THE RELATIONSHIP BETWEEN LIFE CYCLE EMBODIED ENERGY AND FLEXIBLE DESIGN CHARACTERISTICS OF TRADITIONAL OTTOMAN HOUSES IN ANKARA

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ABSTRACT

THE RELATIONSHIP BETWEEN LIFE CYCLE EMBODIED ENERGY AND FLEXIBLE DESIGN CHARACTERISTICS OF TRADITIONAL OTTOMAN HOUSES IN ANKARA

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The lack of adaptability in most buildings to changes in user needs results in a shorter service life of the existing building stock; which is claimed to be around 50 years only. Such redundant buildings are usually demolished and replaced with new ones that meet user needs at the cost of not only increasing the need for energy to rebuild but also a loss of energy embodied in the demolished building. On the other hand, some of the centuries old traditional houses are still occupied because of their ability to adapt to the changes, by virtue of their flexible design characteristics and construction techniques. The aim of this study was to investigate the relationship between the life cycle embodied energy (LCEE) of buildings and their flexible design characteristics within the context of traditional buildings.

To this end, traditional houses in Ankara, belonging to the Ottoman era, that had previously been studied for a PhD dissertation (Şahin 1995) were considered appropriate for this research and 10 of the oldest buildings were selected. The architectural drawings and related information were obtained from the said dissertation and the buildings were visited in August 2021. This information was then used to redrawn the house plans in order to identify the existence of flexible design characteristics compiled from literature. Thereafter, 3D building models were produced in Revit software and the bills of quantities were obtained; which were then multiplied with pertinent proxy data from the Inventory of Carbon and Energy (ICE) v2.0 database to calculate the energy consumed in the construction and use stages. Finally, the initial, recurring, additional initial embodied, and demolition energy values were obtained for the different service life scenarios, for LCEE comparisons.

This study demonstrated that traditional Ottoman houses with a service life of more than 100 years have flexible design strategies that are given in the literature. Although these strategies caused an increase in the building's LCEE by approximately 0.6 to 9.2%; it was still much lower than the energy needed for material replacements, which was 75.7 to 93.1% of LCEE. Additionally, in comparison to buildings with a service-life of 50-year cycles, up to 31% of savings in the total embodied energy were achieved.

Keywords: Traditional Ottoman Houses, Life Cycle Embodied Energy, Building Service Life, Adaptability, Flexible Design.

ÖZ

ANKARA'DAKİ GELENEKSEL OSMANLI EVLERİNİN YAŞAM BOYU GÖMÜLÜ ENERJİ İLE ESNEK TASARIM ÖZELLİKLERİNİN İLİŞKİLENDİRİLMESİ

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Mevcut yapı stoğunun uyarlanabilir özelliklere sahip olmaması, yapıların hizmet ömrünün yaklaşık 50 yıl ile sınırlı kalmasına neden olmaktadır. Bu tür kullanılmayan yapılar genellikle yıkılarak kullanıcı talepleri doğrultusunda yeni yapılar inşa edilir. Böylece hem yapım hem de yıkım aşamaları için enerji sarfiyatı gerçekleşmiş olur.

Ancak geleneksel Osmanlı evlerine bakıldığında, esnek tasarım stratejileri ve yapım teknikleri nedeniyle bazılarının halen hizmet vermekte olduğu görülür. Bu çalışmanın amacı geleneksel Osmanlı konutları kapsamında yapıların yaşam boyu gömülü enerjileri ile esnek tasarım özelliklerinin incelenmesidir.

Bu nedenle uzun süre kullanımda oldukları bilinen, Ankara'da yer alan ve daha önce bir doktora tezi kapsamında çalışılan (Şahin, 1995) 10 adet geleneksel Osmanlı yapısı bu çalışma kapsamında ele alınmıştır. Yapılara ait mimari planlar ve gerekli bilgiler bahsi geçen çalışmadan elde edilmiş olup yapılar Ağustos, 2021 tarihinde yerlerinde ziyaret edilmiştir. Toplanan bilgiler kat planlarının oluşturulması ve literatürden elde edilen esnek tasarım özelliklerinin çalışılacak yapılar bağlamında belirlenmesi için kullanılmıştır. Sonrasında, REVIT programı üzerinden 3 boyutlu yapı modelleri oluşturulmuş ve kullanılan yapı malzemelerinin miktarları hesaplanmıştır. Bulunan değerler uluslararası enerji veri tabanı (ICE, v2.0) yardımı ile yapıların inşası ve kullanımı sırasında harcanan malzemelerin gömülü enerjilerinin hesaplanmasında kullanılmıştır. Sonuçta farklı hizmet ömrü senaryoları için yaşam boyu gömülü enerjisi kapsamında başlangıç, yinelenen, ilave edilen ve yıkım enerjileri hesaplanmıştır.

Sonuçlar, hizmet ömrü 100 yıldan fazla olan Ankara'daki geleneksel Osmanlı evlerinin literatürde bahsi geçen esnek tasarım parametrelerine sahip olduğunu göstermektedir. Esnek tasarım stratejilerinin uygulanması için gereken enerji, yaşam boyu gömülü enerjinin %0,6 ila %9,2'sini oluştursa bile, bu enerji türünün yapı malzemelerin periyodik olarak yenilenmesi için harcanan enerjiye oranla (toplam gömülü enerjinin %75,7 ila %93,1'i) oldukça az bir paya sahip olduğu anlaşılmıştır. Buna ek olarak, 50 yıllık yaşam döngüsüne sahip yapılara kıyasla hizmet süresinin uzamasından kaynaklı olarak toplam gömülü enerjide %31'e varan enerji tasarrufu sağlanmıştır.

Anahtar Kelimeler: Geleneksel Osmanlı Evleri, Yaşam Boyu Gömülü Enerjisi, Bina Hizmet Ömrü, Uyarlanabilirlik, Esnek Tasarım.

To my beloved family and childhood friend

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ABBREVIATIONS

3D	Three Dimensional
3L	Long Life, Loose Fit, Low Energy
AEE	Additional Initial Embodied Energy
BREEAM	Building Research Establishment Environmental Assessment Method
CS01	Case Study (number) 01
CSIRO	Commonwealth Scientific and Industrial Research Organization
DE	Demolition Energy
DEAM	Data for Environmental Analysis and Management
EE	Embodied Energy
EU-28	European Union (consisting of) 28 countries
EX	Extension
FC	Function Change
FDEE	Embodied Energy of Flexible Design Strategies
GJ	Gigajoules
I-O Based	Input-output Based
ICE	Inventory of Carbon and Energy
ID	Integration/division
IEE	Initial Embodied Energy

kWh	Kilowatt-hour
LCE	Life cycle energy
LCEE	Life cycle Embodied Energy
LEED	Leadership in Energy and Environmental Design
METU	Middle East Technical University
MJ	Megajoules
N01	Initial Case (number) 01
PhD	Doctor of Philosophy
R01	Renovated Case (number) 01
R^2	Correlation Coefficient
REE	Recurring Embodied Energy
TMMOB	Türk Mühendis ve Mimar Odaları Birliği (Association of Architects and Engineers in Turkey)
UK	United Kingdom
US	United States
yr	Year

CHAPTER 1

INTRODUCTION

What is good design in architecture and how can it be measured? Langston (2014) claims that many ideologies have been explained in the light of this question. According to Vitruvius the most important features of architecture are function, structure, and beauty; others can be listed as context, cultural background, desires of the users, and cost. On the other hand, Langston (2014) refers to the 3L Principle of Alexander John Gordon (1972) which are based on ‘long life, loose fit and low energy’ and claims that following this principle can help to achieve good architecture worldwide. Today, these three concepts can be renamed as durability, adaptability, and sustainability (Langston, 2014).

Adaptable design allows changes without the need for major alterations in the building structure. The value of the building increases as it corresponds to the user needs. In order to cope with climate change, sustain the building environment, and extend the building service life, adaptability is the fundamental issue that needs to be addressed. Managing the limited resources is another solution this design approach presents (Kamara et al., 2020).

Adaptability in building design contributes to efficiency, longevity (i.e., long service life) and economic feasibility. Therefore, if a building is adaptable, its longer and efficient service life will lead to a lower the life cycle embodied energy (LCEE). Being adaptable comprises strategies that are closely related, i.e., flexibility, convertibility and expandability. Flexibility facilitates the minor changes in spatial organization while convertibility assists changes within the building. Expandability stands for allowing additions by increasing the space size of the building. By extending the lifetime of a building and preventing a building from obsolescence, the energy required for rebuilding the structure can be reduced (Russell & Moffatt, 2001).

Yüksel and Sözer (2019) note that traditional buildings have flexible use of spaces serving the need of the users. Traditional buildings were generally made of timber frame, which is adaptable to reuse and also for redesign of spaces (Şahin Güçhan, 2018). According to Kuban (1995), traditional timber construction techniques allow to build faster but require good craftsmanship and use of timber as a building material became widespread in the 17th century. Adaptability features were present in traditional Ottoman architecture. Kuban (1995) states that the plan layout of these houses was extremely flexible, and describes many changes in their spatial organization. An example of this is the flexible design approach seen in traditional Ottoman houses in Istanbul, which allows to convert a basic plan into complex configurations by closing *eyvan*s and expanding the spaces by adding a room to the courtyards (Kuban 1995).

This design approach fulfils the "loose fit" principle of good design, and also that of "long life", since these houses are still in use; which leaves us the third principle of "low energy" to be evaluated in terms of traditional Ottoman dwellings. As Langston & Langston (2008) also point out, energy concerns influence the design and management of building systems. Operational energy is one side of the medallion, while the other is embodied energy (EE), hence it has a role in the life cycle assessment for both building materials and structures. (Lawson, 2006) Advances in technology and regulations lead to a decrease in operational energy, but an increase in EE (Koezjakov et al., 2018). However, embodied energy calculations are often overlooked because they are complex, multi-stage and not based on a standard methodology (Langston & Langston, 2008).

Initial and recurring embodied energies (REE) are two types of the life cycle embodied energy (LCEE). The first type of EE is used before occupancy while REE is needed throughout the service life of the building such as in the replacement of building materials (Stephan & Stephan, 2014) and repairs, which extend the service life of the building. REE has a significant impact on reducing the LCEE (Dixit et al., 2014) when the service life is extended.

The focal point of this study is the LCEE of traditional houses. The adaptable characteristics and sustainable features of the building materials of the traditional Ottoman houses were the main reason for selecting them as the case study in order to explore the connection between LCEE and flexible design characteristics. In order to limit the scope of the study, the traditional Ottoman houses in Ankara were selected from Şahin (1995)'s dissertation.

1.1 Problem Statement

When the average service life of buildings is taken as 50-60 years, 75% of the energy consumption and carbon footprint is due to the building use phase while the remaining 25% is due to the building construction. (Ministry of Energy and Naturals General Directorate of Renewable Energy, 2016)

The problem of a short service life is due to the lack of adaptability and structural longevity in buildings, which have to be replaced to meet the changing user needs by not only using more energy to rebuild but also losing the LCEE of the redundant buildings.

Flexible design has the ability to extend the service life of buildings and thus reducing energy demands. In contrast to conventional buildings, traditional buildings are seen to have a longer service life, which reflects their ability to adapt to changes because of their flexible plan layouts and timber frame structures.

Current studies on the energy use of traditional houses in Turkey are mostly based on operational energy consumption and they are found successful in this respect. However, the LCEE of traditional houses should also be evaluated in order to develop an understanding of their entire life cycle energy (LCE) consumption.

1.2 Aim and Objectives

A building's design includes not only the planning of spaces and selection of building materials and construction techniques, but also the consideration of adaptability to future user needs. Examining traditional houses may facilitate understanding of how their adaptability affects their service life and LCEE.

Therefore, the main aim of this study is to investigate the impact of adaptable and flexible design features on the embodied energy of traditional Ottoman houses in Ankara.

To achieve that aim, two objectives are established. The first one is related to the evaluation of their adaptability by identifying the flexible design characteristics. The second is to calculate the LCEE of these houses. If the design parameters can also be quantified, the impact on both REE and LCEE can be found out (Figure 1.1).

Figure 1. 1. *Chain of impacts from building design to LCEE that shows the relationship between flexible design strategies and LCEE*

The research questions in line with the objectives and that are limited to traditional Ottoman houses in Ankara in this study are:

- Which flexible design strategies lead to adaptable building design;
- And, which ones can be identified in the plan layouts of the selected traditional buildings?
- What are the embodied energy loads in traditional buildings with respect to initial, recurring, and additional embodied energies, in the building's life cycle?

- What is the relationship between flexibility, service life duration and LCEE?

1.3 Methodology

In order to answer the research questions and conduct the research, the following steps were taken.

Literature review is conducted on adaptability and flexible design strategies; spatial organization, construction techniques, and energy performance of traditional Ottoman houses; and LCEE types, parameters, and calculation methods. Documents and information regarding traditional Ottoman houses in Ankara are collected; such as building plans, photographs, type of building materials, spatial and material changes that occurred during their lifetime. Embodied energy intensity per unit, bulk density and service life of building materials are collected from the literature, for embodied energy calculations.

The flexible design strategies were identified on the plan layouts of the 10 selected Ottoman houses in Ankara. The service life of these buildings is estimated according to their construction periods. The service life is taken from the estimated construction date to last detailed survey date. Based on the collected data, 3D building models are created in Revit in order to obtain material quantities. After all the components are set, initial embodied energy (IEE) calculation is made with regard to the system boundary. Thereafter, REE is calculated considering replacement cycles of initial building materials, additions, and alterations.

The embodied energy of each building material for different stages is found in order to examine LCEE. Finally, in order to quantify the design parameters, the strategies obtained from literature are evaluated. The embodied energy of building materials used for rebuilding and renewal works, and flexible design strategies is found separately to compare the results and relate them to the long service life due to flexibility.

1.4 Disposition

This study consists of six main chapters. The first chapter covers the introduction including research problem, objectives and methodology. The second chapter is composed of the literature review which is divided into three main parts; building adaptability, traditional Ottoman houses, and LCEE. The third chapter includes the research material and methodology of the study. In the fourth chapter, the study results and analyses are presented and discussed. In the last chapter, the conclusion and recommendations for further studies are given.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the importance of adaptability, characteristics of traditional houses, embodied energy, and concluding remarks of literature review are stated. In the first part, adaptable building potentials, flexibility and its contribution to building service life are examined with the assistance of a variety of researches. In the second part, traditional Ottoman houses and their inherent adaptable features related to space optimization, construction type, and energy performance are analyzed. As the third, embodied energy types and parameters, the importance of REE and calculation methods are reviewed. Finally, a short assessment of the review is expressed.

2.1 Building Adaptability

Adaptability stands for being in harmony with the future changes needed during the building's life cycle (Kamara et al., 2020)**.** There is an interrelated definition between adaptability and flexibility. Flexibility is often explained by a design that allows for multifunctional use or a more effective space planning (Russell & Moffatt, 2001)**,** while adaptability technically refers to achieving it (Gijsbers & Lichtenberg, 2012)**.**

There is a strong link between sustainability and adaptability. To reveal this relationship, a case study was examined, interviews were conducted, and a comprehensive literature review was done by Manewa *et al.* (2016). According to a detailed analysis conducted in the United Kingdom (UK) with comprising over a 100-year life span of the building, approximately 60% of the structures changed their original status to another function while 10% of them have undergone functional changes every six years in the last two decades. Thus, it was seen that adaptability contributes to sustainability by allowing ‘change of use’ for the buildings having a service life of more than 100 years. The research highlights the importance of introducing adaptive strategies in the early stages of the design process (Manewa et al., 2016).

2.1.1 Importance of Adaptability

Researchers advocate the value of investigating existing design strategies to support adaptability. In addition, life cycle cost and assessment can provide a better focus on the sustainable built environment (Manewa et al., 2016). Being adaptable refers to being efficient, having a longer service life, and corresponding changes at a lower price. Especially in urban territories, strong optimization of buildings and effective use of energy and building materials are significant. Scarcity of land, vacant building stock, increasing number of renovation projects, generation of more solid waste, and excessive use of building materials derived from natural sources explain the importance of the issue (Russell & Moffatt, 2001).

Efficient use of space inside the building would extend the lifespan of the buildings, ultimately resulting in reduced need for new buildings. Choosing durable building materials is another form of adaptability that assists to extend the service life of building materials (Russell & Moffatt, 2001). Changes to a structure with flexible features require less money and time than building anew (Geraedts, 2008; Slaughter, 2001). Especially for office buildings, improvements to increase the building performance may be required, which is more easily achieved when the building is adaptable. Another benefit of being adaptable is that it is among the methods mentioned for managing climate change and improving energy performance. From a financial point, budget savings will become more important in the near future due to the rapid consumption of fossil fuels (Gosling et al., 2008).

2.1.2 Flexibility in Architectural Design

Flexibility is the ability to respond to the cultural, technological, as well as economic changes. It is a tool for getting rid of waste and extending the building lifespan (Cavalliere et al., 2019). It promotes the resilience of structures against external disturbances without major alterations (Cellucci & Di Sivo, 2015), and affects the service life of both existing and new structures (Blok and Herwijnen, 2005). Fuertes (2017) stated that architecture uses resources that must be protected, such as material and energy.

Sustainability and resiliency are the two concepts that rely on each other. For a more time-resistant building, the building needs to manage changes. The reason why flexibility is so popular today is because of limited land to construct, factors of obsolescence, and depletion of resources (Cavalliere et al., 2019).

The structure of buildings has the longest lifetime. Temporary demands of users determine the functional life of the building, so it is crucial that buildings are designed in a demand-responsive way. Structural flexibility is defined as the ability to transform spaces within the framework of load-bearing potential and space efficiency for at least one building layer without the need to alter the remaining structure (Blok & Herwijnen, 2005).

A number of flexible design strategies derived from literature are listed in Table 2.1.

Table 2. 1. *Flexibility strategies derived from literature*

Flexible Design Strategies	Alaraji, Jusan (2012)	Alkhansarı (2018)	Cellucci, Sivo (2015)	Hasgül, Özsoy (2016)	Hatipoğlu, Ismail (2019)	Till, Schneider (2005)	Geraedts (2008)	De Paris, Lopes (2018)	Raviz et al. (2015)	Slaughter (2001)	Hassanain (2006)	Kim (2013)
Open plan/ structural system	x	x		x	x	x		x	x	x		x
Pre-fabricated modules		x						x				x
Retractable furniture		x	x					x	x			
Similar spaces		x	x									
Multifunction al Space		x	x	x		x	x	x	x	x	x	x
Extendable unit	x	x	x	x	x		x					x
Attachment/ Detachment		x	x				x					
Common space		x										
Portable walls		x	x		x			x	x			
Undefined environmenta l units			x					x				x
Technologica l flexibility			x					x				x
Service space location					x	x		x		x	x	
Layers						x		x		x		
Compact form						x		x	x			x
Plan layout								x	x		x	x

In order to clarify Table 2.1., the terminologies need to be explained. The open plan concept allows for loose placement of the walls as the interior partitions have not loadbearing capacity (Alkhansari, 2018). The floor layout can be modified freely if it has an open plan (De Paris & Lopes, 2018). According to a study conducted on ten projects, it was determined that the common ground of flexibility is the open plan scheme created by keeping wet areas fixed and liberating other spaces (Hasgül & Özsoy, 2016).

Prefabricated modules refer to building components that can be assembled easily and quickly due to their modular systems. They can be used for both original structures and future necessities (Alkhansari, 2018).

Retractable furniture is used to provide versatility. In the traditional houses, especially in the eastern regions, such as Persian or Japanese dwellings, a single space is used multi-functionally by taking advantage of light and mobile furniture (Alkhansari, 2018). The use of mobile equipment includes the assembly/disassembly of building components such as interior partitions, cabinets and other types of furniture. This method is especially effective for small spaces (Cellucci & Di Sivo, 2015). Multifunctionality allows effectual use of space and clustering of the building components (Geraedts, 2008).

Similar spaces (Alkhansari, 2018) and customizing social and private needs (Cellucci & Di Sivo, 2015) are the methods that involve an equal balance between rooms with similar distribution to ensure that the space is suitable for many different functions, facilitating function change in the later stages. Undefined environmental units is related to a fixed surface area, which occurs within a constant total volume and includes alternative design strategies (Cellucci & Di Sivo, 2015).

Multifunctional space can cope with changing environments with satisfactory spatial arrangements (Kim, 2013). It allows the dispersion of daily activities and hierarchizes the spaces according to the needs of occupants (Raviz et al., 2015). Horizontal or vertical space additions in a specific zone can be evaluated under the title of extendable unit (Alkhansari, 2018). It permits additional constructional components both exterior and interior part of the building (Geraedts, 2008). Evolutionary space refers to the ability to increase in total volume or surface area. This can be accomplished within the existing support system by enclosing spaces such as balconies, terraces etc. Increasing the initial volume is another approach to generate new spaces with the addition of new structural systems (Cellucci & Di Sivo, 2015).

Merging or separating of adjoining units refers to attachment and detachment (Alkhansari, 2018). Similarly, dividing a building into units or assigning a part of it for another activity or dwelling is associated with redundancy access. This enables to shrink the size of the space when the spaces are no longer needed. Addition of living units to the building does not affect the initial volume, whereas provides a new unit for an emergent function does, such as a room for a new family member (Cellucci & Di Sivo, 2015). Creating a common space between adjacent spaces allows this area to join other units when deemed necessary (Alkhansari, 2018).

Dynamic elements produce different plan configurations, some of which are called portable walls. An example can be given as non-bearing wooden walls which are attached to ceiling and floor and can be easily dismantled if desired (Alkhansari, 2018).

Technological flexibility relates to innovative assemblies for the building envelope such as mobile facades (Cellucci & Di Sivo, 2015). It can also be described as increasing quality of a house by applying new technologies (De Paris & Lopes, 2018). Easy maintenance applicable to old and new technical systems is the key for minimizing effort with lower cost and flexible use (Cellucci & Di Sivo, 2015).

The location of service spaces is significant for refurbishment processes. The control of service areas can be achieved in three ways: accessibility for users, easy maintenance, and strategic location to facilitate changes (Till & Schneider, 2005). Service spaces such as kitchen and bathroom should be grouped or placed individually and with the consideration of future alterations (De Paris & Lopes, 2018).

Layers of a building can be listed as structure, services, skin, interior dividers and finishes. Another benefit of flexible design is to control and define layers easily (Till & Schneider, 2005).

As the size and height of the space increases, so does the chance of flexibility (Till & Schneider, 2005). As the building has a more compact and regular shape, adaptation becomes easier (De Paris & Lopes, 2018).

Plan layout should be adaptable according to user demands, in flexible design. As the number of the family members increase, the layout should allow a variety of spatial use (Kim, 2013). Planning of the building should be suitable to meet not only the current but also the future occupant needs (Hassanain, 2006).

2.2 Traditional Ottoman Houses

The Anatolian-Turkish houses represent the Ottoman period houses in the Rumelia and Anatolian regions, which remained within the borders of the Ottoman state at that time. (Eldem, 1954) These houses can be also seen in the Middle East and north Africa regions, that were once parts of the Ottoman state in the south (Şahin Güçhan, 2018). In addition to that, some parts of Europe such as Bulgaria, and Greece have also these types of houses due to the Ottoman presence there. Traditional houses reflect Ottoman culture, and have reached a position that prevails over other types from the 15th and 16th centuries (Eldem, 1954).

Kuban (1995) indicates that the majority of dwellings in Istanbul were built with adobe in the 16th century, and the use of timber as a building material became widespread at the beginning of the 17th century. According to Faroqhi (1982) the number buildings with an upper floor increased during the 17th century in Ankara.

Şahin Güçhan (2007) refers to Arel's (1982) description of the traditional Ottoman house based on some of the unique physical characteristics, such as contrasting features of ground and upper floors, tradition of *köşk* which is a special room for guests, and the link between open and closed spaces. She points out that Cerasi (2001) distinguishes traditional Ottoman houses from other buildings by considering their timber frame construction techniques, which enabled rapid establishment of new settlements (Şahin Güçhan, 2018).

2.2.1 Spatial Organization

In spatial planning, there are characteristic spaces with specific names that need to be defined; s*ofa*, *eyvan*, *köşk,* room, and *taşlık* are some of them. The *sofa* serves as a central hub connecting other spaces, and is the place where family members come together. It enables activities such as interaction, socialization, sleeping, eating, working, resting, having a wedding or a feast etc. (Eldem, 1954; Gezer, 2013)**.** An e*yvan* is a reserved place for sitting, and is attached to the sofa. A *köşk* is a spacious place, illuminated by daylight with many windows (Eldem, 1954).

The placement of rooms is the most effective factor in the planning space organization (Eldem, 1954). According to Şahin Güçhan (2018) Tanyeli's (1999) study has shown us that the room in the Ottoman house reached its final configuration in the 17^{th} century. Şahin Güçhan (2018) continues with the definitions of the various elements of the Ottoman house by Küçükerman (1991) and indicates that the size and decoration of the rooms are determined according to the needs of the occupants. The *taşlık* which is a stone paved part of the courtyard, is generally located under the sofa and connects other service areas, such are stables, kitchen etc. The majority of the service areas are located in the courtyard, which may also include a water element in the form of a fountain or pond.

The service areas were mainly located in the ground floor. Kitchen and service areas were designed separately. Because the cooking area was located in the courtyard, it was connected with other service areas such as a pantry, depot, etc. In time, the service areas were included in the building after abandoning the traditional way of living (Kuban, 1995)**.**

According to Sedad Hakkı Eldem, there are four typologies in traditional Ottoman houses with respect to the existence or position of the *sofa.* They are 'without sofa', 'with an open/outer sofa', 'with an inner sofa' and 'with a central sofa' (Eldem, 1954)**.** These can be described as follows:

(a) Without Sofa: It is the oldest plan typology. The rooms are arranged side by side. A garden or outdoor space provides the link between these rooms. If the rooms are on the upper floor, the connection turns into a balcony. This type of house is mainly located in southern regions. (Eldem, 1954)

(b) Outer/Open Sofa: In this type, rooms are connected with the help of a *sofa.* Also, 'L' or 'U' shaped sofas are a result of this plan configuration. The addition of spaces such as *köşk* or room arrangement determines the shape of the *sofa* (Eldem, 1954)**.**

(c) Inner Sofa: Both sides of the sofa open into rooms. The connection between the rooms is strengthened but the interaction between the *sofa* and outside is reduced. This typology is more common in cities (Eldem, 1954)**.**

(d) Central Sofa: The *sofa* is located in the middle, and all four sides of the sofa are surrounded by rooms. For natural light, a space called *eyvan* is positioned between the rooms so that it is aligned with the center of the sofa. The number of *eyvans* can be up to 4. This typology is mostly used in big cities such as İstanbul (Eldem, 1954)**.**

The aforementioned types of the *sofa* can be seen from the image below (Figure 2.1).

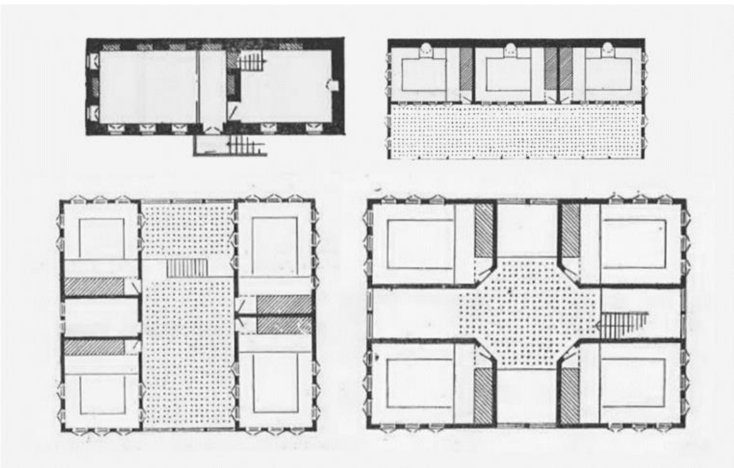


Figure 2. 1. *Without sofa (upper left), outer/open sofa (upper right), inner sofa (below left), and central sofa (below right) plan typologies in traditional buildings. (Source: Eldem, 1954)*

2.2.2 Construction Techniques

Most of the existing Ottoman houses were built with timber constructions which are timber masonry and frame systems. Earlier Ottoman houses dated to the end of the 16th century. They preserved their original features until the beginning of the 18th century. On the other hand, the timber construction techniques evolved, changed, and were preserved until the first quarter of the 20th century (Şahin Güçhan, 2018)**.**

Hımış is a common construction technique, where the ground level is built with masonry and the upper level with timber. This technique was started in the 17th century, and is known to be earthquake resistant. Timber lintels are used in the masonry walls and braces in the timber frame walls to strengthen the structure against lateral forces. The timber frame system also provides rapid installation after natural disasters (Şahin Güçhan, 2018)**.**

The images below demonstrate the detail of timber construction belongs to Ottoman houses (Figure 2.2).

Figure 2. 2. *Hımış technique (left) and timber lintels in the masonry (right) examples from Güdül, Ankara. (Source: Şahin Güçhan, 2018)*

On foundation walls, andesite stone was used, usually with a thickness of approximately 60-80 centimeters in the traditional Ottoman houses in Ankara. The exterior walls of the ground floor are made of masonry, and the interior walls are made of both masonry and timber frame. Timber and floor tile are used as the floor coverings in the Ankara houses, and compressed earth is used in the service areas. The room floorings are usually finished with timber, and the most frequently changed material, floor tile, is applied to the *sofa* and the main hall in most cases. The doors and windows are made of timber (Şahin, 1995).

Floor heights are between 2.50-4.00 meters on the ground level, and 2.60-4.20 meters on the upper floors. Floor beams are 3.00-5.00 meters long, with dimensions of 10x10, 10x15, 15x15, girders are 5x10 cm. Main post size is 10x10 cm if the upper floor is not carried by these posts, otherwise it is 20x20 cm. Secondary posts are 5x10 cm in size. The dimensions of wall plates, braces, and window sills are generally 10x10 cm. The ceiling and floor boards have 2-2.5 cm thickness (Şahin, 1995).

2.2.3 Energy Efficiency of Traditional Ottoman Houses

Residential buildings have a major impact on energy consumption worldwide. In the European Union (EU-28) consisting of 28 countries, there was a 9% decrease in the amount of energy used in residential buildings from 2001 to 2011. However, the situation in Turkey is different, and 48% of the energy increase results from housing. In terms of overall energy consumption, it is known that approximately 32% of the energy is allocated only to residential buildings (Atmaca, 2016)**.**

In traditional houses, the compact form provides minimal surface area with minimum heat loss. The openings, the window to wall ratio, are quite small. Moreover, the use of local building materials, such as adobe and stone, provides insulation to the exterior facade for different climatic conditions. Due to the location and orientation of the houses, natural energy sources such as sun and wind are utilized to provide thermal comfort. The allocation of the areas for winter and summer uses is another positive contribution to energy use (Keskin & Erbay, 2016)**.**

A study carried out with traditional Ottoman houses in the Thrace region has shown that conserving energy by preventing heat loss was the primary concern in the site plan, building and envelope design, and in the selection of construction material and renewable energy resources (Yüksek & Esin, 2013)**.**

The studies on the energy performance of traditional Ottoman houses and type of research carried out are listed in Table 2.2. Most of the studies are seen to have considered operational energy.

Table 2. 2. *Studies on traditional Ottoman houses within the context of energy efficiency*

Source	**Focus area**	**Research Type**
Hasgül *et al*. (2021**)**	Analyzing the passive energy components such as building materials, spatial plan organization, form and orientation of three traditional houses in Küre, Kastamonu.	Mixed
Akyıldız (2020)	Traditional buildings from different climatic regions were examined in terms of energy-efficient design principles.	Qualitative
Pehlivan & Sedes (2019)	Thermal conductivity values of 18 traditional wall types of Safranbolu houses were found and compared.	Quantitative
Yüksel & Sözer (2019)	According to a simulation of traditional Adana house, it was found that this type of house required 40% less energy than a modern house with the same area.	Quantitative
Benchekroun *et al.* (2019)	Indoor air quality, hygrothermal comfort, energy efficiency analysis was conducted on the Ottoman houses in Algiers.	Qualitative
Arpacıoğlu (2016)	62 traditional village houses from three climate zones of Balıkesir were explored in terms of thermal comfort, daylighting, material conditions and energy use.	Quantitative
Keskin & Erbay (2016)	Traditional Anatolian houses live in harmony with nature and climate, and energy saving is achieved thanks to the benefits obtained from natural sources.	Qualitative
Ozorhon & Ozorhon (2014)	Traditional Cumalıkızık houses have sustainable characteristics in their spatial organization, building envelope and settlements.	Qualitative
Gezer (2013)	The sustainable features of Safranbolu houses were explained.	Qualitative
Yüksek & Esin (2013)	Thrace houses have energy-efficient characteristics in terms of layout, orientation, formation, space organization, shell, and material properties.	Qualitative
Harputlugil & Çetintürk (2005)	Thermal comfort analysis was conducted of a traditional Safranbolu house, and annual operational energy consumption was found as 98.6 kWh/m²/yr.	Quantitative

2.3 Life Cycle Embodied Energy

Energy consumption based on fossil fuels has a major impact on climate change. It has been proven that this type of energy has a larger share in the energy sector than expected (Lawson, 2006)**.** Approximately half of the global energy is consumed by buildings. The energy may be supplied from primary or delivered energy sources. (Dixit et al., 2014) In the past decades, primary energy demand has been increased in four sectors; which are industrial, transportation, residential and commercial, respectively (Azari & Abbasabadi, 2018). According to the Australian science agency Commonwealth Scientific and Industrial Research Organization (CSIRO), more than 10% of the life cycle energy for a standard 100-year-old building belongs to embodied energy (Sattary & Thorpe, 2012).

In order to achieve the main target of a decrease in energy use, in residential buildings, there are two types of energy, which are operational and embodied. Operational energy can be defined as the energy need for heating, cooling, hot-water, ventilating and lighting activities (Giordano et al., 2015). LCEE includes energy demand at every step, from extracting raw materials to demolition of a building (Dixit et al., 2014). The energy required to build an entire structure corresponds to the IEE. On the other hand, the energy used for maintenance, repairing, and replacement while the structure is occupied equals REE. Finally, the type of energy used for demolishing and managing the waste is called demolition energy (DE) (Dixit et al., 2014). The last of these has the least share among other types of embodied energy and therefore has a negligible amount of impact. The sum of all types is called LCEE (Azari & Abbasabadi, 2018).

According to Cole & Kernan (1996), Pullen (2000), Ding (2007), Stephan *et al.* (2013), and Dixit *et al.*, (2014), among all types of embodied energy, the REE has the largest share depending on the design and construction phases of the building. Researches have also confirmed that the REE can be greater than the IEE for buildings with a service life of more than 50 years (Dixit, 2019).

The proportion of embodied energy in the LCE has an increase compared to operational energy due to the overall concentration on energy-efficient buildings (Yohanis & Norton, 2002; Azari & Abbasabadi, 2018) and excluding embodied energy in the existing buildings (Mourão et al., 2019). However, considering more than 25 years for office buildings, the ratio of the IEE to operational energy alone can reach up to 67% (Yohanis & Norton, 2002).

The ratio of embodied energy in LCE performance according to building types can be seen in Table 2.3.

Table 2. 3. *Embodied energy share in LCE (%) for different building types*

Source	The ratio of embodied energy to LCE (%)	Building Type
Koezjakov *et al.*, 2018	10-12	Standard homes in Dutch
	31-46	Energy efficient homes in Dutch
Chastas *et al.*, 2016	6-20	Conventional buildings
	11-33	Passive buildings
	26-57	Low energy building
	74-100	Nearly zero building
Ramesh *et al.*, 2010	10-20	73 different residential/office buildings
Adalberth *et al.*, 1997	10-20	Three dwellings in Sweden
Atmaca and Atmaca, 2015	24-27	Two residential buildings in Gaziantep
Crawford and Stephan, 2013	13.1, 28.5, 42.8	Belgian Passive houses

It can be inferred that when a building is entitled as a passive, nearly zero, or low energy building, this designation is only valid for operational energy performance. The difference of energy values between embodied and operational energy is getting higher from conventional to nearly zero houses.

The concept of energy is only used for operational energy for decades. On the other hand, as being the other aspect of the LCE, embodied energy is mostly neglected. (Azari and Abbasabadi, 2018) Mallia and Prizeman (2018), as well as Pacheco-Torgal *et al.* (2013) state that the legal framework of the energy assessment regards only the operational energy as the energy consumption of the building. This limitation does not encourage a holistic study on existing buildings, surroundings, and climate. Besides, current evaluation programs such as LEED and BREEAM do not have any specific borders for refurbishment projects.

Ramesh *et al.* (2010) studied LCE evaluation for 73 different residential and office buildings located in 13 countries. The percentage of operational energy use was found to be 80-90% while embodied energy comprised 10-20% of the building LCE. DE was neglected in these calculations. In the study by Adalberth (1997), the DE was found as 1% of the total energy demand. The paper suggests that minimizing the use of operational energy with both passive and active systems is appropriate even if using these systems leads to a subtle rise in embodied energy. However, over-implementation of energy-intensive building materials may cause the opposite impact on total energy consumption. The research also demonstrated that low energy buildings are more energy-efficient than zero energy buildings in terms of LCE (Ramesh et al., 2010)**.**

Another study demonstrates the differences on embodied energy calculations. Crawford and Stephan (2013) worked on a passive house using three different analysis methods to establish the value of embodied energy during the building's life cycle. The results were changes depends on the calculation methods which are; 13.1% for process analysis, 28.5% for input-output analysis, and 42.8% for process-based hybrid method (Crawford & Stephan, 2013)**.**

2.3.1 Initial Embodied Energy

During the construction phase, direct and indirect energy use may occur during the extracting, processing, transporting, manufacturing, and delivery phases as Dixit (2017), Monteiro *et al.* (2016), and Vukotic *et al.* (2010) indicated. (Dixit & Singh, 2018) Processes that contribute to IEE take place inside and outside the construction site (Dixit, 2017b)**.**

A review with 80 case studies involving offices, schools, and residential buildings revealed that most of the embodied impact belongs to the production phase, which accounts for two-thirds of the life cycle embodied impacts. Secondly, the median value of replacing building materials equals approximately 25%, whereas replacements as reported for five case studies is more than 50% of the life cycle impacts (Moncaster et al., 2019)**.**

The system boundary of cradle to gate covers material, transportation and manufacturing (Figure 2.3). The first one is found by multiplying the mass of the material with its embodied energy intensity per unit. For transport energy, the liters of fuel used by vehicles to carry the materials are multiplied by the embodied energy intensity of the fuel. Manufacturing includes the energy consumed to create the product. Predictions has to be done for the energy required for installation and delivery to the site (Chau et al., 2011).

The life cycle stages from cradle to grave is shown in Figure 2.3.

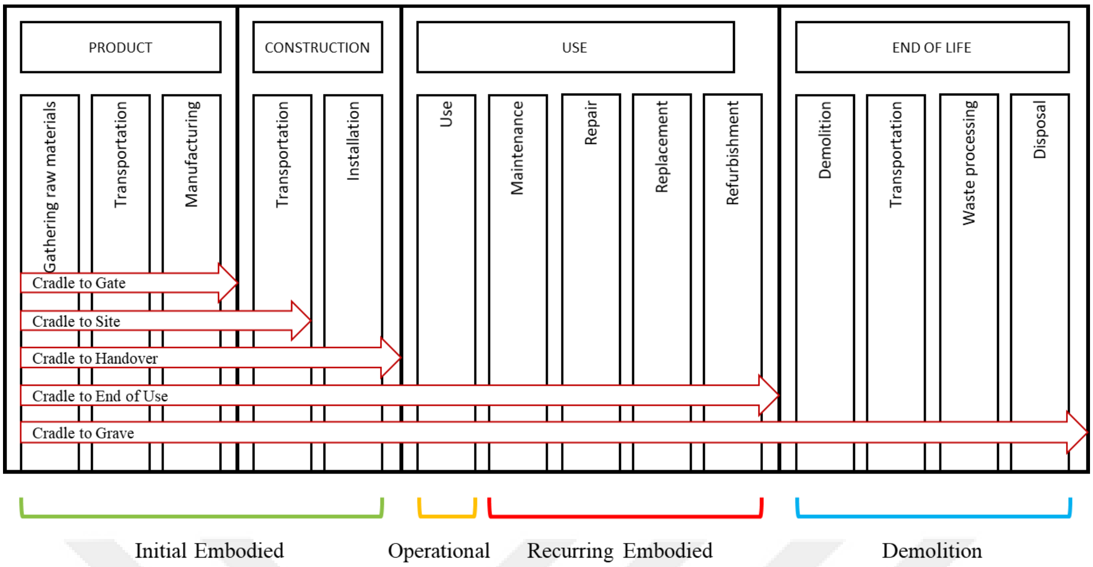


Figure 2. 3. *Life cycle stages of a building (redrawn from Balouktsi & Lützkendorf, 2016)*

2.3.2 Recurring Embodied Energy

REE has controllable and uncontrollable parameters. The controllable design parameters are service life, durability of building components, differential service life of the building materials and building itself, trade-offs, low maintenance and maintainability, local availability, low-embodied energy intensive building materials, recyclability and reusability, consistency with the function, and design. The second group of controllable parameters is associated with management issues which are related to maintenance, replacement, renovation, and retrofit (Dixit, 2019). Refurbishment activities require REE. In order to mitigate the effects of embodied energy at this stage, existing buildings should be renovated to be compatible, adaptable, complementary, durable, and reversible (Azari & Abbasabadi, 2018).

However, it is difficult to predict the uncontrollable parameters of a building over its lifetime. Technology, socio-economic conditions, design and fashion trends, tenancy, and climate change are some of these factors. Dixit (2017), Menzies and

Tsolaki (2016), and Menzies (2011) pointed out that the REE values may not be normally distributed over time. This may be due to these uncontrollable parameters (Dixit, 2019)**.**

Floor area is another factor that affects REE. Wilson and Boehland (2005) specified that as the size of the dwelling shrinks, it will be more efficient with respect to the LCEE. Besides, this decision is more effective than the selection of low-embodied energy material (Dixit, 2019)**.**

Using less building materials is closely related to lowering embodied energy demand. Effective use of floor plans that reduce non-functional areas, interior layouts with an open plan, determination of the plan form by decreasing wall to floor ratio, and also increasing the density of the plans in terms of population per square meter are some possible alternatives (Langston & Langston, 2008)**.**

The most frequently examined controllable parameters are service life, durable building materials, low embodied energy-intensive building materials; which are explained in detail as follows:

(a) Service Life: As Rauf and Crawford (2014) described, service life stands for the period that the components of a building operate effectively and the building is in use. (Dixit, 2019) Operational energy and recurrent embodied energy are both associated with building service life from the point of Chen *et al.* (2001). A study is conducted by Grant and Ries (2013), focusing on life cycle assessment of the building materials and systems in use, maintenance, replacement and repair processes by generating nine combinations of the building envelope. It was claimed that service life is a strong contributor to the life cycle impact, and therefore it is important to predict the lifespan of a building with a methodological approach. The service life gives a clue as to how often to perform periodic maintenance activities that eventually lead to replacement.

The results of the case study from Melbourne, Australia showed that floors, walls, and roof assembly had the highest initial embodied with the ratio of 45%, 16%, and

13%, respectively. When calculating the IEE, it was thought that the building would be reconstructed at the end of its lifespan. For instance, the building would be built annually for a service life of one year. The results have been studied over a 1-150 years range. In conclusion, it was determined that there was a 29% reduction in LCEE when the service life of the dwelling was increased from 50 to 150 years (Rauf & Crawford, 2015)**.**

Depending on the analysis method, the embodied energy parameters and the ultimate results are analyzed within the scope of studies analyzing embodied energy (Table 2.4).

Table 2. 4. *The embodied energy parameters and their impacts on the results*

Source	**Embodied Energy Parameters**	**Analysis Area & Method**	**Analysis Results**
Rauf & Crawford, 2015	*The service life of the building/ building materials (differential service life)	A detached dwelling with a service life of 1-150 years. (I-O based hybrid method)	By extending the service life of a building from 50 to 150 years, a 29% reduction is achieved in LCEE. However, the REE ratio has increased by 22% from 50 to 150 years.
Rauf & Crawford, 2013	*Service life of building materials *Durability	A detached dwelling with three service life scenarios of standard and alternative materials. (Hybrid method)	The REE decreased 48% with the help of materials with longer service life. This reduction reflected to the LCE as 16.5%.
Stephan *et al.*, 2013	*Service life of building materials	Typical passive Belgian house (I-O based hybrid method)	Passive houses can have the same energy consumption with a standard dwelling in total.
Stephan and Stephan, 2016	*Service life of building materials *Durability *Floor area *Prefabricated materials	Apartment building in Lebanon with more than 50-year life cycle. (I-O based hybrid method)	Embodied energy has the least value for the selected studies due to durable materials and small floor area per person. Prefabricated components may produce less waste, resulting in less material and embodied energy use.
Treloar *et al.*, 2000	*Function/Design Consistency *Subjective decisions	Residential house in Melbourne with 30- year service life. (I-O analysis)	The energy required for the replacement and maintenance of the materials increases the IEE by 32%.
Crawford *et al.*, 2010	*Service life of building materials *Subjective decisions	8 residences in Australia with over 50-year service life. (I-O based hybrid method)	The energy need for material replacement can be between 7-110% of the IEE.

(b) Durable Materials: Mora (2007) defined the durability of building materials and components as the preservation of these elements in their original state throughout their service life (Akadiri et al., 2012)**.**

Dixit (2019) introduces a dynamic durability slider with eight factors: environmental, design, maintenance, trends, socio-cultural, political, level of use, and economic. Chen *et al.* (2001) indicated that extending the service life of a building will spread the consumed IEE through a longer time. Therefore, it is important to construct a more durable structure. However, this extension will also bring about an increase in the REE. (Dixit et al., 2014) According to Stephan and Athanassiadis (2018), durable building materials can be selected or the lifetime of the selected building materials can be extended in order to reduce the amount of REE (Dixit, 2019).

(c) Building materials with Low Embodied Energy Intensity: The building envelope with thermal insulation, window, and structural system is basically responsible for most of the embodied energy demand. The building envelope consists of floors, walls, roof and finishes. Therefore, for a standard building, it accounts for nearly 48-50% of embodied energy (Azari & Abbasabadi, 2018)**.**

Using low energy-intensive building materials can save up to 62% of total embodied energy. (Reddy and Jagadish, 2003) Shukla *et al.* (2009) confirms a 50% decrease in total embodied energy due to low embedded energy in building materials in an adobe house compared to a conventional concrete residence. (Ramesh et al., 2010) On the other hand, Federal (2008) indicated that choosing building materials with low embodied energy should not be the only option, even if it leads to a reduction in the initial and REE needs. Service life, operational energy performance are also significant factors in the decision-making process. Among many parameters that affect embodied energy, the top three include service life, durability, and low maintenance (Dixit, 2019)**.**

The REE gives a clue about how the building is used by occupants, the level of user satisfaction, the service life of the building, and the quality of building components and materials (Azari & Abbasabadi, 2018).

Cole and Kernan (1996) noticed that the REE for an effective lifespan of 25-year is 1.3 times the IEE, 3.2 for 50 years and 7.3 for 75 years. Another study made by Ding (2007) for the Australian secondary schools confirmed that the REE accounts for 72% of LCEE with a service life of more than 60 years. Cellura *et al.* (2014) calculated the REE for a dwelling with a serviced life of more than 70 years and concluded that 45% of the LCEE belonged to the REE. Stephan *et al.* (2013) also evaluated the REE to be more than 60% of LCEE for a building with 100-year lifespan. In addition, Treloar *et al.* (2000) and Adalberth (1997) claimed that the REE corresponds to 45% of the initial embodied for a building service life of 50 years and 32% of initial embodied for 30 years (Dixit, 2019).

Investigations on a passive house in Belgium with 80-year service life demonstrated that the REE corresponds to 50.3% of the LCEE. It was revealed that building components such as building envelope, finishes, structure, systems, construction, and other elements have the highest initial and REE contribution (Crawford & Stephan, 2013). Ramesh *et al.* (2010) emphasized that even if embodied energy only accounts for 10-20% of the LCE, the reduction potential should not be overlooked (Ramesh et al., 2010).

2.3.3 Demolition Energy

In the literature review presented by Dixit (2017b), the demolition energy (DE) value of 37 case study buildings were examined. The range of DE is found between 0.1 to 13% of embodied energy of the building materials with an average of 3%, and the standard deviation is 3.0. There is a variety in calculation of DE. For instance, not considering DE at all, preferring to use a fix value (Atmaca and Atmaca, 2015), quantifying via an estimator tool (Leckner and Zmeureanu, 2011), benefitting from a process-based calculation (Junnila et al., 2006) or through energy recovery calculations (Dodoo et al., 2011).

2.3.4 Calculation Methods

Calculating embodied energy has many problems. It can be inferred that lack of accuracy in energy calculation data, limitations of the methods, and arbitrary choices on the system boundary affects failure in results based on the study conducted by Menzies *et al.* (2007) and Reap *et al.* (2008). According to Khasreen *et al.* (2009) and Reap *et al.* (2008), incompleteness and inaccuracy resulting from reliance on secondary data deceptively influence the results (Dixit et al., 2014). Therefore, short periods can be analyzed instead of a lifetime analysis when calculating the REE of a building. This will prevent ignoring the effect of parameters such as fashion, technology, tenant change, etc. (Dixit, 2019).

To detect the annual REE of a building, a replacement factor should be determined. This factor is found by dividing the service life of a building component to the whole building service life as Stephan and Stephan (2016), Rauf and Crawford (2015), Dixit *et al.* (2014), Chen *et al.* (2001), and Chau *et al.* (2007) remarked (Dixit, 2019)**.**

There are three methods for embodied energy calculations which are process-based life cycle analysis, economic input-output analysis and hybrid analysis. These are described in detail as follows:

(a) Process-based Method: Process-based method comprises of four steps: aim and scope description, inventory modeling, impact evaluation, and discussion of the results. The first step also includes a functional unit, that provides comparison for case studies and system boundaries that determine the scope of inputs (Azari & Abbasabadi, 2018)**.** The functional unit can be imperial units kBtu/lb or an International system of units MJ/kg (Dixit et al., 2015)**.** The system boundary can be defined as cradle-to-gate, cradle-to-grave, etc. (Dixit, 2017b)**.**

In the second and third steps, specific information on energy types and quantity is collected. Finally, the findings are converted into GJ, MJ, or kWh. In the data collection process, energy and material quantities are obtained from material manufacturers. The disadvantage of this type of analysis is to overlook other processes such as upstream (in production stage), sideways, and downstream (in use and end of life stages) of the building materials production, all of which consume energy. As Crawford (2008) states, nearly 87% of the calculation would be neglected by applying this option (Crawford, 2012)**.** This method has many limitations and is a time-consuming, complex, and unspecified method to deal with (Azari & Abbasabadi, 2018)**.**

(b) Input-output Method: The method was found by Treloar and approved by Crawford. (Stephan & Stephan, 2016) Input-output (I-O-based) analysis covers financial flows of services and material sectors based on national average data as Treloar *et al.* (2001) explained. Once the main data source is obtained, the monetary input is converted into energy for analysis (Crawford, 2012)**.** Nassen *et al.* (2007) found out that the result is more than 90% higher than the process-based method when studying with I-O based method.

Although it is a more comprehensive method than process-based, its disadvantage is due to sectoral inventory. Input data cannot be determined for a particular context, design or structure (Azari & Abbasabadi, 2018)**.**

(c) Hybrid Method: It is a combination of process-based and I-O based methods to benefit from the advantages of both. According to Bilec *et al.* (2006), this method is divided into four different types which are tiered, I-O-based hybrid, which principally counts on I-O based data; and integrated and augmented process-based methods, which are associated with process-based data (Azari & Abbasabadi, 2018)**.**

In the I-O-based hybrid analysis method, I-O data is used as the main study area. Then, the findings are converted into the process data steps (Menzies, 2011)**.** Langston & Langston (2008) stated that the I-O-based hybrid method is the most reliable one for a life cycle analysis (Dixit et al., 2010)**.**

The annual ratio of REE is given with regards to estimated service life, building type and analysis method in Table 2.5. In the table, a wide range of database use and building types are presented. Due to this diversity, the annual REE share in total LCEE is between 0.2 to 1.8%.

Table 2. 5. *Annual REE ratio due to building types and analysis method (adapted from Dixit, 2019)*

Source	**REE (annual) / LCEE (DE is ignored) (%)**	**Service Life**	**Building type**	**Analysis method**
Barnes & Rankin, 1975	0.3-1.8	25	Bungalows	I-O-based analysis
Adalberth, 1997	0.5-0.6	50	Three prefabricated single-unit houses made of wood	Service life assumptions
Blanchard and Reppe, 1998	0.7-0.8	50	House maintenance, improvements	DEAM and Ecoinvent database
Pullen, 2000	1.3	50	25 dwelling units in South Australia	I-O-based analysis
Thormark, 2002	0.2	50	Cost-efficient passive housing	Interval data from a municipal housing company
Humphrey *et al.*, 2004	1.1	50	40-story residential blocks in Hong Kong	Life cycle costing and assessment
Stephan *et al.*, 2011	0.4	50	Dwellings	Ecoinvent database, I-O-based hybrid
Deng *et al.*, 2011	0.5	50	Residential units	LCE analysis
Rauf & Crawford, 2012	0.7	50	Semi-detached house with min. service life	Material service life over life cycle analysis
Stephan & Stephan, 2014	0.6	50	Residentials in Lebanon	I-O-based hybrid
Cellura *et al.*, 2014	0.7	70	The Leaf house in Italy	An assumption on replacement cycles
Collinge *et al.*, 2013	0.2	75	Institutional building	Renovation and replacement data analysis
Bastos *et al.*, 2014	0.2	75	Three residential buildings in Lisbon	Published replacement cycles
Newton *et al.*, 2000	0.6	80	Detached house and an apartment building	I-O-based analysis
Kohler *et al.*, 1997	0.6	100	Concrete apartment	Process data from Ecoinvent
Paleari, 2013	0.3	100	Residential complex	LCE analysis

Dixit et al. (2010) pointed out that some ignored parameters cause inconsistency and inaccuracy in the calculations of embodied energy, which are:

- Drawing a clear system boundary,
- Choosing the right analysis method to apply,

- Selecting case studies with similar geographical features,
- Considering primary and delivered energy types,
- Paying attention to the age of the data source,
- Counting on a single data source that questioned a variety of data,
- Ensuring the completeness of the data,
- Remarking the technological differences of manufacturing,
- Inclusion of feedstock energy,
- Regarding temporal relationship in new-old technologies. (Dixit et al., 2010)

Some of the studies from the literature review by Dixit (2019) are summarized in Table 2.6. Among these studies, the most frequently used service life is found to be 50 years.

Table 2. 6. *Reported LCEE values depending on the service life (adapted from Dixit, 2019)*

Source	Service Life (year)	REE (MJ/m²/year)	LCEE (DE excluded) (MJ/m²/year)	REE (annual) / Total LCEE (DE excluded) (%)	Gross Floor Area (m²)
Barnes & Rankin, 1975	25	14.4	78.4	0.7	77.0
	25	27.2	62	1.8	73.5
	25	20.8	141.6	0.6	76.0
	25	8.0	100	0.3	77.0
Treloar et al., 2000b	30	125.0	515.7	0.8	123.0
Thormark, 2007	40	27.4	145.1	0.5	120.0
	40	19.7	107.4	0.5	70.5
Utama & Gheewala, 2008	40	1.9	22.4	0.2	55.0
	40	20.0	41	1.2	55.0
Utama & Gheewala, 2009	40	0.6	22.7	0.1	85.0
	40	2.7	26.5	0.3	85.0
Shukla et al., 2009	40	14.8	133.5	0.3	120.0
Leckner & Zmeureanu, 2011	40	30.5	121	0.6	210.0
Pullen, 2000	50	54.8	118	1.3	165.0
Thormark, 2002	50	16.6	139.8	0.2	120.0
Stephan et al., 2011	50	68.0	340.2	0.4	130.0
	50	58.6	292.9	0.4	130.0
	50	52.9	264.6	0.4	130.0
	50	47.1	235.5	0.4	90.0
	50	40.6	202.8	0.4	90.0
	50	36.6	183.2	0.4	90.0
Rauf & Crawford, 2012	50	160.0	428	0.7	291.3
Stephan & Stephan, 2014	50	168.6	544	0.6	904.3
Adalberth, 1997	50	28.8	105.1	0.5	130.0
	50	27.4	100.8	0.5	129.0
	50	24.4	85	0.6	138.0
Blanchard and Reppe, 1998	50	53.1	136	0.8	228.0
	50	45.6	125.2	0.7	228.0
Fay & Treloar, 1998	50	188.0	464	0.8	128.0
	50	188.0	486	0.8	128.0
Fay et al., 2000	50	188.0	470	0.8	128.0
	50	188.0	492	0.8	128.0
Thornmark, 2006	50	21.9	143.3	0.3	120.0
	50	28.2	120.8	0.5	120.0
	50	20.0	151.4	0.3	120.0
Johnstone, 2001	60	24.6	70.2	0.6	93.0

Table 2.6 *(continued)*

Source	Service Life (year)	REE (MJ/m²/year)	LCEE (DE excluded) (MJ/m²/year)	REE (annual) / Total LCEE (DE excluded) (%)	Gross Floor Area (m²)
Randolph et al., 2007	60	65.0	183.3	0.6	167.0
	60	63.3	185	0.6	172.7
	60	71.7	203.3	0.6	312.5
	60	68.3	198.3	0.6	201.3
	60	66.7	193.3	0.6	192.0
	60	55.0	160	0.6	107.3
	60	83.3	243.3	0.6	225.0
	60	78.3	230	0.6	245.0
Cellura et al., 2014	70	254.1	492.4	0.7	482.0
Collinge et al., 2013	75	10.9	67.6	0.2	38900.0
Bastos et al., 2014	75	9.9	55.7	0.2	367.0
	75	9.7	54.4	0.2	472.0
	75	8.6	49.9	0.2	1041.0
Lippke et al., 2004	75	5.3	50	0.1	192.0
	75	5.3	57.9	0.1	192.0
	75	7.3	33.7	0.3	200.0
	75	7.3	37.7	0.3	200.0
Winistorfer et al., 2005	75	7.3	36.7	0.3	200.0
	75	5.1	55.7	0.1	192.0
	75	7.3	36.7	0.3	200.0
Newton et al., 2000	80	54.8	118	0.6	203.0
	80	54.0	116.5	0.6	203.0
	80	52.5	113.8	0.6	203.0
Stephan et al., 2013	100	294.3	486	0.6	330.0
Fay et al., 2000	100	213.0	354	0.6	169.0
	100	213.0	365	0.6	169.0
Paleari, 2013	100	81.4	311.9	0.3	4000.0
Kohler et al., 1997	100	140.0	230	0.6	969.0

2.4 Concluding Remarks of the Literature Review

Adaptability is a term that also includes flexibility however it is used to mean both. Both adaptability and flexibility contribute to the extension of the service life of a building and can also alleviate the negative environmental impacts resulting from energy use in the built environment. By applying adaptable features to design, user needs can be met for a longer period of time. It is an established fact that traditional Ottoman houses inherently have these adaptable characteristics. The timber frame structural system, local building materials with low embodied energy and a long service life led researchers to consider the traditional Ottoman houses as low energy-intensive structures.

On the other hand, certain parameters such as the service life, local material use and low energy intensity are reflected in the REE calculations, such that extending the service life of a building is assumed to cause an increase in the building’s REE. However, the truth of this assumption should be tested by evaluating the weight of REE in the LCEE of buildings with an extended service life.

Embodied energy calculations need to be made systematically and directly, as stated in the literature. It is important to draw the system boundary, to define the functional unit, and to specify the analysis method. Case studies should be selected from the same region. Making use of a single type of database is essential for reliability. Even though the most reliable method for embodied energy calculation is stated as I-O-based hybrid analysis, this method is very detailed and is mostly recommended for life-cycle analysis. Due to the lack of comprehensive embodied energy databases and sectoral energy inputs in Turkey, it was deemed necessary to benefit from the international database (ICE) within the scope of this study.

CHAPTER 3

RESEARCH DESIGN

In this chapter, the limitations and delimitations, the materials and methodology of the research are clarified. The limitations emerged because of the uncontrollable factors, which shaped the selection of the calculation method, the type of proxy data, and service life estimation of the case studies. On the other hand, delimitations have to be determined to draw the boundaries of the research. Research materials are divided into two categories. The first part contains documents of the case studies while the second includes data for energy calculations. Methodology of the research consists of three steps: analysis of the case studies, 3D building modeling and embodied energy calculations.

3.1 Limitations and Delimitations

One of the necessary tools for embodied energy calculation is a database that includes the embodied energy values for a wide variety of building materials. Not many of the building material manufacturers in Turkey disseminate the energy intensity values of their products. Since, there is not adequate information to generate a comprehensive inventory of local materials, an international database has to be used. Among the various available sources, the Inventory of Carbon and Energy (ICE) is selected because it contains building materials belonging to the selected building components in this study. Although the inventory was updated in 2019, the new version contains only the carbon data, and not the embodied energy values. Therefore, the use of the previous version dated 2011 became unavoidable.

Without doubt, buildings constructed 300 years ago had different raw material extraction and manufacturing techniques than the in the present times; and the energy resources used for manufacturing change from country to country. However, due to the non-existence of a database on historical materials and technologies and conventional local materials, a UK-based database had to be selected for evaluating the historical case studies in Ankara, Turkey. On the other hand, as it was indicated in Chapter 2, using a clear systems boundary, and counting on a single database are the fundamental elements in the embodied energy calculations. Even if the selected database is outdated, since it will be used to calculate the different embodied energies of all of the case studies for the sake of comparing their service life impacts, the results will not be affected significantly.

Another limitation is related to the selection of the case studies. Traditional Ottoman houses are considered to be built with flexible design considerations; thus, they are analyzed in the first step of the research. Since they are scattered throughout the territory once ruled by Ottoman Empire, it is necessary to specifically determine a region. Furthermore, in the process of searching for the case studies, another parameter of the energy calculation draws attention to the same concern; selecting case studies from the same geography. Since the research is conducted in Ankara, it was decided to draw the framework of the study around the traditional Ottoman houses in Ankara. In order to perform the study, it was necessary to obtain a considerable amount of data and information, regarding original plans, design alterations, space additions, and the list of the materials of construction. The dissertation of Şahin (1995) was discovered to be a goldmine that contained data regarding traditional Ottoman timber houses located in old-town Ankara. It includes information on the conservation problems of these houses; accordingly, structural and architectural features of these houses were identified from this dissertation.

However, the houses were examined in detail in 1994 and no investigation has been carried out or no change has been recorded in the spatial organization since this date, which draws another limit to the study. Some of the buildings have been demolished, a couple of them have been restored, and a few of them are still in use with minor changes. Based on this fact, the estimated construction date and the last inspection date are taken into consideration while determining the lifetime of the buildings.

Considering the delimitations, the first one can be specified as the selection of the study area. Because traditional Ottoman houses are widespread in different territories such as Anatolia, Europe, North Africa, Middle East, a decision has to be made. Therefore, the closest area containing traditional Ottoman houses, Ankara, is determined as the research area.

Among 20 buildings from the study of Şahin (1995), half of them were selected as case studies. During the selection, attention was paid to the longer service life. The youngest building had more than a 100-year service life,

Information on the types and size of the building components and the building envelope to be included in the energy calculations, was retrieved from the description given in the dissertation. Additionally, inner walls and floor systems affected by the design changes are also included. Even if the traditional Ottoman buildings are raised above the ground level, the entrance level was taken as the ground level during the modeling process, because the height of this level is unknown and varies for each building.

Other delimitation is associated with the scope of the study. Identifying the relationship between flexible design parameters, building’s service life, and LCEE requires calculating, elaborating, and comparing concepts among and even within themselves. The ultimate delimitation stems from the stage of determining the flexible design strategies. Based on the literature findings and case study characteristics a list of flexible design strategies is made.

All of the aforementioned concerns are stated in Table 3.1.

Table 3. 1. *Limitations and delimitations of the study*

LIMITATIONS	DELIMITATIONS
Selection of the Database	Selection of the Study Area, Buildings and Components
Collection of the Case Studies	Scope of the Study
Estimation of the Service Life	Determination of the Flexible Design Parameters

3.2 Research Materials

The research materials can be grouped in five categories. Review and research papers, articles and journals constitute the first group to shape knowledge. The documents of the selected buildings such as plans, photographs, information based on observation and surveys of the latest version of the buildings form the second group. The third group is the sources required for embodied energy calculations such as proxy data, bulk density, and service life of building materials. The fourth group is associated with the material quantities. Revit for 3D modeling and its tools such as material schedules, room schedules, and render engine for illustrations were used. Lastly, it was utilized from Excel for calculations and visualization of the results.

The materials in the first category were included in the literature review. The following four categories will be explained in here.

The data collected for the process-based calculation method, the extraneous factors, and examined building components can be seen in Figure 3.1.

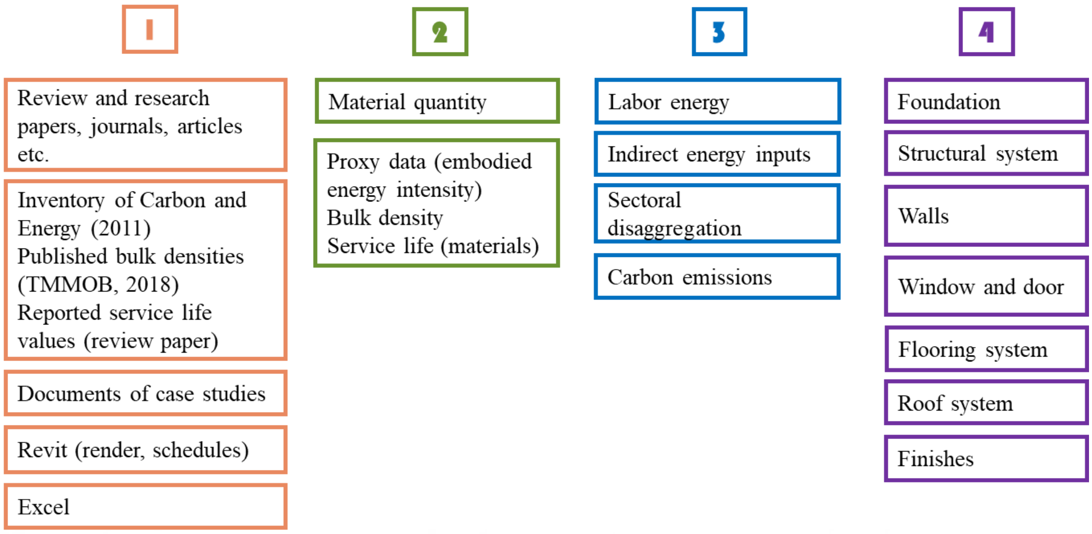


Figure 3. 1. *Research materials (1), information for process-based analysis method (2), extraneous factors (3), and studied building components (4)*

3.2.1 Selection of the Case Studies

In order to evaluate the LCEE of traditional Ottoman houses, there was a need to find case studies in Ankara, with readily available data and information.

The traditional Ottoman houses in Ankara to be selected also had to have sufficient data for LCEE calculation because field research could not be carried out due to the prevailing pandemic. For this reason, 10 buildings were selected from the 20 surveyed in the dissertation of Şahin (1995), who had investigated the structural features, the changes in the building and its spaces, and interventions for the conservation of these traditional Ottoman houses. Most of the houses located in the Kaleiçi, Ulucanlar, Erzurum, and İstiklal neighborhoods in old town Ankara were older than 3 centuries at the time of the survey carried out by Şahin, in 1994. Of these 20 houses 9 were selected from among the oldest ones and one with approximately 100-year service life to understand how adaptive were these houses to changes in user needs, how many flexible design features did they possess and were these the reason for the extended service life of the traditional Ottoman houses.

The buildings were visited in order to check their continued existence and the photographs were taken from the exterior façades. If they were still standing, a short face-to-face interview with the tenants/householders was held on August 27, 2021 to determine the changes in the houses. The Yandex and Google satellite images for different years were examined to learn about the possible restoration or demolition period of the buildings, as proof of their adaptability.

However, some of the houses could not be identified with those surveyed. Hence, to determine the exact location and gather further information on the case study buildings, a meeting was held with Prof. Neriman Şahin Güçhan, the author of the main source of this study. Afterwards, the office of the Ankara Regional Board for Conservation of Cultural Assets was also visited again to check the parcel and lot numbers of the buildings.

Some of the buildings were found to be in similar condition to as they were in 1994 (CS 06 and CS08), whereas some were already demolished (CS 03, 04, and 05) There were also others that underwent reconstruction or renovation (CS 01, 02, 07, 09, 10). The verbal and visual information obtained from site visits and on-site interviews are given in the following pages. The selected case studies are numbered sequentially to facilitate reading. For instance, CS01 refers to the case study number one.

The site plan of the case studies can be seen in Figure 3.2.

Figure 3. 2. Site plan of the selected case studies

Because the changes that may have occurred since 1994 have not been recorded for each house, and no further study has been carried out on the alterations, additions or restorations, the last survey date (1994) is taken into account for the service life estimates, and not the date of the site visit in 2021. The location of the case studies and their latest status is given in Table 3.2.

Table 3. 2. *Status of the traditional Ottoman houses as determined from on-site inspection in August 2021*

Case Study ID	Address	Latest Status
CS01	Kaleiçi Street, No. 10	Restored, in use as an art gallery
CS02	Gelin Street, No. 8	Reconstructed, not original
CS03	Cingöz Street, No. 20	Demolished
CS04	Erzurum Street, No. 46	Demolished
CS05	Sarıkadın Street, No. 43	Demolished
CS06	Eskici Street, No. 2	Original, in use as a dwelling
CS07	Gelin Street, No. 12	Reconstructed, not original
CS08	Öksüzler Street, No. 17	Original, in use as a dwelling
CS09	Cingöz Street, No. 3	Reconstructed, not original
CS10	Sarıkadın Street, No. 67	Restored, in use as a pharmacy

Case Study 01 (CS01)

CS01 is located in Kaleiçi Street, No. 10, and it was still standing and so could be photographed on site. According to the photos recorded in Yandex and Google Earth visual databases, the building is estimated to have undergone restoration between the years of 2011-2018 (Figure 3.3).

Figure 3. 3. *The case study building CS01 in the early 1990s (Source: Şahin, 1995) (A); in 2011 from the street view of Yandex Maps (B); in 2018 taken from the street view of Google Earth Pro (C) and in 2021 (D)*

The building has served many functions over time. Although it was used as a residence for many years, it was converted into a café in the later years. Today, the building is used as an art gallery and store. The plan scheme is seen to be preserved in its original form (Figure 3.4). The function change indicates how adaptable it is.

Figure 3. 4. *The current status of CS01*

Case Study 02 (CS02)

CS02 was on the Gelin Street, No. 8. According to the news bulletin of Municipality of Altındağ dated June, 2019, ten historical houses of Hamamarkası/Ankara were being reconstructed in accordance with their original form. Based on the satellite images taken from Google Earth Pro, it can be said that the images are proof of the regeneration attempts by the municipality. The building is not original, but reconstructed between the years of 2018-2019 (Figure 3.5).

Figure 3. 5. *The case study building CS02 in its reconstruction process in 1/2018 (A); 10/2018 (B), 11/2020 (C), respectively, from Google Earth Pro*

The building is not currently in use. During the on-site survey, it was observed that the reconstruction works were completed to a large extent (Figure 3.6).

Figure 3. 6. *The case study building CS02 in the early 1990s (Source: Şahin, 1995) (A1-A3) and in 2021 (B1-B5)*

Case Study 03 (CS03)

CS03 was located on the Cingöz Street, No. 20. The building was demolished based on the satellite images and field observations in 2021 (Figure 3.7).

Figure 3. 7. *The case study building CS03 in demolishment process in 5/2020 (A), and 11/2020 (B), respectively, from Google Earth Pro*

The building was photographed from the satellite on May 5, 2020. However, in six months, it had disappeared. On-site research confirmed that the plot where it once stood is now vacant (Figure 3.8).

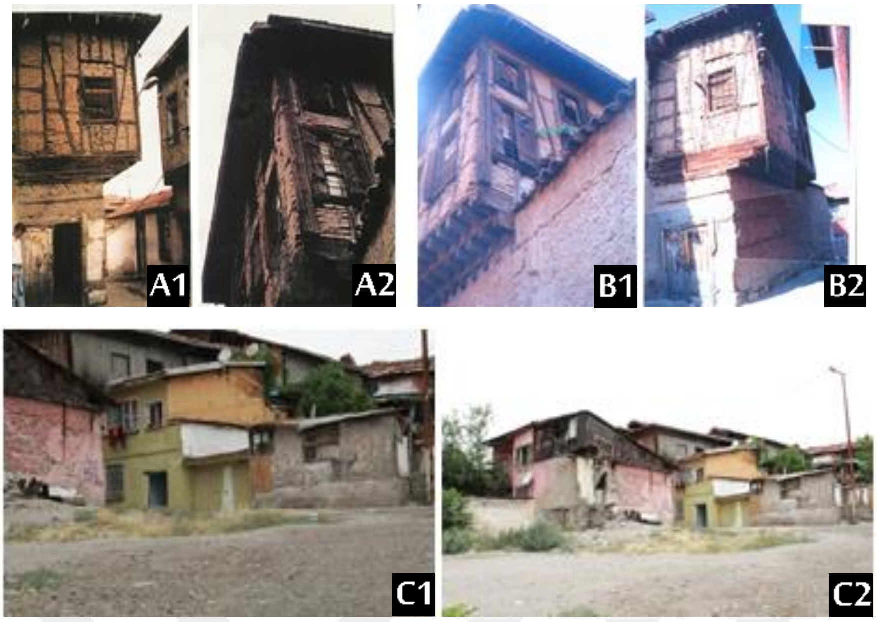


Figure 3. 8. *The case study building CS03 in the early 1990s (Source: Şahin, 1995) (A1-A2) (Source: the archive of Ankara Regional Board of Conservation of Cultural Heritage, 1987) (B1-B2), and in 2021 (C1-C2)*

Case Study 04 (CS04)

CS04 was on the Erzurum Street, No. 46. According to the site visit and information received from the tenant of the next-door house, Özlem Gürbüz, the building was demolished. The ruins were photographed from the backyard of the adjacent house (Figure 3.9).

Figure 3. 9. *The case study building CS04 in the early 1990s (Source: Şahin, 1995) (A) and its ruins in 2021 (B)*

Case Study 05 (CS05)

CS05 was located on the Sarıkadın Street, No. 43. In 2006, rehabilitation projects were initiated in Sarıkadın and Dutlu street. (Poyraz & Gündoğan, 2014) Based on that, the demolition date was indicated as before 2006. Exact location of the building was found from the personal archives of Neriman Şahin (Figure 3.10).

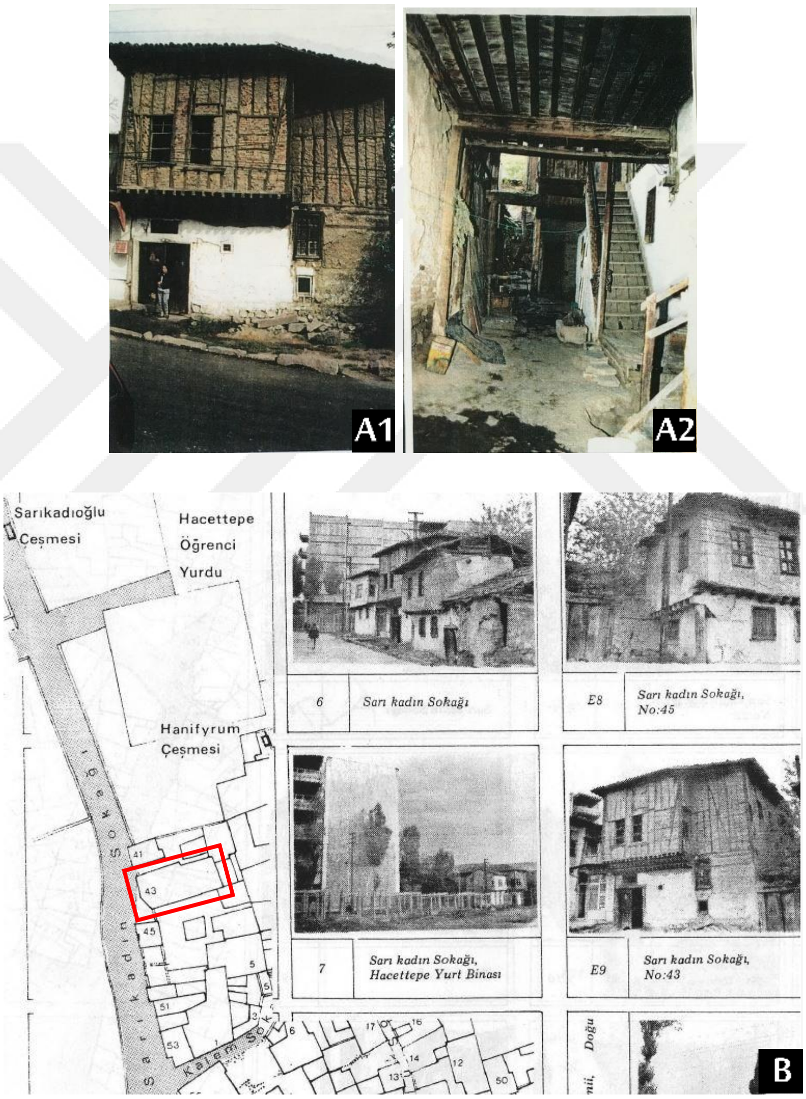


Figure 3. 10. *The case study building CS05 in the early 1990s (Source: Şahin, 1995) (A1-A2) and the exact location of CS05, Sarıkadın Street, No.43 (Akçura et al., 1989) (B)*

Case Study 06 (CS06)

CS06 is located on the Eskici Street, No. 2. Although there are some deteriorations, the building is still standing and is occupied by a tenant (Figure 3.11).

Figure 3. 11. *The case study building CS06 in the early 1990s (Source: Şahin, 1995) (A) and its current status in 2021(B)*

Case Study 07 (CS07)

CS07 was on the Gelin Street, No. 12. The building is adjacent to Gelin Street No. 8. It is not original, but reconstructed during the same period, i.e., in 2018 according to the satellite images. (Figure 3.12).

Figure 3. 12. *The case study building CS07 in the reconstruction process in 1/2018 (A); in 10/2018 (B) from Google Earth Pro*

The building is currently locked and is located behind the remains of another building. Therefore, a photograph could not be taken.

Case Study 08 (CS08)

CS08 is located on the Öksüzler Street, No. 17. The building is still standing and in use by its owner. As a result of the interview with Murat Ilgaz (the householder), it was understood that the general plan of the house is the same as in 1995. It was learned that the building will undergo restoration this year (Figure 3.13).

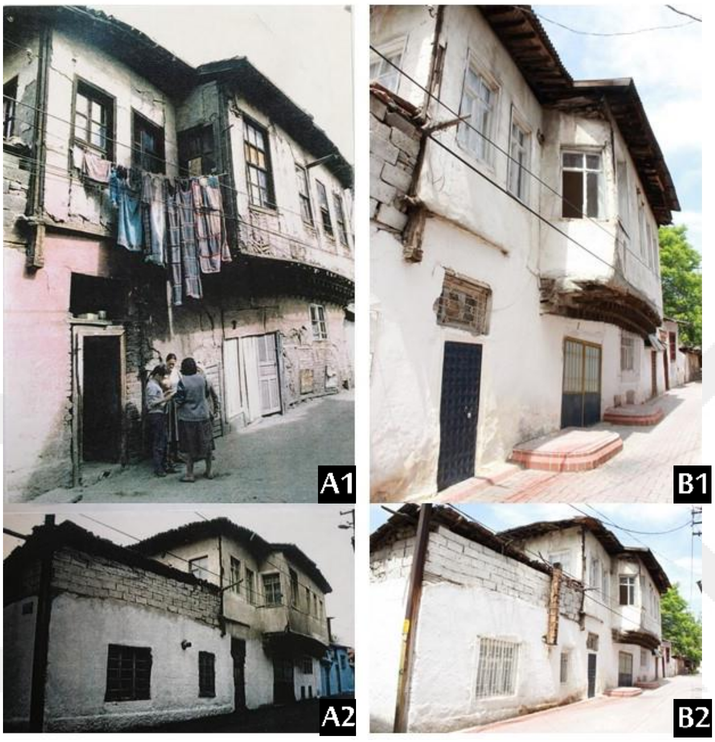


Figure 3. 13. *The case study building CS08 in the early 1990s (Source: Şahin, 1995) (A1-A2) and its current status in 2021 (B1-B2)*

Case Study 09 (CS09)

CS09 was located on the Cingöz Street, No. 3. Cingöz Street is being completely renovated with reconstructed buildings in accordance with the original style. According to the satellite images, the building was completely rebuilt between 2017-2018 (Figure 3.14).

Figure 3. 14. *The case study building CS09 in the reconstruction process in 6/2017 (A); in 09/2017 (B) and in 04/2018 (C), respectively, from Google Earth Pro*

Case Study 10 (CS10)

CS10 is on the Sarıkadın Street, No. 67. As a result of the interview with İzzet Tütüncü (tenant of the building), it was learned that the building underwent restoration in 1996-1997 (Figure 3.15). The entrance of the ground floor, which is used as a pharmacy today, is free from partition walls. This is the area that once housed three shops and now has an open-plan scheme.

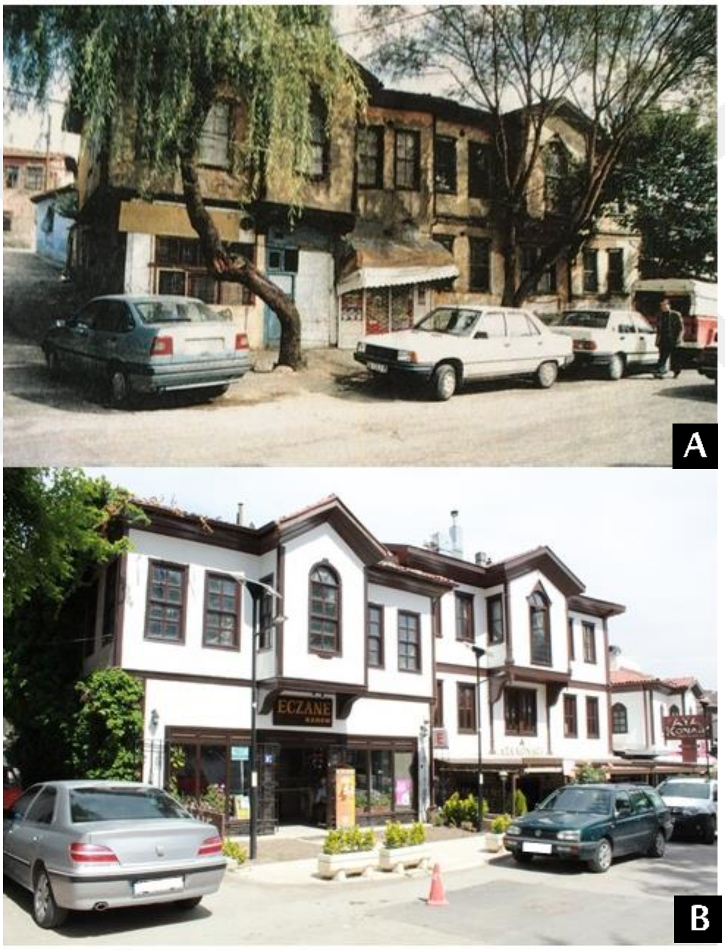


Figure 3. 15. *The case study building CS10 in the early 1990s (Source: Şahin, 1995) (A) and current status in 2021 (B)*

3.2.2 Data Collection for Energy Calculations

In the literature, REE comprises the combined embodied energy for maintenance, replacement, repair and refurbishment processes. However, the energy needed for design alterations and additions to answer user needs during the use phase, was also considered a part of the REE.

In order to establish the relationship between flexible design strategies and LCEE, a large amount of data were required for the three types of embodied energy calculations (IEE, REE, LCEE) such as bulk density, service life, and embodied energy intensities of the building materials.

The bulk densities of the construction material were gathered from the publication of the Union of Chambers of Turkish Engineers and Architects (Türk Mühendis ve Mimar Odaları Birliği, TMMOB) (2018). Since the material bulk densities are given in intervals, the average of the interval range is taken into account in these calculations.

IEE is calculated by considering initial material quantities and energy intensities. However, for REE calculations the service life of the building materials is considered. The material’s service life was obtained mainly from the study of Dixit (2019). Although, the service life of the load-bearing building materials is accepted as equal to the service life of the building itself, only the finishing materials are included in the replacement cycles.

The Inventory of Energy and Carbon (ICE, 2011) database is utilized to find out the embodied energy intensity of the building materials belonging to the building envelope. The reason for choosing an international inventory instead of a local one is the inadequacy of local sources. Even if there are similar embodied energy intensities of some of the building materials such as aluminum, concrete etc. taken from some of the manufacturers, there is no information on local building materials e.g., timber and stone. This situation was a limitation in this study.

The latest version of ICE was released in 2019, but it could not be used in this study because this database contains only the embodied carbon values and not the EE. Since the focus was EE within the scope of this study, data on the majority of the building materials used in the traditional houses during their construction, maintenance and alteration stages, were found from ICE version 2.0.

The IEE and REE of the building materials used for the construction of traditional Ottoman houses was calculated by using embodied energy unit densities obtained for modern construction techniques; which are probably higher than the actual values for traditional construction techniques. On the other hand, if the houses are built by modern methods today the amount of embodied energy would be determined for these traditional houses according to the available data.

The scope of the building components includes foundation, structural system, exterior and interior walls, flooring system, finishes, roofing system, windows, and doors; but not the fittings and fixtures. The list of the building materials and their bulk densities, embodied energy intensities and service life is given in Table 3.3.

Table 3. 3. *Datasets of the selected building components compiled from published sources*

Component	Material	Bulk Density (kg/m³)	Embodied Energy Intensity (MJ/kg or MJ/m²)	Service Life (years)
Wall (Exterior/Interior/ Foundation)	Stone	2400 [a]	1.26 MJ/kg [d]	Lifetime
	Mudbrick	1170-1570 [b]	0 [e]	Lifetime
	Burnt brick	1800-2200 [a]	3 MJ/kg [d]	Lifetime
	Briquette	500-2000 [a]	0.83 MJ/kg [d]	Lifetime
Structural System (Wall/Floor/Roof)	Softwood timber	600 [a]	7.4 MJ/kg [d]	Lifetime
	Hardwood timber	800 [a]	10.4 MJ/kg [d]	Lifetime
Wall Finish	Mud plaster	1170 [b]	0	1[j]
	Lime (inside mud plaster)	1200 [a]	5.3 MJ/kg [d]	1
	Cement plaster	800-1000 [a]	1.8 MJ/kg [d]	Lifetime
	Paint	1400 [a]	59 MJ/kg [d]	10[i]
Covering (Floor/Ceiling/Roof)	Softwood timber	600 [a]	7.4 MJ/kg [d]	55[i]
	Hardwood timber	800 [a]	10.4 MJ/kg [d]	55[i]
	Plywood	800 [a]	15 MJ/kg [d]	35[i]
	Screed	2000 [a]	4.5 MJ/kg [d]	Lifetime
	Ceramic tile	1800-2200 [c]	12 MJ/kg [d]	30[i]
	Roof tile	1400 [a]	6.5 MJ/kg [d]	60[j]
Window	Window frame		2189 MJ/m² [f]	30[i]
	Single glass	2400-2700 [a]	671 MJ/m² [g]	40[i]
Door	Softwood timber	600 [a]	7.4 MJ/kg [d]	30[i]

Sources: [a]TMMOB (2018), [b]Andolsun (2006), [c]Revel (2007), [d]ICE (2011), [e]Henry *et al.* (2014), [f]Hoellinger *et al.* (2017), [g]Utama & Gheewala (2006), [i]Dixit (2019), [j] Shukla *et al.* (2009)

3.3 Research Methodology

The steps of methodology can be listed as analysis of the case studies, 3D building modeling, and LCEE calculation. In the first step, service life estimation is made in order to find annual impact of the recurring and LCEE. Thereafter, the flexible characteristics of the selected traditional Ottoman houses are inspected. As being the last section of the first step, alterations and additions in the spatial arrangement are designated.

The buildings are modeled based on their initial and final versions in the second step. Finally, the LCEE is calculated in detail considering service life scenarios, maintenance and alteration energy (Table 3.4).

Table 3. 4. *The steps of the research methodology*

STEP 01 **Analysis of the Case Studies**	**STEP 02** **3D Building Modeling**	**STEP 03** **Embodied Energy Calculation**
a- Estimation of Service Life	a- Initial Case	a- EE of Building Materials in the Maintenance and Alteration/Addition Stages
b- Examining Changes During Service Life		
c- Identifying the Flexible Design Strategies	b- Final Case	b- Total EE of Three Service Life Scenarios

3.3.1 Analysis of the Case Studies

Information on building materials and case studies are given under the heading of research materials. The estimation of the buildings' service life, flexible design parameters and the changes they had undergone from the construction date to the last comprehensive survey in 1994 by Şahin (1995) are explained and listed in this part.

3.3.1.1 Estimation of Service Life

According to information provided by Şahin (1995) in her PhD dissertation, six of the selected case study houses were built in the late 17^{th} and early 18^{th} centuries, three in late 18^{th} and early 19^{th} centuries, and one in the late 19^{th} and early 20^{th} centuries.

The exact construction date of the buildings is unknown. However, the construction years of the buildings were defined as Early, Early-Mid, Mid-Late and Late periods. Early period comprises the 17th century while Early-Mid refers to the late period of 17th and the beginning of the 18th century. The end of the 18th century and the beginning of the 19th century corresponds to Mid-Late period. Finally, the Late period refers to the years between 1850-1940 (Şahin, 1995)**.** The following method is used for estimating the service life (Table 3.5).

Table 3. 5. *Service life estimation based on estimated construction periods*

Building Number	**Estimated Construction Period**	**Estimated Construction Date**	**Approximate service life until the last survey date (1994)**
01*	1690-1749 (Late 17th to mid-18th century, Early and Early-Mid period)	1690	304
02*		1700	294
03*		1710	284
04*		1720	274
05*		1730	264
06*		1740	254
07*	1750-1849 (Mid-18th to mid-19th century, Mid-Late period)	1750	244
08*		1775	219
09*		1800	194
10		1825	169
11	1850-1940 (Mid-19th century to 1940, Late period)	1850	144
12		1860	134
13		1870	124
14		1880	114
15*		1890	104
16		1900	94
17		1910	84
18		1920	74
19		1930	64
20		1940	54

Note: Those which have the mark (*) were chosen as case studies.

The buildings are listed from the oldest to newest. It is assumed that the first group was built ten years apart, ranking between 1690 and 1750. For the second group, the interval was increased to 25 years and the construction dates were distributed between 1750-1850. The last group is sorted between 1850-1940 with a 10-year interval.

The service life of the buildings was taken until the last detailed survey date which is 1994; because there is uncertainty about the changes that may have occurred after this date. Besides, in the literature, it has been seen that the service life is mostly taken at intervals of 25 years (25, 50, 75, 100 years etc.), or 10 years (30, 40, 50, 60, 70, 80 years etc.) Therefore, changes in this time period have been ignored since it has been 27 years since the last field survey.

3.3.1.2 Examining Changes During Service Life

During the long service life of traditional Ottoman houses, multiple changes occurred in the plan layout. In order to confirm these changes, the final version of the buildings is examined for changes in spaces and building materials. The screed flooring is considered as a material that is re-applied in the following years while timber boards are accepted as the original material used in ceilings and floorings. According to the available datasets for both final and initial versions of the structures, the missing or unspecified parts of the buildings, such as floor and ceiling materials, are based on estimations. For instance, the floor covering is specified as soil in areas such as stables and storages located on the ground floors for the initial case if there is no information about the material, and as timber floor board on the first floors. On the other hand, for undefined ceiling materials, it is assumed that the ceiling is uncovered for auxiliary spaces except rooms on the ground floors, and timber ceiling boards are used on the first floors. The changes associated with flexible design strategies derived from the literature in order to identify the inherent flexible characteristics of the traditional Ottoman houses.

The initial plan was drawn according to the statements obtained from the last survey presented in the study of Şahin (1995) while the final plan layout of each building is redrawn based on the plans obtained from Şahin (1995). According to the assumptions and recorded changes the original plan layout as well as the last condition of space layout are presented in Figure 3.16.

Figure 3. 16. *The plan layout of initial and renovated condition of CS01 (adapted from Şahin, 1995)*

N01 refers to the initial case while R01 stands for the altered case (for recurrent embodied energy calculation) of the building plan layout. All information that has been given so far is displayed in an information sheet for each building. An example of this can be seen in Figure 3.17, while the rest are given in Appendix A.

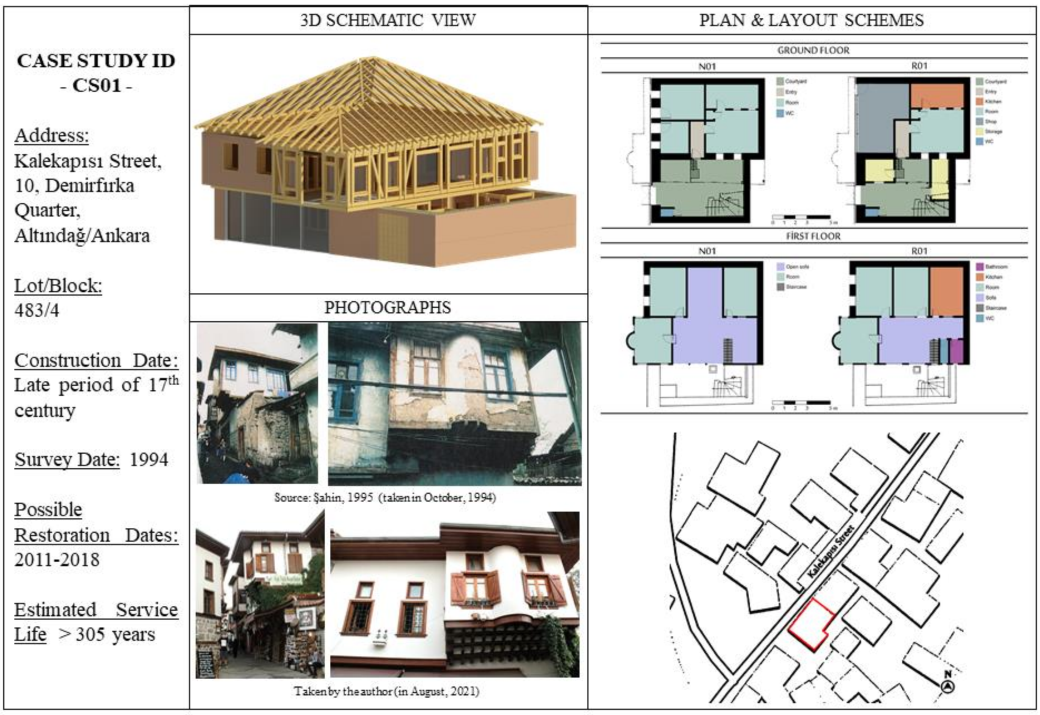


Figure 3. 17. *An example of the information sheet*

3.3.1.3 Identifying the Flexible Design Strategies

The flexibility potential of the case studies had to be examined because it contributes to the long service life of the traditional Ottoman houses in Ankara. Therefore, in this section, flexibility parameters, which are accepted as one of the adaptability approaches, and their potentials for initial and final versions are examined. Comprehensive papers on flexible design are evaluated together to create a general parameter table. The flexible design parameters were determined from the literature review, and then similar or related flexible design strategies were gathered under the same title. Thus, six parameters are derived from various papers and investigated in the case studies in the plan layout.

These flexibility parameters are given in Table 3.6. The scope of the related parameter, the method of evaluation, the focus area, and original definitions from the literature are indicated with the referenced sources.

Table 3. 6. *Flexible design strategies and target space/component in traditional Ottoman houses*

Flexible Design Strategies	Target Space/Component in Traditional Ottoman Houses	Related Flexibility Parameters From Literature
FUNCTION	Sofa, Eyvan, Köşk, Room	Design for Adaptation (Till& Schneider, 2005) Multifunctionality (Geraedts, 2008; Kim, 2013)
INTEGRATION/ DIVISION	Integrated - Divided Spaces	Partitionability (Geraedts, 2008) Using closures (Cellucci & Sivo, 2015) Attachment/Detachment (Alkhansarı, 2018)
EXTENSION	Added spaces especially in the courtyard	Spatial Evolutionary flexibility (Cellucci & Sivo, 2015) Extendable Unit (Alkhansarı, 2018)
MOBILITY	Reused timber partition walls	Using mobile equipment (Cellucci & Sivo, 2015) Portable walls (Alkhansarı, 2018)
CONSTRUCTION	Non-load bearing timber frame walls	Technological flexibility relating to construction techniques (Cellucci & Sivo, 2015) Construction (Till& Schneider, 2005)
LOCATION	Bathroom, WC, Kitchen	Services (Till& Schneider, 2005; Slaughter, 2001; Hassanain, 2006))

Before continuing with an analysis of the flexible design parameters, the terms used in this research are defined below, in order to avoid ambiguity.

Function: Purpose of using space. This strategy is commonly linked to the ‘multifunctional space’ in the literature. Functional space defines multifunctional activities. However, service areas are dedicated to only one function. In traditional Ottoman houses in Ankara, sofa, *eyvan* and room are accepted as functional spaces. For the calculation of embodied energy of flexible design strategies, a new terminology is created; denoted as FDEE, in order to evaluate all strategies together.

Integration/division: Merging or splitting inner spaces. Enables distinction of private and social use of the spaces. This strategy is commonly known as 'attachment-detachment' in the literature. It has a variety of uses in traditional Ottoman houses, and calculated as a part of FDEE.

Extension: Expanding towards outside the building with increasing the total volume. Creates more space for future needs. This strategy is generally indicated as 'extendible unit' in the literature. In the case studies, the courtyard is regarded as where extensions generally occur as well as the upper floors. As new materials are added to the exterior of the existing building independently, the energy demand of these changes should be named 'additional initial EE'. However, it is calculated under the scope of FDEE since it is included in flexible design strategies.

Mobility: Using mobile equipment. Easy installation and removal skills of these partition walls serve spatial flexibility. This strategy has similar features with 'portable walls' as it is known in the literature. In some of the case studies, it was benefitted from reused timber panels to separate spaces in the scope of this strategy. Last three flexible design strategies are not included in the energy calculations. They are seen as catalysts of the top three strategies.

Location: Location of the service areas such as bathroom, WC, and kitchen. Grouping them in a region provides more space to be freely planned, increasing flexibility. Easy access and maintenance of services are other concerns of this parameter. It is named 'service space location' in the literature.

Construction: The construction technique of the walls. A typical plan layout indicates that inner walls on the ground floor have the capacity to carry loads. If the plan schemes of the floors are different and there is no wall transferring the load from the upper floor in the same alignment, the inner walls may not be load-bearing.

Replacement: The replacement of the building materials due to deterioration or expiration of the service life. The energy used for the cycles of new building materials is evaluated as REE.

Rebuilding and renewal works: Rebuilding of the collapsed areas and changing existing materials with a different type, e.g., replacing timber ceiling board with plywood without any consideration of flexibility. This type of changes is evaluated as additional initial embodied energy (AEE).

Maintenance: Includes activities which are cyclic replacement of the building materials and rebuilding-renewal works.

Alterations and Additions: Changing and/or adding space, component and/or material to the building due to user demand. All flexible design strategies; function, Integration/division, extension, mobility, location, and construction are evaluated in this category.

Design parameters derived from the literature are explained and identified in the plan schemes:

(a) Function: Functional spaces are used for daily activities and do not require any particular systems, whereas service areas are built with infrastructures which are harder to relocate. Functional spaces in the case studies such as room, *sofa*, *eyvan* etc. have been subjected to processes such as extension, detachment/attachment throughout their service lives, creating different spatial combinations. Moreover, these spaces also permit multifunctional purposes in daily life. Thus, they contribute to spatial flexibility.

Design for adaptation strategy is observed especially in the original conditions of the early built traditional Ottoman houses in Ankara. The case studies mostly have service areas in the exterior space; thus, the whole inner space works as a functional space. Service areas are mostly placed in a group in order to distribute the functional spaces in the plan layout.

In the case studies, only rooms and sofas are considered functional areas. The distribution of functional spaces, the base area and the changes they underwent over time is shown in Figure 3.18.

Figure 3. 18. *The functional areas and original space boundaries shown on the floor plans of case studies CS01, CS02, CS03 and CS04, are indicative of the existence of the flexible design parameter called 'Function'*

It was observed that the functional area, which is shown as shaded in red in Figure 3.21 above, changed over time in most of the houses. These changes show that the spaces are convertible and adaptable for different use.

(b) Integration/division: Integration/division stands for combining or separating at least two spaces. It is possible to come across many examples of this strategy in the case studies. The principle of 'customizing privacy/social needs' (Cellucci & Di Sivo, 2015) is seen in the case studies where the distinction as sofa and room is made. Even special spaces for guests or occupants to participate in social activities are created as a part of sofas such as *eyvan* and *köşk*. The distribution of the rooms in neutral size can be associated with an 'undefined environmental unit'(Cellucci & Di Sivo, 2015). The rooms can be used for multiple purposes, as a main room, private room etc. 'Common space' (Alkhansari, 2018) includes potential for future attachments. In the following years, it is observed that social areas such as sofa were partially divided and used for private use in traditional Ottoman houses in Ankara. For instance, in CS01, the sofa and eyvan were separated with a wall and the eyvan started to be used as a room. The 'similar spaces' (Alkhansari, 2018) mostly appeared when the division was applied.

The integrated and divided spaces can be seen in Figure 3.19.

Figure 3. 19. *The integrated-divided areas shown on the floor plans of case studies CS01, CS02 and CS07, are indicative of the existence of the flexible design parameter called 'Integration/division'*

In the vast majority of the buildings, this flexible design strategy of integration/division was attributed to function change, as in CS01, the inclusion of the wet areas inside the building as in CS02, or to allocate one area to multiple users as in CS07.

(c) Extension: Extensions are inspected as the third parameter. The courtyard is accepted as the empty space with the potential for further additions.

The courtyard can be called as a ‘defined zone’ (Alkhansari, 2018) where extension occurs in the case of traditional Ottoman houses in Ankara. There are additions at the upper floor levels in some of the building plans. This kind of additions can be considered in the frame of ‘increasing the surface area within the existing support’ (Cellucci & Di Sivo, 2015) strategy.

The extended spaces both in the courtyard and upper floors can be seen in Figure 3.20.

Figure 3. 20. *The extended areas shown on the floor plans of case studies CS01, CS02, CS04 and CS06, are indicative of the existence of the flexible design parameter called 'Extension'*

Increasing the floor area based on the need for more space, adding new spaces according to the evolving needs, as in CS06, taking advantage of the areas left empty in the original design, and arranging these areas as desired, as in CS01 and CS02, and combining adjacent buildings, as in CS04, are some of the reasons why this flexible design strategy (Extension) is applied in the case studies.

(d) Mobility: This parameter is related to dynamic elements. They contribute to flexibility with their easy installation and removal skills. Traditional Ottoman houses do not have any exact retractable furniture system or equipment. However, reused timber walls can be evaluated under this category. They can provide division and expansion of the fixed volume space for multifunctional purposes. R03, R04, R05, R06, R07 are examples of the use of partition panels made of reused building materials such as timber (Figure 3.21).

Figure 3. 21. *The reused timber panels shown on the floor plans of case studies CS03, CS04, CS05, CS06 and CS07, are indicative of the existence of the flexible design parameter called 'Mobility'*

(e) Construction: Utilization from removable timber frame partition walls in construction contributes to flexibility. They enable integration and division to occur between adjacent units. Locally available building materials such as mudbrick and timber facilitate the construction process.

Whether the walls are load-bearing or not is shown on the ground floor plan layout. If the ground and upper plan layouts are not typical, it is highly possible that the interior walls of the ground floors are non-load bearing partition walls. CS01, CS05, and CS08 can be given as examples for this parameter (Figure 3.22).

Figure 3. 22. *The non-load bearing timber frame walls shown on the floor plans of case studies CS01, CS05 and CS08, are indicative of the existence of the flexible design parameter called 'Construction'*

(f) Location: The location of the services is significant because of their ease of maintenance and accessibility. The wet areas and cooking zones were located inside the courtyard in original traditional Ottoman houses, which allows the interior space to be freely planned. After being included in the building in the next years, it was seen that these spaces were generally located in the areas close to the facades of the buildings and close to each other as in CS01, CS02, CS06, CS09, CS10. (Figure 3.23).

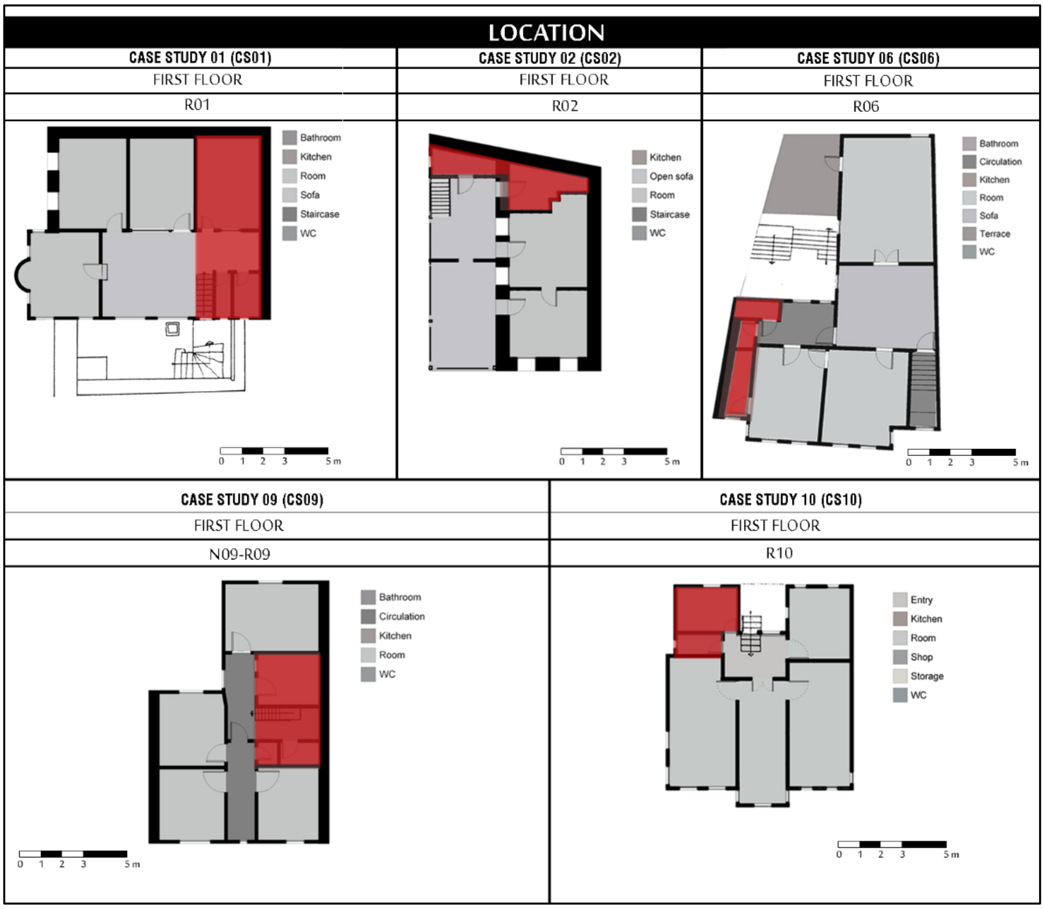


Figure 3. 23. *The location of the service areas shown on the floor plans of case studies CS01, CS02, CS06, CS09 and CS10, are indicative of the existence of the flexible design parameter called 'Location'*

The flexible design characteristics of the case studies were examined under six categories and spatial flexibility of these houses was determined. These analyses shows that traditional Ottoman houses in Ankara have adaptable characteristic inherently. Adaptability contributes the extension of the service life. Therefore, it is believed that traditional Ottoman houses owe their longevity to these adaptive principles. Changes that occurred in the structure are categorized to understand the changes that signal these flexible design strategies. In order to analyze the effect of flexible design on energy, the amount of FDEE corresponding to alterations/additions, and LCEE have to be determined.

3.3.2 3D Building Modeling

The 3D modeling of the dwellings consists of two steps. At first, final version of the building is modeled in Revit. The virtual model of building components includes foundation, exterior and interior walls, wall finishes, structural system (post, wall plate, foot plate, window sill, bracing), floor system (girder and joist) and flooring, ceiling covering, roof system (rafter) and roof cladding (Figure 3.24). Secondly, the same components are modeled for the initial case. Thus, the material quantity is determined for both cases.

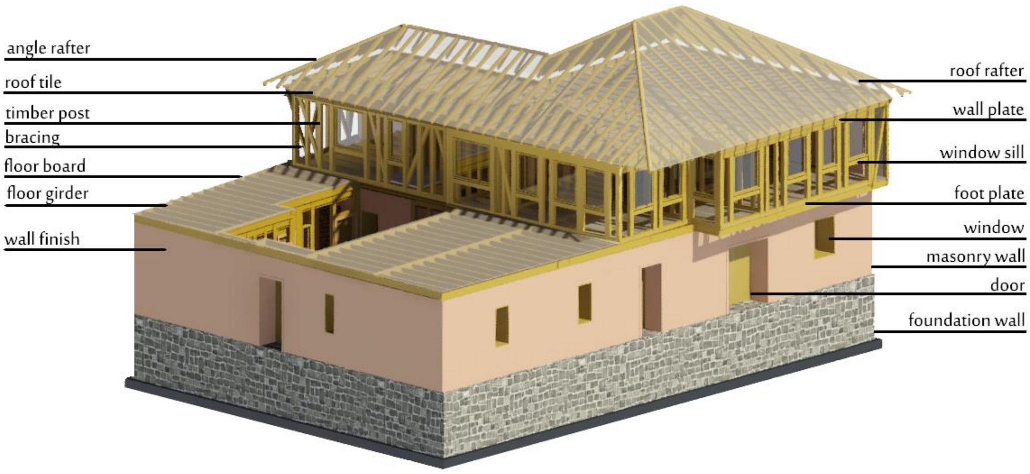


Figure 3. 24. *Example 3D model of building components (CS08)*

Assumptions and limitations in the modeling process are as the following:

- The floor height of the ground and first floors, if indicated, is taken from the dissertation (Şahin, 1995) Otherwise, they are estimated by using proportional scaling of the photographs imported into AUTOCAD.
- The part between building entrance and ground level is ignored in the model and calculations as the height of this part is unknown. Therefore, the entrance level is considered as the first level in the model.
- The depth of the foundation level is accepted as 2 meters and the thickness of the stone masonry walls are set as 0.80 meter.
- The dimension of foot and wall plates, window sills and braces are 10x10 centimeter.
- Floor joists (5x10 cm) are placed at every 50 cm. The dimension of floor girder is 10x15 cm.
- Main posts are placed at every 150 cm, inner posts in 50 cm. The dimensions of the corner posts are 10x10 cm, and inner posts are 5x10 cm.
- The roof rafters are placed in every 50 cm. The dimensions of rafters are 5x10 cm, and angle rafters are 10x10 cm.
- The length of the eave is specified as 50 cm. The roof slope is 30°.
- Exterior walls of the ground floor are modeled as stone masonry, and 1 meter above the ground. The masonry exterior wall dimensions vary from 0.5 meter to 0.8 meter while the interior timber frame wall thickness is 0.15 meter.
- The window sills embedded in the masonry walls, stairs, fireplaces and cupboards are excluded from the 3D model.
- The window frame thickness is taken as 5 cm.
- The roofing of the additional parts was ignored.
- Until the 19^{th} century, WC was not located inside the building but in the courtyard. For this reason, while modeling the initial state of the building, the WC was located in the courtyard. If not specified, the location and size of the WC in the courtyard are estimated based on the other layout plans of the buildings.

- Likewise, the cooking area is considered in the courtyard for the initial case. Therefore, the kitchen is not included in the building in the early period structures.

3.3.3 Embodied Energy Calculations

The proxy data was obtained from the Inventory of Carbon and Energy (ICE), version 2.0. This source contains the delivered energy converted to primary energy.

The calculation method was chosen as process-based. Even if most of the energy-consuming steps are ignored in the process-based analysis, the incompleteness will affect all of the case studies and will be reflected in the results evenly. Since the main purpose is to compare case studies with each other in terms of service life and LCEE, the results will be reliable.

While calculating the IEE for each residence, system boundary is established as ‘cradle to gate’. It is assumed that little amount of energy is used during the transportation stage from production to construction site due to the local availability of building materials. The buildings were built between 17^{th} and 20^{th} century; therefore, estimations and uncertainties may lead to inaccurate results, as construction techniques and equipment may differ. Therefore, installation energy is not included in the system boundary. As the functional unit, MJ/ m^2/year is used.

The calculation is made by multiplying the embodied energy intensity per unit by the mass of building material. The amount of material is taken from Revit as volume, and then multiplied by the bulk density to find the material mass. An example for IEE calculation can be seen from Table 3.7.

Table 3. 7. *Sample calculation table of the IEE, belonging to CS01 (actual service life scenario)*

Component	**Material**	**Density (kg/m³)**	**Volume (m³) or Area* (m²)**	**Mass (kg)**	**EE Intensity (MJ/kg or MJ/m²**)**	**IEE (MJ)**
Foundation	Stone	2400	86.0	206,496	1.26	260,185
Wall Assembly	Stone	2400	23.3	55,944	1.26	70,489
	Mud brick	1370	126.9	173,798	0	0
	Lime	1200	25.4	30,446	5.3	161,366
	Brick	2000	26.2	52,400	3	157,200
Finish	Mud plaster	1170	17.2	20,077	0	0
	Lime	1200	3.4	4,118	5.3	21,828
	Whitewash	1400	8.6	12,012	59	708,708
Structural System	Timber (posts)	600	3.3	1,992	7.4	14,741
	Timber (foot-wall plate, window sill, brace)	600	1.4	846	7.4	6,260
Floor/Ceiling	Timber (girder, joist)	600	4.1	2,430	7.4	17,982
Finish	Timber (floor board, hardwood)	800	7.1	5,696	10.4	59,238
	Timber (ceiling board, hardwood)	800	4.3	3,416	10.4	35,526
Window	Timber (frame, softwood)		2.9*		2189**	6,282
	Glass		14.1*		671**	9,481
Interior Door	Timber (softwood)	600	0.8	480	7.4	3,552
Roof	Timber (rafter, beam)	800	1.8	1,424	10.4	14,810
Finish	Roof tile	1400	2.7	3,738	6.5	24,297

3.3.3.1 Embodied Energy in the Life Cycle Stages

The REE required for maintenance and alteration/addition is calculated for each case study. The maintenance interval is determined according to the replacement cycles found in the literature. REE is found by multiplying the embodied energy intensity of the material by building service life/replacement interval. Only the wall finishes, floor, ceiling, and roof coverings are included in the energy computation. The service life of building materials that belongs to the structural system is regarded as the same as the estimated lifespan of the building. The REE calculation based on the replacement of the initial building materials is shown in Table 3.8.

Table 3. 8. *Calculating the energy demand of the recurring building materials, belonging to CS01*

Building Component	Recurring Material	IEE (MJ)	REE (MJ)	Service Life (year)
Wall Finish	Plaster (lime)	21,828	6,657,394	1
	Paint (whitewash)	708,708	21,261,240	10
	Timber (floor board, hardwood)	59,238	328,504	55
	Timber (ceiling board, hardwood)	35,526	197,010	55
Window	Timber (frame, softwood)	6,282	62,824	30
	Glass	9,481	71,109	40
Interior Door	Timber (softwood)	3,552	35,520	30
Roof	Roof tile	24,297	121,485	60

Apart from cyclic replacement, other maintenance activities such as rebuilding and renewal works, which include such activities as rebuilding damaged parts of the structure, also require extra building materials in the use stage and their embodied energy may be considered as additional IEE but in this study the differentiation require a different term, which is chosen as additional EE that is abbreviated as AEE. However, the embodied energy for new spaces built as extensions is evaluated as additional IEE, and since the building extension is identified as a flexible design strategy, it is called the flexible design embodied energy or FDEE, to differentiate between the two in the calculations for comparison.

The energy depending on the flexible design changes in the spatial organization is analyzed under the heading of alterations and additions. When there is a change in the spatial layout, the building materials are also affected by that modification. In particular, it is assumed that floor materials are renewed due to the new function or change in the plan layout. When a wall component is added as a result of division strategy, finishing materials will be added as well as the wall system, resulting in the need for more energy. It is also valid for the addition of built-up exterior spaces.

The energy used in the construction stage equals to IEE. In the use stage, two main sources of EE are identified specific to this study, which are maintenance and alteration/addition. Maintenance stage covers periodic replacement of the building materials and rebuilding and renewal works. Both activities are evaluated with different EE types. The former one (cyclic replacement) is analyzed with REE while the latter is examined within the frame of AEE. On the other hand, alteration/addition stage is related with the application of flexible design strategies. These activities are evaluated as FDEE. Only the demolition energy is considered at the end-of-life stage. LCEE consists of the summation of all these energy types. The EE types of the activities in the use stage resulting from maintenance and alteration/addition are shown in Table 3.9.

Note: The system boundary has been set as cradle-to-gate; and labor has been ignored in the EE calculations; i.e., only material has been taken into consideration.

Table 3. 9. *The sources and types of LCEE stages*

SOURCE	Construction	Maintenance		Alterations/ Additions	End-of-life	Total
ACTIVITY	Gathering raw materials, Transportation, Manufacturing	Cyclic Replacement	Rebuilding and Renewal Works	Applying Flexible Design Strategies (FC, ID, EX)	Demolition	
EE TYPE	IEE	REE	AEE	FDEE	DE	LCEE

IEE = Initial Embodied Energy; REE = Recurring Embodied Energy; AEE = Additional Initial Embodied Energy; FDEE = Embodied Energy of Flexible Design Strategies; DE = Demolition Energy; LCEE = Life Cycle Embodied Energy; FC = Function Change; ID = Integration/Division; EX = Extension parameter.

3.3.3.2 Embodied Energy of Three Service Life Scenarios

Three different service life scenarios are compared in order to analyze the impact of the building's service life on the LCEE values.

In the first scenario, the service life is taken as 50 years, which is frequently given as the estimated service life in the literature. Hence, the buildings are considered to be demolished and rebuilt after every 50 years, to add up to the actual service life duration. For instance, for a building with a service life of 104 years, the LCEE was calculated by assuming that the building would have to be demolished and rebuilt twice. Hence, IEE is added three times and DE, which is taken as 3% of the building materials LCEE from the literature, is added two times to the LCEE. No alterations or additions were included in the first scenario (Table 3.10).

Table 3. 10. *A sample calculation table showing the cyclic energy distribution for the first scenario, belonging to CS10*

Period (years)	IEE (MJ)	REE (MJ)	DE (MJ)	LCEE (MJ)
0-10		642,838		
11-20		642,838		
21-30	1,111,527	655,692	130,467	
31-40		653,171		
41-50		642,838		
51-60		642,838		10,130,819
61-70		642,838		
71-80	1,111,527	655,692	130,467	
81-90		653,171		
91-100		642,838		
101-104	1,111,527	60,547	0	
TOTAL (MJ)	3,334,582	6,535,303	260,934	

The building materials shaping the main load-bearing part of the building are assumed as non-replaced components, and the energy requirement for repair of these building materials is neglected. During the REE calculation, the energy demand of doors, windows, floor and ceiling covering, paint and plaster based on estimated replacement cycles is calculated. The replacement interval is determined according to the replacement cycles found in the literature. REE is found by multiplying the embodied energy intensity of the material by building service life/replacement interval. The calculation table on material scale of the IEE and REE for the first 50 years can be seen from Table 3.11.

Table 3. 11. *Sample calculation table of the IEE, REE, DE and LCEE (first service life scenario), belonging to CS01*

Component	Material	IEE (MJ)	Service Life (years)	REE (MJ)	DE (MJ)	LCEE (MJ)
Foundation	Stone	260,185	50 (lifetime)	0	186,785	6,226,176
Wall Assembly	Stone	70,489	50 (lifetime)	0		
	Mud brick	0	50 (lifetime)	0		
	Lime	161,366	50 (lifetime)	0		
	Brick	157,200	50 (lifetime)	0		
	Mud plaster	0	1	0		
	Lime	21,828	1	1,091,376		
	Paint (whitewash)	708,708	10	3,543,540		
Structural System	Timber (posts)	14,741	50 (lifetime)	0		
	Timber (foot-wall plate, window sill, brace)	6,260	50 (lifetime)	0		
Floor/Ceiling	Timber (girder, joist)	17,982	50 (lifetime)	0		
	Timber (floor board, hardwood)	59,238	55 (max.)	0		
	Timber (ceiling board, hardwood)	35,526	55 (max.)	0		
Window	Timber (frame, softwood)	6,282	30	6,282		
	Glass	9,481	40	9,481		
Interior Door	Timber (softwood)	3,552	30	3,552		
Roof	Timber (rafter, beam)	14,810	50 (lifetime)	0		
	Roof tile	24,297	60 (max.)	0		

In the second scenario, the service life was determined as shown in the ‘service life estimation’ (Table 3.2). IEE is the same with the first scenario. However, for the cyclic replacement activities, the energy demand of the materials increases due to the longer service life. Since the buildings were standing at the time of the survey carried out by Şahin in 1994, DE is ignored for the second and third scenarios in

LCEE calculations. The REE calculation based on the replacement (REE) and rebuilding and renewal works (AEE) of the initial building materials for the second scenario is shown in Table 3.12.

Table 3. 12. *Sample calculation table of the IEE, REE, AEE and LCEE (second service life scenario), belonging to CS01*

Component	Material	IEE (MJ)	REE (MJ) and AEE* (MJ)	LCEE (MJ)
Foundation	Stone	260,185	0	30,586,222
Wall Assembly	Stone	70,489	0	
	Mud brick	0	0	
	Lime	161,366	0	
	Brick	157,200	0	
Wall Finish	Mud plaster	0	0	
	Lime	21,828	6,635,566	
	Paint (whitewash)	708,708	21,544,723	
Structural System	Timber (posts)	14,741	0	
	Timber (foot-wall plate, window sill, brace)	6,260	0	
Floor/Ceiling	Timber (girder, joist)	17,982	0	
	Screed		15,379*	
	Timber (floor board, hardwood)	59,238	327,427	
	Timber (ceiling board, hardwood)	35,526	196,364	
Window	Timber (frame, softwood)	6,282	63,662	
	Glass	9,481	72,057	
Interior Door	Timber (softwood)	3,552	35,994	
Roof	Timber (rafter, beam)	14,810	0	
Covering	Roof tile	24,297	123,105	

For the third scenario, the additions and alterations due to the flexible design strategies are also considered. The building materials which are added to the original structure later and have replacement cycles such as paint and plaster, it is assumed that the intervention was applied within the last 50 years of the building service life.

Although, the repairs and rebuilding of a damaged area in traditional buildings may be considered in the scope of additional IEE, they are calculated together within the context of maintenance works and denoted as additional EE (AEE); as they both occurred after the original building was erected. The replacement cycles of the building materials are taken from the literature. On the other hand, specified design changes in the spatial plan organization are thought to be for once during the lifetime. However, the replacement cycles of newly added materials are considered within the scope of FDEE. The reason of adding new materials is flexible design strategies, therefore the energy caused by these strategies should be considered together with the periodic replacement of the relevant building materials (Table 3.13).

Table 3. 13. *Sample calculation table of the IEE, REE, AEE, FDEE and LCEE (third service life scenario), belonging to CS01*

IEE (MJ)	**REE (MJ)**	**Component**	**Material (newly added)**	**AEE (MJ)**	**FDEE (MJ)**	**LCEE (MJ)**
1,571,946	28,998,898	Wall Assembly	Brick		48,000	31,138,880
			Mud plaster		0	
			Lime		95,400	
			Paint (whitewash)		309,750	
		Glazing	Storefront		30,000	
		Structural System	Timber (posts)		4,973	
			Timber (foot-wall plate, window sill, brace)		5,905	
			Screed	15,379	46,137	
		Window	Timber (frame, softwood)		3,328	
			Glass		7,032	
		Interior Door	Timber (softwood)		2,132	

CHAPTER 4

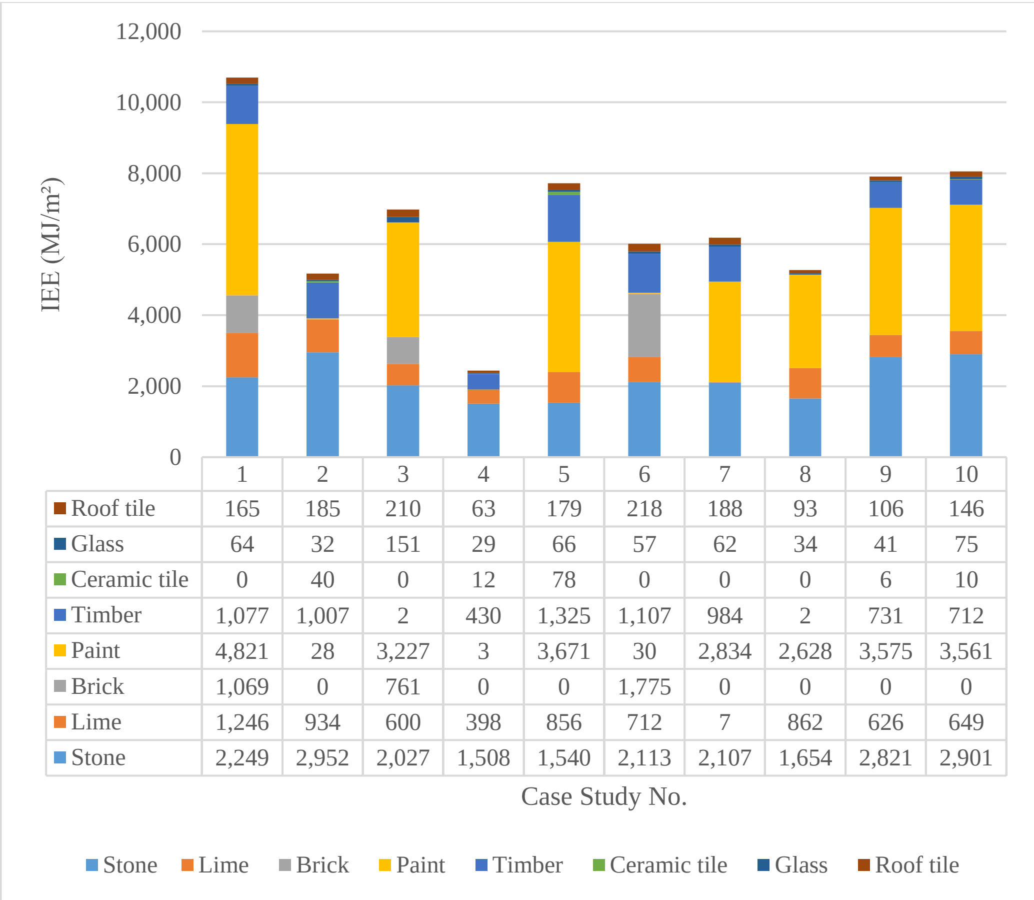
ANALYSIS AND RESULTS

In this chapter, the results and analyses are explained, followed by the discussion of the results. In the analysis part, construction, maintenance and alteration/addition stages of the building materials and the impact of flexible design parameters on LCEE via service life scenarios are evaluated. The first part consists of evaluating the EE of building materials for the construction, and use stages. In the second part, three service life scenarios are assessed in order to understand the effect of extending service life and flexible design strategies on LCEE. EE savings are found at the end of the comparisons. Lastly, there is a comprehensive discussion that includes the results of the analyses and the impact of flexible design parameters on total LCEE among other embodied energy types.

4.1 Energy Demand of the Building Materials

Embodied energy calculations are made by considering building materials. They are subjected to changes, alterations, additions, and replacement during the lifespan of the building. In this part, each building material was put under the scope and their energy demand for three stages, construction, maintenance, alteration/addition is analyzed.

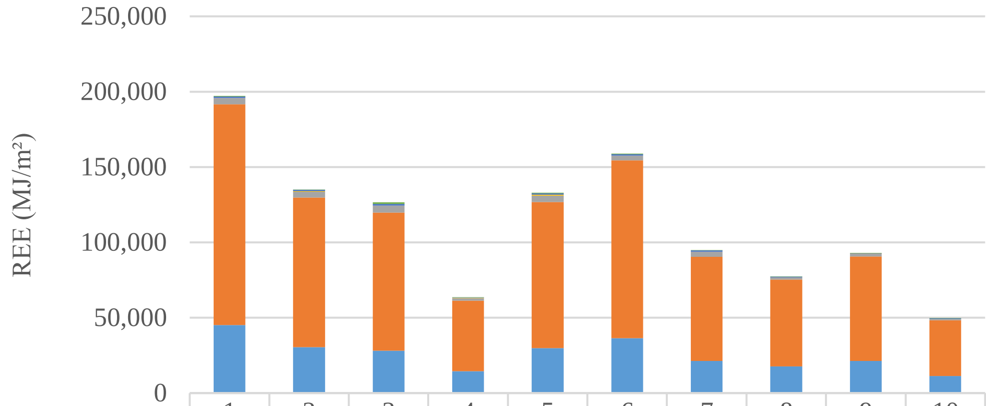
When examining the IEE of eight building materials, the most energy-intensive one is found as paint up to 4,821 MJ/m² followed by stone in the range of 1,508-2,952 MJ/m², timber up to 1,328 MJ/m², lime up to 1,246 MJ/m², and roof tile with 63-218 MJ/m². The lowest energy use is by glass with 29-151 MJ/m² among the building materials used in each building. Ceramic tile and brick were not applied to all of the case studies (Figure 4.1).



	1	2	3	4	5	6	7	8	9	10
Roof tile	165	185	210	63	179	218	188	93	106	146
Glass	64	32	151	29	66	57	62	34	41	75
Ceramic tile	0	40	0	12	78	0	0	0	6	10
Timber	1,077	1,007	2	430	1,325	1,107	984	2	731	712
Paint	4,821	28	3,227	3	3,671	30	2,834	2,628	3,575	3,561
Brick	1,069	0	761	0	0	1,775	0	0	0	0
Lime	1,246	934	600	398	856	712	7	862	626	649
Stone	2,249	2,952	2,027	1,508	1,540	2,113	2,107	1,654	2,821	2,901

Figure 4. 1. *Energy share distribution of the building materials in the construction stage*

During the maintenance stage, energy demand of paint was in the range of 37, 038 – 146,563 MJ/m², and 11,407 - 45,140 MJ/m² of lime used for the mud plaster and mudbrick require the most energy. Ceramic tile is in the range of 35 - 684 MJ/m², glass is between 188 – 1,071 MJ/m² and roof tile is between 254 – 995 MJ/m². Timber represents the floor and ceiling coverings, window frames and doors with the values of 810 – 4,666 MJ/m² (Figure 4.2).



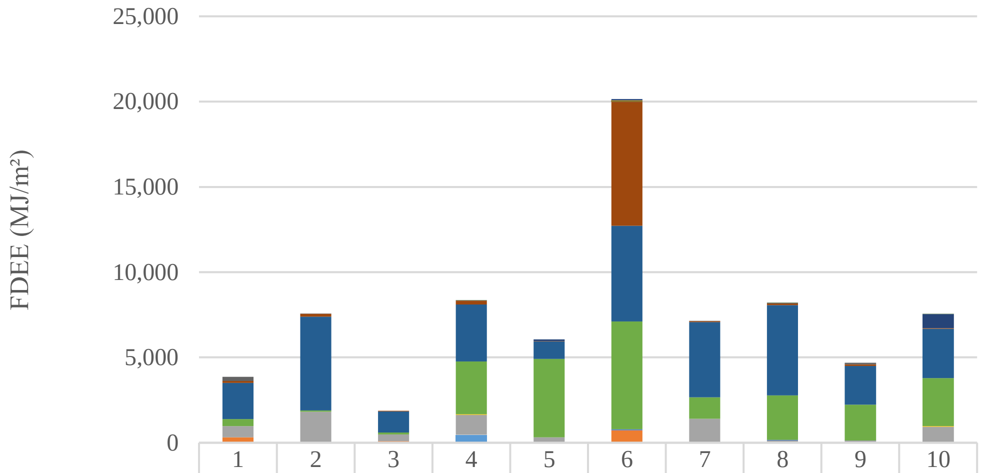
	1	2	3	4	5	6	7	8	9	10
Glass	490	233	1,071	198	438	362	378	188	199	195
Roof tile	837	907	995	289	787	922	763	340	344	254
Ceramic tile	0	392	0	106	684	0	0	0	36	35
Timber	4,241	3,867	4,666	1,666	4,316	3,104	3,428	1,587	1,755	810
Paint	146,56	99,161	91,651	46,932	96,917	118,06	69,145	57,563	69,364	37,038
Lime	45,140	30,541	28,228	14,455	29,850	36,363	21,296	17,729	21,363	11,407

Case Study No.

Lime Paint Timber Ceramic tile Roof tile Glass

Figure 4. 2. *Energy share distribution of the building materials for the maintenance stage*

Various building materials were added to the structures in the process of use such as plywood, cement plaster, screed, and briquette. Due to its great embodied energy intensity, paint ranks first in energy demand, followed by screed. In later periods, 1,033-5,615 MJ/m² of paint and 121-1,817 MJ/m² of lime were added to the structures. In the alteration/addition stages, almost all structures were subjected to the addition of screed flooring. It has high energy demand with a range of 75-4,609 MJ/m². Plywood and cement plaster were applied in three of the buildings in the following years for a more durable layer, and briquette was implemented in two. Newly added building materials to the original structures are briquette, cement plaster, screed, and plywood (Figure 4.3).



	1	2	3	4	5	6	7	8	9	10
Roof tile	0	0	0	7	0	0	0	23	0	15
Plywood	0	0	0	0	97	72	0	0	0	817
Ceramic tile	0	0	0	0	0	60	0	0	0	0
Glass	252	27	0	27	0	28	12	25	92	0
Timber	111	157	25	224	18	7,261	61	103	89	46
Paint	2,107	5,507	1,249	3,333	1,033	5,615	4,405	5,281	2,269	2,873
Screed	418	75	101	3,091	4,609	6,324	1,259	2,610	2,094	2,822
Cement Plaster	0	0	0	0	0	57	0	41	18	0
Briquette	0	0	0	48	0	0	0	0	0	32
Lime	649	1,817	397	1,150	312	0	1,413	134	121	944
Brick	327	0	100	0	0	733	0	0	0	0
Stone	0	0	0	477	0	0	0	0	0	0

Figure 4. 3. *Energy share distribution of the building materials for the alteration/addition stage*

While the wall finishes, paint and lime inside the mud plaster, require the highest amount of energy in the construction (IEE), maintenance (REE), and alteration/addition (FDEE) stages due to its high embodied energy intensity. The stone has also higher energy demand during the construction stage (IEE). Stone walls are built with large wall thicknesses, and it was used in the foundation, ground and upper levels. Therefore, the high energy demand can be understood in the construction stage. In the alteration/addition stage, almost all structures were subjected to the addition of screed flooring. Its large share can be explained with the wide application area.

The total amount of energy is summed up for each material and divided into total area of ten buildings. The result can be seen from the pie charts below for each stage. (Figure 4.4)

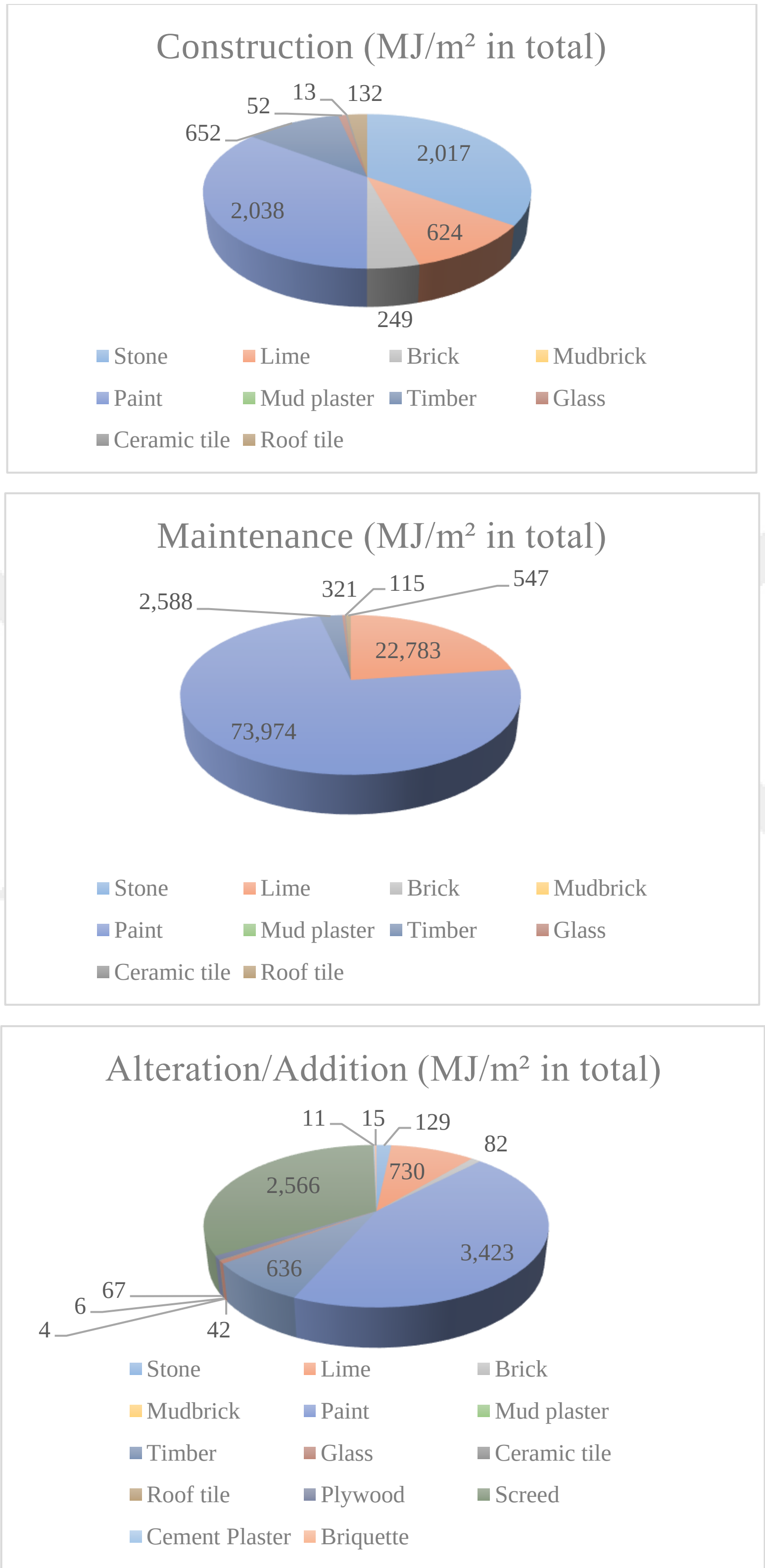


Figure 4. 4. *Total energy values of the building materials (MJ/m²) for different life cycle stages*

4.2 Comparison of the Service Life Scenarios

One of the parameters that affects REE is the service life of a building. As the time passes, the REE will increase. The case studies, selected from the traditional Ottoman houses in Ankara, have a long service life from 100 to 300 years. Therefore, the higher amount of embodied energy will be divided into a longer service life.

Three service life scenarios were created in order to understand the effect of flexible design strategies and extended service life on LCEE. For the first scenario with 50-year demolish-rebuild cycles for the actual service life duration taken from construction date to the last detailed survey date, i.e. 1994, the LCEE was found by summing up the IEE, REE (only the maintenance energy due to material replacement), and DE.

For the second scenario, the embodied energy related to the maintenance works made during the actual service life as rebuilding/renewal and cyclic replacements of the building materials were taken into consideration to determine the AEE and REE, respectively; which was added to the IEE to calculate the LCEE.

For the third scenario, which is the actual case that includes the additions and alterations in the spaces that were identified as flexible design strategies and the embodied energy related to all maintenance activities in the building (IEE, REE, AEE and FDEE) were included in the LCEE calculations.

According to the calculations, total IEE is between 3,334 – 14,201 GJ while total REE is between 6,550 – 34,841 GJ, and total DE is 260 – 1,318 GJ for the 50-year cyclic service life scenario.

Table 4. 1. *IEE, REE and DE values for the 50-year service life cycles during the actual service life of the case studies*

Case Study ID	Service Life (year)	No of 50-year service life cycles	IEE (MJ)	Total IEE (MJ)	Total REE (MJ)	Total DE (MJ)	Total EE (MJ)
CS01	304	7	1,571,946	11,003,623	28,012,700	1,120,712	40,137,035
CS02	294	6	1,022,662	6,135,974	15,494,564	552,440	22,182,977
CS03	284	6	1,110,148	6,660,890	15,495,414	579,827	22,736,130
CS04	274	6	2,366,883	14,201,296	34,841,583	1,318,502	50,361,380
CS05	264	6	1,388,922	8,333,533	22,763,824	862,271	31,959,628
CS06	254	6	1,626,442	9,758,651	23,458,001	944,421	34,161,073
CS07	244	5	1,474,713	7,373,566	17,553,929	613,564	25,541,059
CS08	219	5	1,569,331	7,846,655	20,422,700	745,511	29,014,866
CS09	194	4	1,683,947	6,735,790	19,133,839	601,841	26,471,470
CS10	104	3	1,111,527	3,334,582	6,550,439	260,934	10,145,956

For the second scenario, with rebuilding and renewal works, the IEE is found between 1,022 – 2,366 GJ, the REE is between 6,864 – 36,277 GJ, and AEE is in the range of 0 – 894 GJ.

Table 4. 2. *IEE, REE, AEE and LCEE(MJ) values for the actual service life (approximately 100-300 years) according to 1994 survey; without additions and alterations to the spaces*

Case Study ID	Service Life (years)	IEE (MJ)	REE (MJ)	AEE (MJ)	LCEE (MJ)
CS01	304	1,571,946	28,998,898	15,379	30,586,223
CS02	294	1,022,662	16,212,039	0	17,234,701
CS03	284	1,110,148	16,332,804	126,457	17,569,409
CS04	274	2,366,883	36,277,692	880,870	39,525,444
CS05	264	1,388,922	23,938,758	548,851	25,876,531
CS06	254	1,626,442	24,299,028	894,429	26,819,898
CS07	244	1,474,713	18,526,988	61,798	20,063,498
CS08	219	1,569,331	20,822,374	237,800	22,629,506
CS09	194	1,683,947	19,822,040	223,020	21,729,007
CS10	104	1,111,527	6,864,015	251,100	8,226,642

For the third scenario with additions and extensions as well as rebuilding and renewal works, IEE, REE and AEE have the same values with the second service life scenario. However, LCEE increases because of the FDEE, and is calculated in the range of 114 – 3,882 GJ.

Table 4. 3. *Total IEE, REE, AEE and FDEE (MJ) value for the actual service life of the real situation with the flexible design strategies (additions and alterations to the spaces).*

Case Study ID	**Service Life (years)**	**IEE (MJ)**	**REE (MJ)**	**AEE (MJ)**	**FDEE (MJ)**	**LCEE (MJ)**
CS01	304	1,571,946	28,998,898	15,379	552,656	31,138,879
CS02	294	1,022,662	16,212,039	0	909,959	18,144,660
CS03	284	1,110,148	16,332,804	126,457	114,898	17,684,307
CS04	274	2,366,883	36,277,692	880,870	3,882,762	43,408,207
CS05	264	1,388,922	23,938,758	548,851	546,022	26,422,553
CS06	254	1,626,442	24,299,028	894,429	1,359,465	28,179,363
CS07	244	1,474,713	18,526,988	61,798	1,384,815	21,448,314
CS08	219	1,569,331	20,822,374	237,800	2,043,052	24,672,557
CS09	194	1,683,947	19,822,040	223,020	777,362	22,506,369
CS10	104	1,111,527	6,864,015	251,100	834,965	9,061,607

The total annual embodied energy values per year is found for all of the service life scenarios in order to make a fair comparison. The values are between 617-1190 MJ/m²/year for the first service life scenario; 480-934 MJ/m²/year for second service life scenario; and 278-725 MJ/m²/year for third one (Table 4.4).

Table 4. 4. *Total EE (IEE, REE, DE) and LCEE (IEE, REE, AEE, FDEE) (MJ/m²/year) values for each service life scenario*

Case Study ID	1st service life scenario	2nd service life scenario	3rd service life scenario
	50-year service life cycles during the actual service life	Actual service life without additions and alterations to the spaces	Actual service life with flexible design strategies
	Total EE (MJ/m²/year)	LCEE (MJ/m²/year)	LCEE (MJ/m²/year)
CS01	957	729	697
CS02	755	586	514
CS03	621	480	483
CS04	666	523	278
CS05	673	545	556
CS06	1190	934	725
CS07	675	530	451
CS08	1086	847	419
CS09	700	574	545
CS10	774	628	631

When three scenarios are evaluated, considering the same period, based on the estimated service lives, the total embodied energy values differ for each case study and scenario. The reasons for the difference between the case studies of the same scenario are the diversity of buildings materials, their embodied energy intensities, bill of quantities, replacement cycles, material additions etc.

On the other hand, in the case of the first service life scenario some of the reasons for the difference between the service life scenarios are the inclusion of DE and IEE for each 50 year cycle as well as resetting the replacement cycles (REE). These stages are all energy-intensive, and increase the embodied energy when compared to a long-lasting structure. In addition to that, more raw materials will be used; more energy for labor, transportation to the site, and disposal will be consumed; and more waste will be occurred in the first case. Therefore, the first service life scenario has the higher score in all of the LCEE stages, and also in annual EE calculations. Although third service scenario values are more than the second one due to the alterations and additions in the scope of flexible design strategies, the case studies of second service life scenario need more energy annually (Figure 4.5).

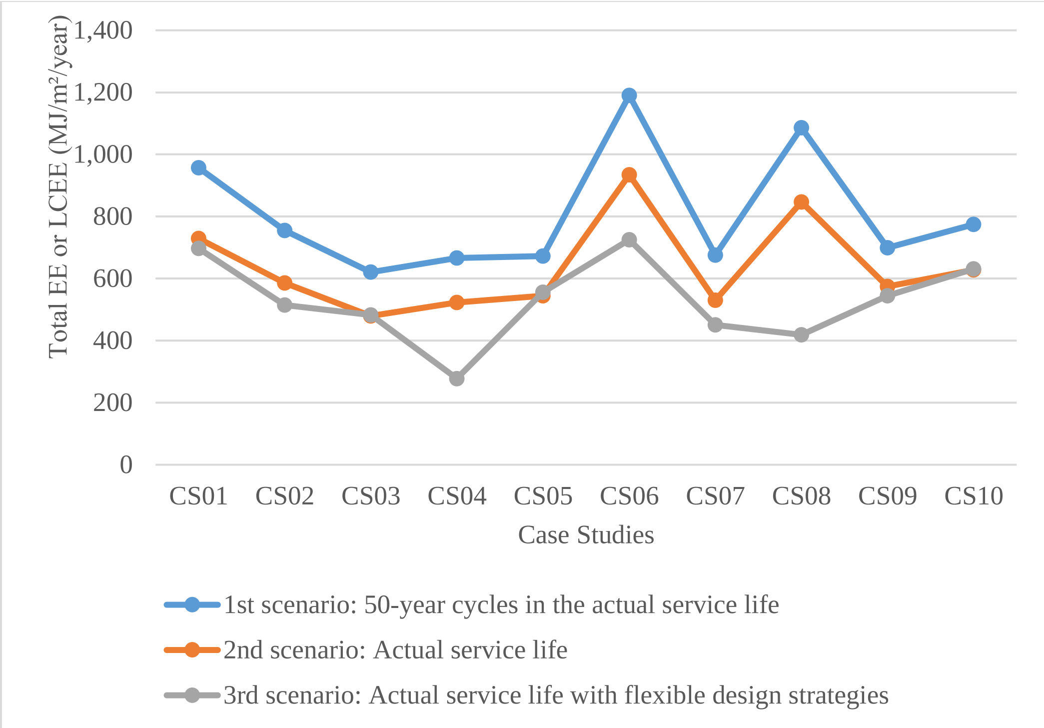


Figure 4. 5. *Comparison of the three service life scenarios on total EE for the first scenario and LCEE for the second and third scenarios (MJ/m²/year)*

In addition to these results, the case studies of second service life scenario (actual service life) were taken as a control group, and they were compared with the first and third scenarios in order to find out the total savings for each case.

When the first and second service life scenarios were compared, it was seen the total LCEE was saved by 22-31% in the second service life scenario thanks to longevity. (Figure 4.3).

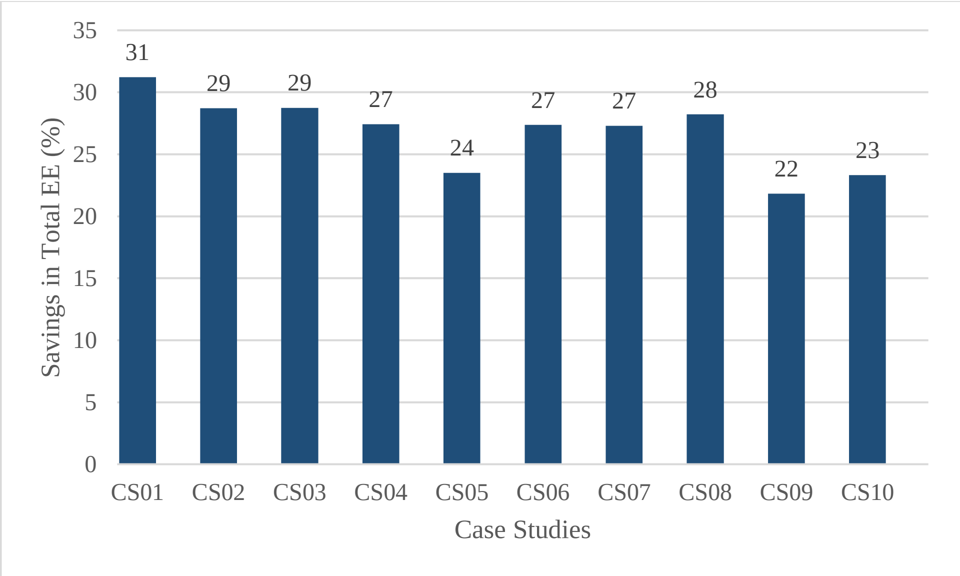


Figure 4. 6. *The total saving in LCEE (IEE, REE, AEE) (%) in the 2nd scenario in comparison to the 1st scenario*

Thereafter, the second and third scenarios were compared. Second service life scenario is created in order to see the impact of flexible design strategies on the total energy demand of building materials. In the absence of these strategies, the buildings could not survive so long because they could not correspond to user demands without any alterations. Therefore, the only difference between these service life scenarios is the implementation of flexible design strategies. It was found that in the third scenario, there is an increase in LCEE with a range of 1-9%, depending on the presence of the flexible design strategies and FDEE, correspondingly. (Figure 4.7).

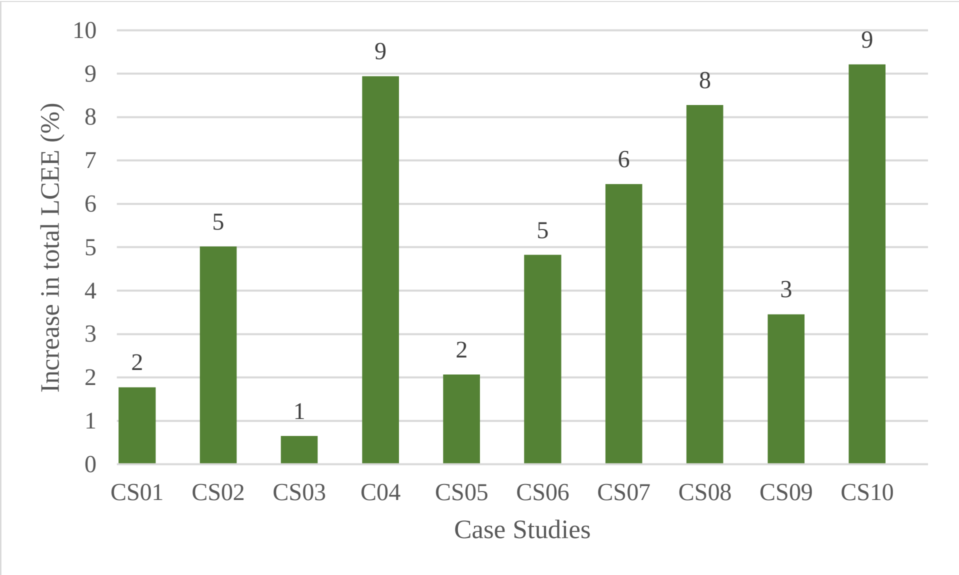


Figure 4. 7. *Increase in LCEE (%) due to FDEE in the 3rd scenario in comparison to the 2nd scenario*

4.3 Discussion of the Results

The impact of annual REE on total LCEE, floor area on LCEE, embodied energy share of alterations/additions, and overall impact of the flexible design parameters on LCEE are discussed in this part.

The share of REE in LCEE is much higher than the IEE for the buildings that are operated for longer period of time. Therefore, a natural link is established between REE and service life. In embodied energy calculations, annual REE is found to be strongly related with total LCEE in the literature with an R^2 of 0.86 (Dixit, 2017b). In this study a moderate polynomial relationship was found with R^2 of 0.65. The relationship increases when the building with lowest service life (CS10) is accepted as an outlier (r^2 =0.87). The importance of annual REE in reducing total LCEE can be seen from in Figure 4.8. Therefore, when viewed from this aspect, understanding the parameters that affect annual REE is significant.

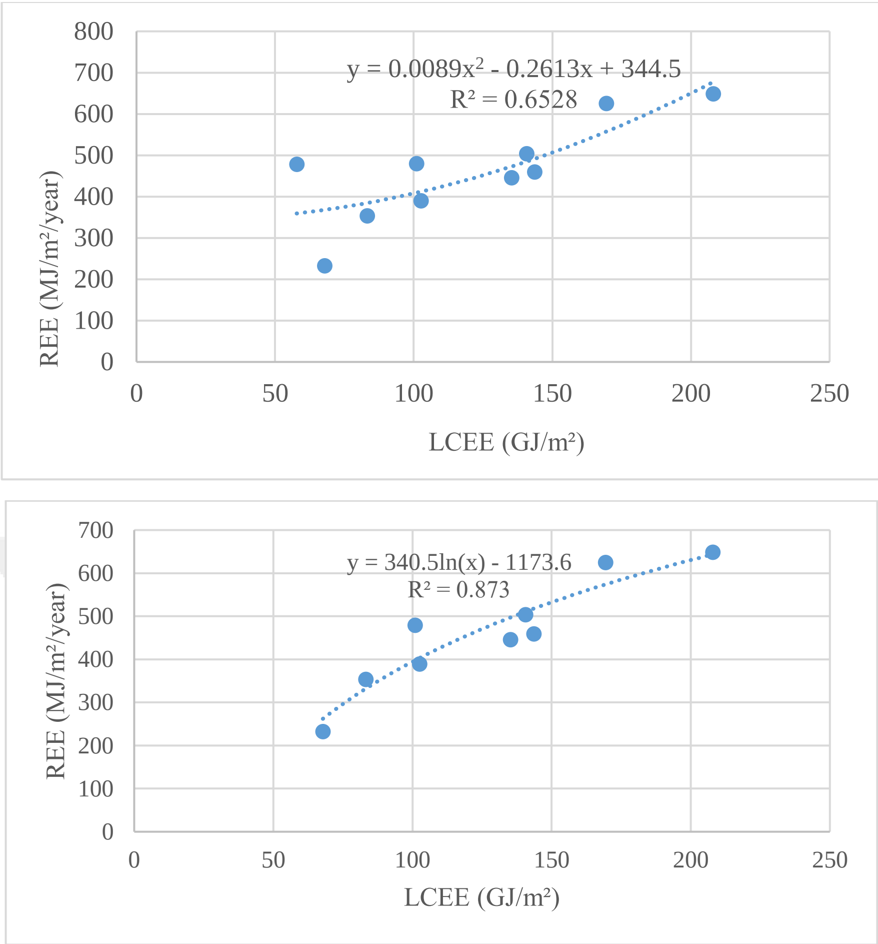


Figure 4. 8. *The relationship between annual REE (MJ/m²/year) and LCEE (the total of IEE, REE, AEE, and FDEE) (GJ/m²) with (top) and without (below) an outlier*

Apart from service life, another variable that affects LCEE is the floor area as it was stated in the literature. When the gross floor area and LCEE is compared for the actual case (third service life scenario), a linear relationship was found with an R^2 of 0.7, showing that more space requires more energy (Figure 4.9).

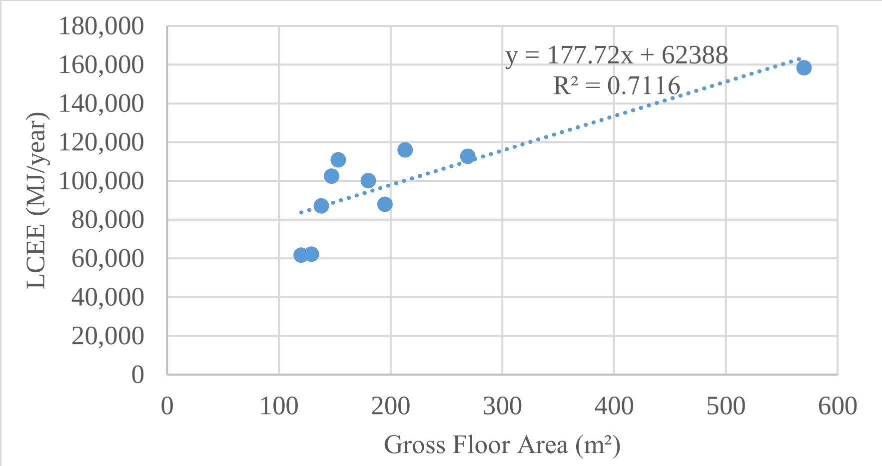


Figure 4. 9. *The relationship between LCEE and gross floor area*

4.3.1 Flexible Design Strategies Identified in the Case Studies

In the literature, there is not any concepts denoted as AEE and FDEE. The reason why the energy demand of building materials in the renewal and extension stages are evaluated under the scope of additional IEE and FDEE, respectively, is that these changes occur while the building is still in use, whereas it is a controversial approach to consider external additions within the frame of the existing building fabric, i.e. REE. Therefore, a new type of EE has to be identified specific to them. In other words, REE is often taken into account by refurbishment, repair, and maintenance activities occurring in the existing fabric. Because these changes are add-ons to existing structures and also a part of flexible design strategies, another type embodied energy (FDEE) needs to be used as terminology. Other additions apart from flexibility are evaluated as AEE in order to differentiate these two types of additions and to reveal the share of embodied energy belonging to the flexible design strategies.

The embodied energy intensity of the building materials in the construction and use stages would be different from each other. However, the same proxy data is used for all stages without considering the improving construction technology in time.

Another point is the frequency of the implemented flexible design strategies derived from the literature. The flexibility parameters were selected in line with the inherent design characteristics of traditional Ottoman houses. According to results, it was found that all case studies have at least half of the selected flexible design strategies (Table 4.5). Traditional Ottoman houses in Ankara shows inherent adaptable characteristics due to their spatial planning, construction techniques; and local, low energy-intensive and reused material utilization.

During the construction of these types of houses, local building materials were used with much lower energy demand due to traditional construction techniques. This conjures up the fact that the IEE is much lower than it was found in the study, and supports the idea that they are built with sustainable considerations. From the perspective of adaptable design characteristics, the courtyard was used as a defined area for future user demands. Integrated-divided spaces were seen in all of the case studies. Function changes also had a wide range of applications.

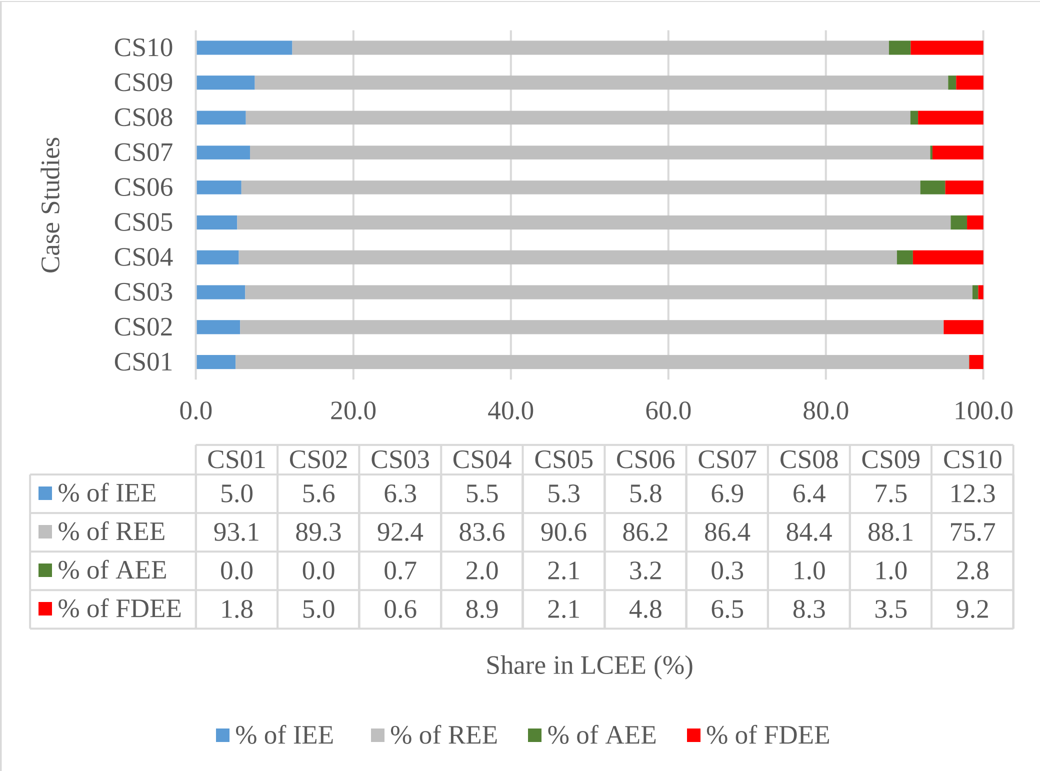
Table 4. 5. *The presence of flexible design strategies in the case studies*

CASE STUDY NO	FUNCTION CHANGE	INTEGRATION-DIVISION	EXTENSION	MOBILITY	LOCATION	CONSTRUCTION
CS01	✓	✓	✓		✓	✓
CS02	✓	✓	✓		✓	
CS03	✓	✓		✓		
CS04		✓	✓	✓		
CS05	✓	✓		✓		✓
CS06	✓	✓	✓	✓	✓	
CS07	✓	✓	✓	✓		
CS08	✓	✓	✓			✓
CS09		✓	✓		✓	
CS10		✓	✓		✓	

4.3.2 Relationship Between Flexible Design Strategies and LCEE

A comparison was made between different service life cases in the previous part. However, the life cycle of the actual case is considered for each case study in this part. When IEE, maintenance and alterations/additions were examined, it was discovered that most of the share in LCEE belongs to replacement (REE), followed by IEE.

It was discovered that the embodied energy resulting from flexible design strategies (FDEE) is much less than the others. Even if the alterations/additions were assumed to be made for once in a lifetime, it is obvious that there is a huge difference compared to energy generated by the replacement of the building materials. The results showed that allowing changes in spatial organization through flexible design parameters has a rather small effect on LCEE. The values are found to be between 0.6 to 9.2% of LCEE for alterations/additions while they are 75.7 - 93.1% for REE. IEE forms 5.0 to 12.3% of the LCEE as seen in Figure 4.10.



	CS01	CS02	CS03	CS04	CS05	CS06	CS07	CS08	CS09	CS10
% of IEE	5.0	5.6	6.3	5.5	5.3	5.8	6.9	6.4	7.5	12.3
% of REE	93.1	89.3	92.4	83.6	90.6	86.2	86.4	84.4	88.1	75.7
% of AEE	0.0	0.0	0.7	2.0	2.1	3.2	0.3	1.0	1.0	2.8
% of FDEE	1.8	5.0	0.6	8.9	2.1	4.8	6.5	8.3	3.5	9.2

Figure 4. 10. *Distribution of IEE, REE, AEE and FDEE in LCEE for the actual service life scenario with flexible design strategies (%)*

CHAPTER 5

CONCLUSION

Due to the lack of adaptability, the existing building stock has approximately 50 to 60 years of service life. This situation brings about an increase in both IEE to rebuild and DE to demolish the redundant buildings. On the other hand, traditional Ottoman houses have a longer service life with the help of their inherent adaptable characteristics and timber frame structural system that allows rapid installation and flexible plan layout. In this study, the impact of flexible design strategies on LCEE was questioned.

To achieve that aim, 10 traditional Ottoman houses located in Ankara, were selected due to their long service lives as case studies, from a PhD dissertation (Şahin, 1995). The service life estimation was made considering the period between the construction and the last detailed survey date, which is 1994. The changes in the lifespan of the buildings were determined; and initial and final plan layouts were created based on the information obtained from the dissertation (Şahin, 1995). Thereafter, a list of flexible design strategies, including function (change), Integration/division, extension, mobility (reused timber panels), location (of services), and construction (non-load bearing timber frame walls), was made in consideration of the adaptable characteristics of traditional Ottoman houses. These flexibility strategies were examined through the floor plans, and the changes that occurred during the service life were matched with these strategies.

The components selected for the embodied energy evaluations were the foundation, exterior and interior walls and finishes, structural system, floor and roof systems and their coverings, windows, and doors. 3D building models of the initial and final house plans were created in Revit software in order to obtain the volume of the building materials used in the construction.

Embodied energy intensity, bulk density, and service life of the building materials were obtained from the literature for energy calculations. Data was obtained from an international inventory (ICE, v2.0) to multiply the building mass with the embodied energy intensity of the building material. Thus, the energy demand of building materials in the construction and use stages were found. Thereafter, three service life scenarios were established. LCEE stages were identified as construction (IEE), maintenance (REE, AEE), alterations/additions (FDEE), and end-of-life (DE). Maintenance includes replacement cycles of the building materials (REE), and rebuilding-renewal works (AEE). Two terminologies had to be described, as additional initial embodied energy; denoted as AEE, and embodied energy of flexible design strategies; denoted as FDEE, in order to differentiate flexible design strategies from other interventions.

For the first service life scenario, the buildings are considered to be rebuilt and demolished every 50 years during the actual service life period of the original buildings. For this case, the total EE consisting of IEE, REE, and DE were calculated. In the second case, the estimated (actual) service life is taken into consideration, and flexible design strategies were ignored. The LCEE consisting of IEE, REE, and AEE were calculated. In the third case, the service life is taken the same as in the second one. The only difference is the implementation of flexible design strategies to the spaces. IEE, REE, AEE, and FDEE were calculated for the LCEE calculation. DE is not included in the second and third service life scenarios because the buildings were still standing in the last detailed survey date, 1994. The findings of the EE demand of building materials and service life scenarios are as follows:

- It was found that paint is the most energy-intensive material in all stages (construction, maintenance, and alteration/addition) due to its high embodied energy intensity. The reason for the larger share of stone in the construction stage can be explained by its high amount of quantity due to the masonry wall thickness. In the maintenance, lime has a notable value because it is used as an ingredient of mud plaster, which is replaced annually. The share of screed flooring is greater in the alteration/addition stage because it has a wide range of applications when a more durable layer is needed.

- When the service life scenarios are compared, it was noted that in the first service life scenario (50-year cycles), the annual EE has the greatest range with 617 to 1190 MJ/m²/year. It is followed by the second scenario (actual service life) with 480 to 934 MJ/m²/year. The third service life scenario has the smallest range with 278 to 725 MJ/m²/year due to the extension of the spaces with the help of flexible design strategies.
- In the third service life scenario, the LCEE increased by 10% compared to the second one. However, in the second case, 22 to 31% of saving in total EE can be achieved in comparison to the first case due to the extension of service life.
- The embodied energy share of maintenance in LCEE, i.e., 75.7-93.1%, which is much more than that for alterations/additions (FDEE), which was found to be between 0.6-9.2%.
- As expected, a correlation exists between annual REE and total LCEE, especially for buildings with longer service life ($R^2 = 0.65$).
- Correlation also exists between the floor area and the LCEE ($R^2 = 0.7$).

A small increase (0.6 to 9.2%) in the amount of LCEE, as a result of the implementation of the flexible design strategies in traditional Ottoman houses, helped to greatly extend their service life by meeting the changing user needs and demands.

In other words, traditional Ottoman houses have the characteristics of a ‘good design’; because their inherent flexible design allows them to have a long service life (long life), adaptable design (loose fit), and LCEE savings (low energy); i.e., the 3L Principle of good architecture.

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APPENDICES

A. Information on the Case Studies

Detailed information on the selected buildings is given in the following pages.

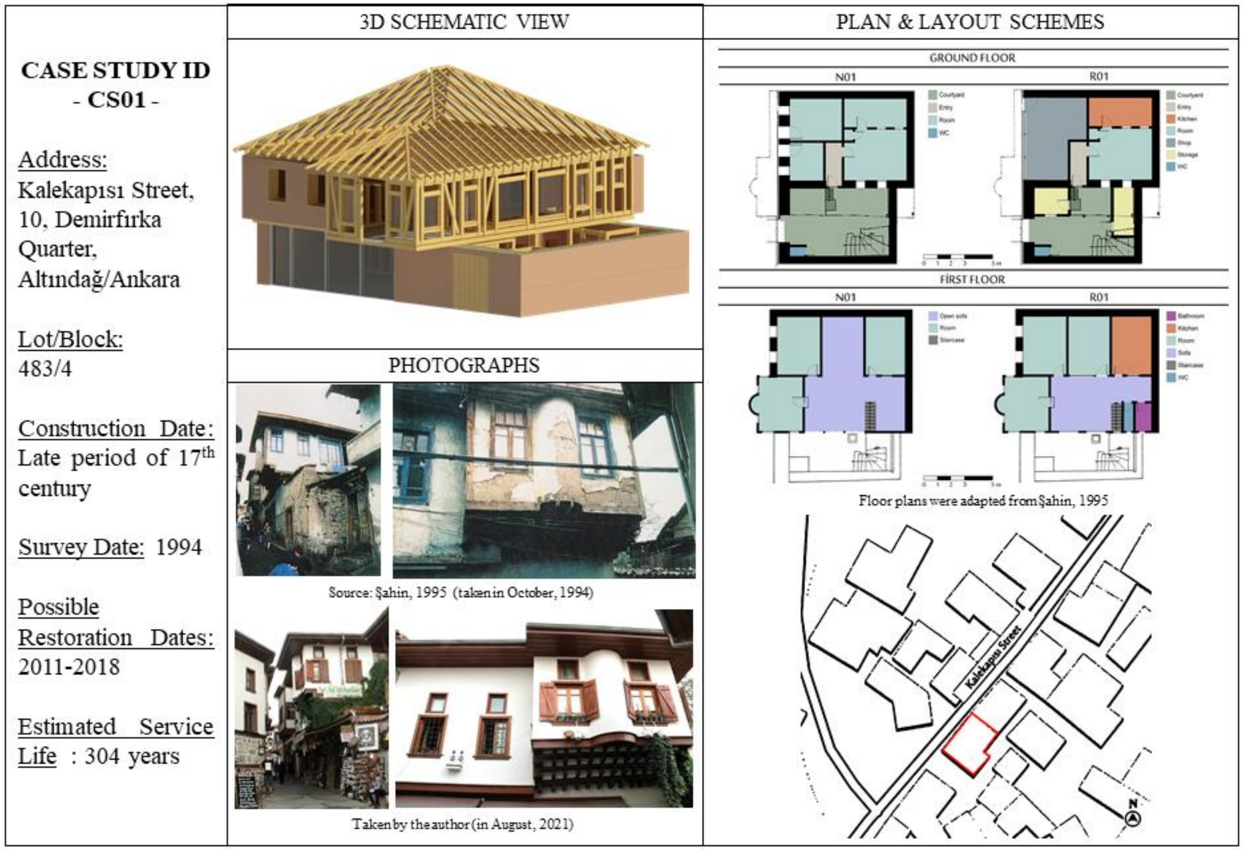


Figure A. 1. *Information sheet of CS01 in 483/4 (lot/block)*

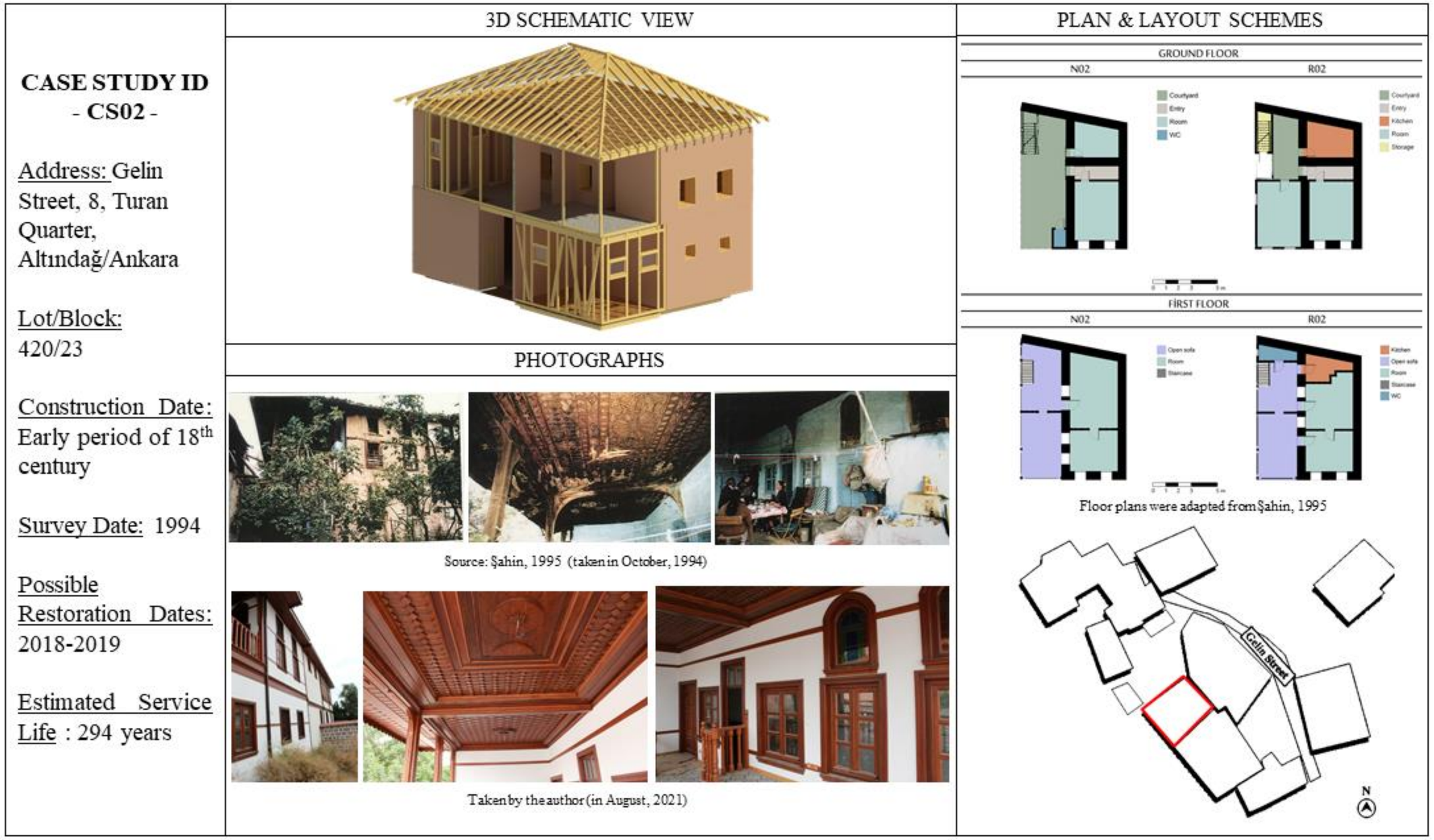


Figure A. 2. *Information sheet of CS02 in 420/23 (lot/block)*

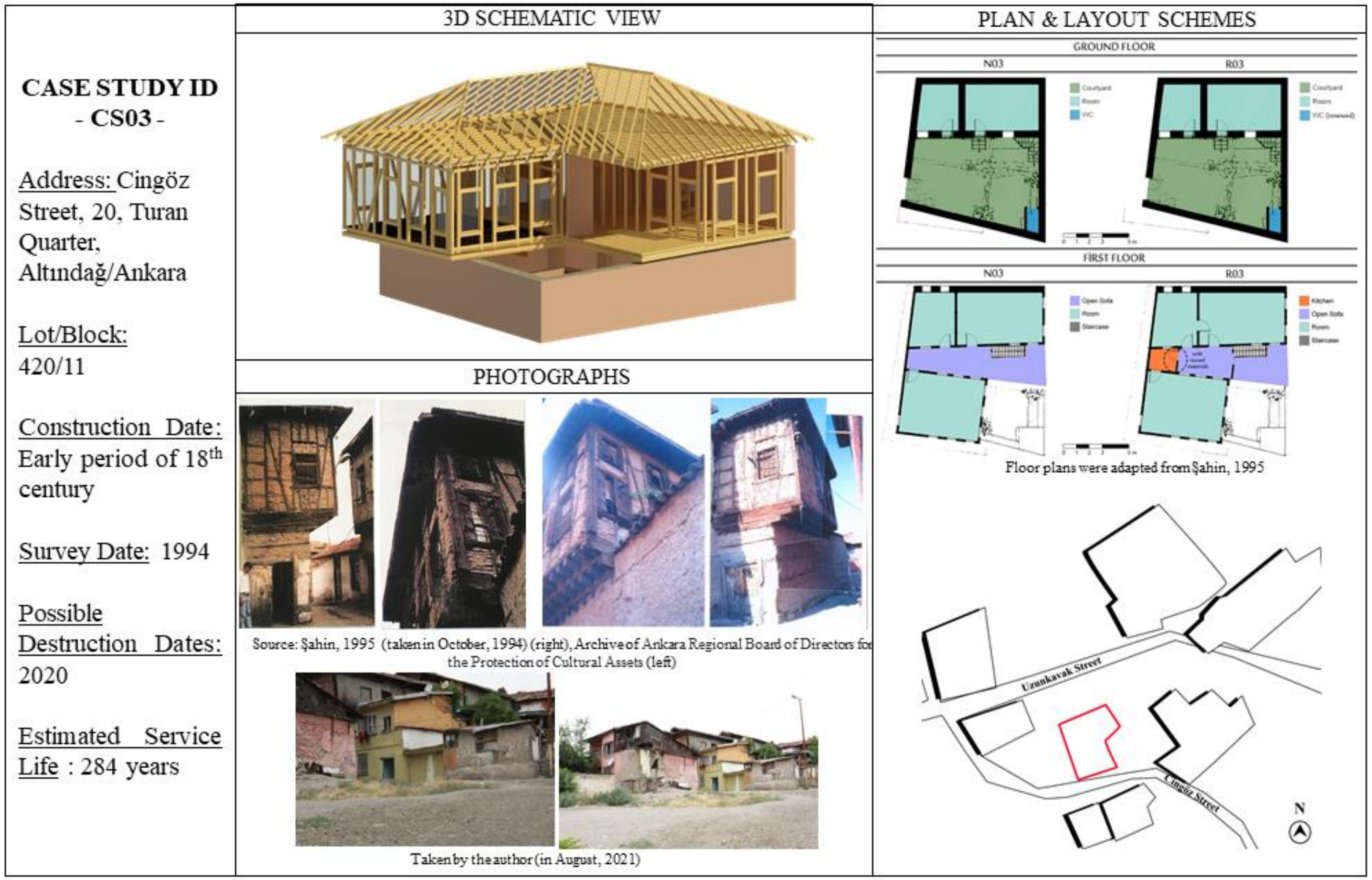


Figure A. 3. *Information sheet of CS03 in 420/11 (lot/block)*

CASE STUDY ID
- CS04 -

Address: Erzurum Street, 46, Sümer Quarter, Altındağ/Ankara

Lot/Block: 4331/21

Construction Date: Early period of 18th century

Survey Date: 1994

Possible Destruction Date: unknown

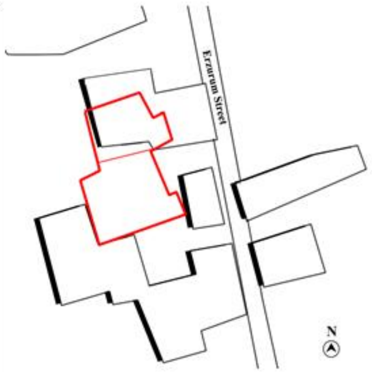
Estimated Service Life : 274 years

3D SCHEMATIC VIEW

PHOTOGRAPHS

Source: Şahin, 1995 (taken in October, 1994)

Taken by the author (in August, 2021)



PLAN & LAYOUT SCHEMES

Floor plans were adapted from Şahin, 1995

Figure A. 4. *Information sheet of CS04 in 4331/21 (lot/block)*

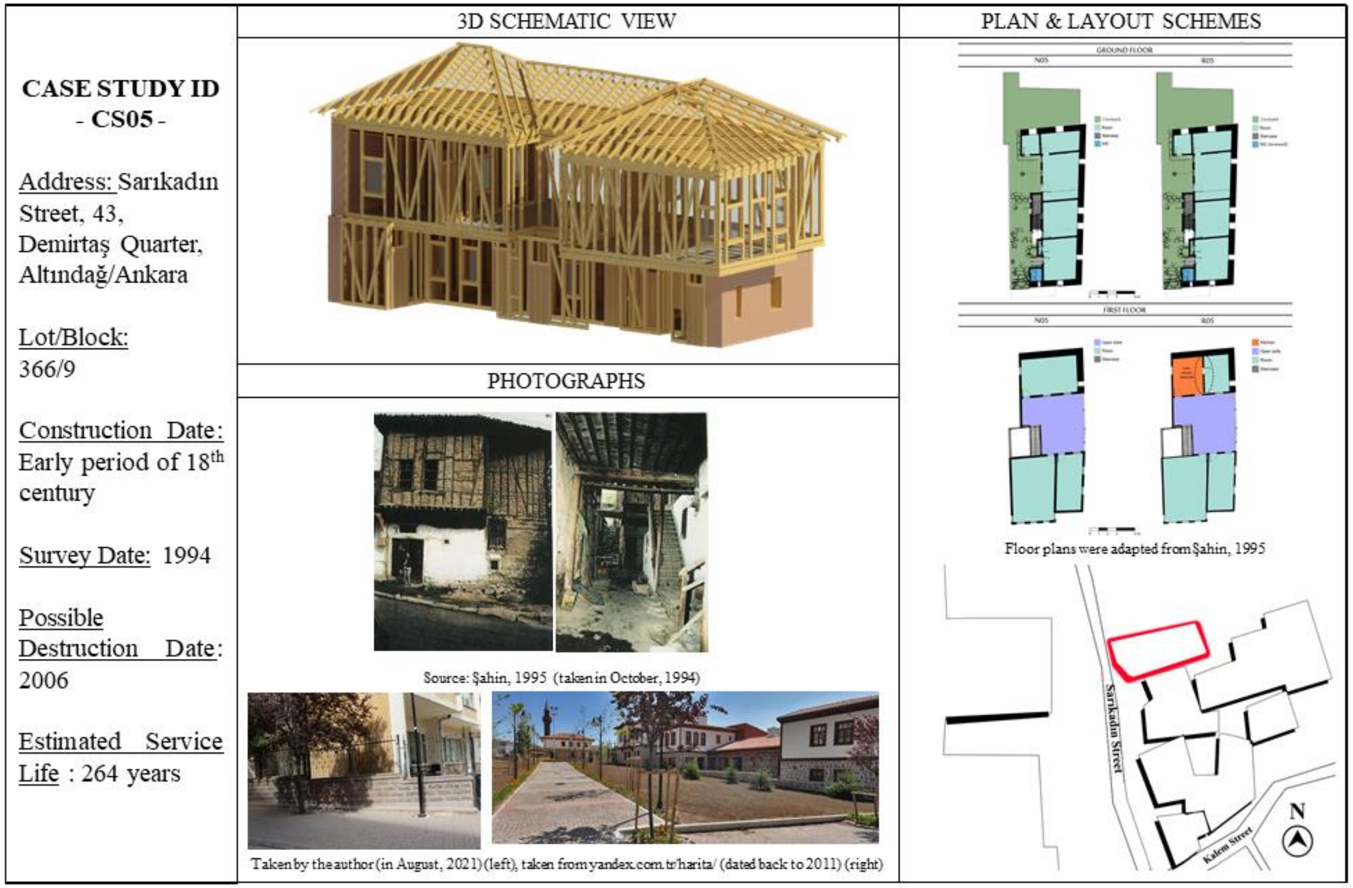


Figure A. 5. *Information sheet of CS05 in 366/9 (lot/block)*

CASE STUDY ID
- CS06 -

Address: Eskici Street, 2, İstiklal Quarter, Altındağ/Ankara

Lot/Block: 1453/5

Construction Date: Early period of 18th century

Survey Date: 1994

Building Status: Standing

Estimated Service Life : 254 years

3D SCHEMATIC VIEW

PHOTOGRAPHS

Source: Şahin, 1995 (taken in October, 1994)

Taken by the author (in August, 2021)

PLAN & LAYOUT SCHEMES

Floor plans were adapted from Şahin, 1995

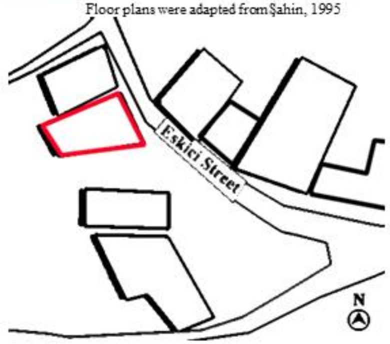


Figure A. 6. *Information sheet of CS06 in 1453/5 (lot/block)*

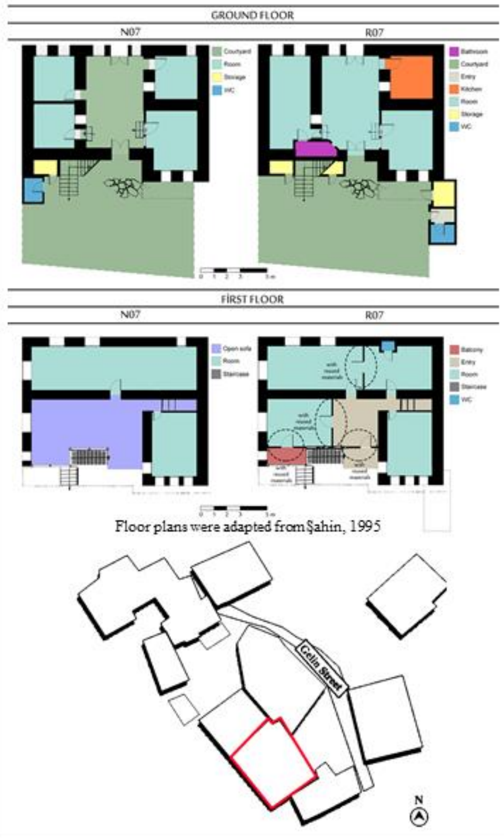
CASE STUDY ID **- CS07 -** Address: Gelin Street, 12, Turan Quarter, Altındağ/Ankara Lot/Block: 420/25 Construction Date: Late period of 18th century Survey Date: 1994 Possible Reconstruction Date: 2017 Estimated Service Life : 244 years	3D SCHEMATIC VIEW  PHOTOGRAPHS  Source: Şahin, 1995 (taken in October, 1994)	PLAN & LAYOUT SCHEMES 

Figure A. 7. *Information sheet of CS07 in 420/25 (lot/block)*

CASE STUDY ID - CS08 -	3D SCHEMATIC VIEW	PLAN & LAYOUT SCHEMES
Address: Öksüzler Street, 17, Akalar Quarter, Altındağ/Ankara Lot/Block: 425/1 Construction Date: Late period of 18th century Survey Date: 1994 Building Status: Standing Estimated Service Life : 219 years	 PHOTOGRAPHS  Source: Şahin, 1995 (taken in October, 1994) Taken by the author (in August, 2021)	 Floor plans were adapted from Şahin, 1995 

Figure A. 8. *Information sheet of CS08 in 425/1 (lot/block)*

CASE STUDY ID
- CS09 -

Address: Cingöz Street, 3, Turan Quarter, Altındağ/Ankara

Possible Lot/Block: 419/6

Construction Date: Early period of 19th century

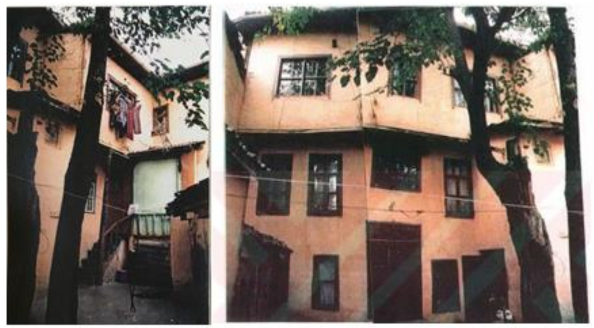
Survey Date: 1994

Possible Restoration Dates: 2017-2018

Estimated Service Life : 194 years

3D SCHEMATIC VIEW

PHOTOGRAPHS



Source: Şahin, 1995 (taken in October, 1994)

PLAN & LAYOUT SCHEMES

Floor plans were adapted from Şahin, 1995

Figure A. 9. *Information sheet of CS09 in 419/6 (lot/block)*

CASE STUDY ID
- CS10 -

Address: Sarıkadın Street, 67, Sümer Quarter, Altındağ/Ankara

Lot/Block:
372/6

Construction Date:
Late period of 19th century

Survey Date: 1994

Possible Restoration Dates:
1996-1997

Estimated Service Life : 104 years

3D SCHEMATIC VIEW

PHOTOGRAPHS

Source: Şahin, 1995 (taken in October, 1994)

Taken by the author (in August, 2021)

PLAN & LAYOUT SCHEMES

Floor plans were adapted from Şahin, 1995

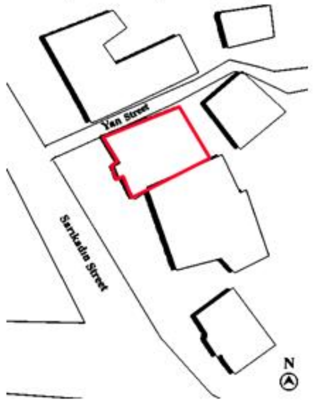


Figure A. 10. *Information sheet of CS10 in 372/6 (lot/block)*

B. Examining Changes During the Service Life

A list of alterations occurred in the buildings' service life is given in the following pages.

Table B. 1. *The last known condition of the buildings according to the last comprehensive building survey in 1994. Data gathered from Şahin (1995)*

Case Study ID	Walls	Structural System	Floors & Ceilings	Finishes
CS01	**Foundation-Ground:** Stone-Mudbrick **First:** Brick infill	**Ground-First:** Masonry, timber frame	**Floor:** Timber, screed **Ceiling:** Timber	Mud plastered and whitewashed
CS02	**Foundation-Ground:** Stone-Mudbrick **First:** Mudbrick infill	**Ground-First:** Masonry, timber frame	**Floor:** Timber **Ceiling:** Timber	Mud plastered and whitewashed
CS03	**Foundation-Ground:** Stone-Mudbrick **First:** Brick infill	**Ground:** Masonry **First:** Masonry, timber frame	**Floor:** Timber, screed **Ceiling:** Timber	Mud plastered and whitewashed
CS04	**Foundation-Ground-Mezzanine:** Stone-Mudbrick **First:** Mudbrick infill	**Ground-Mezzanine-First:** Masonry, timber frame	**Floor:** Timber, screed **Ceiling:** Timber	Mud plastered and whitewashed
CS05	**Foundation-Ground:** Stone-Mudbrick **First:** Mudbrick infill	**Ground-First:** Masonry, timber frame	**Floor:** Timber, screed, ceramic tile **Ceiling:** Timber, plywood	Mud plastered and whitewashed
CS06	**Foundation-Ground:** Stone-Mudbrick **First:** Brick infill	**Ground-First:** Masonry, timber frame	**Floor:** Timber, screed, ceramic tile **Ceiling:** Timber, plywood	Cement based plastered and whitewashed
CS07	**Foundation-Ground:** Stone-Mudbrick **First:** Mudbrick infill	**Ground-First:** Masonry	**Floor:** Timber, screed **Ceiling:** Timber	Mud plastered and whitewashed
CS08	**Foundation-Ground:** Stone-Mudbrick **First:** Mudbrick infill	**Ground-First:** Masonry, timber frame	**Floor:** Timber, screed **Ceiling:** Timber	Cement based plastered and whitewashed
CS09	**Foundation-Basement-Ground:** Stone-Mudbrick **First:** Mudbrick infill	**Basement-Ground-First:** Masonry, timber frame	**Floor:** Timber, screed **Ceiling:** Timber	Cement based plastered and whitewashed
CS10	**Foundation-Ground:** Stone-Mudbrick **First:** Mudbrick infill	**Ground:** Masonry, timber frame **First:** Timber frame	**Floor:** Timber, screed **Ceiling:** Timber, plywood	Mud plastered and whitewashed

Table B. 2. *Estimation of the initial condition of the buildings at the date of construction*

Case Study ID	Floor Covering	Ceiling Covering
CS01	**Ground-First-Roof:** Timber floor board	**Ground-First:** Timber ceiling board
CS02	**Ground:** Timber floor board **First:** Ceramic floor tile (sofa), timber floor board (rooms) **Roof:** Timber floor board	**Ground-First:** Timber ceiling board
CS03	**Ground-First-Roof:** Timber floor board	**Ground-First:** Timber ceiling board
CS04	**Ground:** Earth (storage, stable), timber floor board (entry) **Mezzanine:** Timber floor board (room), ceramic tile (service) **First-Roof:** Timber floor board	**Ground:** Uncovered (stable, storage), timber ceiling board (entry) **Mezzanine-First:** Timber ceiling board
CS05	**Ground:** Timber floor board **First:** Timber floor board (rooms), ceramic floor tile (sofa) **Roof:** Timber floor board	**Ground-First:** Timber ceiling board
CS06	**Ground:** Earth (WC, storage), timber floor board (room) **First-Roof:** Timber floor board	**Ground:** Uncovered (WC, storage), timber ceiling board (room) **First:** Timber ceiling board
CS07	**Ground-First-Roof:** Timber floor board	**Ground-First:** Timber ceiling board
CS08	**Ground:** Earth (storage), timber floor board (rooms) **First-Roof:** Timber floor board	**Ground:** Uncovered (storage), timber ceiling board (rooms) **First:** Timber ceiling board
CS09	**Basement:** Timber floor board **Ground:** Timber floor board **First:** Ceramic tile (WC, bathroom), timber floor board (kitchen, rooms) **Roof:** Timber floor board	**Ground-First:** Timber ceiling board
CS10	**Ground:** Earth (stable, storage), timber floor board (entry, room), ceramic tile (WC) **First:** Timber floor board, ceramic tile (WC) **Roof**: Timber floor board	**Ground:** Uncovered (stable), timber ceiling board **First:** Timber ceiling board

C. Evaluation of the Design Parameters

The area distribution of the design parameters shown in the plan schemes is given in the following pages.

Table C. 1. *The alterations occurred during use stage due to flexible design strategies (function change, integrations division, extension)*

CASE STUDY ID	FUNCTION CHANGE	INTEGRATION/DIVISION	EXTENSION
CS01	WC and bathroom (first) From room to kitchen (ground and first)	WC and bathroom (first) From rooms to a shop (ground) From eyvan to a room (first)	Shop storage (ground) Storage (under the stair)
CS02	WC (first) Kitchen (first) From WC to room (ground) From room to kitchen (ground)	WC (first) Kitchen (first)	Storage (under the staircase) Room (ground)
CS03	Kitchen (first)	Kitchen (first) The partition wall of sofa (first)	
CS04		Room (ground) The windows of room (ground) Sofa closure (first)	WC (ground) Storages (ground) Ground and mezzanine floor dwelling additions WC (first) Room was enlarged (first)
CS05	Kitchen (first)	Kitchen (first)	
CS06	From wc+storage to a room (ground) From storage to kitchen (first)	Bathroom-wc-corridor (first)	Kitchenette (ground) Two rooms and a hall (ground) Terrace (first) Services (the union was established between two adjacent buildings) (ground) From wc+storage to a room (ground)
CS07	From room to kitchen (ground)	Bathroom (ground) The integration of rooms (ground) The walls between balcony-room, room-entry and between rooms (made of reused materials) (first) WC (first) Windows of the köşk/balcony (first) Second door for a room (first)	Storage (under the staircase) Storage, entry, wc (ground)
CS08	From room to kitchen (ground) The outer door of kitchen (ground) From sofa to circulation area (first)	The division wall in the sofa (first)	New dwelling addition (ground) Storage (x2), WC, kitchen (x2) (ground) The outer door of kitchen (ground) Kitchenette, room (first)
CS09		The wall in the circulation area (first)	Units in the courtyard: storages and wc (basement) WC (ground)
CS10		Exterior glazing and division walls of the shop (ground)	Exterior walls of a room made of briquette (ground) Window belongs to a room (ground) Kitchen (first)

Table C. 2. *The alterations occurred during use stage due to flexible design strategies (mobility,location, construction) and rebuilding-renewal works*

MOBILITY	LOCATION	CONSTRUCTION	RENEWAL	REBUILDING
	Bathroom-WC-kitchen (first)	Interior walls (ground)	Screed floor to taşlık (courtyard)	
	WC-kitchen (first)			WC (ground)
Kitchen division (first)			Room floor finish from floor tiles to earth.	WC (ground)
Kitchen division (mezzanine)			Screed floor addition	
Kitchen division (first)		Interior walls (ground)	Screed floor addition to the rooms Ceiling board change from timber to plywood	WC (ground)
Kitchenette (made with reused materials) (ground)	Kitchen-WC-bathroom (first)		From open hall to an inner hall (first) Screed floor addition	
The walls between balcony-room, room-entry and between rooms (made of reused materials) (first)			Windows of the köşk/balcony (first) The screed floor pavement of taşlık and entry From taşlık to living room (ground)	
		Room/kitchen wall (ground)	Window of sofa/circulation (first) Screed floor addition	
	Kitchen-WC-bathroom (first)		The screed floor addition to room and courtyard	
	WC-kitchen (first)		Ceiling materials change from timber to plywood of kitchen and a room (first) Screed floor addition	

Figure C. 1. *Distribution of the functional areas for the 'Function' parameter (CS01, CS02, CS03, and CS04)*

Figure C. 2. *Distribution of the functional areas for the 'Function' parameter (CS05, CS06, CS07, and CS08)*

Figure C. 3. *Distribution of the functional areas for the 'Function' parameter (CS09, and CS10)*

Figure C. 4. *Distribution of the merged-split areas for the 'Integration/division' parameter (CS01, CS02, CS03, and CS04)*

Figure C. 5. *Distribution of the merged-split areas for the 'Integration/division' parameter (CS05, CS06, CS07, and CS08)*

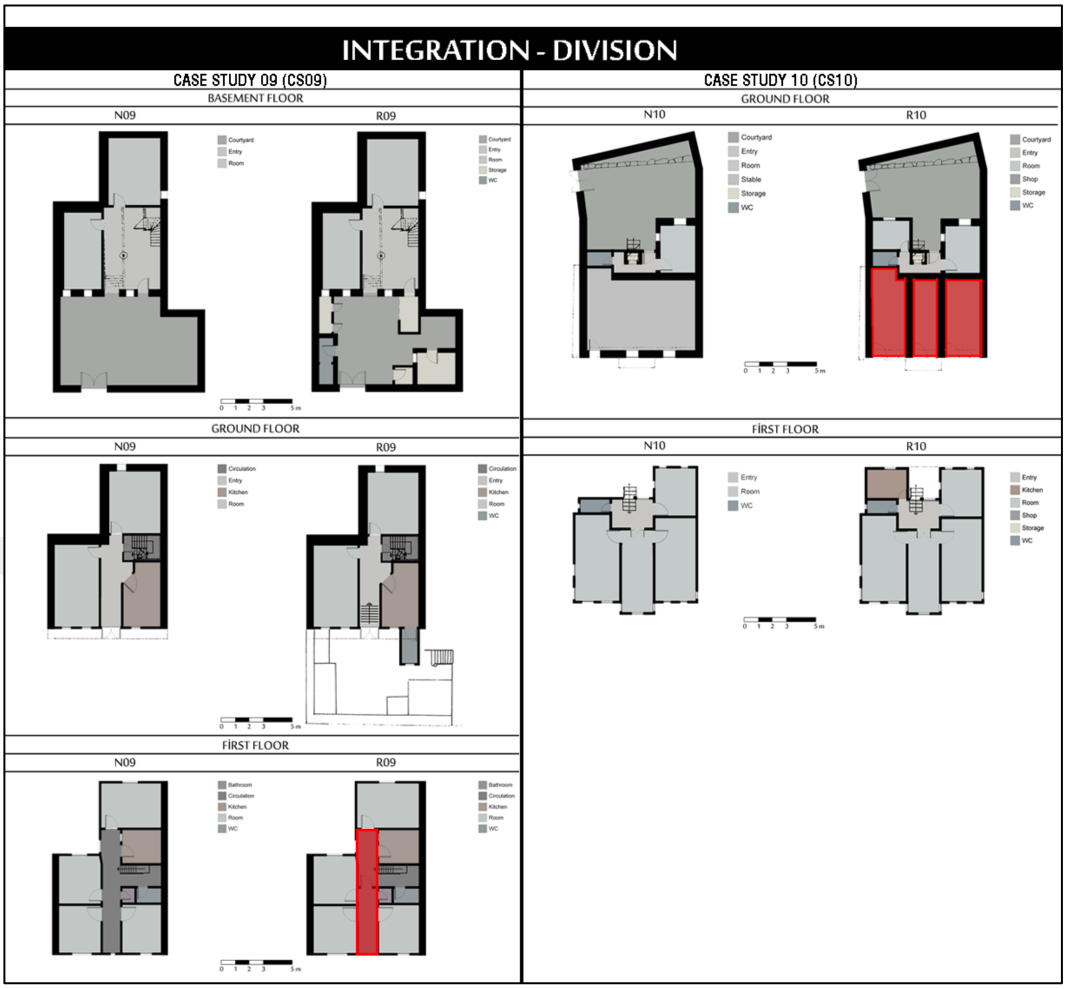


Figure C. 6. *Distribution of the merged-split areas for the 'Integration/division' parameter (CS09, and CS10)*

Figure C. 7. *Distribution of the extended areas for the 'Extension' parameter (CS01, CS02, CS04, and CS06)*

Figure C. 8. *Distribution of the extended areas for the 'Extension' parameter (CS07, CS08, CS09, and CS10)*

D. Embodied Energy Calculation of the Case Studies

The LCEE (IEE, REE, AEE, FDEE) calculations of each case study are given in the next pages.

Table D. 1. *LCEE calculation table of CS01*

CS01	Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	IEE (MJ)	REE (MJ)
	Foundation	Stone		206,496	1.26		260,185	
	Wall Assembly	Stone		55,944	1.26		70,489	
		Mud brick		173,798	0		0	
		Lime (20%)		30,446	5.3		161,366	
		Brick		52,400	3		157,200	
		Stucco (mudplaster)		20,077	0		0	0
		Lime (20%)		4,118	5.3		21,828	6,635,566
		Paint (whitewash)		12,012	59		708,708	21,544,723
	Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		1,992	7.4		14,741	
		Timber (foot-wall plate: 10x10, softwood)		846	7.4		6,260	
		Timber (window sill: 10x10, softwood)						
		Timber (brace: 10x10, softwood)						
	Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		2,430	7.4		17,982	
		Timber (floor board, hardwood)		5,696	10.4		59,238	327,427
		Timber (ceiling board, hardwood)		3,416	10.4		35,526	196,364
	Window	Timber (frame, softwood)	2.9			2189	6,282	63,662
		Glass	14.1			671	9,481	72,057
	Interior Door	Timber (softwood)	20	480	7.4		3,552	35,994
	Roof	Timber (roof rafter: 5x10, beam: 10x10, hardwood)		1,424	10.4		14,810	
		Roof tile		3,738	6.5		24,297	123,105
	Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	AEE (MJ)	FDEE (MJ)
	Wall Assembly	Brick		16,000	3			48,000
		Stucco (mudplaster)		1,755	0			0
		Lime (20%)		360	5.3			95,400
		Paint (whitewash)		1,050	59			309,750
	Glazing	Storefront		2,000	15			30,000
	Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		672	7.4			4,973
		Timber (foot-wall plate: 10x10, softwood)		798	7.4			5,905
		Timber (window sill: 10x10, softwood)						
		Timber (brace: 10x10, softwood)						
		Screed		13,640	4.51		15,379	46,137
	Window	Timber (frame, softwood)	0.8			2189		3,327
		Glass	5.2			671		7,032
	Interior Door	Timber (softwood)	6.0	144	7.4			2,131

Table D. 2. *LCEE calculation table of CS02*

CS02

Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	IEE (MJ)	REE (MJ)
Foundation	Stone		129,936	1.3		163,719	
Wall Assembly	Stone		151,200	1.3		190,512	
	Mudbrick		107,312	0.0		0	
	Lime (20%)		18,799	5.3		99,636	
	Stucco (mudplaster)		11,466	0.0		0	
	Lime (20%)		2,352	5.3		12,466	3,664,886
	Paint (whitewash)		6,860	59.0		404,740	11,899,356
Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		546	7.4		4,040	
	Timber (foot-wall plate: 10x10, softwood)						
	Timber (window sill: 10x10, softwood)		402	7.4		2,975	
	Timber (brace: 10x10, softwood)						
Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		1,968	7.4		14,563	
	Timber (floor board, hardwood)		4,296	10.4		44,678	238,826
	Timber (ceiling board, hardwood)		3,224	10.4		33,530	179,231
	Ceramic tile		480	10.0		4,800	47,040
Window	Timber (frame, softwood)	1.33			2,189	2,911	28,531
	Glass	5.67			671	3,805	27,964
Interior Door	Timber (softwood)	10	240	7.4		1,776	17,405
Roof	Timber (roof rafter: 5x10, beam: 10x10, hardwood)		1,568	10.4		16,307	
	Roof tile		3,416	6.5		22,204	108,800

Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	FDEE (MJ)
Wall Assembly	Mudbrick		15,577	0.0		0
	Lime (20%)		2,729	5.3		14,463
	Stucco (mudplaster)		3,744			0
	Lime (20%)		768	5.3		203,520
	Paint (whitewash)		2,240	59.0		660,800
Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		534	7.4		3,952
	Timber (foot-wall plate: 10x10, softwood)		246	7.4		1,820
Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		906	7.4		6,704
	Screed		2,000	4.5		9,020
	Timber (floor board, hardwood)		104	10.4		1,082
Window	Timber (frame, softwood)	1			2,189	2,495
	Glass	2			671	3,261
Interior Door	Timber (softwood)	8	192	7.4		2,842

Table D. 3. *LCEE calculation table of CS03*

CS03

Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	IEE (MJ)	REE (MJ)
Foundation	Stone		207,552	1.3		261,516	
Wall Assembly	Stone		48,000	1.3		60,480	
	Mudbrick		69,500	0.0		0	
	Lime (20%)		12,175	5.3		64,529	
	Brick		32,720	3.0		98,160	
	Stucco (mudplaster)		11,794	0.0		0	0
	Lime (20%)		2,419	5.3		12,822	3,641,380
	Paint (whitewash)		7,056	59.0		416,304	11,823,034
Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		1,074	7.4		7,948	
	Timber (foot-wall plate: 10x10, softwood)		792	7.4		5,861	
	Timber (window sill: 10x10, softwood)						
	Timber (brace: 10x10, softwood)						
Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		2,274	7.4		16,828	
	Timber (floor board, hardwood)		5,760	10.4		59,904	309,322
	Timber (ceiling board, hardwood)		3,104	10.4		32,282	166,690
Window	Timber (frame, softwood)	5			2,189	11,164	105,685
	Glass	29			671	19,459	138,159
Interior Door	Timber (softwood)	12	288	7.4		2,131	20,175
Roof	Timber (roof rafter: 5x10, beam: 10x10, hardwood)		1,312	10.4		13,645	
	Roof tile		4,172	6.5		27,118	128,359
Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	AEE (MJ)	FDEE (MJ)
Wall Assembly	Mudbrick		1,740	0.0		0	0
	Lime (20%)		305	5.3		808	808
	Brick		4,280	3.0		6,420	6,420
	Stucco (mudplaster)		913	0.0		0	0
	Lime (20%)		187	5.3		24,804	24,804
	Paint (whitewash)		546	59.0		80,535	80,535
Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		246	7.4		910	910
Floor/Ceiling	Screed		220	59.0		12,980	0
Interior Door	Timber (softwood)	4	96	7.4		0	1,421

Table D. 4. *LCEE calculation table of CS04*

CS04

Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	IEE (MJ)	REE (MJ)
Foundation	Stone		343,104	1.3		432,311	
Wall Assembly	Stone		339,312	1.3		427,533	
	Mudbrick		211,871	0.0		0	
	Lime (20%)		37,116	5.3		196,715	
	Stucco (mudplaster)		27,659	0.0		0	0
	Lime (20%)		5,674	5.3		30,070	8,239,202
	Paint (whitewash)		16,548	59.0		976,332	26,751,497
Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		2,400	7.4		17,760	
	Timber (foot-wall plate: 10x10, softwood)						
	Timber (window sill: 10x10, softwood)		624	7.4		4,618	
	Timber (brace: 10x10, softwood)						
Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		3,390	7.4		25,086	
	Timber (floor board, hardwood)		10,704	10.4		111,322	554,584
	Timber (ceiling board, hardwood)		4,992	10.4		51,917	258,640
	Ceramic tile		660	10.0		6,600	60,280
Window	Timber (frame, softwood)	6			2,189	12,083	110,361
	Glass	25			671	16,440	112,611
Interior Door	Timber (softwood)	16	384	7.4		2,842	25,953
Roof	Timber (roof rafter: 5x10, beam: 10x10, hardwood)		1,848	10.4		19,219	
	Roof tile		5,544	6.5		36,036	164,564
Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	AEE (MJ)	FDEE (MJ)
Foundation	Stone		156,408	1.3			197,074
Wall Assembly	Stone		59,592	1.3			75,086
	Mudbrick		76,090	0.0			0
	Lime (20%)		13,330	5.3			70,647
	Briquette		32,850	0.8			27,266
	Stucco (mudplaster)		10,764	0.0			0
	Lime (20%)		2,208	5.3			11,702
	Paint (whitewash)		6,440	59.0			379,960
Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		1,218	7.4			9,013
	Timber (foot-wall plate: 10x10, softwood)		420	7.4			3,108
Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		3,246	7.4			24,020
	timber ceiling board (hardwood)		5,808	10.4			60,403
	Screed		29,860	59.0		880,870	1,761,740
Window	Timber (frame, softwood)	3			2,189		5,823
	Glass	12			671		7,717
Interior Door	Timber (softwood)	48	1,152	7.4			8,525
Roof	Timber (roof rafter: 5x10, beam: 10x10, hardwood)		240	10.4			2,496
	Roof tile		574	6.5			3,731

Table D. 5. *LCEE calculation table of CS05*

CS05

Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	IEE (MJ)	REE (MJ)
Foundation	Stone		177,744	1.3		223,957	
Wall Assembly	Stone		42,288	1.3		53,283	
	Mudbrick		144,083	0.0		0	
	Lime (20%)		25,241	5.3		133,776	
	Stucco (mudplaster)		18,720	0.0		0	0
	Lime (20%)		3,840	5.3		20,352	5,372,928
	Paint (whitewash)		11,200	59.0		660,800	17,445,120
Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		3,774	7.4		27,928	
	Timber (foot-wall plate: 10x10, softwood)		1,800	7.4		13,320	
	Timber (window sill: 10x10, softwood)						
	Timber (brace: 10x10, softwood)						
Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		2,796	7.4		20,690	
	Timber (floor board, hardwood)		9,200	10.4		95,680	459,264
	Timber (ceiling board, hardwood)		4,248	10.4		44,179	212,060
	Ceramic tile		1,400	10.0		14,000	123,200
Window	Timber (frame, softwood)	4			2,189	9,150	80,520
	Glass	18			671	11,957	78,918
Interior Door	Timber (softwood)	16	384	7.4		2,842	25,006
Roof	Timber (roof rafter: 5x10, beam: 10x10, hardwood)		2,384	10.4		24,794	
	Roof tile		4,956	6.5		32,214	141,742
Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	AEE (MJ)	FDEE (MJ)
Wall Assembly	Mudbrick		1,644	0.0		0	0
	Lime (20%)		288	5.3		1,526	0
	Stucco (mudplaster)		1,053	0.0		0	0
	Lime (20%)		216	5.3		28,620	28,620
	Paint (whitewash)		630	59.0		92,925	92,925
Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		240	7.4		1,776	0
Floor/Ceiling	Screed		14,060	59.0		0	829,540
	Plywood		584	15.0		0	17,520
Interior Door	Timber (softwood)	4	96	7.4		474	947

Table D. 6. *LCEE calculation table of CS06*

CS06

Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	IEE (MJ)	REE (MJ)
Foundation	Stone		204,456	1.3		257,615	
Wall Assembly	Stone		52,152	1.3		65,712	
	Mudbrick		93,708	0.0		0	
	Lime (20%)		16,416	5.3		87,005	
	Brick		90,520	3.0		271,560	
	Stucco (mudplaster)		20,147	0.0		0	0
	Lime (20%)		4,133	5.3		21,904	5,563,575
	Paint (whitewash)		12,054	59.0		711,186	18,064,124
Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		2,796	7.4		20,690	
	Timber (foot-wall plate: 10x10, softwood)						
	Timber (window sill: 10x10, softwood)		1,338	7.4		9,901	
	Timber (brace: 10x10, softwood)						
Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		2,826	7.4		20,912	
	Timber (floor board, hardwood)		5,712	10.4		59,405	274,342
	Timber (ceiling board, hardwood)		2,440	10.4		25,376	117,191
Window	Timber (frame, softwood)	3			2,189	6,655	56,342
	Glass	13			671	8,723	55,391
Interior Door	Timber (softwood)	18	432	7.4		3,197	27,066
Roof	Timber (roof rafter: 5x10, beam: 10x10, hardwood)		2,240	10.4		23,296	
	Roof tile		5,124	6.5		33,306	140,995

Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	AEE (MJ)	FDEE (MJ)
Wall Assembly	Brick		37,400	3.0		37,400	74,800
	Stucco (cement plaster)		4,842	1.8		2,905	5,810
	Paint (whitewash)		3,766	59.0		370,323	740,647
Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		1,008	7.4		0	7,459
	Timber (foot-wall plate: 10x10, softwood)					0	4,129
	Timber (window sill: 10x10, softwood)		558	7.4			0
	Timber (brace: 10x10, softwood)						0
Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		270	7.4		0	1,998
	Timber (floor board, hardwood)		768	10.4		0	7,987
	Ceramic tile		460	10.0		0	9,200
	Plywood		368	15.0		0	11,040
	Screed		16,400	59.0		483,800	483,800
Window	Timber (frame, softwood)	1			2,189	0	3,327
	Glass	3			671	0	4,294
Interior Door	Timber (softwood)	14	336	7.4		0	4,973

Table D. 7. *LCEE calculation table of CS07*

CS07

Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	IEE (MJ)	REE (MJ)
Foundation	Stone		225,216	1.3		283,772	
Wall Assembly	Stone		100,944	1.3		127,189	
	Mudbrick		273,219	0.0		0	
	Lime (20%)		47,863	5.3		253,675	
	Stucco (mudplaster)		15,655	0.0		0	
	Lime (20%)		3,211	5.3		17,019	4,152,724
	Paint (whitewash)		9,366	59.0		552,594	13,483,294
Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		264	7.4		1,954	
	Timber (foot-wall plate: 10x10, softwood)		246	7.4		1,820	
	Timber (window sill: 10x10, softwood)						
	Timber (brace: 10x10, softwood)						
Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		3,126	7.4		23,132	
	Timber (floor board, hardwood)		8,000	10.4		83,200	369,105
	Timber (ceiling board, hardwood)		4,320	10.4		44,928	199,317
Window	Timber (frame, softwood)	4			2,189	8,756	71,215
	Glass	18			671	12,078	73,676
Interior Door	Timber (softwood)	20	480	7.4		3,552	28,890
Roof	Timber (roof rafter: 5x10, beam: 10x10, hardwood)		2,352	10.4		24,461	
	Roof tile		5,628	6.5		36,582	148,767

Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	AEE (MJ)	FDEE (MJ)
Wall Assembly	Mudbrick		11,864	0.0		0	0
	Lime (20%)		2,078	5.3		0	11,016
	Stucco (mudplaster)		4,867	0.0		0	0
	Lime (20%)		998	5.3		0	264,576
	Paint (whitewash)		2,912	59.0		0	859,040
Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		768	7.4		0	5,683
	Timber (foot-wall plate: 10x10, softwood)		360	7.4		0	2,664
	Timber (window sill: 10x10, softwood)						0
	Timber (brace: 10x10, softwood)						0
Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		174	7.4		0	1,288
	Timber (floor board, hardwood)		4,080	10.4		0	42,432
	Timber (ceiling board, hardwood)		568	10.4		0	5,907
	Screed		4,160	59.0		61,360	184,080
Window	Timber (frame, softwood)	0			2,189	438	876
	Glass	2			671	0	2,281
Interior Door	Timber (softwood)	14	336	7.4		0	4,973

Table D. 8. *LCEE calculation table of CS08*

CS08

Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	IEE (MJ)	REE (MJ)
Foundation	Stone		260,832	1.3		328,648	
Wall Assembly	Stone		92,304	1.3		116,303	
	Mudbrick		226,297	0.0		0	
	Lime (20%)		39,643	5.3		210,109	
	Stucco (mudplaster)		20,030	0.0		0	
	Lime (20%)		4,109	5.3		21,777	4,769,084
	Paint (whitewash)		11,984	59.0		707,056	15,484,526
Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		1,530	7.4		11,322	
	Timber (foot-wall plate: 10x10, softwood)		876	7.4		6,482	
	Timber (window sill: 10x10, softwood)						
	Timber (brace: 10x10, softwood)						
Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		2,292	7.4		16,961	
	Timber (floor board, hardwood)		5,200	10.4		54,080	215,337
	Timber (ceiling board, hardwood)		3,360	10.4		34,944	139,141
Window	Timber (frame, softwood)	3.2			2,189	7,070	51,614
	Glass	13.8			671	9,240	50,587
Interior Door	Timber (softwood)	16.0	384	7.4		2,842	20,744
Roof	Timber (roof rafter: 5x10, beam: 10x10, hardwood)		1,680	10.4		17,472	
	Roof tile		3,850	6.5		25,025	91,341
Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	AEE (MJ)	FDEE (MJ)
Wall Assembly	Mudbrick		38,840	0.0		0	0
	Lime (20%)		6,804	5.3		0	36,061
	Stucco (cement plaster)		6,192	1.8		0	11,146
	Paint (whitewash)		4,816	59.0		0	1,420,720
Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		1,320	7.4		0	9,768
	Timber (foot-wall plate: 10x10, softwood)		774	7.4		0	5,728
	Timber (window sill: 10x10, softwood)						0
	Timber (brace: 10x10, softwood)						0
Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		1,548	7.4		0	11,455
	Timber (floor board, hardwood)		2,800	10.4		0	29,120
	Timber (ceiling board, hardwood)		2,320	10.4		0	24,128
	Screed		11,900	59.0		234,033	468,067
Window	Timber (frame, softwood)	1.1			2,189	1,561	3,123
	Glass	4.9			671	2,205	4,411
Interior Door	Timber (softwood)	26.0	624	7.4		0	9,235
Roof	Timber (roof rafter: 5x10, beam: 10x10, hardwood)		384	10.4		0	3,994
	Roof tile		938	6.5		0	6,097

Table D. 9. *LCEE calculation table of CS09*

	Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	IEE (MJ)	REE (MJ)
CS09	**Foundation**	Stone		238,704	1.3		300,767	
	Wall Assembly	Stone		238,104	1.3		300,011	
		Mudbrick		118,245	0.0		0	
		Lime (20%)		20,714	5.3		109,786	
		Stucco (mudplaster)		21,575	0.0		0	
		Lime (20%)		4,426	5.3		23,456	4,550,402
		Paint (whitewash)		12,908	59.0		761,572	14,774,497
	Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		1,770	7.4		13,098	
		Timber (foot-wall plate: 10x10, softwood)		1,104	7.4		8,170	
		Timber (window sill: 10x10, softwood)						
		Timber (brace: 10x10, softwood)						
	Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		2,790	7.4		20,646	
		Timber (floor board, hardwood)		5,200	10.4		54,080	190,755
		Timber (ceiling board, hardwood)		2,768	10.4		28,787	101,540
		Ceramic tile		120	10.0		1,200	7,760
	Window	Timber (frame, softwood)	3			2,189	6,567	42,467
		Glass	13			671	8,723	42,307
	Interior Door	Timber (softwood)	34	816	7.4		6,038	39,048
	Roof	Timber (roof rafter: 5x10, beam: 10x10, hardwood)		1,768	10.4		18,387	
		Roof tile		3,486	6.5		22,659	73,264
	Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	AEE (MJ)	FDEE (MJ)
	Wall Assembly	Mudbrick		27,866	0.0		0	0
		Lime (20%)		4,882	5.3		0	25,872
		Stucco (cement plaster)		2,106	1.8		0	3,791
		Paint (whitewash)		1,638	59.0		0	483,210
	Structural System	Timber (foot-wall plate: 10x10, softwood)		126	7.4		0	932
		Timber (window sill: 10x10, softwood)					0	0
		Timber (brace: 10x10, softwood)					0	0
	Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		210	7.4		0	1,554
		Timber (ceiling board, hardwood)		112	10.4		0	1,165
		Screed		7,560	59.0		223,020	223,020
	Window	Timber (frame, softwood)	3			2,189	0	14,579
		Glass	15			671	0	19,687
	Interior Door	Timber (softwood)	10	240	7.4		0	3,552

Table D. 10. *LCEE calculation table of CS10*

	Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	IEE (MJ)	REE (MJ)
CS10	**Foundation**	Stone		236,904	1.3		298,499	
	Wall Assembly	Stone		80,808	1.3		101,818	
		Mudbrick		80,172	0.0		0	
		Lime (20%)		14,045	5.3		74,437	
		Stucco (mudplaster)		13,923	0.0		0	
		Lime (20%)		2,856	5.3		15,137	1,574,227
		Paint (whitewash)		8,330	59.0		491,470	5,111,288
	Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		1,686	7.4		12,476	
		Timber (foot-wall plate: 10x10, softwood)						
		Timber (window sill: 10x10, softwood)		1,500	7.4		11,100	
		Timber (brace: 10x10, softwood)						
	Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		1,536	7.4		11,366	
		Timber (floor board, hardwood)		1,984	10.4		20,634	39,016
		Timber (ceiling board, hardwood)		1,680	10.4		17,472	33,038
		Ceramic tile		140	10.0		1,400	4,853
	Window	Timber (frame, softwood)	4			2,189	7,902	27,395
		Glass	15			671	10,333	26,867
	Interior Door	Timber (softwood)	20	480	7.4		3,552	12,314
	Roof	Timber (roof rafter: 5x10, beam: 10x10, hardwood)		1,320	10.4		13,728	
		Roof tile		3,108	6.5		20,202	35,017
	Component	Material	Area (m²)	Mass (kg)	Energy Intensity per Unit (MJ/kg)	Energy Intensity per Unit (MJ/m²)	AEE (MJ)	FDEE (MJ)
	Wall Assembly	Mudbrick		8,795	0		0	0
		Lime (20%)		1,541	5.3		0	8,166
		Briquette		5,313	0.83		0	4,409
		Stucco (mudplaster)		2,246	0		0	0
		Lime (20%)		461	5.3		0	122,112
		Paint (whitewash)		1,344	59		0	396,480
	Glazing	Storefront		1,500	15		0	22,500
	Structural System	Timber (post: corner: 10x10, inner: 5x10, softwood)		258	7.4		0	1,909
		Timber (foot-wall plate: 10x10, softwood)					0	1,554
		Timber (window sill: 10x10, softwood)		210	7.4			0
		Timber (brace: 10x10, softwood)						0
	Floor/Ceiling	Timber (joist&girder, (5x10, 10x15))		180	7.4		0	1,332
		Timber (floor board, hardwood)		1,816	10.4		0	18,886
		Plywood		3,760	15		56,400	56,400
		Screed		6,600	59		1,421	387,979
	Interior Door	Timber (softwood)	8	192	7.4		0	2,842
	Roof	Timber (roof rafter: 5x10, beam: 10x10, hardwood)		152	10.4		0	1,581
		Roof tile		322	6.5		0	2,093

E. 50-year Service Life Scenario Calculations

The calculations made for the first service life scenario (50-year cycles in the actual service life) is given in the following pages.

Table E. 1. *Calculations of the 50-year cycles for the first scenario*

CS01				CS02				CS03				CS04			
Period (years)	**IEE (MJ)**	**REE (MJ)**	**DE (MJ)**	**Period (years)**	**IEE (MJ)**	**REE (MJ)**	**DE (MJ)**	**Period (years)**	**IEE (MJ)**	**REE (MJ)**	**DE (MJ)**	**Period (years)**	**IEE (MJ)**	**REE (MJ)**	**DE (MJ)**
0-10		926,983		0-10		529,396		0-10		544,522		0-10		1,277,033	
11-20		926,983		11-20		529,396		11-20		544,522		11-20		1,277,033	
21-30	1,571,946	936,818	186,785	21-30	1,022,662	538,883	110,488	21-30	1,110,148	557,817	115,965	21-30	2,366,883	1,298,558	263,700
31-40		936,464		31-40		533,201		31-40		563,981		31-40		1,293,472	
41-50		926,983		41-50		529,396		41-50		544,522		41-50		1,277,033	
51-60		926,983		51-60		529,396		51-60		544,522		51-60		1,277,033	
61-70		926,983		61-70		529,396		61-70		544,522		61-70		1,277,033	
71-80	1,571,946	936,818	186,785	71-80	1,022,662	538,883	110,488	71-80	1,110,148	557,817	115,965	71-80	2,366,883	1,298,558	263,700
81-90		936,464		81-90		533,201		81-90		563,981		81-90		1,293,472	
91-100		926,983		91-100		529,396		91-100		544,522		91-100		1,277,033	
101-110		926,983		101-110		529,396		101-110		544,522		101-110		1,277,033	
111-120		926,983		111-120		529,396		111-120		544,522		111-120		1,277,033	
121-130	1,571,946	936,818	186,785	121-130	1,022,662	538,883	110,488	121-130	1,110,148	557,817	115,965	121-130	2,366,883	1,298,558	263,700
131-140		936,464		131-140		533,201		131-140		563,981		131-140		1,293,472	
141-150		926,983		141-150		529,396		141-150		544,522		141-150		1,277,033	
151-160		926,983		151-160		529,396		151-160		544,522		151-160		1,277,033	
161-170		926,983		161-170		529,396		161-170		544,522		161-170		1,277,033	
171-180	1,571,946	936,818	186,785	171-180	1,022,662	538,883	110,488	171-180	1,110,148	557,817	115,965	171-180	2,366,883	1,298,558	263,700
181-190		936,464		181-190		533,201		181-190		563,981		181-190		1,293,472	
191-200		926,983		191-200		529,396		191-200		544,522		191-200		1,277,033	
201-210		926,983		201-210		529,396		201-210		544,522		201-210		1,277,033	
211-220		926,983		211-220		529,396		211-220		544,522		211-220		1,277,033	
221-230	1,571,946	936,818	186,785	221-230	1,022,662	538,883	110,488	221-230	1,110,148	557,817	115,965	221-230	2,366,883	1,298,558	263,700
231-240		936,464		231-240		533,201		231-240		563,981		231-240		1,293,472	
241-250		926,983		241-250		529,396		241-250		544,522		241-250		1,277,033	
251-260		926,983		251-260		529,396		251-260		544,522		251-260		1,277,033	
261-270		926,983		261-270		529,396		261-270	1,110,148	544,522	0	261-270	2,366,883	1,277,033	0
271-280	1,571,946	936,818	186,785	271-280	1,022,662	538,883	0	271-280		557,817		271-274		141,805	
281-290		936,464		281-290		533,201		281-284		70,746		TOTAL (MJ)	14,201,296	34,811,513	1,318,502
291-300		926,983		291-294		49,862		TOTAL (MJ)	6,660,890	15,494,416	579,827	%	28	69	3
301-304	1,571,946	87,310	0	TOTAL (MJ)	6,135,974	15,482,098	552,440	%	29	68	3				
TOTAL (MJ)	11,003,623	28,012,700	1,120,712	%	28	70	2								
%	27	70	3												

Table E. 1. *(continued)*

CS05				CS06				CS07				CS08			
Period (years)	**IEE (MJ)**	**REE (MJ)**	**DE (MJ)**	**Period (years)**	**IEE (MJ)**	**REE (MJ)**	**DE (MJ)**	**Period (years)**	**IEE (MJ)**	**REE (MJ)**	**DE (MJ)**	**Period (years)**	**IEE (MJ)**	**REE (MJ)**	**DE (MJ)**
0-10		864,320		0-10		930,224		0-10		722,788		0-10		924,822	
11-20		864,320		11-20		930,224		11-20		722,788		11-20		924,822	
21-30	1,388,922	890,312	172,454	21-30	1,626,442	940,076	188,884	21-30	1,474,713	735,096	153,391	21-30	1,569,331	934,734	186,378
31-40		876,277		31-40		938,947		31-40		734,866		31-40		934,062	
41-50		864,320		41-50		930,224		41-50		722,788		41-50		924,822	
51-60		864,320		51-60		930,224		51-60		722,788		51-60		924,822	
61-70		864,320		61-70		930,224		61-70		722,788		61-70		924,822	
71-80	1,388,922	890,312	172,454	71-80	1,626,442	940,076	188,884	71-80	1,474,713	735,096	153,391	71-80	1,569,331	934,734	186,378
81-90		876,277		81-90		938,947		81-90		734,866		81-90		934,062	
91-100		864,320		91-100		930,224		91-100		722,788		91-100		924,822	
101-110		864,320		101-110		930,224		101-110		722,788		101-110		924,822	
111-120		864,320		111-120		930,224		111-120		722,788		111-120		924,822	
121-130	1,388,922	890,312	172,454	121-130	1,626,442	940,076	188,884	121-130	1,474,713	735,096	153,391	121-130	1,569,331	934,734	186,378
131-140		876,277		131-140		938,947		131-140		734,866		131-140		934,062	
141-150		864,320		141-150		930,224		141-150		722,788		141-150		924,822	
151-160		864,320		151-160		930,224		151-160		722,788		151-160		924,822	
161-170		864,320		161-170		930,224		161-170		722,788		161-170		924,822	
171-180	1,388,922	890,312	172,454	171-180	1,626,442	940,076	188,884	171-180	1,474,713	735,096	153,391	171-180	1,569,331	934,734	186,378
181-190		876,277		181-190		938,947		181-190		734,866		181-190		934,062	
191-200		864,320		191-200		930,224		191-200		722,788		191-200		924,822	
201-210		864,320		201-210		930,224		201-210		722,788		201-210	1,569,331	924,822	0
211-220		864,320		211-220		930,224		211-220		722,788		211-219		924,822	
221-230	1,388,922	890,312	172,454	221-230	1,626,442	940,076	188,884	221-230	1,474,713	735,096		TOTAL (MJ)	7,846,655	20,422,700	745,511
231-240		876,277		231-240		938,947		231-240		734,866		%	27	70	3
241-250		864,320		241-250		930,224		241-244		68,077	0				
251-260	1,388,922	864,320	0	251-254	1,626,442	87,615	0	TOTAL (MJ)	7,373,566	17,536,910	613,564				
261-264		81,408		TOTAL (MJ)	9,758,651	23,436,097	944,421	%	29	69	2				
TOTAL (MJ)	8,333,533	22,743,472	862,271	%	29	69	3								
%	26	71	3												

Table E. 1. *(continued)*

CS09				CS10			
Period (years)	**IEE (MJ)**	**REE (MJ)**	**DE (MJ)**	**Period (years)**	**IEE (MJ)**	**REE (MJ)**	**DE (MJ)**
0-10		996,129		0-10		642,838	
11-20		996,129		11-20		642,838	
21-30	1,683,947	1,009,934	200,614	21-30	1,111,527	655,692	130,467
31-40		1,004,852		31-40		653,171	
41-50		996,129		41-50		642,838	
51-60		996,129		51-60		642,838	
61-70		996,129		61-70		642,838	
71-80	1,683,947	1,009,934	200,614	71-80	1,111,527	655,692	130,467
81-90		1,004,852		81-90		653,171	
91-100		996,129		91-100		642,838	
101-110		996,129		101-104	1,111,527	60,547	0
111-120		996,129		TOTAL (MJ)	3,334,582	6,535,303	260,934
121-130	1,683,947	1,009,934	200,614	%	33	65	3
131-140		1,004,852					
141-150		996,129					
151-160		996,129					
161-170		996,129					
171-180	1,683,947	1,009,934	0				
181-190		1,004,852					
191-194		93,823					
TOTAL (MJ)	6,735,790	19,110,384	601,841				
%	25	72	2				