the more it reflects the reality the more reliable the result is. Thus to structure the study, the authors declare that realistic goal and scope definition is significant. Depending on the same source, prominent aspects of this part are definition of product, function, total life cycle, functional unit, allocation schema, system boundaries, relevant data, assumption and impact assessment. Among all, the importance of a functional unit statement and reference flows definition is underlined by Weidema *et al*. (2004) that is shortly explained as follows:

> "The functional unit describes and quantifies those properties of the product, which must be present for the studied substitution to take place. These properties (the functionality, appearance, stability, durability, ease of maintenance etc.) are in turn determined by the requirements in the market in which the product is to be sold. The reference flows translate the abstract functional unit into specific product flows for each of the compared systems, so that product alternatives are compared on an equivalent basis, reflecting the actual consequences of the potential product substitution. The reference flows are the starting points for building the necessary models of the product systems" (Weidema *et al*., 2004: 9).

Additionally, Goedkoop *et al.* (2008) attract attention to the point that, since some processes result in several outputs at the same time, the environmental process should be shared out which is nominated as allocation procedure. The authors state that there is no one right way for allocation and structuring the process, hence referring to the nature of study is the best route.

(ii) Inflows and outflows: Goedkoop *et al.* (2008) state that one other crucial part of LCA is the stage of relevant data collection which is called the life cycle inventory stage. During this stage, LCA tools can be used as a reliable guide since they present data sets based on statistical information.

(iii) Impact assessment: According to Goedkoop *et al.* (2008) impact assessment phase is the evaluation stage of collected information according to several evaluation criteria sets depending on the selected impact category.

(iv) Interpretation : Referring to all evaluation stages, the speculations are presented in this phase. The basic description of the phase is as follows:

"The purpose of this stage is to analyze results, to give references and to lead to conclusions and recommendations that allow taking future decisions. It is a rational and systematic evaluation of the needs and opportunities to reduce environmental burdens, in terms of energy and material consumption and waste emissions by a product, process or activity. The final output of the analysis should be a set of improvement scenarios, which will help reduce the environmental burdens brought on by a product or process" (Sustainable and Ecological Management Working Group, 2012).

Briefly, Tukker (1999) schematically illustrates all the explained stages in Figure 2.25. In the Figure first, he summarizes all stages of a product under system boundaries title. Second he indicates the emissions owing to the production stages. Lastly he declares which emissions cause what impact on the environment.

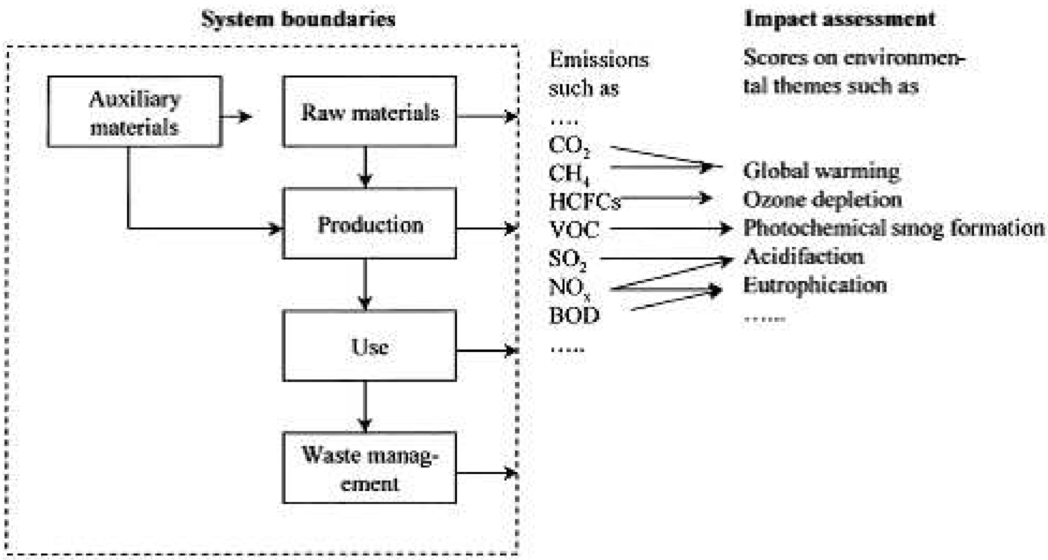

Figure 2.25 LCA process (Tukker, 1999: 446)

2.3.3 Evaluation tools and SimaPro life cycle inventory software

Referring to the report prepared by Trusty (2000) LCA software products are categorized into three main groups: Level 1 tools examine the cycle in terms of natural environment including all material and processes such as Bees, SimaPro and Team. Level 2 tools are described as the arbiter of environment, cost and energy related concerns which require specialized knowledge on some professions such as energy simulation. Common examples are Athena, Envest, EcoQuatum, EE4 and E10.

Lastly, the author states that level 3 tools examine relatively larger scale in terms of environmental economic and social aspects such as BREEAM Green Leaf, LEED and Green Globes.

- SimaPro life cycle inventory software

According to the official web page of SimaPro (PRé.nl, 2012) the software provide user to simulate products with the aid of life cycle parameters referring to the ISO recommendations. SimaPro provides ecoinvent database which covers about 2500 processes on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services and transport services.

For instance ecoinvent unit processor, a set presented in ecoinvent database, covers the material and process related with architectural discipline and construction industry. Besides the data sets, according to Goedkoop *et al.* (2008) ecoinvent also houses several impact assessment categories such as CML 2001, Cumulative energy demand, Cumulative exergy demand, Eco-indicator 99, Ecological footprint, Ecological scarcity 1997, Ecosystem damage potential, Environmental design of industrial products, EPS 2000, IMPACT 2002+, IPCC 2001 and TRACI. Goedkoop *et al.* (2008) also state that each assessment includes and excludes several impact types e.g. including noise pollution or excluding smog pollution. The authors declare that there is no one right way for impact assessment selection and it is directly related to the scope of the study. Among the impact assessment categories, eco-indicator 99 reveals the level of impacts in three main titles i.e. human health, ecosystem quality and resource as illustrated in Figure 2.26.

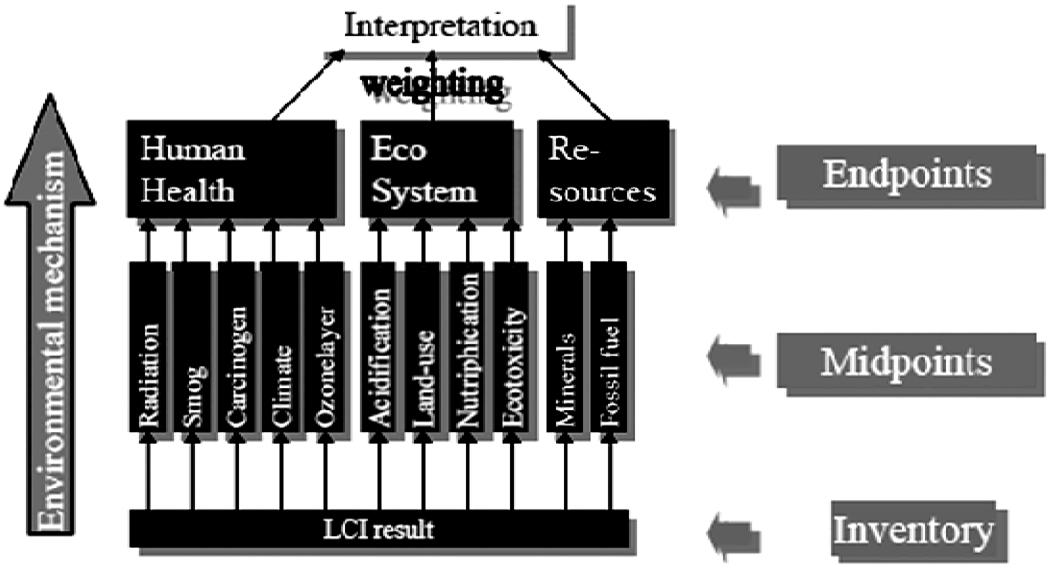

Figure 2.26 Impact assessment phase in eco-indicator 99 (Goedkoop *et al*., 2008: 23)

The results are presented in equivalent scores in terms of points. The authors state that the statistical ratios are used to compare the scales of impacts for score detection, which is explained as follows:

> "Once the impact categories are defined and the LCI results are assigned to these impact categories, it is necessary to define characterization factors. These factors should reflect the relative contribution of an LCI result to the impact category indicator result. For example, on a time scale of 100 years the contribution of 1 kg CH_4 to global warming is 42 times as high as the emission of 1 kg CO_2. This means that if the characterization factor of CO_2 is 1, the characterization factor of CH4 is 42. Thus, the impact category indicator result for global warming can be calculated by multiplying the LCI result with the characterization factor" (Goedkoop *et al*., 2008: 23).

Furthermore some indicators are used to obtain the statistical values as explained below:

> "In methods like the Eco-indicator 99, the indicator for climate change is expressed in Disability Adjusted Life Years (DALY). This is a unit used by the WHO and World Bank to evaluate health statistics. The impact category indicator for Acidification is expressed in the percentage of decreased biodiversity over an area during a certain period" (Goedkoop *et al*., 2008: 23).

Lastly, the authors underline the difficulty level of concern and therefore attract attention to the degree of accuracy that is described as follows:

> "These indicators are of course much more difficult to calculate, as the complete environmental model has to be taken into account, and in that model many assumptions have to be made. They are thus more uncertain. On the other hand, their meaning is easier to understand and evaluate. There is a typical trade-off between uncertainty in the model of the environmental mechanism and the uncertainty in the interpretation. It depends on the goal and scope and the ability of the targeted audiences to understand aggregated or disaggregated results, which choice is made" (Goedkoop *et al*., 2008: 23).

2.4 Critical Analysis of the literature review

There were about 100 sources examined. The exact concern was to find out the existing knowledge on the LCA of masonry wall construction. After examinations, it was concluded that although there are several studies including detailed information on masonry and environmental issues, there are not many documents that examine them concurrently. Since exact information is not available, the scope of the literature review is organized in order to combine the existing information on masonry and information on LCA.

Referring to the sources including historical and modern examples of masonry, it is concluded that while the materials have been improved incredibly, construction techniques have not changed radically. One other attracting point is that some studies excludes the title of mortarless masonry and over emphasize the masonry with mortar. However, in recent studies mortarless masonry is highlighted especially for speedy construction. For instance, while the book by Beall in 1987 does not even mention mortarless masonry, the author attracts attention to the mentioned technique in her subsequent book published in 2001.

The last point to underline is that, although there was a tradition of reuse of readymade masonry units, the issue is mostly examined in a scientific way only after 2000.

In terms of LCA, since the concern is relatively new compared to history of masonry, it is not surprising that the most of available studies are in the experiment stage.

In brief, it was concluded that there is a gap between the studies on masonry and LCA. Therefore this study intends to fill a part of the gap.

CHAPTER 3

MATERIAL AND METHOD

This chapter is presented in order to specify the material used throughout the research and the way it was evaluated. With the help of literature review, information on masonry construction is presented which provided the base for the material and method chapter.

Basically, the material is main masonry wall types and the method is the organization and the comparison of possible life cycle scenarios in terms of environmental load through the LCA simulation software tool, SimaPro.

3.1 Material

The main groups of masonry materials are clay products, cementitious masonry units and natural stone (Beall, 1987 and 2001). Among the listed major material groups, most common ones are selected and used for the formulation of LCA. Referring to literature survey, right after the development of mortar, masonry with mortar is by far more common compared to mortarless masonry (Beall, 1987). Therefore masonry with mortar built with the widely used materials is used as inputs of this study. Additionally, it was observed that although there are several similarities, almost each masonry material has a specific mortar such as mud mortar and cement based mortar as well as specific bonding technique such as full or partial mortaring (Kömürcüoğlu, 1962; Beall, 1987 and Lyons, 2007).

3.1.1 Common masonry wall materials

(i) Clay brick with Portland cement mortar: Several types of both clay brick and cement mortar are widely used (TS EN 771-1, 2005 and TS EN 998-2, 2006). Among them fired clay brick and Portland cement mortar combination is one of the most preferred combination (http://www.tukder.org, last access 02.08.2012). These bricks may be solid or hollow which are also used with a layer of thermal insulation material such as XPS or EPS.

(ii) Cementitious block with adhesive mortar: One of the most widely used type of this group is autoclaved aerated concrete (AAC) block (Aksoy, 2008 and Öz, 2011). The binder is a special adhesive mortar (AKG catalog, 2012 and Ytong catalog, 2012).

(iii) Natural stone unit with Portland cement mortar: Several types of stone are used in the construction industry (Şengün, *et al*., 2009; Daloğlu & Emir, 2010 and Sancak, *et al*., 2010). Compact-tuff stone that is historically known as Küfeki has availability of several sources in Anatolia that made it one of the most used stone types in masonry wall construction (Sancak *et al.*, 2010). Although this kind of stone was mostly used with a specific mortar (Horasan Mortar) in history, it is used with the common cement mortar in recent times, since the use of Horasan Mortar is no longer being produced.

(iv) Mud brick with mud mortar: Mud brick masonry belongs to the clay products group. Although the ingredients of mud brick differ according to the properties of local sources, the basic definitions in literature was used as the substance for mud brick for this study (Kömürcüoğlu, 1962; Acun & Gürdal, 2003; Gürfidan, 2006 and Chel & Tiwari, 2009).

3.1.2 Determination of walls for LCA

In order to formulate the LCA, some other parameters of the wall are needed to be defined besides the properties of materials. One of the main parameters is the design of the walls either for load-bearing purpose or for infill. The walls for this study are taken as infill walls in other words disregarding the structural requirements. On the other hand, during the determination of the walls two main requirements are included, i.e. wall thickness that is commonly used and thickness needed to provide the required thermal insulation. The scope determining the common thickness of the wall and thermal requirements is defined according to Turkish standards.

(i) Wall A with conventional thickness: Wall A refers to the 1 m^2 masonry wall built in solid clay brick, hollow clay brick, AAC block, stone block or mud brick, with thicknesses commonly used in Turkey. A study on the subject indicates that described dimensions are; 19 cm for clay brick types (Aksoy, 2008), 25 cm for AAC block (Aksoy, 2008 and Nuh Catalog, 2012), 40 cm for stone block (http://www.karamankultur.gov.tr, last access 08.02.2012) and 48 cm for mud brick masonry walls (Kömürcüoğlu, 1962). The mentioned 1 m^2 masonry wall can be produced by the units in several dimensions since the market offers many types of units. Therefore the selection of the largest available unit for the production of 1 m^2 wall is stated as the delimitation for this study which is illustrated in Figure 3.1.

Right after the illustration of the stated masonry walls in Figure 3.1, information on the stated five types of wall is given under three major headings i.e. the basic building unit, type of joints and the wall type in Table 3.2. These headings are further divided into information on the description of the component, its density, dimensions, and the wastage percentage during construction.

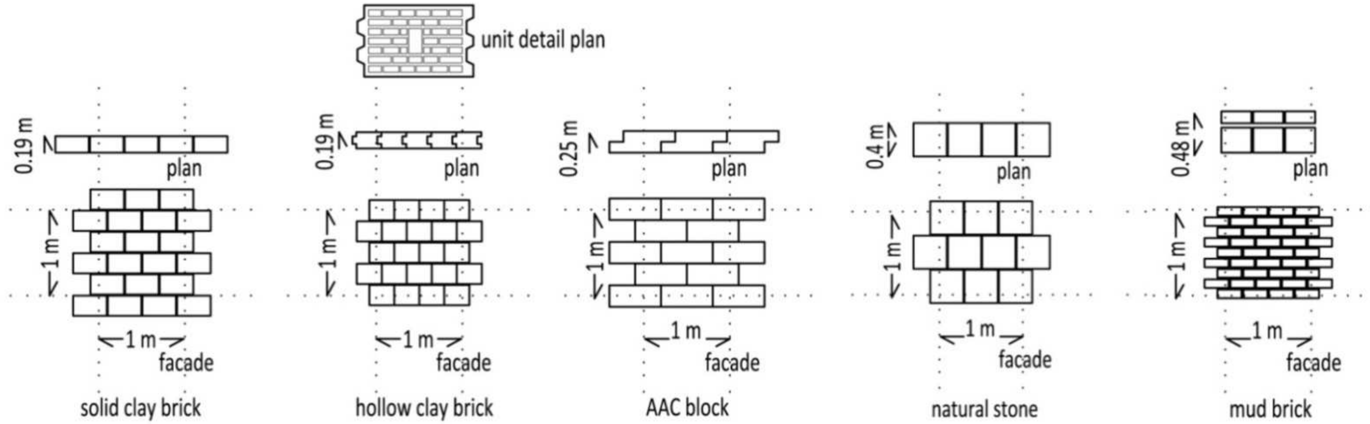

Figure 3.1 Drawings of the options for Wall A

Table 3.1 Recovery rates of reusable units for Wall A

Factors affecting recoverability ratio	**Maximum condition**	**Minimum condition**	**Solid clay brick**	**Hollow clay brick**	**AAC block**	**Stone block**
risks in the environment	3	1	3	3	3	3
area of joint faces /	0/100= 0%	100/100=100%	1.17/3.17=46%	1.97/4.88=40%	1/4.5=22%	2.5/5.3=46%
area of all faces	3	1	2.08	2.2	2.56	2.08
adhesion level of joint	3	1	2	1	1	2
damage to material	3	1	2	1	1	2
accessibility of joint	3	1	3	1	3	3
tool complexity	3	1	3	3	3	3
time requirement	3	1	3	2	3	3
total point	21	7	18.08	13.2	16.56	18.08
equivalent percentage	**100%**	**0%**	**79%**	**44%**	**68%**	**79%**

Table 3.2 Information on the options of Wall A

Masonry wall type	Unit				Jointing				Wall	
	Description	Density kg/m^3	Dimensions mm	Wastage %	Description	Density kg/m^3	Remarks	Wastage %	Description	Actual thickness m
solid clay brick	high density, solid, fired clay brick[I]	1600 [I]	390x 190x 235 [I]	8% [II]	1 unit Portland cement[III] 1 unit lime[III] 6 unit sand[III] water[III]	1400 [IV]	12 mm flush joint[V] 50% of outer face repointing in each 25 years[VI]	50% [VII]	solid wall, running bond, bare wall	0.19 [VIII]
hollow clay brick	W class, low density, hollow, fired clay brick[I]	650 [I]	290x 190x 235 [I]	8% [II]	1 unit portland cement[III] 1 unit lime[III] 6 unit sand[III] water[III]	1400 [IV]	12 mm flush joint[V], 10 mm entering of mortar through the voids of bricks only bed mortar[I] 50% of outer face repointing in each 25 years[VI]	50% [VII]	solid wall of hollow units, running bond, bare wall	0.19 [VIII]
AAC block	light concrete masonry product[IX]	600 [X]	600x 250x 250[X]	3% [XI]	adhesive mortar, thin bed application[X, XII]	1400 [XIII]	2.5 mm flush joint[XIII] only bed mortar[X, XII]	50% [VII]	solid wall, running bond, bare wall	0.25 [XIV]
stone unit	compact-tuff stone [XVI]	1600 [XV]	400x 400x 300	10% [XI]	mortar [III]	1400 [XIII]	12 mm flush joint[V] 50% of outer face repointing in each 25 years[VI]	50% [VII]	solid wall, running bond, bare wall	0.40 [XVII]
mud brick[XXI]	1 unit clay[XVIII] 1 unit aggregate[XVIII] straw 3% of the weight[XVIII] water[XVIII]	900 [XIX]	290x 350x 100 [XIX] 140x 350x 100 [XIX]	clay and aggregate= 20% [XX] straw= 20% [XX] water= 50% [XX]	same as unit definition	900 [XIX]	20 mm flush joint[XVIII] 20 mm renewal of 10 % of outer face in each 10 years	same as unit wastage ratio	solid wall, running bond, bare wall	0.48 [XXII]

[I] TS EN 771-1, 2005
[II] Samsun Ticaret Odası, 2002
[III] TS EN 998-2, 2006; Işıklar brick catalog, 2012 and Kilsan brick catalog, 2012
[IV] Bostik, 2008
[V] TS EN 1745, 2004
[VI] Lippiatt, 2007
[VII] Bossink & Brouwers, 1996
[VIII] Aksoy, 2008
[IX] Beall, 1987
[X] Kurç & Anıl, 2008 and AKG catalog, 2012
[XI] Didim Ticaret Odası, 2010
[XII] Ytong catalog, 2012
[XIII] Fixkim, 2012
[XIV] Aksoy, 2008 and Nuh Catalog, 2012
[XV] Sancak, et al., 2010
[XVI] Sancak, et al., 2010
[XVII] http://www.karamankultur.gov.tr, last access 08.02.2012
[XVIII] Kömürcüoğlu, 1962
[XIX] Gürfidan, 2006
[XX] Ege Bölgesi Sanayi Odası Vakfı, 1993
[XXI] Mud brick is indicated in a more detailed way compared to the other materials hence
it is not available in the used database. Therefore it is obtained by combining the sub-ingredient the average values are taken from Kömürcüoğlu (1962)
[XXII] Kömürcüoğlu, 1962

(ii) Wall B with thickness satisfying thermal insulation standards: According to the report on Thermal Insulation Requirements for Buildings, Turkey is comprised of four thermal zones (TS 825, 2008). Zone 1 is the region having mildest climate and the 4 has the harshest climate. The building in any zone must fulfill the requirements stated in the Thermal Regulations Document. These regulations specify the minimum conditions for the various components and spaces, such as fenestration dimensions, roof insulation and basement conditions. In addition, maximum heat transmission value for external walls is specified. Among the zones, 3rd one encompasses the largest region of the country. Thus the requirements for Zone 3 were followed for the formulation of Wall B scenarios. According to the regulations, maximum heat transmission value, U, is 0.50 W/m^2K. Wall B refers to the masonry wall built in solid clay brick, hollow clay brick, AAC block, stone block or mud brick in the thickness for each to satisfy the required heat transmission value.

On the other hand, the masonry wall that satisfies this thermal value can be produced by the units in several dimensions. Therefore the selection of the largest available unit for the production of 1 m^2 wall is stated as the delimitation of the study which is also illustrated in Figure 3.2. Right after the presentation of the walls, Table 3.4 indicates the information on the stated five types of wall under four major headings i.e. the basic building unit, wall type, recovery rate of reusable units and the fate in the end-of-life phase. The heading containing the information on the wall itself is further divided into three i.e. thermal conductivity which presents the specific value of each wall type, required thickness that indicates the estimated equivalent thickness for each wall type according to heat transmission value and actual thickness that indicates the thickness of the each wall type that is built with the units available in the construction material market. The jointing detail as well as the transportation and heat treatment requirements for Wall B is not presented in the Table since all the inputs are the repetition of the inputs used for Wall A.

Finally, in the Table, the information on the mud brick are given in a more articulated way i.e. the sub ingredients of the mud brick since there is no exact option available in the eco-invent database of SimaPro software.

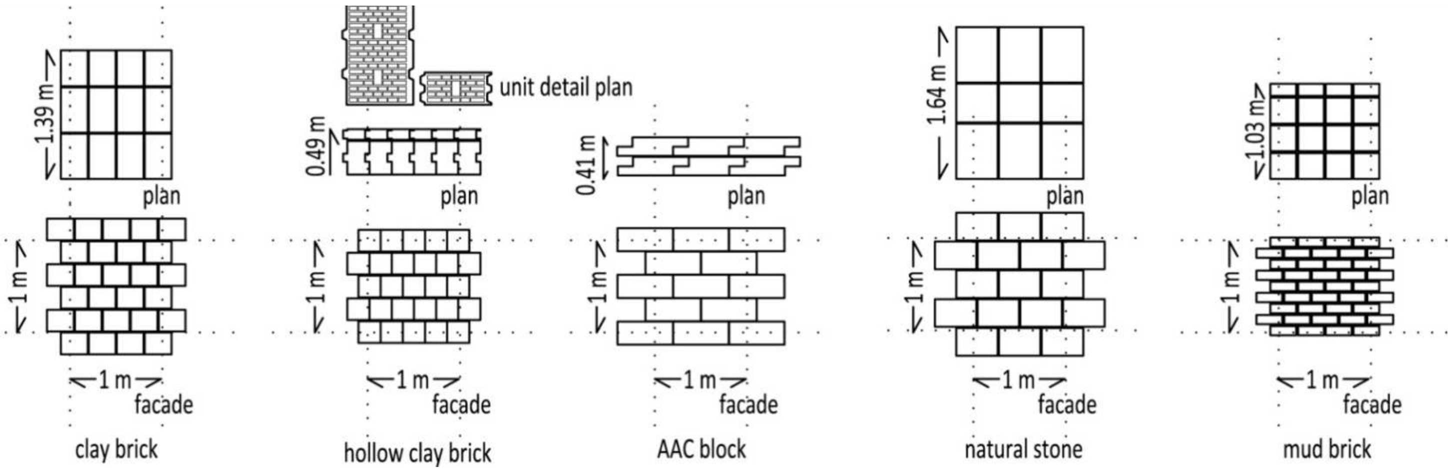

Figure 3.2 Drawings of the options for Wall B

Table 3.3 Recovery rates of reusable units for Wall B

Factors affecting recoverability ratio	**Maximum condition**	**Minimum condition**	**Solid clay brick**	**Hollow clay brick**	**AAC block**	**Stone block**
risks in the environment	3	1	3	3	3	3
area of joint faces / area of all faces	0/100= 0%	100/100=100%	12.82/17.90=71%	5.2/9=57%	2.64/6.89=38%	11/18=61%
	3	1	1.58	1.86	2.22	1.78
adhesion level of joint	3	1	2	1	1	2
damage to material	3	1	2	1	1	2
accessibility of joint	3	1	1	1	3	1
tool complexity	3	1	3	3	3	3
time requirement	3	1	1	1	3	1
total point	21	7	13.58	11.86	16.22	13.78
equivalent percentage	**100%**	**0%**	**47%**	**35%**	**67%**	**49%**

Table 3.4 Information on the options of Wall B

Masonry wall type	Unit	Wall		
	Dimensions mm	Heat conductivity (λh) W/mK	Required thickness m	Actual thickness m
solid clay brick	290x 490x 235 [I]	0.68 [II]	1.36 [III]	1.39 [III]
	290x 390x 235 [I]			
hollow clay brick	240x 365x 235 [I]	0.23 [II]	0.46 [III]	0.49 [III]
	240x 115x 235 [I]			
AAC block	600x 200x 250 [IV]	0.19 [II]	0.38 [III]	0.41 [III]
stone block	450x 600x 300	0.81 [II]	1.62 [III]	1.64 [III]
	450x 420x 300			
mud brick	280x 280x 100 [V]	0.5 [VI]	1 [III]	1.03 [III]
	280x 130x 100 [V]			

[I] TS EN 771-1, 2005
[II] TS 825, 2008
[III] Required thickness refers to the estimated thickness according to the requirements declared in TSE 825, 2008 and actual thickness refers to the thickness built with available units in the market
[IV] Nuh Catalog, 2012
[V] Gürfidan, 2006
[VI] Chel & Tiwari, 2009

3.2 Method

The information presented in the material section is grouped according to certain criteria to formulate possible life cycle scenarios for each type of masonry wall. The broadest division is according to the commonly used thickness of the unplastered 1 m^2 wall as well as the thickness for equivalent heat transmission value. In that respect two types of walls are organized i.e. Wall A refers to the wall having specific thicknesses of widespread use of solid or hollow clay brick, AAC block, stone block and mud brick in Turkey while Wall B refers to the wall satisfying the 0.50 W/m^2K heat transmission value, as required by TS 825 (2008), again built in the above mentioned materials. After organizing the main division of the collected information in two groups i.e. Wall A and wall B, another division is made by means of service life periods of the walls. Since there are two types of information on useful lifetime i.e. collected from literature and estimated from sample cities, evaluations of Wall A and Wall B are further divided into two. In these groups the walls are assumed to either attain useful age as determined in published sources (see Tab. 3.6) or as determined according to the age of the registered historical buildings in the selected cities (see Tab A.1) Accordingly, the maximum lifetime of a stone wall is taken as 400 years (see Tab. 3.6) and 800 years (see Tab. 3.7) respectively, while the rest of the wall types are equalized for the sake of comparison by repeating the life cycles to add up to the lifetime of a stone wall i.e. 400 and 800 years.

Finally, the last division is made according to the specific possible end-of-life scenarios of each masonry wall, namely: varying percentages of landfill, reuse, recycling and incineration. Referring to the literature and background information five scenarios for solid clay brick, five scenarios for hollow clay brick, four for AAC block, one for stone and one for mud brick masonry were designed accordingly. All the organization of described information is applied in SimaPro software to obtain equivalent environmental scores in order to detect the level of environmental impacts (see Tab. 3.5). The way of evaluation is prepared according to the LCA concept i.e. each wall obtained a score that refers to its level of impact on nature during its life cycle. Since the available database that can be used in the software do not contain the exact data for Turkey, input for the variances in the software, data for the most similar materials and processes are selected.

Table 3.5 The variables that are put in the LCA software, SimaPro

Wall title	Description
Wall A	1 m^2 masonry wall with conventional thickness commonly used in Turkish construction sector

Specific thickness	
solid clay brick	0.19 m
hollow clay brick	0.19 m
AAC block	0.25 m
stone block	0.40 m
mud brick	0.48 m

Service life of walls according to literature(I)		Number of cycles in 400 years*
solid clay brick	200 years	2
hollow clay brick	200 years	2
AAC block	100 years	4
stone block	400 years	1
mud brick	250 years	1.6

* maximum age reported in literature is 400 years as indicated in the footnote

solid clay brick scenario	
1	landfill
2	reuse, landfill
3	reuse, landfill
4	reuse, recycling, landfill
5	reuse, recycling, landfill
hollow clay brick scenario	
1	landfill
2	reuse, landfill
3	reuse, landfill
4	reuse, recycling, landfill
5	reuse, recycling, landfill
AAC block scenario	
1	landfill
2	recycling, landfill
3	reuse, landfill
4	reuse, recycling, landfill
stone block scenario	
1	reuse, landfill
mud brick scenario	
1	reuse, landfill, incineration

Service life of walls according to observed data(II)		Number of cycles in 800 years**
solid clay brick	200 years	4
hollow clay brick	200 years	4
AAC block	100 years	8
stone block	800 years	1
mud brick	200 years	4

** maximum age observed from sample data is 800 years as indicated in the footnote

solid clay brick scenario	
1	landfill
2	reuse, landfill
3	reuse, landfill
4	reuse, recycling, landfill
5	reuse, recycling, landfill
hollow clay brick scenario	
1	landfill
2	reuse, landfill
3	reuse, landfill
4	reuse, recycling, landfill
5	reuse, recycling, landfill
AAC block scenario	
1	landfill
2	recycling, landfill
3	reuse, landfill
4	reuse, recycling, landfill
stone block scenario	
1	reuse, landfill
mud brick scenario	
1	reuse, landfill, incineration

Wall title	Description
wall B	1 m^2 masonry wall with the thicknesses satisfying Turkish thermal insulation standards (0.50 W/m^{2}K)

Specific thickness	
solid clay brick	1.39 m
hollow clay brick	0.49 m
AAC block	0.41 m
stone block	1.64 m
mud brick	1 m

Service life of walls according to literature(I)		Number of cycles in 400 years*
solid clay brick	200 years	2
hollow clay brick	200 years	2
AAC block	100 years	4
stone block	400 years	1
mud brick	250 years	1.6

* maximum age reported in literature is 400 years as indicated in the footnote

solid clay brick scenario	
1	landfill
2	reuse, landfill
3	reuse, landfill
4	reuse, recycling, landfill
5	reuse, recycling, landfill
hollow clay brick scenario	
1	landfill
2	reuse, landfill
3	reuse, landfill
4	reuse, recycling, landfill
5	reuse, recycling, landfill
AAC block scenario	
1	landfill
2	recycling, landfill
3	reuse, landfill
4	reuse, recycling, landfill
stone block scenario	
1	reuse, landfill
mud brick scenario	
1	reuse, landfill, incineration

Service life of walls according to observed data(II)		Number of cycles in 800 years**
solid clay brick	200 years	4
hollow clay brick	200 years	4
AAC block	100 years	8
stone block	800 years	1
mud brick	200 years	4

** maximum age observed from sample data is 800 years as indicated in the footnote

solid clay brick scenario	
1	landfill
2	reuse, landfill
3	reuse, landfill
4	reuse, recycling, landfill
5	reuse, recycling, landfill
hollow clay brick scenario	
1	landfill
2	reuse, landfill
3	reuse, landfill
4	reuse, recycling, landfill
5	reuse, recycling, landfill
AAC block scenario	
1	landfill
2	recycling, landfill
3	reuse, landfill
4	reuse, recycling, landfill
stone block scenario	
1	reuse, landfill
mud brick scenario	
1	reuse, landfill, incineration

(I) Table 3.6 indicates the lifetime values in literature
(II) Table 3.7 indicates the estimated lifetime values

The basic properties of stated masonry types were easily obtained from related academic studies and the documents presented by production firms. On the other hand, the information on the disassembly process of the masonry walls as well as unit recovery statistics is also needed since LCA study requires such information for the formulation of end-of-life scenarios. Therefore Table 2.1, which is already presented as a method for reliable unit recovery assumptions, is modified in order to derive a unique tool for this study as presented in Table 3.1 and Table 3.3.

According to presented methodology, the walls gain points between 1 and 3 for each question. When the points are summed up, the equivalent percentage of recovery rate is calculated. Yet, the crucial aspect of this system is that the recovery rates are relatively estimated that means that are correct only for the defined scope. In other words, the recovery rate of Wall A is reliable only if the recovery rate of Wall B is also estimated referring to this method. For instance, two of the questions are risks in the environment and tool complexity. In this sense all of the walls gain the same point since none of them emit toxic chemicals during disassembly as well as requiring advanced tools for demounting. On the other hand, the ratio of the joint face area to the all faces area differs from wall to wall. Hence, a low rate results in lower score that means it is more convenient to recover.

Additionally, the adhesion level of mortar is also decisive i.e. mortar with chemical additions is more adhesive than cement based mortar (Fixkim, 2012). The other decisive question is damage to material, in this sense if the area of mortared faces is more; the damage to material during separation is also increased. Since the disassembly of units is done manually, the accessibility of mortar for removal is crucial. Therefore the accessibility is a question for recovery rate. Finally the last question is the time requirement of disassembly, if there is larger area to clean up from the mortar; the time requirement is a lot which is a negative aspect in terms of recovery. Taking all these aspects into consideration, each wall type gained a relative recovery score that is illustrated in Table 3.1 and 3.3.

Besides the materials evaluated in the study, one more type of wall i.e. thermally insulated hollow clay brick masonry wall is also evaluated since this type of wall is also a common masonry type. Since this type is only valid for the thermally insulated wall group i.e. Wall B, its evaluation is presented under as an additional group of scenarios in accordance with the structure of evaluation used for the main masonry materials.

In addition to the determination of prevalent masonry types and expected lifetime periods, the last point to determine is the varying transportation distances that emerge during the life phases of walls i.e. transportation of auxiliary material to production plant, transportation of masonry units and connectors to construction site, transportation for the materials that are used for maintenance and lastly transportation for the disposal of the debris. All of the information needed for the determination of presented distances, the values for the selected five sample cities (see Tab A.1) that are declared by General Directorate of Highways and some other websites are used that are presented in a detailed manner in the following sections.

3.2.1 Useful lifetime determination of selected masonry types

In literature there are several studies to detect the lifetime of buildings, components and materials. Almost all of the studies argue that estimating the exact useful lifetime of any product is highly complicated owing to several factors affecting the period e.g. conditions of the environment and the behavior of the users. Therefore available studies mostly assume the lifetime periods of products such as the useful lifetime of the selected masonry walls which are indicated in Table 3.6 below.

At this point it is important to note that since this study does not refer to a specific building, the lifetime definitions are broad assumptions based on available information in published sources (see Tab. 3.6). The main source of presented values is either sample buildings or the assumptions by researchers cited in this study. Therefore the ages presented here are used as generalized periods for materials and masonry wall types. For instance, although accepting the term ‘’stone’’ as representative for all types of stones is not a reliable method, this term is used for the sake of simplicity without the complexity of detecting the possible lifetime periods for each type i.e. specific environmental conditions are quite determinants in addition to the behavior of the user.

Besides all, the materials mentioned in the table i.e. clay brick, AAC block, stone block and mud brick differ from production plant to production plant as well as from construction traditions of countries which makes the lifetime detection much more complicated.

Consequently, although it is not the most appropriate method of lifetime detection of masonry walls, the available information is used as inputs for this study as illustrated in Table 3.6.

Table 3.6 Lifetime assumptions in literature for selected masonry wall types

Wall type	**Useful lifetime**
clay brick masonry	about 200 years (Lippiatt, 2007)
AAC block masonry	about 100 years (Institute Construction and Environment, 2011)
stone block masonry	about 400 years (Lyons, 2007)
mud brick masonry	about 250 years (Kömürcüoğlu, 1962)

In addition to the information provided by the literature, useful lifetime information on the selected types of walls was also collected within the scope of Turkey. Thermal Zone 3, containing the largest region in the country, is the limit for the estimations of useful life periods. Five sample cities were randomly selected from the zone since it is scattered into five separate parts within the country (see Fig. 3.3).

A list of registered historical buildings in each city can be found from the Ministry of Culture and Tourism (İl Kültür Turizm Müdürlüğü) websites. The list of stated buildings in the five sample cities, namely, Kırklareli, Karaman, Artvin, Tunceli and Iğdır were collected from the websites and then the related buildings were taken as the population for this study.

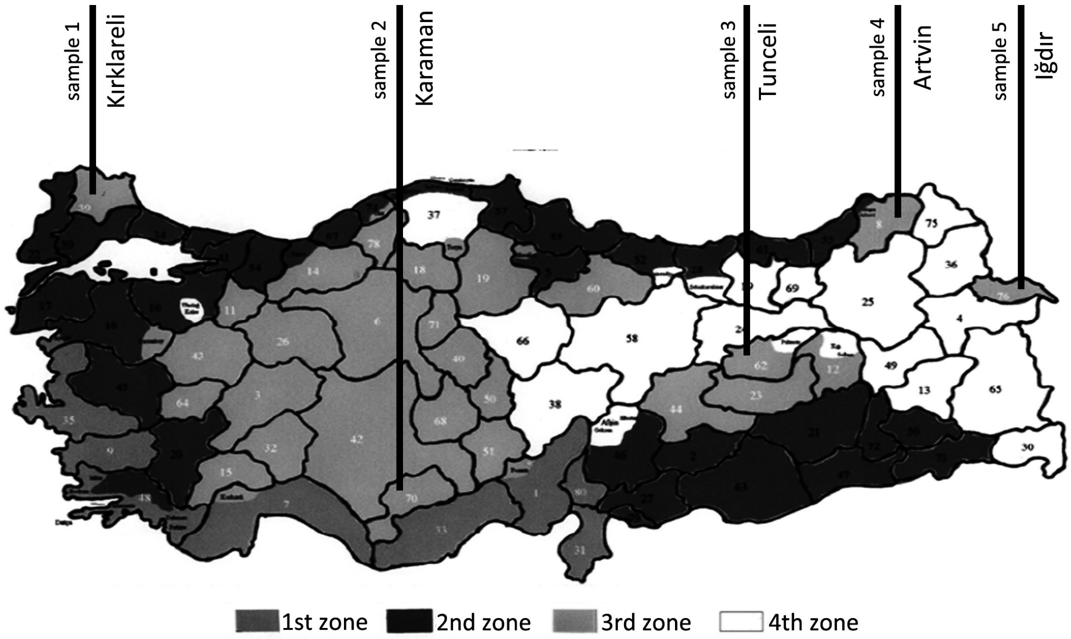

Figure 3.3 Sample cities in Thermal Zone 3 (TS 825, 2008: 75)

The building either in livable condition or in damaged condition was regarded as a valid member of the population. Conversely, some members of the population were eliminated according to certain criteria i.e. bath houses (hamam), bridges and fountains since such buildings have special finishes i.e. unique plaster or ceramics, to tackle with water problem since the construction is in direct relation with water. In addition, castles and fortresses, that are built extremely safe for defense and had over strong walls, were also excluded. One other exclusion criterion is renovation since the useful lifetime is significantly affected by restoration and repairs. Besides the restrictions, there are also some limitations imposed by the available information. For example, limitation imposed owing to traditions of decorating building is the use of plaster. Thus, information on plastered stone masonry was analyzed instead of information on bare wall (see Tab A.1 for the types of buildings). The existing buildings built with several kinds of stones in selected cities are regarded as valid for this study although it would be better only to detect and analyze the buildings in compact-tuff stone. Further limitation of the context is the rapid changes in dwelling architecture owing to the unsteady social conditions. Thus, dwellings in stone masonry were excluded since they are mostly demolished by social needs rather than end-of-life phase. Consequently, it was observed that clay and mud brick were preferred rather than stone in dwelling architecture hence the collection of mud brick information was ensured from the history of dwelling architecture. Although stone was used in all sample cities, clay and mud brick were not preferred on account of local climatic factors. Since AAC block is not a historical material, it was not possible to collect information on it among the registered historical buildings of sample cities. Therefore AAC walls were not part of the population.

At this point, it is important to note that selected buildings (see Tab. A.1) are still standing therefore their age has been taken as their current age and indicated in Table 3.7 below. If they continue to exist a 100 years from now, their life would be increased by 100 for the sake of evaluation for that time.

Table 3.7 Estimations for the lifetime of selected masonry walls according to information collected from sample cities

Wall type	**Lifetime of walls in sample cities**					**Average age**
	Kırklareli[(I)]	Karaman[(I)]	Artvin[(I)]	Tunceli[(I)]	Iğdır[(I)]	
clay brick masonry	200	data not avaliable	data not avaliable	a few buildings exist but specific names are not avaliable	data not avaliable	**200 years**
AAC block masonry	data not avaliable					**100 years**
stone block masonry	617	1000	1100	774	800	**800 years**
mud brick masonry	200	200	not common owing to extreme humidity (Sen *et al*., 2010)	200	data not avaliable	**200 years**

3.2.2 Determination of distance from production plant to construction site

Masonry walls selected for this study were made of four types of materials i.e. clay brick, AAC block, stone block or mud brick. In most cases, mud brick is shaped by hand from the available mud source, composed of clay and aggregate, and the stone is obtained from quarries but clay brick and AAC block production requires specialized plants. Therefore, in order to build any type of masonry wall, the builder needs to transport the masonry units from the resource, quarry or plant up to the construction site. The locations of the production plants and the quarries in Turkey were determined in order to estimate the transportation distances for material supply. The supply centers were chosen according to their proximity to the selected five cities. Since the most preferred way of freight transportation is via highway in Turkey, the road distances provided by related websites were collected, mean values were estimated and used for the scenarios. During the estimations, the imaginary location of the construction site for clay brick, AAC block and stone block masonry is selected as the city center of each sample cities.

In terms of mud brick the distance is regarded within the scale of village that is described in further sections.

Figure 3.4 (http://www.tukder.org, last access 02.08.2012) indicates the cities that contain at least five brick production plants. On this Figure, one more location i.e. Tunceli, Akpazar is labeled since there is only one brick factory (Arguç *et al*., 2005) close to Tunceli.

Figure 3.4 Locations of brick factories close to the study areas derived from Arguç *et al*. (2005) and (http://www.tukder.org, last access 02.08.2012)

After detecting the closest clay brick factories, the highway distances are obtained from the related websites and the average distance is estimated and indicated in Table 3.8.

Table 3.8 Highway distances between the sample cities and the closest clay brick production plants

Sample city	**Closest brick production plant**	**Highway distance[I]**
Kırklareli	Tekirdağ	121 km
Karaman	Konya	119 km
Artvin	Tokat, Erbaa	595 km
Tunceli	Tunceli, Akpazar	45 km
Iğdır	Tunceli, Akpazar	41 km
Mean of the distances		**184 km**

In terms of AAC block production, the number of plants is much lower than clay brick plants. Referring to the information provided by Yıldırım (2002) the cities having AAC plants were labeled in black and one other city i.e. Bilecik (http://www.akg-gazbeton.com, last access 08.02.2012) was labeled in dark gray and thus Figure 3.5 is obtained.

Figure 3.5 AAC plant locations in Turkey
derived from Yıldırım (2002)
and (http://www.akg-gazbeton.com, last access 08.02.1012)

Referring to the obtained image and the collected transportation distances, average distance was estimated and indicated in Table 3.9 below.

[I] The highway distances are collected from the listed websites below:
http://www.kgm.gov.tr, last access 08.02.2012
http://www.e-sehir.com , last access 08.02.2012
http://www.illerarasimesafe.com, last access 08.02.2012

Table 3.9 Highway distances between the sample cities and the closest AAC block production plants

Sample city	Closest AAC block production plant	Highway distance[I]
Kırklareli	Tekirdağ, Çorlu	115 km
Karaman	Isparta	370 km
Artvin	Mardin	645 km
Tunceli	Mardin	371 km
Iğdır	Mardin	372 km
Mean of the distances		**424 km**

In the case of stone, compact-tuff (Küfeki) which has several quarries scattered throughout the country (Sancak *et al.*, 2010) was used for the estimation of the distances (Fig 3.6).

Figure 3.6 Compact-tuff quarries in Turkey
derived from Özkahraman & Işık (?), Yaşar *et al.* (2009), Daloğlu & Emir (2010) and Sancak *et al.* (2010)

Referring to the compact-tuff quarry locations, the transportation distances are collected and the average transportation distance is estimated (see Tab. 3.10).

[I] The highway distances are collected from the listed websites below:
http://www.kgm.gov.tr, last access 08.02.2012
http://www.e-sehir.com , last access 08.02.2012
http://www.illerarasimesafe.com, last access 08.02.2012

Table 3.10 Highway distances between the sample cities and the closest compact-tuff quarries

Sample city	Closest tuff quarry	Highway distance
Kırklareli	Tekirdağ	121 km$^{(I)}$
Karaman	Konya	119 km$^{(I)}$
Artvin	Artvin, Murgul	48 km$^{(I)}$
Tunceli	Tunceli, Murgul	31 km$^{(I)}$
Iğdır	Iğdır	4 km$^{(II)}$
Mean of the distances		**65 km**

The construction site for buildings in clay brick, AAC block and stone block is assumed to be the city center. However when the case is mud brick, it is not realistic since it is known that, mud brick constructions are mostly preferred in rural areas. Therefore the villages that are managed by the central city were analyzed and the distances within the border of the villages were collected. Referring to the documents (http://maps.google.com, last acess 08.02.2012), villages are schematically illustrated as pentagon with about 500 m radius. One sample village near each of the five sample cities is illustrated with a line scale in Figure 3.7 below. Since the distance between the central point and the border of the villages are about 500 m, the transportation distance for mud brick is assumed as 500 m.

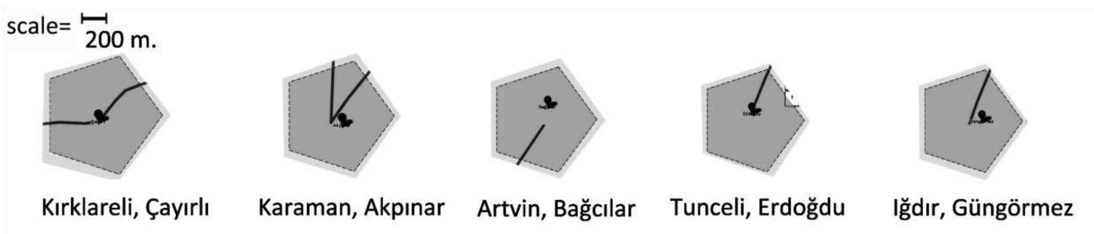

Figure 3.7 Schematic borders of the selected villages (http://maps.google.com, last access 08.02.2012)

$^{(I)}$ Referring to Figure 3.8 the average distance between the center and the border of the city
$^{(II)}$ The highway distances are collected from the listed websites below:
http://www.kgm.gov.tr, last access 08.02.2012
http://www.e-sehir.com , last access 08.02.2012
http://www.illerarasimesafe.com, last access 08.02.2012

3.2.3 Determination of distance from demolition site to disposal point

The transportation of materials to the construction site is not the only transportation during the lifetime of masonry walls. When the useful life period ends, debris is transported to a dumping site for landfill, to a plant for recycling or to a location for reuse. By default the dumping sites are located within the city borders. In addition, the distance for reuse can be assumed as within the city scale since it is logical to reuse any product nearby. Therefore, In order to determine the average transportation distances for dumping and reuse, the borders of the selected five cities were collected and illustrated in Figure 3.8 below.

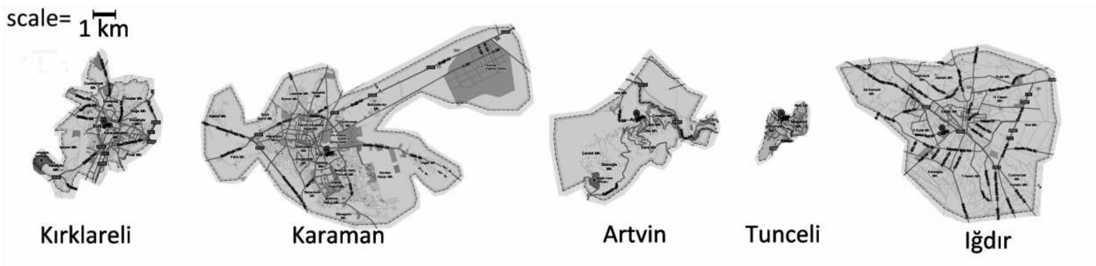

Figure 3.8 Maps of the selected cities (Google maps, 2012)

Referring to this figure, a list indicating average distances between the central point and the border of the cities were obtained and illustrated in Table 3.11 below.

Table 3.11 Highway distances between the center and the border of the city

Sample city	**Mean of the distances between the central point and the border of the city** [I]
Kırklareli	3 km
Karaman	5 km
Artvin	3 km
Tunceli	1 km
Iğdır	4 km
Mean of the distances	**3 km**

[I] Referring to Figure 3.8 the average distance between the center and the border of the city

The estimated values are used for clay brick, AAC block and stone block masonry walls since the dumping sites contain any kind of construction debris. Additionally, the distance for dumping the mud brick debris is again assumed as 500 m.

Briefly, the information on masonry walls in terms of materials, useful lifetimes and requirements during the life cycles was analyzed and presented in the material section. The following section i.e. method describes the way of evaluating the collected information.

3.2.4 Formulation of LCA scenarios for SimaPro

(i) Scenarios for Wall A

- Solid clay brick masonry wall scenarios: Using the information presented in Table 3.5, five scenarios were developed for solid clay brick masonry wall. For the formulation of the scenarios, similar studies were used as input. For instance, a report by Ozkan & Düzgüneş (2002) reveals that most of the construction debris is landfilled in Turkey. Thus, the first end-of-life scenario was defined as demolition and landfill.

In addition, although Lippiatt (2007) asserts that the service life of the clay brick wall can be assumed as 200 years, Bown (2009) argues that clay brick can serve up to 650 years under the right conditions. Hence, these values were used as input for the end-of-life phase of second scenario. Since reuse of clay bricks is possible, the framework suggested by Thormark (2001) in Table 2.1 was articulated and used to determine possible reliable percentage for a realistic recovery scenario that is illustrated in Table 3.1 and Table 3.3. The third scenario was based on the experiment of Dijk *et al*. (2002) that focuses on heat treatment recovery.

Finally, the inputs for the fourth and fifth scenarios were taken from the experiment of Demir & Orhan (2003) on the recycling of new bricks in the end-of-life phase as well as the recycled content of secondary brick production. Additionally, referring to the close loop concept [I] presented by Addis (2006) the recycled content ratio was returned to the new production cycle in the end-of-life phase in order to sustain the continuity of the cycle. By default, recycling has several possible meanings but here it means crushing of waste bricks and transportation up to the production plant. Hence, in clay brick wall scenarios the waste material only needs to be crushed and transported in order to be converting into recycled content. The formulation of the scenarios is presented in Table 3.12.

- Hollow clay brick masonry wall scenarios: For the formulation of hollow clay brick masonry wall scenarios, the inputs used for the formulation of solid clay brick masonry wall scenarios are used and presented in Table 3.13. On the other hand, the rate for recovery and reuse of units differ as indicated in Table 3.1, since the masonry unit is different than the previous one that affects the rates which changes the end-of-life formulation.

- AAC block masonry wall scenarios: Using the information presented in Table 3.5, four scenarios were developed for AAC block masonry wall. For the formulation of the scenarios, similar studies were used as inputs and consequently two realistic as well as two imaginary scenarios were developed.

End-of-life scenario of the first case was stated as demolition and landfill since it is reported as the most preferred option in reality (AUB, 2005 and Institute Construction and Environment, 2011) Additionally, although the application is quite rare, recycling and recycled content are stated as possible options. Thus, the second scenario was shaped by secondary material and recycling in the end-of-life phase.

[I] Addis (2006) states that there are two types of loop for products. First one is the open loop which refers to the take-make-waste application. The other one is close loop that refers to the recycling of waste that satisfies the continuity of the cycle. In this study, the secondary materials are forced to recycling in order to follow the described concept.

The third and the fourth scenarios are imaginary scenarios since the reuse option after 100 years service lifetime is not clear because the material has started to be produced since 1920 (AUB, 2005) and has not completed the expected service lifetime of one cycle i.e. 100 years yet. The scenarios are illustrated in Table 3.14.

- Stone unit masonry wall scenarios: A look at the history of the masonry reveals that stone units were always regarded as valuable building material and recovered for reuse which formulated this scenario.

- Mud brick masonry wall scenarios: Mud brick with mud mortar is a common type of masonry especially in rural settlements. Any chemical reaction exists during the production of mud brick and mortar which means the material in the end-of-life phase can still be accepted as raw material. Therefore, the final stage of the scenario was defined as recovery for reuse (see Table 3.16). In the Table, the information on the mud brick are given in a more articulated way i.e. the sub ingredients of the mud brick since there is no exact option available in the eco-invent database of SimaPro software.

(ii) Scenarios for Wall B

The structure of the Wall B scenarios is the same as Wall A therefore only the different aspects are indicated in Table 3.17

Table 3.12 Information on the solid clay brick option of Wall A

Scenario	Assembly requirements		Useful life period requirements		Fate at the end-of-life			
1	solid clay brick including wastage mortar including wastage transportation to the construction site[I]	man power and basic hand tools	repointing mortar including wastage transportation to the construction site[I]	man power and basic hand tools	100% landfill transportation to the dumping site[II]	demolition is done manually with basic hand tools		
2	same as scenario 1		same as scenario 1		100% disassembly on the construction site	disassembly is done manually with basic hand tools	100% separation of bricks either in good quality or crushed form 100% separation of mortar	72% reuse of bricks[III] 28% landfill of bricks 100% landfill of mortar[IV] transportation for reuse, landfill of bricks and landfill of mortar[V]
3	same as scenario 1		same as scenario 1		100% of the wall is broken into smaller pieces on the construction site transportation to the workshop for heat treatment[V]	disassembly is done manually with basic hand tools and heat treatment is in an industrial furnace[VI]	100% separation of bricks either in good quality or crushed form 100% separation of mortar	41% reuse of bricks[VI] 59% landfill of bricks 100% landfill of mortar[IV] transportation for reuse, landfill of bricks and landfill of mortar[V]
4	same as scenario 1 but with secondary bricks[VII]		same as scenario 1		100% disassembly on the construction site	disassembly is done manually with basic hand tools	100% separation of bricks either in good quality or crushed form 100% separation of mortar	70% reuse of bricks[VIII] 30% recycling of bricks[VII] 100% landfill of mortar[IV] transportation for reuse of bricks and landfill of mortar[V] transportation and crushing of bricks for recycling[I]
5	same as previous scenario 4		same as scenario 1		100% of the wall is broken into smaller pieces on the construction site transportation to the workshop for heat treatment[V]	disassembly is done manually with basic hand tools and heat treatment is in an industrial furnace[VI]	100% separation of bricks either in good quality or crushed form 100% separation of mortar	41% reuse of bricks[VI] 30% recycling of bricks[VII] 29% landfill of bricks 100% landfill of mortar[IV] transportation for reuse, landfill of bricks and landfill of mortar[V] transportation and crushing of bricks for recycling[I]

[I] Referring to the estimations presented in Table 3.8, average distance is 184 km
[II] Referring to the estimations presented in Table 3.11, average distance is 3 km
[III] Although recovery rate is 79% in Table 3.1, the result is 72% when the wastage is subtracted
[IV] Referring to literature review, recovery and recycling of mortar is not the case for Turkey
[V] Referring to the estimations presented in Table 3.11, average distance is 3 km for inner city transportation
[VI] Dijk *et al*. (2002) state that about 540 °C heating during disassembly results in about 45% recovery of units in reusable form and quality. The result is 41%, when the wastage is subtracted. The energy is natural gas in industrial furnace > 100kW
[VII] Possible recycled content rate for secondary clay brick production is 30% (Demir & Orhan, 2003)
[VIII] Remaining after recycling

Table 3.13 Information on the hollow clay brick option of Wall A

Scenario	Assembly requirements		Useful life period requirements		Fate at the end-of-life			
1	hollow clay brick including wastage mortar including wastage transportation to the construction site[I]	man power and basic hand tools	repointing mortar including wastage transportation to the construction site[I]	man power and basic hand tools	100% landfill transportation to the dumping site[II]	demolition is done manually with basic hand tools		
2	same as scenario 1		same as scenario 1		100% disassembly on the construction site	disassembly is done manually with basic hand tools	100% separation of bricks either in good quality or crushed form	40% reuse of bricks[III] 60% landfill of bricks 100% landfill of mortar[IV]
							100% separation of mortar	transportation for reuse, landfill of bricks and landfill of mortar[V]
3	same as scenario 1		same as scenario 1		100% of the wall is broken into smaller pieces on the construction site transportation to the workshop for heat treatment[V]	disassembly is done manually with basic hand tools and heat treatment is in an industrial furnace[VI]	100% separation of bricks either in good quality or crushed form	41% reuse of bricks[VI] 59% landfill of bricks 100% landfill of mortar[IV]
							100% separation of mortar	transportation for reuse, landfill of bricks and landfill of mortar[V]
4	same as scenario 1 but with secondary bricks[VII]		same as scenario 1		100% disassembly on the construction site	disassembly is done manually with basic hand tools	100% separation of bricks either in good quality or crushed form	40% reuse of bricks[III] 30% recycling of bricks[VII] 30% landfill of bricks 100% landfill of mortar[IV] transportation for reuse, landfill of bricks and landfill of mortar[V]
							100% separation of mortar	transportation and crushing of bricks for recycling[I]
5	same as previous scenario 4		same as scenario 1		100% of the wall is broken into smaller pieces on the construction site transportation to the workshop for heat treatment[V]	disassembly is done manually with basic hand tools and heat treatment is in an industrial furnace[VI]	100% separation of bricks either in good quality or crushed form	41% reuse of bricks[VI] 30% recycling of bricks[VII] 29% landfill of bricks 100% landfill of mortar[IV] transportation for reuse, landfill of bricks and landfill of mortar[V]
							100% separation of mortar	transportation and crushing of bricks for recycling[I]

[I] Referring to the estimations presented in Table 3.8, average distance is 184 km
[II] Referring to the estimations presented in Table 3.11, average distance is 3 km
[III] Although recovery rate is 79% in Table 3.1, the result is 72% when the wastage is subtracted
[IV] Referring to literature review, recovery and recycling of mortar is not the case for Turkey
[V] Referring to the estimations presented in Table 3.8, average distance is 3 km for inner city transportation
[VI] Dijk *et al*. (2002) state that about 540 °C heating during disassembly results in about 45% recovery of units in reusable form and quality. The result is 41%, when the wastage is subtracted. The energy is natural gas in industrial furnace > 100kW
[VII] Possible recycled content rate for secondary clay brick production is 30% (Demir & Orhan, 2003)

Table 3.14 Information on the AAC block option of Wall A

Scenario	Assembly requirements		Useful life period requirements	Fate at the end-of-life			
1	AAC block including wastage	man power and basic hand tools	no need	100% landfill	demolition is done manually with basic hand tools		
	adhesive mortar including wastage						
	transportation to the construction site[I]			transportation to the dumping site[II]			
2	same as scenario 1 but with secondary blocks[III]		same as scenario 1	100% disassembly on the construction site	disassembly is done manually with basic hand tools	100% separation of blocks either in good quality or crushed form	5% recycling of blocks[III]
							95% landfill of blocks
							100% landfill of mortar[IV]
							transportation for landfill of blocks and mortar[II]
						100% separation of mortar	transportation and crushing of blocks for recycling[I]
3	same as scenario 1		same as scenario 1	100% disassembly on the construction site	disassembly is done manually with basic hand tools	100% separation of blocks either in good quality or crushed form	66% reuse of blocks[V]
							34% landfill of blocks
							100% landfill of mortar[IV]
						100% separation of mortar	transportation for reuse, landfill of blocks and landfill of mortar[II]
4	same as scenario 1 but with secondary blocks[III]		same as scenario 1	100% disassembly on the construction site	disassembly is done manually with basic hand tools	100% separation of blocks either in good quality or crushed form	66% reuse of blocks[V]
							5% recycling of blocks[III]
							29% landfill of blocks
							100% landfill of mortar[IV]
							transportation for reuse, landfill of blocks and landfill of mortar[II]
						100% separation of mortar	transportation and crushing of blocks for recycling[I]

(I) Referring to the estimations presented in Table 3.9, average distance is 424 km
(II) Referring to the estimations presented in Table 3.11, average distance is 3 km
(III) Possible recycled content rate for secondary AAC block production is 5% (Evcin *et al.,* 2006)
(IV) Referring to literature review, recovery and recycling of mortar is not the case for Turkey
(V) Although recovery rate is 68% in Table 3.1, the result is 66% when the wastage is subtracted

Table 3.15 Information on the stone block option of Wall A

Scenario	Assembly requirements		U. life requirements		Fate at the end-of-life			
1	compact-tuff stone block including wastage	man power and basic hand tools	repointing mortar including wastage	man power and basic hand tools	100% disassembly on the construction site	disassembly is done manually with basic hand tools	100% separation of blocks either in good quality or crushed form	71% reuse of blocks[II]
								29% landfill of blocks
	mortar including wastage							100% landfill of mortar[III]
	transportation to the construction site[I]		transportation to the construction site[I]				100% separation of mortar	transportation for reuse, landfill of blocks and landfill of mortar[IV]

[I] Referring to the estimations presented in Table 3.10, average distance is 74 km
[II] Although recovery rate is 79% in Table 3.1, the result is 71% when the wastage is subtracted
[III] Referring to the estimations presented in Table 3.11, average distance is 3 km
[IV] Referring to literature review, recovery and recycling of mortar is not the case for Turkey

Table 3.16 Information on the mud brick option of Wall A

<table>
<tr><th>Scenario</th><th colspan="2">Assembly requirements[I]</th><th colspan="2">Useful life period requirements</th><th colspan="4">Fate at the end-of-life</th></tr>
<tr><td rowspan="5">1</td><td>clay and aggregate including wastage (mud mixture)</td><td rowspan="5">man power and basic hand tools</td><td rowspan="3">renewing mixture including wastage [III]</td><td rowspan="5">man power and basic hand tools</td><td rowspan="5">demolition of the wall</td><td rowspan="5">demolition is done manually with basic hand tools</td><td>%100 separation of mud mixture</td><td rowspan="2">98% reuse of mud mixture[V]</td></tr>
<tr><td>straw including wastage</td><td>%100 separation of wood (mould)</td></tr>
<tr><td>water including wastage</td><td>100% decay of straw</td><td>2% decay of mud mixture[V]</td></tr>
<tr><td>wood (mould)</td><td rowspan="2">transportation to the construction site[IV]</td><td>100% evaporation of water</td><td>98% reuse of wood</td></tr>
<tr><td>transportation to the construction site[II]</td><td>transportation for reuse of mud mixture[II]</td><td>2% incineration of wood</td></tr>
</table>

[I] Assembly requirements for mud brick is indicated in a more detailed way compared to the other materials hence it is not available in the used database.
Therefore it is obtained by combining the sub-ingredients
[II] Referring to the estimations presented in Figure 3.7, average distance is 500 m
[III] According to Kömürcüoğlu (1962), mud brick is vulnerable to water penetration.
Thus the parts of the wall face are periodically renewed
[IV] Referring to Figure 3.7, average distance is 500 m.
However since the volume of the needed material for renewing is very small, the transportation is via trolley that means there is no need for additional energy
[V] Since there is no chemical reaction during the assembly of mud brick wall, all of the used material in the end-of-life phase can be regarded as raw material.
For this study, only 2% of the whole is assumed as wasted in case of the affects of natural factors

Table 3.17 Information on the options of Wall B

Masonry wall type	Fate at the end-of-life				
	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
solid clay brick	100% landfill	43% reuse of bricks[II]	41% reuse of bricks[IV]	43% reuse of bricks[II]	41% reuse of bricks[IV]
		57% landfill of brick	59% landfill of bricks	30% recycling of bricks[V]	30% recycling of bricks[V]
				27% landfill of bricks	29% landfill of bricks
		100% landfill of mortar[III]	100% landfill of mortar[III]	100% landfill of mortar[III]	100% landfill of mortar[III]
hollow clay brick	100% landfill	32% reuse of bricks[VI]	41% reuse of bricks[IV]	32% reuse of bricks[VI]	41% reuse of bricks[IV]
		68% landfill of brick	59% landfill of bricks	30% recycling of bricks[V]	30% recycling of bricks[V]
				38% landfill of bricks	29% landfill of bricks
		100% landfill of mortar[III]	100% landfill of mortar[III]	100% landfill of mortar[III]	100% landfill of mortar[III]
AAC block	100% landfill	5% recycling of blocks[VII]	65% reuse of blocks[VIII]	65% reuse of blocks[VIII]	
		95% landfill of blocks	35% landfill of blocks	5% recycling of blocks[VII]	
				30% landfill of blocks	
		100% landfill of mortar[III]	100% landfill of mortar[III]	100% landfill of mortar[III]	
stone block	44% reuse of stone blocks[IX]				
	56% landfill of stone blocks				
	100% landfill of mortar[III]				
mud brick	98% reuse of mud mixture[X]				
	2% decay of mud mixture[X]				
	100% decay of straw				
	100% evaporation of water				
	98% reuse of wood (mould)				
	2% incineration of wood (mould)				

[I] Table 3.3
[II] Although recovery rate is 47% in Table 3.3, the result is 43% when the wastage is subtracted
[III] Referring to literature review, recovery and recycling of mortar is not the case for Turkey
[IV] Dijk *et al*. (2002) state that about 540 °C heating during disassembly results in about 45% recovery of units in reusable form and quality. The result is 41%, when the wastage is subtracted. The energy is natural gas in industrial furnace > 100kW
[V] Possible recycled content rate for secondary clay brick production is 30% (Demir & Orhan, 2003)
[VI] Although recovery rate is 35% in Table 3.3, the result is 32% when the wastage is subtracted
[VII] Possible recycled content rate for secondary AAC block production is 5% (Evcin *et al.,* 2006)
[VIII] Although recovery rate is 67% in Table 3.3, the result is 65% when the wastage is subtracted
[IX] Although recovery rate is 49% in Table 3.3, the result is 44% when the wastage is subtracted
[X] Since there is not a chemical reaction during the production of mud brick, the mixture is reusable, only 2% is accepted as not reusable

CHAPTER 4

RESULTS AND DISCUSSION

The information that is needed for life cycle scenarios is presented in the material section and the formulation of the scenarios is stated in the method section so far. During the formulation of the scenarios, all the structure was created in the LCA software, SimaPro, and with the help of the software each life cycle alternative has gained a score that refers to its environmental load. Environmental load here refers to the level of the environmental impact, for example if the score is higher environmental damage level is higher. Similar to the method section, the obtained scores here are presented under two major headings i.e. Wall A scores and Wall B scores. Wall A refers to the wall having conventional thickness of solid clay brick, hollow clay brick, AAC block, stone block and mud brick masonry that is commonly used throughout Turkey. Wall B refers to the wall which is built in above mentioned materials and has thickness that can satisfy the thermal insulation standard of U=0.50 W/m^2K. Right after the major division, the obtained scores are further divided into two groups owing to the alternative lifetime i.e. 400 and 800 years respectively.

4.1 Results

Referring to the main and sub divisions described above, all the obtained scores are categorized under four groups all of which indicate the scores both in numerical form and column chart form. Additionally, the scores are indicated in terms of human health, ecosystem quality and resources as well as total scores. Referring to literature assumptions, the stone masonry has the longest lifetime i.e. 400 years among the selected masonry types while stone masonry can serve for 800 years, which is again the longest period among all according to estimations. The life cycles of the other walls are repeated in order to complete the 400 and 800 years service life in order to meet the same need that makes all of them comparable. As a result, the scores of all the selected walls are presented as follows:

4.1.1 Results for Wall A

As indicated before, Wall A refers to the masonry walls with conventional thicknesses disregarding the thermal properties. The masonry options that satisfy this requirement have several life cycle scenarios as illustrated in Tables starting from 3.12 up to 3.16 there are five scenarios for solid clay brick masonry, five for hollow clay brick masonry, four for AAC block masonry, one for stone block masonry and one for mud brick masonry. The scenarios include the several rates of landfill, reuse and recycling.

(i) Scores of Wall A with a lifetime of 400 years

The cycles of the walls are repeated to satisfy the 400 years. In order to complete the 400 years, solid and hollow clay wall life cycles are repeated two times, AAC block four times, stone block one time and mud brick one point six times.

Consequently, each scenario gained a score referring to its level of negative impact and presented in Table 4.1 and Figure 4.1. The second scenario of AAC block masonry gained the highest score that means it is the most harmful scenario to nature.

(ii) Scores of Wall A with a lifetime of 800 years

The cycles of the walls are repeated to satisfy the 800 years. In order to complete the 800 years, solid and hollow clay wall life cycles are repeated four times, AAC block eight times, stone block one time and mud brick four times.

Consequently, each scenario gained a score referring to its level of negative impact and presented in Table 4.2 and Figure 4.2. The second scenario of AAC block masonry gained the highest score that means its environmental impact level is highest.

Table 4.1 Environmental load scores of Wall A with a lifetime of 400 years

Masonry type		**Solid clay brick**					**Hollow clay brick**					**AAC block**				**Stone b.**	**Mud b.**
Wall thickness		19 cm					19 cm					25 cm				40 cm	48 cm
Lifetime		200 years					200 years					100 years				400 years	250 years
Number of cycles in 400 years		2					2					4				1	1.6
Alternative scenario		1	2	3	4	5	1	2	3	4	5	1	2	3	4	1	1
Damage category	Human Health	19	8	13	9	14	5	4	4	4	4	23	23	8	9	9	3
	Ecosystem Quality	14	6	9	6	10	4	3	3	3	3	14	14	5	5	6	2
	Resources	22	8	18	12	22	5	4	8	5	9	38	39	15	16	6	0
	Total points	**55**	**22**	**41**	**27**	**45**	**14**	**11**	**15**	**12**	**16**	**74**	**76**	**28**	**30**	**21**	**5**

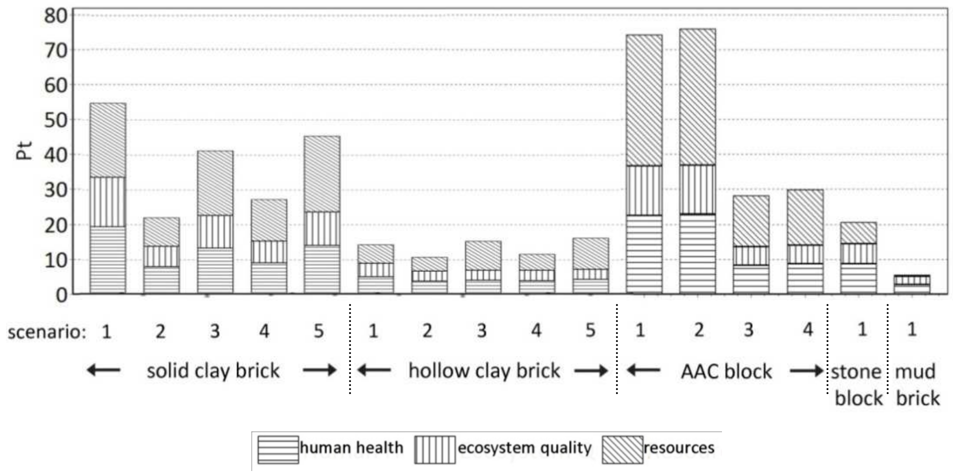

Figure 4.1 Environmental load scores of Wall A with a lifetime of 400 years, column chart

Table 4.2 Environmental load scores of Wall A with a lifetime of 800 years

Masonry type		Solid clay brick					Hollow clay brick					AAC block				Stone b.	Mud b.
Wall thickness		19 cm					19 cm					25 cm				40 cm	48 cm
Lifetime		200 years					200 years					100 years				800 years	200 years
Number of cycles in 800 years		4					4					8				1	4
Alternative scenario		1	2	3	4	5	1	2	3	4	5	1	2	3	4	1	1
Damage category	Human Health	39	16	27	18	28	10	8	8	8	9	45	46	17	17	9	7
	Ecosystem Quality	28	12	19	13	19	8	6	6	6	6	28	28	10	10	6	6
	Resources	43	17	37	24	43	11	8	17	9	18	75	78	29	32	6	1
	Total points	**110**	**44**	**82**	**54**	**91**	**29**	**21**	**31**	**23**	**32**	**149**	**152**	**56**	**60**	**21**	**14**

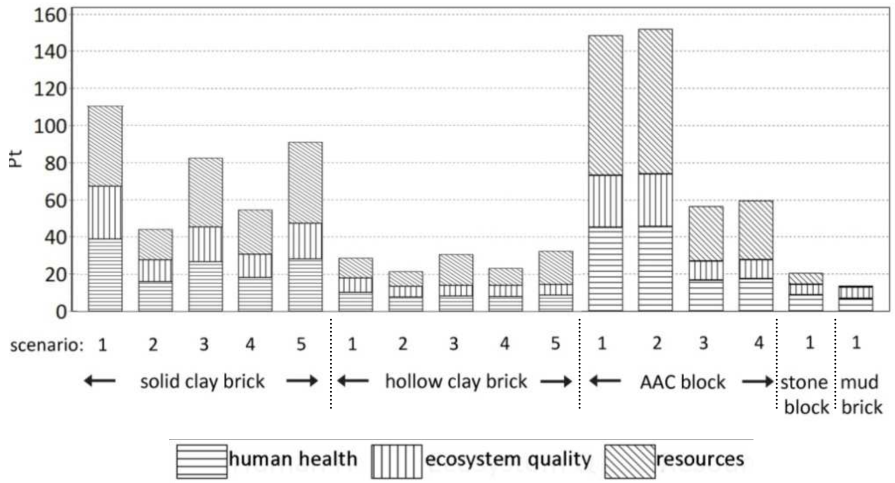

Figure 4.2 Environmental load scores of Wall A with a lifetime of 800 years, column chart

4.1.2 Results for Wall B

Wall B refers to the masonry walls with thicknesses satisfying equivalent heat transmission value. The masonry options that satisfy this requirement have several life cycle scenarios. There are five scenarios for solid clay brick masonry, five for hollow clay brick masonry, four for AAC block masonry, one for stone block masonry and one for mud brick masonry. The scenarios include the several rates of landfill, reuse and recycling.

(i) Scores of Wall B with a lifetime of 400 years

The cycles of the walls are repeated to satisfy the 400 years. In order to complete the 400 years, solid and hollow clay wall life cycles are repeated two times, AAC block four times, stone block one time and mud brick one point six times.

Consequently, each scenario gained a score referring to its level of environmental impact and presented in Table 4.3 and Figure 4.3. The first scenario of the solid clay brick masonry gained the highest score that means it is the most harmful scenario.

(ii) Scores of Wall B with a lifetime of 800 years

The cycles of the walls are repeated to satisfy the 800 years. In order to complete the 800 years, solid and hollow clay wall life cycles are repeated four times, AAC block eight times, stone block one time and mud brick four times.

Consequently, each scenario gained a score referring to its level of impact and presented in Table 4.4 and Figure 4.4. The first scenario of the solid clay brick masonry gained the highest score that means it is the most harmful scenario.

Table 4.3 Environmental load scores of Wall B with a lifetime of 400 years

Masonry type		**Solid clay brick**					**Hollow clay brick**					**AAC block**				**Stone b.**	**Mud b.**
Wall thickness		139 cm					49 cm					41 cm				164 cm	100 cm
Lifetime		200 years					200 years					100 years				400 years	250 years
Number of cycles in 400 years		2					2					4				1	1.6
Alternative scenario		1	2	3	4	5	1	2	3	4	5	1	2	3	4	1	1
Damage category	Human Health	136	88	91	93	96	18	14	13	15	14	36	36	13	14	57	6
	Ecosystem Quality	98	64	66	66	67	13	10	10	10	10	22	23	8	8	37	5
	Resources	151	96	104	118	126	19	15	18	17	20	60	62	23	25	42	1
	Total points	**386**	**248**	**261**	**277**	**290**	**50**	**39**	**41**	**42**	**44**	**118**	**121**	**45**	**48**	**136**	**11**

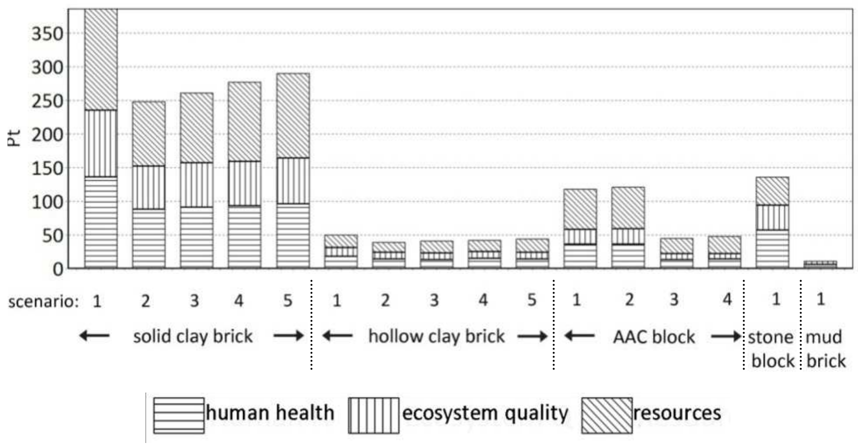

Figure 4.3 Environmental load scores of Wall B with a lifetime of 400 years, column chart

Table 4.4 Environmental load scores of Wall B with a lifetime of 800 years

Masonry type		Solid clay brick					Hollow clay brick					AAC block				Stone b.	Mud b.
Wall thickness		139 cm					49 cm					41 cm				164 cm	100 cm
Lifetime		200 years					200 years					100 years				800 years	200 years
Number of cycles in 800 years		4					4					8				1	4
Alternative scenario		1	2	3	4	5	1	2	3	4	5	1	2	3	4	1	1
Damage category	Human Health	272	176	182	186	192	35	28	27	29	28	72	72	27	28	57	14
	Ecosystem Quality	197	128	131	131	135	26	20	19	21	19	45	45	17	17	37	13
	Resources	303	192	209	236	253	38	29	36	34	41	120	124	47	51	42	1
	Total points	**772**	**496**	**523**	**554**	**580**	**99**	**78**	**82**	**84**	**88**	**236**	**241**	**90**	**96**	**136**	**28**

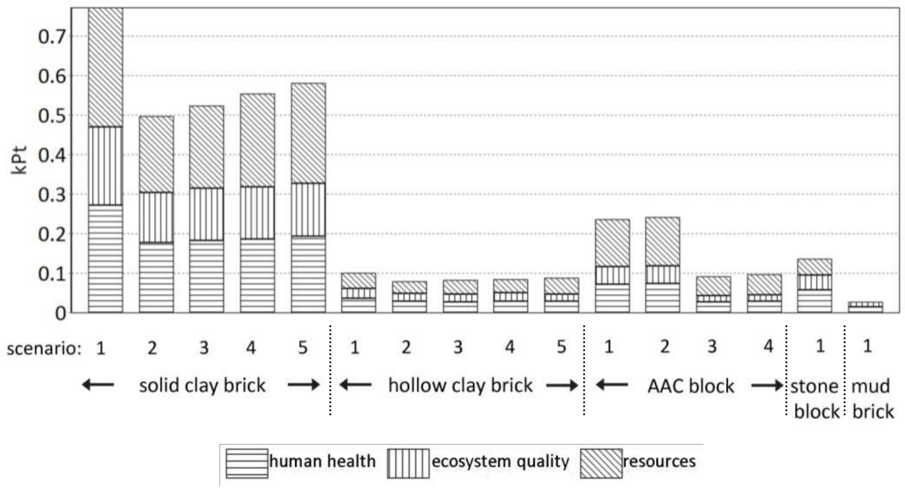

Figure 4.4 Environmental load scores of Wall B with a lifetime of 800 years, column chart

4.2 Discussion

The environmental impact score of each scenario alternative obtained via SimaPro is presented in the results section. The comparisons of results are presented and discussed in this section under four categories i.e. score comparison in terms of end-of-life alternatives, score comparison in terms of masonry types, generalization of the comparisons and additional comparison for Wall B as follows:

4.2.1 Score comparison in terms of end-of-life alternatives

Several end-of-life alternatives for the masonry walls were stated. Referring to the graphs that are presented in results section, it is clear that alternative end-of-life phases highly change the environmental impact scores. In order to analyze the impact levels; solid clay brick, hollow clay brick and AAC block masonry life cycles, containing varying percentages of landfill, reuse and recycling in the end-of-life phase are presented in the following sections.

(i) Alternative scenario scores of solid clay brick masonry

There are five end-of-life alternatives for solid clay brick masonry (see Tab 3.5). The model illustrating the variants among the scenario alternatives is indicated in Figure 4.5.

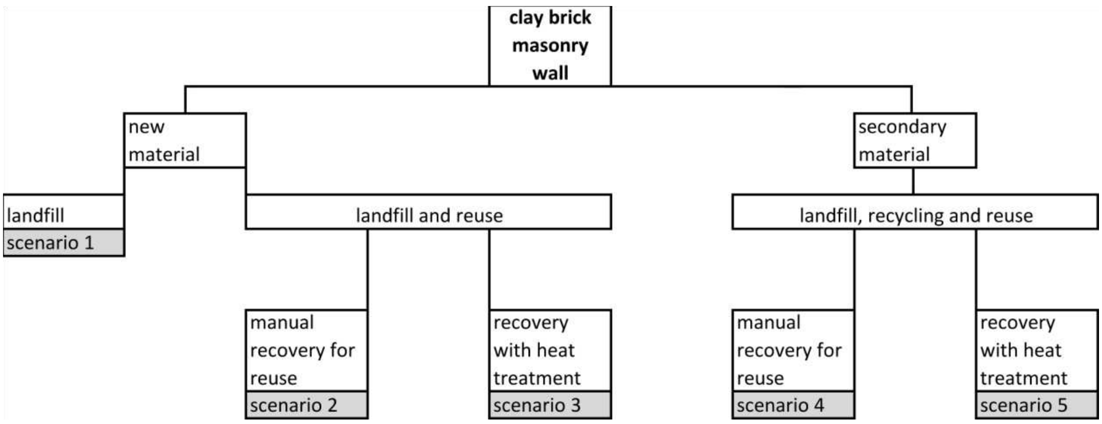

Figure 4.5 Structure of solid clay brick masonry scenario alternatives

In order to grasp the environmental impact level of five life cycle scenarios of solid clay brick masonry wall, Table 4.5 is prepared. The Table contains one rank of scores for Wall A and one for Wall B.

Table 4.5 Score rank of alternative scenarios

Masonry material	Wall type	Actual lifetime	Wall thickness	Scoring					recommended scenario
				scenario 1	scenario 2	scenario 3	scenario 4	scenario 5	
solid clay brick	A	200 years	19 cm	▲▲▲▲▲	▲	▲▲▲	▲▲	▲▲▲▲	scenario 2
	B	200 years	139 cm	▲▲▲▲▲	▲	▲▲	▲▲▲	▲▲▲▲	scenario 2

▲▲▲▲▲ highest score (most harmful scenario)

▲ lowest score (least harmful scenario)

Although, all the scenarios do not have the same impact for both the walls, they do share the best and the worst scenarios i.e. Scenario 1 is the most harmful one among all the alternatives, while Scenario 2 is the least harmful option. Landfill entails manual demolishing, transportation up to dumping site and landfill of the debris while reuse entails manual recovery of units and transportation up to new location. Obviously, the impact level of landfill is greater than the impact level of reuse for both walls. Therefore it is clear that manual recovery for reuse decreases the environmental impact compared to the 100% landfill alternative.

The variant between scenario 2 and scenario 3 as well as scenario 4 and 5 is the manual disassembly versus disassembly with the aid of heat treatment. Since the scores for both walls indicate the same rank, it is clear that manual disassembly is a more environmental friendly method compared to disassembly with heat treatment, since the amount of heating energy is quite high during the disassembly. Additionally, although the heating energy is quite high, the recovery rate is relatively low since the process results in serious cracks on the face of the bricks which obstruct the reuse option.

On the other hand, in comparison to the high recovery rate of manual disassembly, heat treatment offers a very speedy disassembly. Since time limitation for architectural projects is one of the most restrictive aspects, the heat recovery can make sense for many cases in real life, although it is not environmentally preferable.

Lastly, the variant between scenario 2 and 4 as well as scenario 3 and 5 is the new material versus secondary material. Referring to similarity of the results it is clear that secondary material has higher environmental impact compared to new material. Actually, the expected result is exactly the opposite since the reason for the evolution of secondary material is decreasing the environmental degradation. Although the recycled content, that replaces the equivalent percentage of new material, reduces the demand of extraction of auxiliary material in addition to the energy used in the building machine and transportation vehicle, it results in higher environmental damage since it requires special treatment i.e. recycling in the end-of-life phase. In other words, the equivalent ratio of the recycled content is recycled in the end-of-life that means crushing of the debris and transportation up to production plant. Since the transportation distance of debris up to production plant for recycling is relatively long and the energy needed for crushing increases the energy use, the negative impact level of secondary clay brick has exceeded the level of new brick.

Therefore recycling of clay brick is not environmentally reasonable within the scope of this study owing to the selected transportation distances and possible recycled content ratio. However if the scope would be different e.g. higher recycled content rate and shorter transportation distances, the results would be quite different.

After analyzing the score rank for solid clay brick masonry in terms of five possible end-of-life alternatives, the results belonging to hollow clay brick masonry scenarios are discussed in a similar manner as follows:

(ii) Alternative scenario scores of hollow clay brick masonry

The model that is presented for the solid clay brick masonry scenario alternatives i.e. Figure 4.5 is also valid for the end-of-life alternatives of hollow clay brick masonry wall. Therefore, there are five end-of-life alternatives containing the varying percentages of landfill, reuse and recycling.

Table 4.6 Score rank of alternative scenarios

Masonry material	Wall type	Actual lifetime	Wall thickness	Scoring					recommended scenario
				scenario 1	scenario 2	scenario 3	scenario 4	scenario 5	
hollow clay brick	A	200 years	19 cm	▲▲▲	▲	▲▲▲▲	▲▲	▲▲▲▲▲	scenario 2
	B	200 years	49 cm	▲▲▲▲▲	▲	▲▲	▲▲▲	▲▲▲▲	scenario 2

▲▲▲▲▲ highest score (most harmful scenario)

▲ lowest score (least harmful scenario)

Although the structure of the life cycle scenario alternatives is the same as the solid clay brick masonry, the rank of scores present differences (Tab. 4.6).

First difference is the appearance of Scenario 5 as the most harmful option and besides, Scenario 3 is the second most harmful alternative. The striking similarity of scenario 3 and 5 is the recovery with heat treatment which results in quite high damage level that even exceeds the degradation level of landfill. On the other hand, the landfill alternative score is higher compared to recovery with heat treatment score for solid clay brick masonry but it is exactly the opposite here. Referring to the variant between the both walls, weight of the recovered mass compared to used energy amount, it is clear that, if the impact of recovered mass for reuse is greater than the impact of heat treatment during recovery, the resultant impact level can be lower but if only quite small amount of units is recoverable than the used energy can make the impact level extremely high even the most harmful level that means exceeding the impact level of landfill alternative.

The other comparisons indicate the same logic of rank as solid clay brick masonry scenario alternatives that can be summarized as follows:
Manual recovery for reuse decreases the environmental injury compared to the landfill alternative. Additionally, manual disassembly is a more environmental friendly method compared to disassembly with heat treatment. Lastly, secondary material has higher environmental impact compared to new material.

After analyzing the score rank for hollow clay brick masonry in terms of five possible end-of-life alternatives, the results belonging to AAC block masonry scenarios are discussed in a similar manner as follows:

(iii) Alternative scenario scores of AAC block masonry

In order to compare the environmental damage level of possible life cycle scenarios of AAC block masonry wall (Fig. 4.6), Table 4.7 is presented. The Table contains one rank of scores for Wall A and one for Wall B.

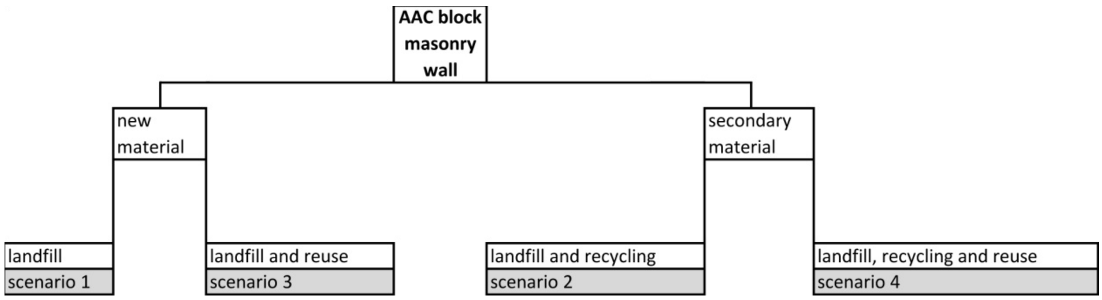

Figure 4.6 Structure of AAC block masonry scenario alternatives

Table 4.7 Score rank of alternative scenarios

Masonry material	Wall type	Actual lifetime	Wall thickness	Scoring				recommended scenario
				scenario 1	scenario 2	scenario 3	scenario 4	
AAC block	A	100 years	25 cm	▲▲▲	▲▲▲▲	▲	▲▲	scenario 3
	B	100 years	41 cm	▲▲▲	▲▲▲▲	▲	▲▲	scenario 3

▲▲▲▲ highest score (most harmful scenario)

▲ lowest score (least harmful scenario)

Referring to the Table, there is one rank of scores that is valid for stated two walls. Actually Wall A is 25 cm thick and Wall B is 41 cm thick, so the walls can be regarded more or less the same. Thus indicating the same order of scores is not surprising. Before starting to discuss the logic of the rank, one important aspect of this scenario group should be underlined. Since the AAC block is relatively new material which has been produced from 1920 onward, it has not completed the expected life cycle period i.e. 100 years yet. Therefore it is still a question how the material would behave after the expected useful life. From an optimistic perspective, the material would still be in usable quality under the right conditions hence the third and the fourth scenarios have been formulated according to this prediction.

First, the variant between scenario 1 and 3 as well as the scenario 2 and 4 is the 100% landfill versus partial reuse. The landfill entails the manual demolishing, transportation up to dumping site and landfill of the debris while reuse entails the manual recovery of units and transportation up to new location. Results indicate that impact level of landfill is greater than the level of reuse. Therefore it is clear that manual recovery for reuse decreases the environmental damage compared to landfill alternative.

Second and the last, the variant between Scenario 1 and 2 as well as scenario 3 and 4 is the new material versus secondary material. It is clear that secondary material has higher environmental damage compared to new material though the expected result is exactly the opposite. Although the recycled content reduces the demand of material in addition to the energy used, it results in higher environmental impact level since it requires recycling in the end -of-life phase i.e. crushing and transportation up to production plant. Since the transportation distance of debris up to production plant for recycling is relatively long and the energy needed for crushing increases the energy use the environmental impact level of secondary block has exceeded the level of new block. Therefore recycling of AAC block is not environmentally reasonable within the scope of this study owing to the selected transportation distance and possible recycled content ratio. However if the scope would be different e.g. higher recycled content rate and shorter transportation distances, the results would be quite different.

Briefly, the alternative scenarios for solid clay brick, hollow clay brick and AAC block were discussed up to this point. Among the results, there are striking similarities that may lead to the generalized interpretations that are summarized as follows:
First of all, reuse option that is satisfied by manual disassembly i.e. disassembly without additional energy, lowers the environmental damage level compared to landfill. On the other hand when the case is repeated with additional energy use, the results may be reversed. Additionally, the secondary material that obliges recycling in the end-of-life phase (owing to the scope of this study) may falsify the expectations since it may result in higher

environmental damage compared to new material owing to the reasons that were already discussed for solid and hollow clay brick masonry walls.

Right after obtaining the interpretations on alternative end-of-life phases on environmental impact level, impact level comparisons are discussed in terms of masonry types in the following section.

4.2.2 Score comparison in terms of masonry types

First of all, a route is described in order to compare the results in terms of masonry types that can lead to detect the most and the least harmful walls among the solid clay brick, hollow clay brick, AAC block, stone block and mud brick masonry. Hence, rank of the highest scored scenario alternative of each masonry type is presented in addition to the rank of the lowest scored scenario alternative in Table 4.8. This Table presents the rank of scores under the two main groups i.e. Wall A and Wall B. The ranks are further divided into 400 years and 800 years lifetime and the lifetime scenarios are further divided into highest and lowest scores. With the aid of these ranks, the following questions can be answered i.e.

Which scenario of which masonry type is the least harmful one?
Which scenario of which masonry type is the most harmful one?

Referring to the results, it is not possible to present a score rank that is valid for all the options of Wall A and Wall B yet; there are some striking similarities and differences that are discussed as follows:

- Initial evaluation: Before going deep into detail, regarding the prevalence of the score ranks, some basic interpretations can be obtained from Table 4.8.

First of all, AAC block masonry is the most harmful masonry type for Wall A regardless of the lifetime and the type of the scenario while solid clay brick masonry is the most harmful masonry type for Wall B. In other words, AAC block masonry has the highest negative impact for the case of the commonly preferred thickness and solid clay brick wall is the most harmful type for the case of satisfying the 0.50 W/m^2K heat transmission value.

On the other hand, mud brick masonry is certainly the least harmful type among all alternatives that underlines the low environmental impact of this construction method.

The impacts of the various end-of-life scenarios for both types of walls are discussed in detail in the following paragraphs.

Table 4.8 Score rank in terms of masonry type

Wall		Masonry type	**Solid clay brick**					**Hollow clay brick**					**AAC block**				**Stone block**	**Mud brick**
		actual lifetime	200 years					200 years					100 years				400 and 800 years	250 and 200 years
		thickness	Wall A= 19 cm			Wall B= 139 cm		Wall A= 19 cm			Wall B= 49 cm		Wall A= 25 cm		Wall B= 41 cm		A=40 cm B=164 cm	A=48 cm B=100 cm
type	lifetime	scenario	1	2	3	4	5	1	2	3	4	5	1	2	3	4	1	1
A	400 years	highest score	▲▲▲▲									▲▲		▲▲▲▲▲			▲▲▲	▲
		lowest score		■■■■					■■						■■■■■		■■■	■
	800 years	highest score	▲▲▲▲									▲▲▲		▲▲▲▲▲			▲▲	▲
		lowest score		■■■■					■■■						■■■■■		■■	■
B	400 years	highest score	▲▲▲▲▲					▲▲						▲▲▲			▲▲▲▲	▲
		lowest score		■■■■■					■■						■■■		■■■■	■
	800 years	highest score	▲▲▲▲▲					▲▲						▲▲▲▲			▲▲▲	▲
		lowest score		■■■■■					■■						■■■		■■■■	■

▲ highest scored scenario alternative of each masonry type (most harmful scenario of each material)

■ lowest scored scenario alternative of each masonry type (least harmful scenario of each material)

- Evaluation of Wall A: Table 4.8 indicates that AAC block masonry is exactly the most harmful type when it is built according to the needs of Wall A i.e. conventional wall thickness. Additionally, solid clay brick masonry is the second most harmful type. Stone block or hollow clay brick masonry takes either the third or the fourth order according to lifetime variant. Impact level of hollow clay brick wall is lower than stone masonry when the case is 400 years. Because, the brick cycle is repeated 2 times (since the useful lifetime is assumed as 200 years) while the stone cycle is repeated 1 time (since the useful lifetime is assumed as 400 years). Additionally, for 800 years case, the brick cycle is repeated 4 times (since the useful lifetime is assumed as 200 years) while the stone cycle is repeated 1 time (since the useful lifetime is assumed as 800 years). In other words, the impact level of hollow clay brick is lower when the cycle is only repeated 2 times compared to the cycle repetition of 4 times.

Therefore it is clear that if the useful lifetime of a wall can be longer, its environmental impact is by far lower. Additionally, mud brick masonry wall is the least harmful option regardless of lifetime variant. Thus mud brick masonry is the most preferable options for the sake of environment.

Referring to the interpretations up to this point, it is clear that when the case is common thickness for walls, the least harmful and so the most preferable type is exactly the mud brick masonry.

- Evaluation of Wall B: Referring to Table 4.8, the score ranks of Wall B indicate that solid clay brick masonry is the most harmful option and mud brick is the least harmful alternative. Since Wall B refers to the wall satisfying the thermal insulation standards, it is clear that, when the case is equivalent thermal insulation (U=0.50 W/m^2K), clay brick masonry built with solid units has the highest environmental damage, while mud brick has the lowest environmental impact. Additionally, hollow clay brick masonry is the second least harmful option regardless of lifetime variant.

In terms of AAC block and stone block; the rank changes according to lifetime variant and end-of-life scenario. In other words, these masonry types share the rank of the third or the fourth most harmful levels that are presented in Table 4.8. Therefore it is not logical to point out the exact rank for these masonry types since there are possible ways to increase and decrease the impact levels of each wall by changing the ratios for landfilling, recycling or reuse of materials in the end-of-life phase.

Referring to the interpretations up to this point, it is clear that when the case is equivalent thermal insulation for walls, the most preferable type is again mud brick masonry.

4.2.3 Generalization of the comparisons

Results section covers several categories for the presentation of obtained impact scores, however in order to obtain the broadest interpretations on the score comparisons, a representation tool i.e. Table 4.9, indicating mean score of each masonry type is prepared.

The table covers the mean value of the scores belonging to the scenario alternatives of solid clay brick, hollow clay brick, AAC block, stone block and mud brick masonry. Five different alternatives for clay brick masonry are in application in real life, therefore collecting the scores of five cases and presenting the mean value score as a representative of clay brick masonry is realistic and logical. Additionally, all of four life cycle alternatives for AAC block masonry can be regarded as in application therefore mean value score of four alternatives can realistically represent the average score for AAC block masonry. Similarly, the stone and mud brick masonry has one scenario for each case and mean value of the cases again refers to the representative score for them.

Table 4.9 Mean values of environmental load scores

Wall type	**Wall A**		**Wall B**		**Mean of scores**	**Impact order of scores**
lifetime	400 years	800 years	400 years	800 years		
solid clay brick	38	76	292	585	248	▲▲▲▲▲
hollow clay brick	14	27	43	86	43	▲▲
AAC block	52	104	83	166	101	▲▲▲▲
stone block	21	21	136	136	78	▲▲▲
mud brick	5	14	11	28	14	▲

▲▲▲▲▲ highest score (most harmful scenario)

▲ lowest score (least harmful scenario)

The mean score rank that are presented in the last column of the Table indicate the most generalized environmental impact level for each masonry type. Therefore it is logical to label the solid clay brick wall as the most harmful type while the second most harmful wall is the AAC block. The stone masonry gets the third level in the score rank while the hollow clay brick masonry gains the fourth level and lastly, mud brick is the least harmful masonry type.

Moreover, some other interpretations can be obtained from the Table. For instance, when the mean scores of Wall A and Wall B are analyzed, it is clear that the thicker wall i.e. Wall B has by far higher injury to the environment. Therefore it is reliable to conclude that the thicker wall built in same material has higher environmental damage. Yet, the point should be kept in mind that, energy need for space heating is out of the scope of this study. If the space heating was included the thicker wall satisfying better thermal insulation would most probably result in lower environmental impact compared to thinner wall that cannot ensure enough insulation.

Additionally the effect of lifetime variant is visible when the scores for mud brick for 400 years and 800 years are compared. The variant is visible only via mud brick scores since the lifetime periods and repetition of life cycles differ only for mud brick. The useful lifetime of mud brick masonry is regarded as 250 years for 400 years case and 200 years for 800 years case. Thus, referring to comparison of 400 years 800 years cases, it is clear that the longer useful lifetime ensures less environmental damage.

Right after the evaluation of environmental load scores in terms of masonry types, one more masonry type i.e. thermally insulated hollow clay brick masonry with its alternative end-of-life phases is described and discussed in a similar manner as follows:

4.2.4 Additional comparison for Wall B

In addition to the mentioned wall types, one more option i.e. thermally insulated hollow clay brick masonry is presented in this part since it is also a prevalent wall option in Turkey when the requirement is thermal insulation. By default, the location of the information on this masonry should be in material and method section of this report. However, the information takes place here since it is out of the structure of the study - the study contains the wall types that are valid for two cases i.e. the conventional thickness and thickness of equivalent thermal insulation. This wall type is presented under four titles i.e. information on thermally insulated hollow clay brick masonry, environmental impact scores, score comparison in terms of end-of-life scenarios and score comparison in terms of masonry types.

- Information on thermally insulated hollow clay brick masonry: Besides the solid and hollow clay brick walls, one more type i.e. thermally insulated hollow clay brick masonry is also commonly used throughout Turkey (Aksoy, 2008). In order to detect the environmental impact level of this wall type, the needed information is collected and presented in Table 4.10, which contains the information under five major headings i.e. the basic building unit, insulation layer, the properties of plastic anchors, wall properties and the fate in the end-of-life phase. These headings are further divided into information on the description of the component, its density, dimensions, and the waste percentage during construction. Additionally, the thermal conductivity value and resultant heat transmittance value of the wall is indicated.

The end-of-life alternatives can be grasped in two groups i.e. the end-of life scenario for the insulation layer and for the bricks. Disposal method of Insulation layer is the same for the five scenarios i.e. recycling and incineration of XPS as well as recycling and landfill of plastic anchors while the end-of-life options for the bricks are varying percentages of reuse, landfill and recycling as given in the following tables.

Table 4.10 Information on the thermally insulated hollow clay brick option of Wall B

Unit	**Insulation layer**					**Anchors to fix the XPS boards**			**Wall**			
	description	density kg/m^3	dimension mm	remarks	heat conductivity (λh)	description	dimensions	remarks	description	U value	thickness mm	remarks
hollow, fired clay brick dimensions in mm= 290x 190x 235 [I]	50% recycled content, secondary extrude polystyrene board (XPS) [II]	30 [III]	1250x 600x 35 [IV]	wastage 2% [V] renewal in each 50 years[VI]	0.03 W/mK [VII]	50% recycled content, secondary plastic[VIII]	4 cm^3 in 1 m^2 surface	wastage 10% renewal in each 5 years[IX]	solid wall, running bond, insulation board face material	0.5 W/ m^2K [X]	190 mm clay brick and 35 mm XPS board	the face of wall is covered with XPS boards, repointing is excluded

Table 4.11 Information on the thermally insulated hollow clay brick option of Wall B

Fate at the end-of-life				
scenario 1	scenario 2	scenario 3	scenario 4	scenario 5
100% landfill of bricks	40% reuse of bricks[XI]	41% reuse of bricks[XIII]	40% reuse of bricks[XI]	41% reuse of bricks[XIII]
100% landfill of mortar	60% landfill of bricks	59% landfill of bricks	30% recycling of bricks[XIV]	30% recycling of bricks[XIV]
50% recycling of XPS[II]	100% landfill of mortar[XII]	100% landfill of mortar[XII]	30% landfill of bricks	29% landfill
50% incineration of XPS[II]	50% recycling of XPS[II]	50% recycling of XPS[II]	100% landfill of mortar[XII]	100% landfill of mortar[XII]
50% recycling of plastic[VIII]	50% incineration of XPS[II]	50% incineration of XPS[II]	50% recycling of XPS[II]	50% recycling of XPS[II]
50% landfill of plastic	50% recycling of plastic[VIII]	50% recycling of plastic[VIII]	50% incineration of XPS[II]	50% incineration of XPS[II]
	50% landfill of plastic	50% landfill of plastic	50% recycling of plastic[VIII]	50% recycling of plastic[VIII]
			50% landfill of plastic	50% landfill of plastic

[I] Unit is the same as the brick stated in Table 3.2
[II] Possible recycled content ratio is 50% for XPS and Incineration under right conditions does not have any more impact than wood (Fabian *et al*., 2004)
[III] TS 11989, 2003
[IV] Özpor, 2012
[V] No wastage during construction (XPS Türkiye, 2012)
therefore only 2% assumed for this study
[VI] Lifetime of XPS is as long as the life of building (Exiba, 2010).
About 50 years (Arvai, 2009)
[VII] TS 825, 2008
[VIII] Possible recycled content ratio is 50% for plastic (Duchin & Lange, 1997)
[IX] Expected lifetime of a kind of plastic shopping bag is assumed as 2 years in the report of James & Grant (2005)
The life of plastic anchors is assumed as 5 years in this study
[X] Estimated value according to the requirements of TS 825, 2008
[XI] Although recovery rate of clay brick masonry is 44% in Table 3.1, the result is 40% when the wastage is subtracted
[XII] Referring to literature review, recovery and recycling of mortar is not the case for Turkey
[XIII] Dijk *et al*. (2002) state that about 540 °C heating during disassembly results in about 45% recovery of units in reusable form and quality. The result is 41%, when the wastage is subtracted. The energy is natural gas in industrial furnace > 100kW
[XIV] Possible recycled content rate for secondary clay brick production is 30% (Demir & Orhan, 2003)

- Score results: Referring to the systematic division for other walls, the obtained scores are categorized under two groups i.e. lifetime equal to 400 years as well as 800 years. The scores are again indicated in terms of human health, ecosystem quality and resources as well as total scores, as presented below:

Table 4.12 Environmental load scores of
thermally insulated hollow clay brick wall with a lifetime of 400 years

Masonry type		**Thermally insulated hollow clay brick**				
Wall thickness		19 cm hollow brick + 3.5 cm XPS board				
Lifetime		200 years				
Number of cycles in 400 years		2				
Alternative scenario		1	2	3	4	5
Damage category	Human Health	5	4	4	4	4
	Ecosystem Quality	4	3	3	3	3
	Resources	7	5	9	6	10
	Total points	**15**	**12**	**16**	**13**	**17**

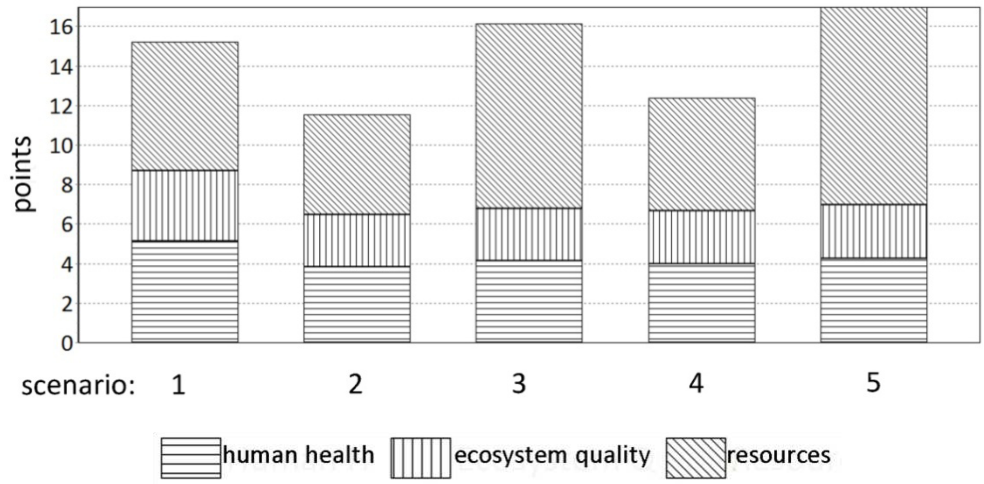

Figure 4.7 Environmental load scores of
thermally insulated hollow clay brick wall with a lifetime of 400 years, column chart

Table 4.13 Environmental load scores of

thermally insulated hollow clay brick wall with a lifetime of 800 years

Masonry type		**Thermally insulated hollow clay brick**				
Wall thickness		19 cm hollow brick + 3.5 cm XPS board				
Lifetime		200 years				
Number of cycles in 800 years		4				
Alternative scenario		1	2	3	4	5
Damage category	Human Health	10	8	8	8	9
	Ecosystem Quality	7	5	5	5	5
	Resources	13	10	19	11	20
	Total points	**30**	**24**	**32**	**26**	**34**

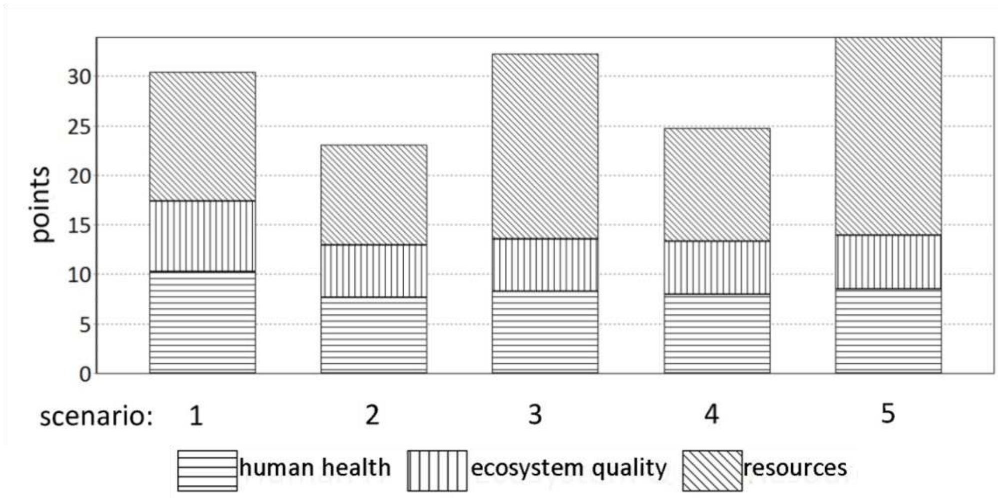

Figure 4.8 Environmental load scores of

thermally insulated hollow clay brick wall with a lifetime of 800 years, column chart

- **Score comparison in terms of end-of-life scenarios:** Similar to the other clay brick walls, five possible end-of-life scenarios were also formulated for the thermally insulated hollow clay brick masonry. Table 4.14 indicates the rank of impact scores of each alternative. The Table presents the same rank as hollow clay brick masonry, which is already discussed and can be summarized as follows:

Table 4.14 Score rank of alternative scenarios

Masonry material	Wall type	Actual lifetime	Wall thickness	Scoring					recommended scenario
				scenario 1	scenario 2	scenario 3	scenario 4	scenario 5	
hollow clay brick + XPS	B	200 years	19 cm + 3.5 cm	▲▲▲	▲	▲▲▲▲	▲▲	▲▲▲▲▲	scenario 2

▲▲▲▲▲ highest score (most harmful scenario)

▲ lowest score (least harmful scenario)

Recovery with heat treatment results in quite high impact level that even exceeds the level of landfill. Additionally, manual recovery for reuse decreases the environmental injury compared to the landfill alternative. Lastly, manual disassembly is a more environmental friendly method compared to disassembly with heat treatment. Moreover, secondary material has higher environmental impact compared to new material.

After summarizing the points of the general impact levels for the wall type, one other aspect is also discussed here that evaluates the environmental impact of thermal insulation. Since all of the five end-of-life alternatives stated for insulation layer are the same i.e. recycling and incineration of XPS boards as well as recycling and landfill of plastic anchors, the scores presented here i.e. Table 4.14 cannot be used to detect the impact level of only insulation layer. On the other hand, the difference between the thermally insulated hollow clay brick masonry stated for Wall B and hollow clay brick masonry stated for Wall A is the existence of XPS thermal insulation, which can be used in order to detect the score difference caused by thermal insulation. Therefore comparing the scores of both masonry options indicates the affect of XPS boards in terms of environmental load.

Checking the scores in Tables 4.12 and 4.13 with 4.1 and 4.2, it is clear that the load of XPS boards only changed the scores up to 1 point. Therefore the affect of insulation layer in terms of environment is quite low even neglectable within the scope of this study. The basic property resulting in this positive environmental aspect must be the high recyclability i.e. 50% as well as the quite harmless incineration option of XPS that leads to the use of material as heating energy source in the end-of-life phase.

After analyzing the score rank for thermally insulated hollow clay brick masonry in terms of five possible end-of-life alternatives, the results in terms of masonry type are discussed in a similar manner as follows:

- Score comparison in terms of masonry type: The route used for comparison of the scores in terms of masonry types in the previous sections is also used here in order to renew the results with the addition of thermally insulated wall version. Hence, In addition to previous wall options, thermally insulated clay brick masonry is also tested with the others in a similar manner which is indicated in Table 4.15. Besides the similarities of interpretations obtained from previous score rank, the low impact level of thermally insulated hollow clay brick masonry type among all is striking. Referring to three of the four options thermally insulated clay brick masonry is the second least harmful type among all types, while the remaining one option indicate that it is the least harmful one. Since the environmental impact level of this masonry type is quite low, even lower than the impact of mud brick if the second scenario is followed, it is quite recommendable when the case is thermal insulation.

On the other hand, some aspects should also be regarded. First of all, since it requires renewal of plastic anchors once in 5 years as well as renewal of XPS boards once in 50 years it is quite time consuming and costly. Although these aspects are out of the evaluation method of the study, it should be kept in mind for the realistic vision. Since all the renewal would require payment for manual labor and new material as well as time requirement for the application, although it is environmentally preferable it seems quite avoidable within realistic scope.

Table 4.15 Score rank in terms of masonry type

Wall		Masonry type	Solid clay brick					Hollow clay brick				
		actual lifetime	200 years					200 years				
		thickness	139 cm					49 cm				
type	lifetime	scenario	1	2	3	4	5	1	2	3	4	5
B	400 years	highest score	▲▲▲▲▲▲					▲▲▲				
		lowest score		■■■■■■					■■■			
	800 years	highest score	▲▲▲▲▲▲					▲▲▲				
		lowest score		■■■■■■						■■■		

Wall		Masonry type	Thermally insulated hollow clay brick					AAC block			
		actual lifetime	200 years					100 years			
		thickness	19 cm + 3.5 cm					41 cm			
type	lifetime	scenario	1	2	3	4	5	1	2	3	4
B	400 years	highest score					▲▲		▲▲▲▲		
		lowest score		■■						■■■■	
	800 years	highest score					▲▲		▲▲▲▲▲		
		lowest score		■						■■■■	

Wall		Masonry type	Stone block	Mud brick
		actual lifetime	400 and 800 years	250 and 200 years
		thickness	164 cm	100 cm
type	lifetime	scenario	1	1
B	400 years	highest score	▲▲▲▲▲	▲
		lowest score	■■■■■	■
	800 years	highest score	▲▲▲▲	▲
		lowest score	■■■■■	■■

▲ highest scored scenario alternative of each masonry type (most harmful scenario of each material)

■ lowest scored scenario alternative of each masonry type (least harmful scenario of each material)

CHAPTER 5

CONCLUSION

The aim of this report is to present the process of a LCA study on some masonry wall types. Referring to obtained results, mud brick masonry is labeled as one of the most environmental friendly wall types in terms of environmental impact during its total life cycle. Besides labeling the most environmental friendly masonry type for selected cases, this study also declares the crucial points that positively or negatively affect the impact level of the wall on nature e.g. transportation distances, lifetimes, etc. For the study two main scopes are mentioned i.e. walls according to thermal insulation standards and commonly used thickness.

To summarize and generalize the information, the most important aspects are presented in this chapter under five categories i.e. manufacturing phase, assembly phase, useful lifetime, maintenance requirements and end-of-life scenarios. However, each aspect here declares one stage of the LCA study that refers to only one part of the whole. Hence taking into consideration only one aspect presented under each title below is misleading while regarding all of them concurrently is the right way to conduct a LCA study.

- Manufacturing phase: The first step of the masonry units in terms of LCA is manufacturing phase that has several affects on the environmental impact level. Within the scope of this study, the level is high for clay brick and AAC production while it is low for natural stone block and mud brick production, since clay brick and AAC block require specialized production plants and great amount of energy during production. In terms of clay brick, basic needs are excavation, transportation of auxiliary material up to production plant, mixing, firing, cooling and transportation to the construction site, while for AAC blocks it includes excavation, transportation of auxiliary material up to production plant, mixing, steaming, cooling and transportation to the construction site.

On the other hand for natural stone block and mud brick no production plant is needed that leads to the exclusion of transportation of auxiliary material to the plant. The need for stone block production is only cutting in quarry and transportation to the construction site while for mud brick production is only shaping by hand and transportation from resource to the construction site. In this sense, the production stage of clay brick and AAC block is more harmful compared to natural stone block and mud brick. Additionally, since the production phase excludes some stages that require extra energy and inputs natural stone unit and mud brick are less harmful.

- Assembly phase: After the manufacturing of units, the assembly phase i.e. jointing the units with appropriate technique comes into play. Since building is done manually within the scope of the study, transportation of units is the main need of this phase. In terms of transportation two criteria are decisive i.e. the distance between the production plant, quarry or clay resource and construction site, besides the weight of the mass. In terms of distance, AAC block is the most harmful owing to the fewer number of production plants within the country that leads to the longer distances and mud brick is the least harmful owing to proximity of resources.

On the other hand AAC block with the lowest density among all selected masonry units has the least harmful impact in terms of low weight for carrying while the clay brick and stone block with the highest density has the highest impact in terms of carrying to site. On the other hand, the hollow version of clay brick is comparatively lighter than the solid version that lowers its environmental impact level.

- Maintenance: During the useful lifetime periods, clay brick, stone block and mud brick masonry types require periodical renewals, though AAC block does not. Clay brick and stone masonry needs repointing of mortar once in about 25 years while mud brick needs face renewing about every 10 years. From this perspective, clay brick, stone block and mud brick are relatively more harmful than AAC block masonry.

- Useful lifetime: Useful lifetimes of the walls differ according to endurance of the components. The longer lifetime offered by the wall lowers the level of negative impacts since it excludes the need for construction of a new wall owing to its long existence. For one option stated for this study, the useful lifetime of natural stone block masonry is about 800 years while AAC block masonry is only about 100 years. Therefore during the existence of stone masonry wall, AAC block wall is built 7 times. From this perspective the environmental damage of stone is by far lower owing to its long useful lifetime compared to AAC block masonry.

- End-of-life scenarios: The fate in the end-of-life phase is crucial in environmental injury. Although possible end-of-life scenario alternatives differ from material to material, the most common types are landfill, reuse and recycling; all of which have different damage levels. If the material still has usability in the end-of-life phase, the option of landfill instead of reuse is relatively harmful. For the options stated for this study, separation, i.e. recovery of masonry units is required in the end-of-life phase for reuse. For most of the cases, manual separation is preferred and only for few cases additional energy i.e. heat treatment is applied.

Referring to the results of the evaluation reuse with the aid of manual recovery is certainly less harmful compared to landfill since it requires no additional energy but if energy requirement is quite high for separation, it may result in higher environmental damage. The concern is more or less the same in terms of recycling since recycling itself requires additional energy. For this study recycling is stated as crushing and transportation of separated debris in the end-of-life phase in order to exclude the excavation of equivalent weight of new material. If the impacts of energy needed for recycling is higher, compared to energy needed during excavation and transportation then recycling can be labeled as more harmful compared to landfill. For the scope of this study, recycling of clay brick and AAC is not environmentally preferable although reuse is. Regarding the additional requirements during the end-of-life phase, the environmental impacts may differ in terms of impact levels, namely, the level of negative impact of landfill, reuse and recycling may differ according to the demands of the case.

Right after examining all processes of LCA, it is clear that, all the stages forming the masonry wall have several environmental impacts starting from the very first manufacturing phase i.e. production of units up to end-of-life phase i.e. landfill, reuse or recycling. Therefore, for the most reliable results, all the stages of masonry wall were examined in a detailed manner and possibly the realistically assumptions were used during the LCA study. This method of assessment should be carried out in further studies. Lastly the missing aspects of the method used for this study can be pointed out as the cost estimations, time requirements and the equivalent value of manual power.

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APPENDIX A

SELECTED HISTORICAL BUILDINGS

Table A.1

Registered historical buildings in the selected cities that are appropriate for the study

Sample city	Clay brick masonry	Construction date	Stone unit masonry	Construction date	Mud brick masonry	Construction date
Kırklareli[I]	names of specific buildings not listed but known to exist in dwelling architecture	19-20th century	Kadı camii	1577	names of specific buildings not listed but known to exist in dwelling architecture	19-20th century
			Bayezid camii	16th century		
			Karakaşbey camii	1628		
			Hızırbey camii	1383		
			Kapan camii	1640		
			Sokullu camii	14th century		
			Fatih camii	1467		
			Hasan bey camii	14th century		
			Sadri bey camii	16th century		
			Sokullu mehmet paşa külliyesi	1569		
			Arasta	1383		
Karaman[II]	data not avaliable	data not avaliable	Fisandon camii	9-10th century	Nalıncılar evi	19th century
			İbrala camii	1649		
			Çelebi camii	15th century		
			Halil efendi camii	14th century		
			Yeni minare camii	1522	Tartan evi	19th century
			Davgandos camii	16th century		
			Toraman mescidi	1590		
			Burhan han	1368		
			Gelindi han	Karamanoğulları	28 nolu ev	19th century
			Kozak han	Karamanoğulları		
			Aladdin bey kümbeti	15th century		
			Cambazkadı türbesi	Karamanoğulları 2. ibrahim bey	Tahir Özyol evi	19th century
			Demirgömlek türbesi	15th century		
			Halilefendi türbesi	16th century		
			Karabaş veli türbesi	1465	Kavas evi	1840
			İbrahim bey türbesi	1460		
			Kızlar türbesi	Karamanoğulları 2. ibrahim bey		
			Yunus emre türbesi	13th century		
Artvin[III]	a few buildings exist but specific names not avaliable	data not avaliable	Zeytinlik camii ve türbeleri	1857	not common owing to extreme humid[VI]	not applicable
			Oruçlu camii	1907		
			Ortahopa camii	19th century		
			Murgul camii	1863		
			İşhan manastırı	759- 861		
			Dört kilise	9th century		
			Porta manastırı	896- 918		
			Tibeti	899- 914		
			Yeni rabat	11th century		
Tunceli[IV]	data not avaliable	data not avaliable	Sağman camii	1555	names of specific buildings not listed but known to exist in dwelling architecture	end of 19th century
			Ferruh şad türbesi	1551		
			Elti hatun türbesi	13th century		
			Elti hatun camii	1252		
			Çoban baba türbesi	15th century		
			Uzun hasan türbesi	1572		
			Süleymaniye camii	15- 16th century		
			Yelmaniye camii	14th century		
			Hamidiye medresesi	1861		
			Kilise	18th century		
Iğdır[V]	data not avaliable	data not avaliable	Çakırtaş kul yusuf kümbeti	1485	data not avaliable	data not avaliable
			Aralık hacı ibrahim kümbeti	1321		
			Iğdır kervansarayı	14th century		

[I] http://www.kirklarelikulturturizm.gov.tr, last access 08.02.2012

[II] http://www.karamankultur.gov.tr, last access 08.02.2012

[III] http://www.artvinkulturturizm.gov.tr, last access 08.02.2012

[IV] http://www.tuncelikulturturizm.gov.tr, last access 08.02.2012

[V] http://www.igdirkulturturizm.gov.tr, last access 08.02.2012

[VI] Sen *et al.*, 2010

APPENDIX B

INTERFACES OF SIMAPRO

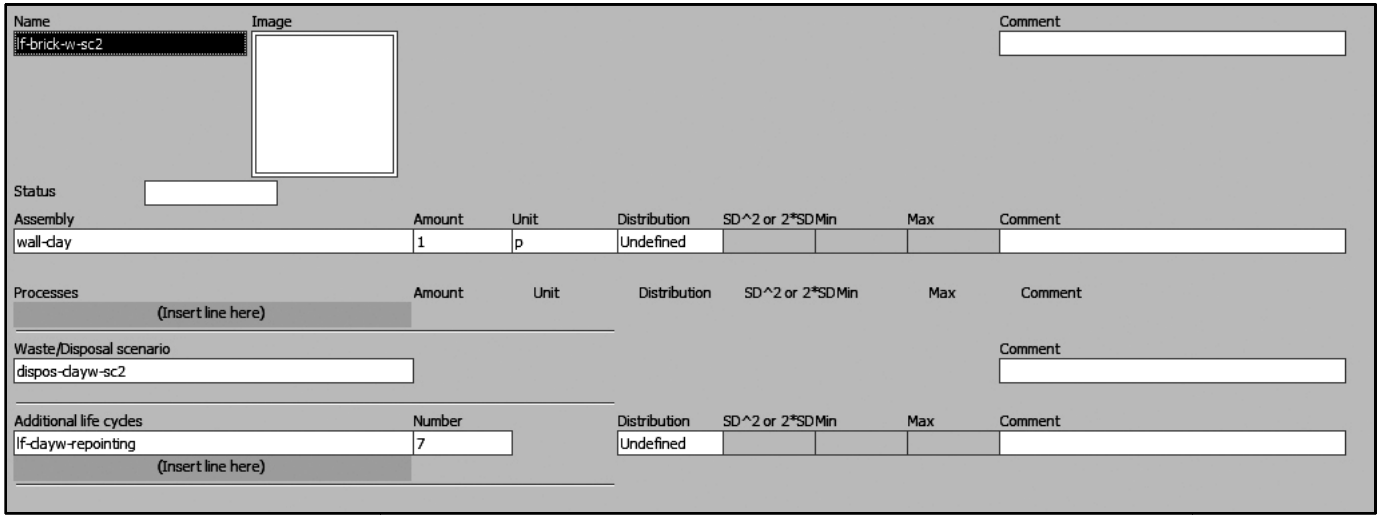

Figure B.1 Interface of SimaPro during life cycle phase formulation

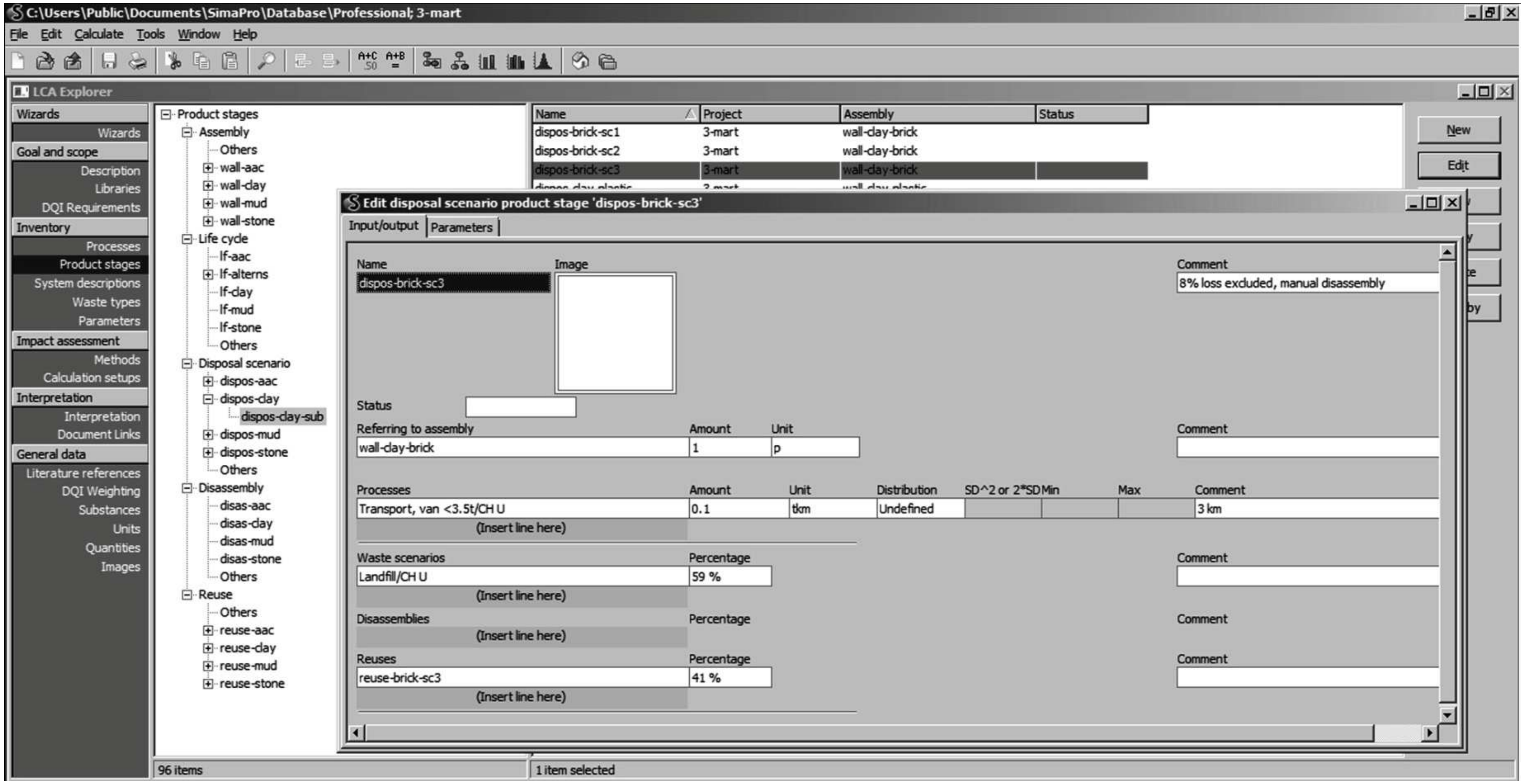

Figure B.2 Interface of SimaPro during disposal phase formulation

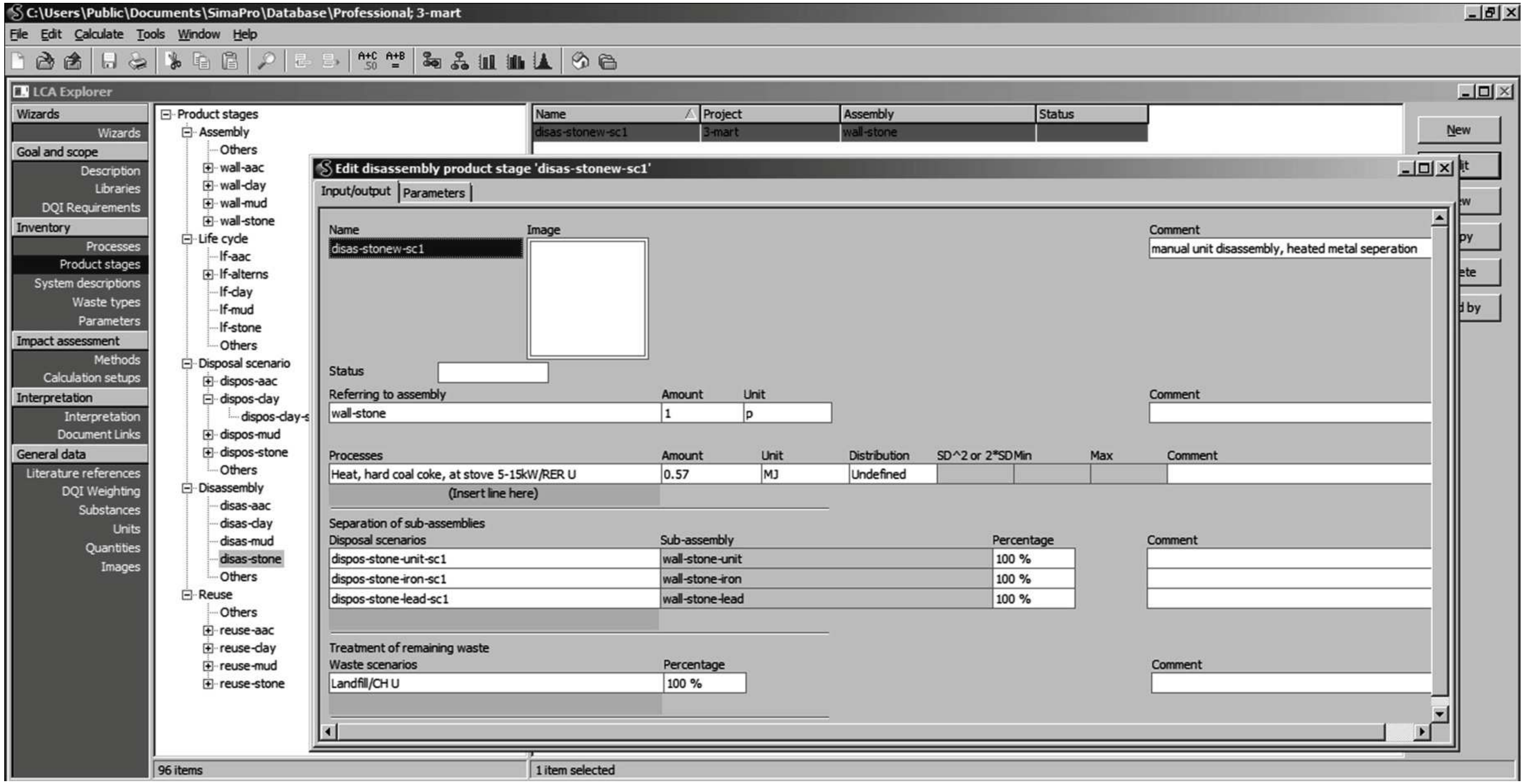

Figure B.3 Interface of SimaPro during disassembly phase formulation

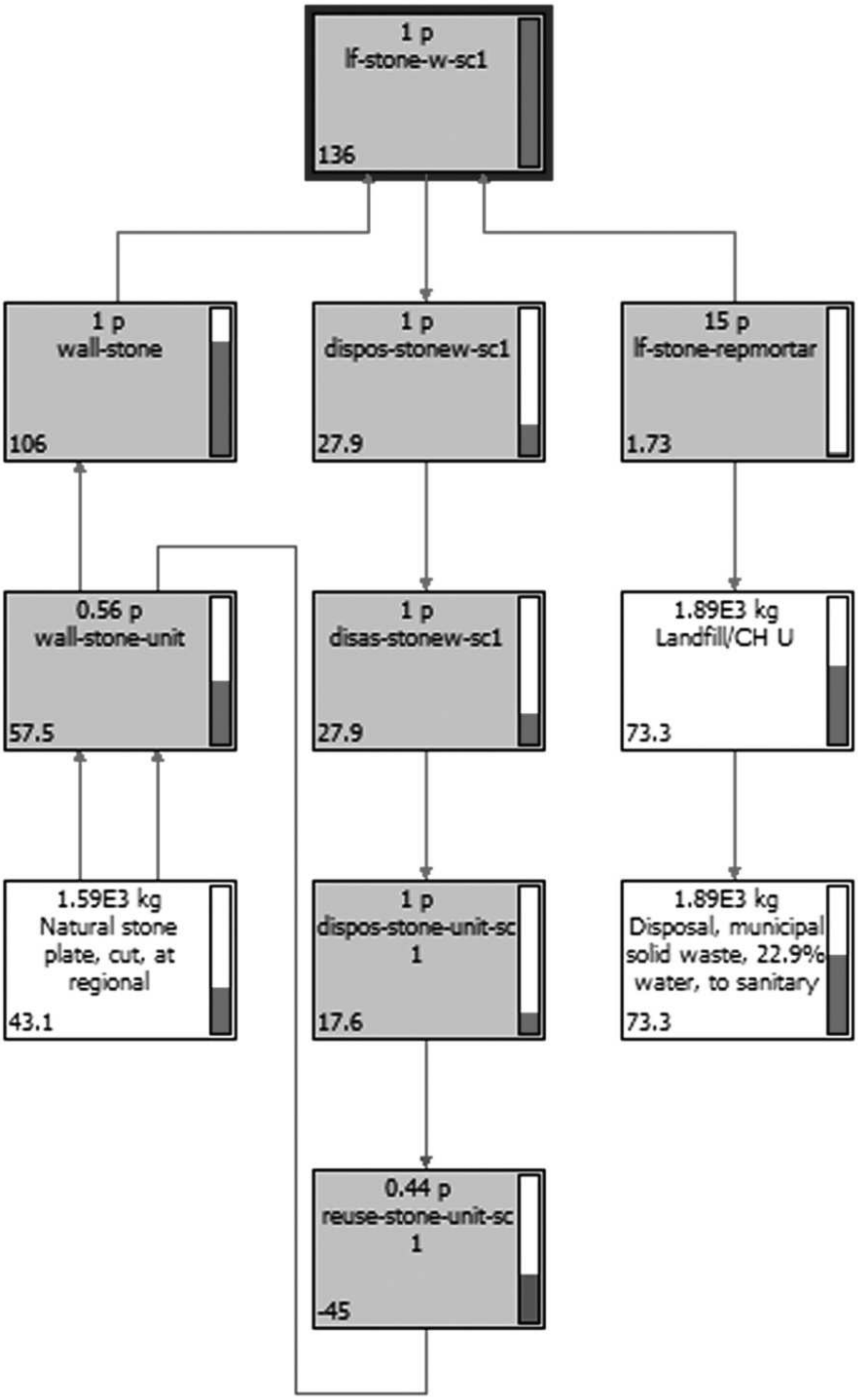

Figure B.4 Interface of SimaPro illustrating flow chart of life cycle of stone masonry

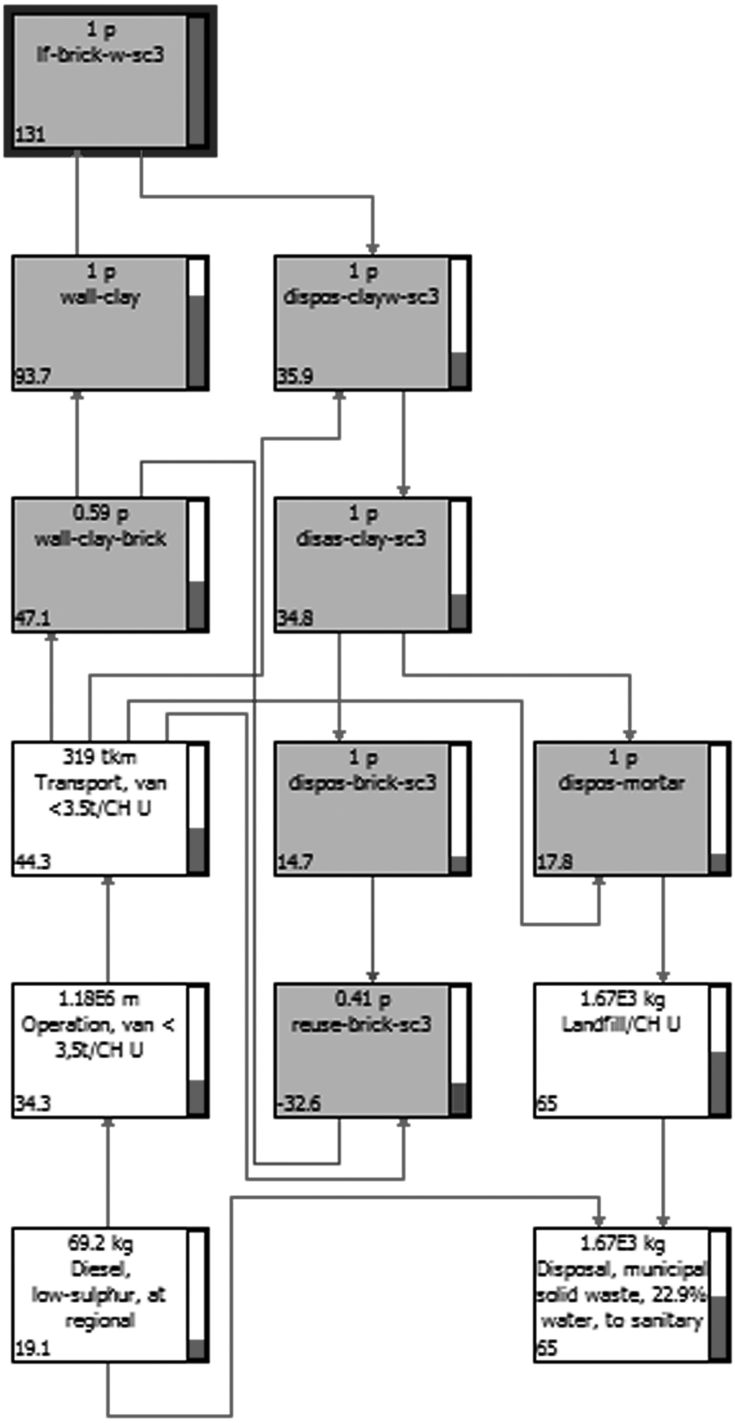

Figure B.5 Interface of SimaPro illustrating flow chart of life cycle of brick masonry