A LIFE CYCLE COSTING BASED DECISION SUPPORT TOOL FOR COST-OPTIMAL ENERGY EFFICIENT DESIGN AND/OR REFURBISHMENTS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ŞEYDA EMEKCİ

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY
IN
ARCHITECTURE

OCTOBER 2018

Approval of the thesis:

A LIFE CYCLE COSTING BASED DECISION SUPPORT TOOL FOR COST-OPTIMAL ENERGY EFFICIENT DESIGN AND/OR REFURBISHMENTS

submitted by **ŞEYDA EMEKCİ** in partial fulfillment of the requirements for the degree of **Doctor of Philosophy in Architecture Department, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Cânâ Bilsel
Head of Department, Architecture

Assoc. Prof. Dr. Ali Murat Tanyer
Supervisor, **Architecture, METU**

Examining Committee Members:

Prof. Dr. Ali Türel
City and Regional Planning Dept., Çankaya University

Assoc. Prof. Dr. Ali Murat Tanyer
Architecture, METU

Assoc. Prof. Dr. İpek Gürsel Dino
Dept. of Architecture, METU

Assist. Prof. Dr. Burcu Özdemir Sarı
City and Regional Planning Dept., METU

Prof. Dr. Gülser Çelebi
Dept. of Architecture, Çankaya University

Date: 11.10.2018

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Surname: Şeyda EMEKCİ

Signature:

ABSTRACT

A LIFE CYCLE COSTING BASED DECISION SUPPORT TOOL FOR COST-OPTIMAL ENERGY EFFICIENT DESIGN AND/OR REFURBISHMENTS

Emekci, Şeyda
Doctor of Philosophy, Architecture
Supervisor: Assoc. Prof. Dr. Ali Murat Tanyer

October 2018, 213 pages

In construction sector, deciding on building investment / refurbishments can be a complex process because it involves multiple criteria and generally conflicting objectives. For this reason, in the early phase, it is necessary to carry out an analysis that can enhance the predictability of these decisions taken, determine the optimum points of conflicting decisions and at the same time increase the social, environmental and economic sustainability. In the analysis, the total cost incurred building life cycle period, including the energy demand, must be taken into consideration, instead of only considering the investment cost. In order to choose the most cost optimal option among the unlimited number of solution proposals, a computer-aided Decision Support Tool (DST) is required. The DST should also be systematic, transparent, integrated with life cycle cost (LCC).

This study aims to develop an LCC-based decision support tool which life cycle costing and optimization have been successfully combined in order to provide jointly cost optimization of energy efficient design and refurbishment. The constructed DST purposes to create the most optimal set of solutions by calculating the building life cycle costs and energy demands individually that can result from constructing about one-million different hypothetical buildings, instead of calculating a limited number of alternatives.

Keywords: Cost Optimal Design, Energy Efficiency, Life Cycle Costing, Decision-Support Tool, Optimization,

ÖZ

MALİYET ETKİN ENERJİ VERİMLİ TASARIM VE/VEYA YENİLEMESİ İÇİN YAŞAM DÖNGÜSÜ MALİYETİ TABANLI KARAR DESTEK SİSTEMİ

Emekci, Şeyda
Doktora, Mimarlık
Tez Danışmanı: Doç. Dr. Ali Murat Tanyer

Ekim 2018, 213 sayfa

İnşaat sektöründe bina yatırım / yenileme faaliyetleri birden fazla kriteri ve genellikle çakışan hedefleri içerdiğinden karmaşık bir süreç olabilir. Bu nedenle, erken aşamada, alınan kararların öngörülebilirliğini artıracak, çelişen kararların optimum noktalarını belirleyecek ve aynı zamanda sosyal, çevresel ve ekonomik sürdürülebilirliği artıracak bir analizi gerekmektedir. Bu analizde, yalnızca yatırım maliyeti değil, binanın yaşam döngüsü boyunca oluşacak enerji ihtiyaçlarını da içeren toplam maliyet dikkate alınmalıdır. Sınırsız sayıda olan çözüm önerilerinden en optimum seçeneğin seçilebilmesi için bilgisayar destekli bir Karar Destek Sistemine (KDS) ihtiyaç duyulmaktadır. Bu KDS'nin de şeffaf, Yaşam Döngüsü Maliyeti (YDM) ile entegre ve sistematik olması gerekmektedir.

Bu çalışmanın amacı, enerji verimli tasarım ve yenilemenin maliyet optimizasyonunu sağlamak amacıyla, yaşam döngüsü maliyet analizi ve optimizasyonunun başarılı bir şekilde birleştirildiği YDM tabanlı karar destek sistemi geliştirmektir. Geliştirilen bu KDS, sınırlı sayıda alternatifi hesaplamak yerine, yaklaşık 1 milyon farklı varsayımsal binanın yaşam döngüsü maliyetlerini ve enerji taleplerini tek tek hesaplayarak en uygun çözüm setini yaratmayı hedeflemektedir.

Anahtar Kelimeler: Maliyet-Etkin Tasarım, Enerji Verimliliği, Yaşam Döngüsü Maliyeti, Karar Destek Sistemi, Optimizasyon

To

My Husband: Hakan Emekci

ACKNOWLEDGMENTS

I would like to thank the many people who have helped me on the path towards this dissertation, both during and before my time at METU.

I want to express my special thanks to my PhD advisors, Assoc. Prof. Dr. Ali Murat Tanyer, for guiding me during these past four years. I next thank the members of my committee for their time and energy in helping me improve this document.

I also have to thank my parents, who supported me with love and understanding. Without you, I could never have reached this current level of success.

I especially thank my best friend, soul-mate, and husband Hakan Emekci for providing great support.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

CHAPTER 1

INTRODUCTION

The introduction chapter consists of the study motivation and argument, aim and objectives, and methodology including the general procedure followed, and the “Disposition” are presented in the relevant subheadings.

1.1. Motivation and Argument

Energy is one of the main issues on the agenda of developed and developing countries that interest in all nations. The depletion of energy is one of the most important concerns for the future because it is an indispensable source of activities that ensure the continuity of everyday life. According to the European Commission, the world's latest energy consumption in 2014 is 30% higher than in 1995 (European Commission, 2016). This rapid increase after a while has caused concerns about the severe environmental impact such as global warming, climate change.

Energy is needed to construct building and operate them. All over the industrialized world, in addition to other sectors, buildings are responsible for approximately 40% of energy consumption (European Commission, 2017a). The European Union (EU) has therefore set a number of targets to reduce the energy consumption and impacts caused by buildings and aims to achieve an energy efficiency target of 20% energy savings by 2020 and 27% by 2030 and also 80% by 2050 (European Commission, 2017b). In accordance with these aims, since the late 1990s, the European Commission has implemented serious action plans to improve energy efficiency (European Commission, 2017b). In 1993, Directive 93/76/EEC that limits carbon emissions by increasing energy efficiency was published. The European Parliament and Council indicated that the building sector had achieved some saving with Directive 93/76 /

EEC but required complementary legislation. It was stated that this complementary legislation should also be compatible with the Kyoto protocol that an international agreement was adopted by United Nations Framework Convention on Climate Change in 1997 (UNFCCC, 1997). Therefore in 2002, Energy Performance of Buildings Directive 2002/91/EC (EPDB) entered into force (European Commission, 2003). According to the Directive, all EU countries have to determine the minimum energy performance levels at the buildings and certify the buildings according to their energy performance levels (EU, 2002).

After that Directive, 2010/31/EU known as recast EPBD was enacted in 2010 (EU, 2010). The directive is clearer and more robust than its previous version. It is therefore aimed to reduce carbon dioxide emissions to produce buildings that consume nearly zero energy and to achieve *"cost-optimal levels"* with minimum energy performance requirements by 2020 (EU, 2010).

In 2012, The Energy Efficiency Directive was approved. With this new directive, Directive 2004/8/EC and Directive 2006/32/EC have been repealed. The Energy Efficiency Directive fills the existing gaps in the capture of 2020 EU targets for energy saving. The Directive covers all sectors except transport (European Council, 2012).

Deciding on building investment can be a complex process because it involves multiple criteria and occasionally conflicting objectives. For this reason, in the early design phase, it is necessary to carry out an analysis that can enhance the predictability of these decisions taken, determine the optimum points of conflicting decisions and at the same time increase the social, environmental and economic sustainability. However, the directive did not include requirements or guidance regarding the level of ambition of the minimum energy performance levels. As a result of this uncertainty, Member States have developed their building regulations by setting different approaches which are influenced by different building traditions, political processes and individual market conditions. This resulted in different ambition levels where in many cases cost optimality principles could justify higher ambitions. In other words, countries were trying to save as much energy as possible by ignoring cost. Energy-saving is one of the important pieces of the puzzle. However, rather than just thinking about energy saving, it is necessary to consider energy saving and cost together, because it is very difficult to achieve sustainability by ignoring the costs incurred in building life cycle period involved with energy efficiency investments.

Generally, in early design phase the costs including electricity, heating, water utilities *etc.* are ignored. Therefore, building lifecycle cost and energy demand are unclear. In the literature, it is seen that the investment cost has lower rate than the maintenance and operational costs in the total life-cycle cost of the building (Mithraratne & Vale, 2004; Pellegrini-Masini *et al.*, 2010; Wang *et al*., 2005; Wong *et al*., 2010) (see Appendix I). According to Fankhauser and Tepic (2007), a typical household spends a considerable part of monthly income on housing utilities such as electricity, heating, and water. Hence, operational and maintenance costs incurred in building life cycle period must be calculated to produce the cost-optimal housings.

Prior to the cost optimality, studies have mostly focused only on energy saving achievements (Azari, 2014; Gustavsson & Joelsson, 2010) and generally, in economic calculations, only the initial cost was taken into account; usage cost was ignored (Dolmans, 2011). After the publication of the recast EPDB Directive (EU, 2010), in economic calculations, the life cycle costing including pre-usage, usage and end of the usage costs began to be taken into account. However, although the studies take into account the entire life-cycle costs of the building, they calculate the building investment cost using the unit prices to construct the whole building based on typology and function (see *eg.* Becchio *et al.,* 2015; Corrado *et al.,* 2014; Ferrara *et al.,* 2014; Ganiç & Yılmaz, 2014). This type of calculation is based on a general template and includes some building classifications labelled Class A, Class B and Class C *etc.* According to the classifications, for each building class, a unit price for m^2 is assigned. The investment cost is calculated by multiplying the unit price determined by the building class by the building's construction area. In other words, the investment cost is the same for every building in that building class even if the materials and/or systems are different. In order to get more accurate results, building investment cost must be calculated for each building based on bill of quantities and unit prices.

Furthermore, in the cost-optimality literature some studies focus on specific parts of the building (*e.g.* window, wall, insulation) and only make improvements on those parts (Becchio *et al.*, 2015; Ferrara *et al.*, 2016; Pikas *et al.*, 2014; Tsalikis & Martinopoulos, 2015). However, building should be considered as a whole in energy calculations and suggestions for all necessary systems should be made to achieve cost optimum level.

The recast EBPD consists of different steps. The first one in these steps is to define a reference building. Secondly, it is necessary to define a set of EE measures and combine them with the Global Cost Function to improve the energy performance of the building. Thirdly, optimum energy performance requirements levels need to be derived. Finally, the distance between the cost optimal performance and the reference building can be assessed and the policy required to reduce this distance can be directed. (EU, 2010). In addition to this, according to the European Commission, when possible design solutions are applied to the reference building, the energy performance should not be less than 10% (BPIE, 2013).

The main problem with this calculation methodology is that it is limited and proportionate to a few applications for reducing the primary and final energy used on the building (Ferrara *et al.*, 2014; Hamdy *et al.*, 2013). In other words, this approach does not guarantee to offer the most cost-optimal solution for that building because it only explores some of its existing combinations of design options. The higher the number of proposals in the solution package presented, the closer the calculated economic optimum option will be.

The cost optimal methodology offers evaluation of all building variables investment costs and at the same time calculation of the usage costs including operational and maintenance costs. Therefore, this methodology can contain a large number of independent variables and alternatives of these variables. In this sense, the cost optimality method should be considered as a complex optimization problem rather than offering few alternatives to improve the reference building.

In addition, while energy efficiency can be assessed on a global scale, a cost-optimal building design is strictly related to the local scale (Kurnitski *et al.*, 2011). It is influenced by many variables such as optimal design solutions from both energy and cost point of view, climate data, existing technologies and materials. Black-box models has focused on general. They are not dominated by a majority of local dynamics in certain countries because it is used in many countries. In addition, they require large amounts of training and may not always reflect what is desired. Therefore, models should be constructed for specific purposes, taking into account the local dynamics of that country, using specific methodologies and standards.

Cost optimality and energy efficiency measurement in building are the most important concepts in order to provide sustainability, social equity, protect environment completely and saving energy. To ensure social and economic well-being, these must be a political, economic and environmental strategy. These important concepts can be measured simultaneously by means of life cycle thinking methods. Life cycle costing which is one of these methods has been utilized in a sustainability context for buildings (BS ISO 15686-5, 2012). It is described as the "*cost of an asset or its parts throughout its life cycle, while fulfilling the performance requirements*" and LCC as the methodology for the assessment of the costs; *"methodology for systematic economic evaluation of life-cycle costs over a period of analysis, as defined in the agreed scope*" (BS ISO 15686-5, 2012).

1.2. Aim and Objectives

This study aims to develop an LCC-based decision support tool which life cycle costing and optimization have been successfully combined in order to jointly to provide cost optimization of energy efficient design and refurbishment. This model purposes to create the most optimal set of solutions by calculating the building life cycle costs and energy demands individually that can result from constructing about one-million different hypothetical buildings, instead of calculating a limited number of alternatives. The decision support tool (DST) has a transparent computable, measurable and extendable structure which is constructed using standards and legislation (if any) and/or literature.

In particular, this study aims at addressing the following objectives:

- Constructing the LCC-based model

The main purpose of this model is to calculate the life-cycle cost of the building for each selected option. It is aimed that the model has a transparent computable, measurable structure which is constructed using standards and legislation (if any) and/or literature specific to Turkey. It also allows the designer to learn about the total cost and energy demand of the building in the early phases of the design. Thus, the designer will be able to identify the hot spots that make up the total cost and energy demand and take precautions related to them during the design phase of the building.

- Optimizing the results of the LCC-based model

In order to determine a cost-optimal set of solution, the results of the LCC based model need to be optimized. An optimization tool that is perfectly compatible with the LCC-based model will be created for this purpose. The objective of the tool is to provide the most optimal value of materials and system among one million alternatives. "LCC based model" and "optimization tool" constitute decision support tool.

- Implementation of Decision Support Tool

The empirical study to be implemented by the decision support tool was selected from the single-family low-cost housing typology because of housing cost is very important for people living in this typology. The decision support system will be implemented on TOKI Mamak Karakusunlar project and the optimum results will be obtained. Then, these obtained results will be compared with the existing project. Hence, if the most optimal set of solution is selected, how much energy and cost will be saved in the lifetime of the housing will be determined.

- Determining Effects of Cost Optimal Solution on Affordable Housing

The study aims to contribute the housing policy in Turkey to produce lifetime affordable housing. It also informs policymakers and occupants in terms of the effectiveness of existing low-cost housing projects in the long-term maintenance and operational affordability.

1.3. Methodology

A general literature survey has been conducted to identify cost-optimal building and determine energy efficiency design. In this context, in order to obtain an introductory outlook, firstly, informative and broad explanation is given on energy efficiency policies in construction sector. Some important milestones of the energy efficient policies at global scale were stated in this chapter. The cost optimality methodologies and related studies in the literature were included. LCC as a calculation methodology was examined. Different approaches to LCC are determined by looking into their historical background, principles, purposes, advantages and disadvantages. At the end of the stage, the gaps and problems were identified as a result of an extensive literature survey on cost optimality and energy efficiency design.

As a solution to these gaps and problems, the decision support tool has been constructed by using standards and the literature. The DST provides quantifying total cost and energy demand incurred in building lifetime and finding the best set of solution from given constraints and alternatives.

The decision support tool consists of two parts.

- LCC-based model
- Optimization tool

LCC-based model the first part of the developed the decision support tool is a program that finds total LCC of buildings under the specific design conditions and project-specific boundary conditions. The model is designed to calculate the total cost and energy demand of building (investment cost, operational cost/energy, maintenance cost, disposal cost *etc.*) in the design phase of the building over a 30 years period. The usage of the developed model provides many advantages that take into account the lifespan and lifecycle costs of a building for future energy saving methods selection.

The second part of the decision support tool, the optimization tool tries to calculate all linear dependent variables and decide afterward which set of solution is the best. The objective of the tool is to present the most optimal value of materials and systems. Therefore, the designer will be able to identify the hot spots that make up the total cost and energy demand and take precautions related to them during the design phase of the building. The part calculates nearly one-million alternatives.

After that, Delphi technique was used to validate the DST. The technique has been carried out with 13 experienced experts in the field. The selected experts in this study were consulted through a questionnaire containing 10 questions that would allow validation of the model revealed by the literature review. Experts were asked to provide feedback expressing their level of agreement with the questions. With these feedbacks, the model has been improved. The technique has been implemented as 3 rounds; at the end of round 3, the consensus was reached among the experts.

Then, implementation of the DST as a first user was done on the TOKİ low cost housing typology. Results were presented. The sensitivity analysis about energy costs were prepared. Three scenarios are created and compared to the reference case. The results obtained did not make a difference on the cost optimal set of solution.

Afterwards, the contribution of the DST to the construction sector; innovations offered by the DST and the future remarks have been discussed.

The steps are explained in detail below with a flow chart.

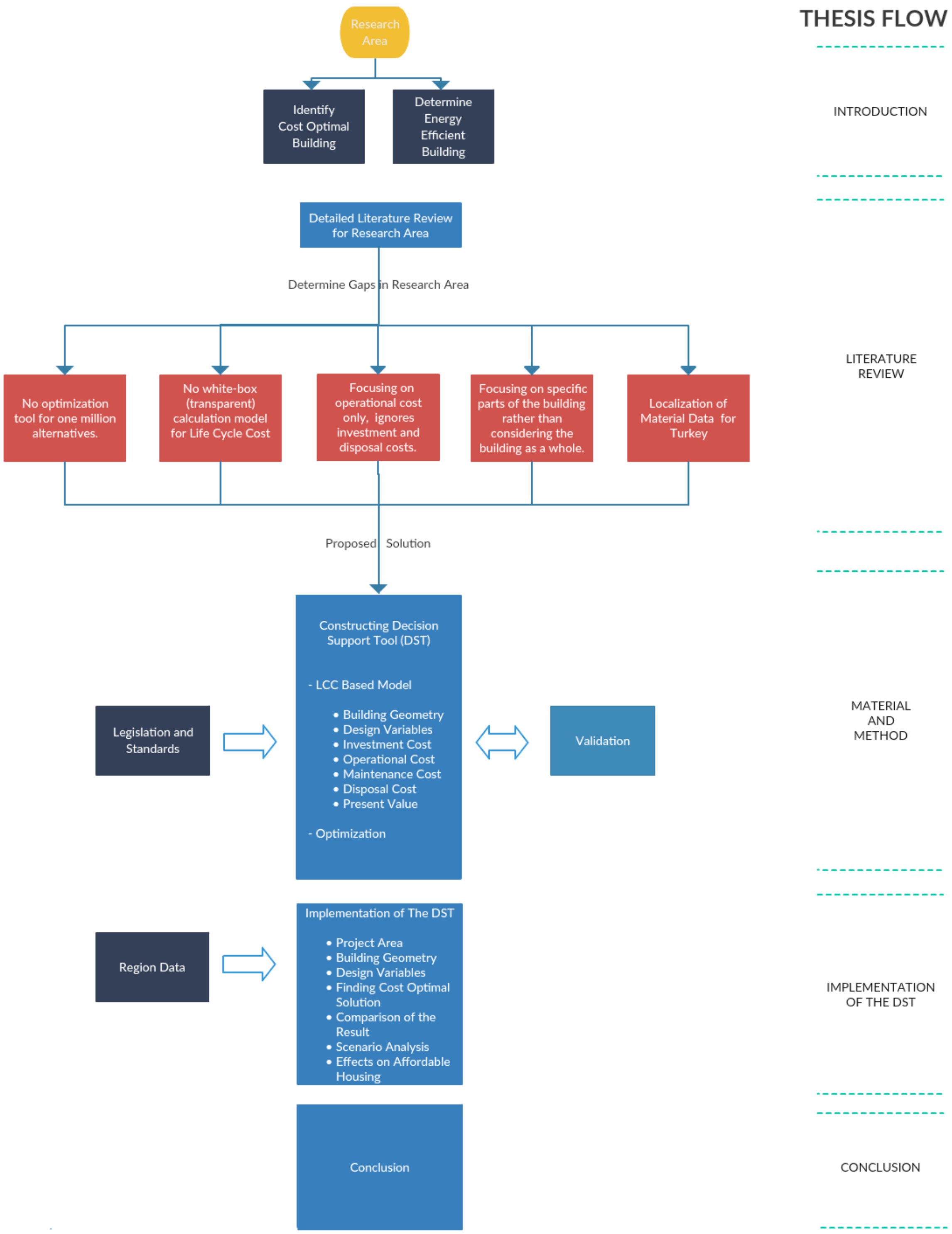


Figure 1: Thesis Flow

1.4. Disposition

This study consists of six parts. The first chapter contains the study motivation and argument, aim and objectives of the study, methodology, and disposition. The second chapter consists of a literature review on international building energy performance legislations and standards, cost optimality, life-cycle costing as part of a wider sustainability assessment, related studies, and criticisms on literature. The third chapter includes methodology of the study and the calculation methods. In the fourth part, the results of the decision support tool and its implementation will be discussed extensively. The fifth chapter then discusses interpreting the results and the critical issues that are of great potential in the literature and explains future studies regarding these issues.

CHAPTER 2

LITERATURE REVIEW

The literature review presents the topics related to energy efficiency, cost optimality, life-cycle costing (LCC). General concepts such as sustainability and international building energy performance legislations and standards are given in order to explain the concept in which LCC methodology and cost optimality are used. Then, information, all fields of application and standards about the cost optimality, and LCC methodology and related research areas are given concisely. Usage of LCC and general LCC approaches in literature are examined. Related LCC studies are presented as a final subtopic. Then for a better reading experience, general terminologies are given. To emphasize the originality of the study, the criticism on literature part are included.

2.1. Energy Efficiency Policies in Construction Sector

In the construction sector energy efficiency is important for sustainable development, climate and resource protection. About one third of energy-related emissions and about 40% of global energy consumption are related to construction sector (IEA, 2008). Energy savings up to 90% of energy consumption can be achieved when considered in the early design phase (Thomas *et al.*, 2015). To achieve this, there is a need for politics to increase research on building energy efficiency, to strengthen market-specific incentives and to help them overcome various barriers.

Rules and regulation in the construction sector are not new inventions. The oldest known regulation used for buildings is the Hammurabi laws. Of the 282 rules, 6 are related to the construction of houses and the penalties for the builders (Aydın, 2017).

While setting the rules and regulations for new buildings initiated in many countries or cities due to urban problems have a long tradition, the rules and regulations laid down in the field of energy efficiency are relatively new in most countries. The 1973/74 oil crisis was the turning point for this issue. Prior to the oil crises, most of energy efficiency regulations in the buildings were located in northern regions where climate could significantly affect public health. After that, the development of energy efficiency requirements for buildings accelerated. In the 1980s and 1990s, energy efficiency requirements were determined in most OECD countries. These measures were also a response to the Kyoto Protocol target for reducing CO_2 emissions. (International Energy Agency, 2008).

Since the late 1990s, the European Commission has implemented serious action plans to improve energy efficiency (European Commission, 2017b). In 1993, Directive 93/76 / EEC that limits carbon emissions by increasing energy efficiency was published. The Directive refers to (European Commission, 1993):

- Energy certification of buildings,
- The billing of heating, air-conditioning and hot water costs on the basis of actual consumption,
- Third-party financing for energy efficiency investments in the public sector,
- Thermal insulation of new buildings, and regular inspection of boilers.

The European Parliament and Council indicated that the building sector had achieved some saving with Directive 93/76/EEC but required complementary legislation. It was stated that this complementary legislation should also be compatible with the Kyoto protocol that an international agreement was adopted by United Nations Framework Convention on Climate Change in 1997 (UNFCCC, 1997). Therefore in 2003, Energy Performance of Buildings Directive 2002/91/EC (EPDB) entered into force (European Commission, 1993). According to the Directive, all EU countries have to determine the minimum energy performance levels at the buildings and certify the buildings according to their energy performance levels (EU, 2002).

After that Directive 2010/31/EU known as recast EPBD was enacted in 2010 (EU, 2010).The directive is clearer and more robust than its previous version. It is therefore aimed to reduce carbon dioxide emissions to produce buildings that consume nearly zero energy and to achieve cost-optimal levels with minimum energy performance requirements by 2020 (EU, 2010).

In 2012, The Energy Efficiency Directive was approved. With this new directive, Directive 2004/8/EC - and Directive 2006/32/EC have been repealed. The Energy Efficiency Directive fills the existing gaps in the capture of 2020 EU targets for energy saving. The Directive covers all sectors except transport (European Council, 2012).

There exist many standards related to EPBD (Energy Performance of Buildings Directive). European Standard EN 15459 includes a calculation method related to economic issues of heating systems and other systems that are involved in the energy demand and energy consumption of all types of buildings (EN 15459, 2008). German Standard DIN V 18599 implements the EPBD in Germany. The standard includes calculation method for a "*comprehensive energy balance for buildings, including the building envelope, building services for heating, cooling and air conditioning, lighting with all their primary or source and site energy consumption*" (DIN V 18599, 2011). EN 13790 standard specifies calculation methods for assessing annual energy use for space heating and cooling of a building or part of a residential or non-residential building (EN ISO 13790, 2008). EN 15193 specifies the calculation methodology for the evaluation of lighting energy requirements (BS EN 15193, 2017). EN 15251 standard covers indoor parameters that have an impact on the energy performance of buildings (EN 15251, 2007). EN 15217 sets out ways of expressing energy performance and for energy certification of buildings (EN 15217, 2007).

European Union continue to work on the optimum cost levels of energy performance requirements. To comply with these directives and to follow developments are important for Turkey which is a country dependent on foreign energy, and currently only 26% of total energy demand can be met from its own domestic resources. In spite of that, Turkey has experienced a significant increase in energy demand among the

Organization for Economic Cooperation and Development (OECD) countries in the last 15 years (Ministry of Foreign Affairs, 2018).

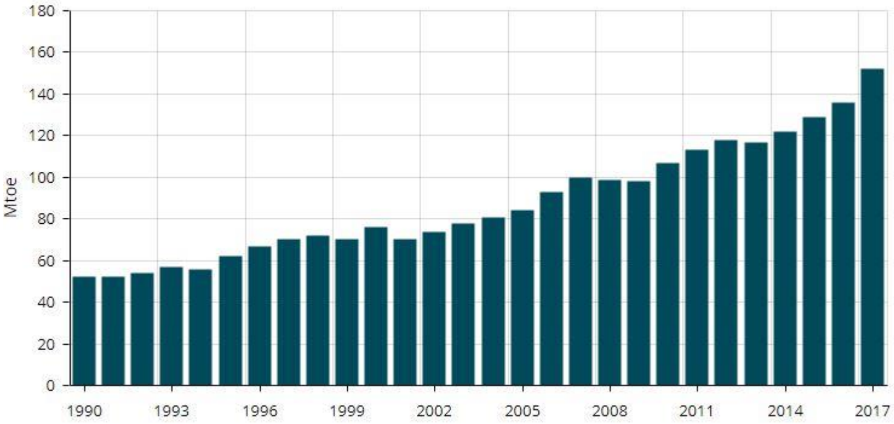
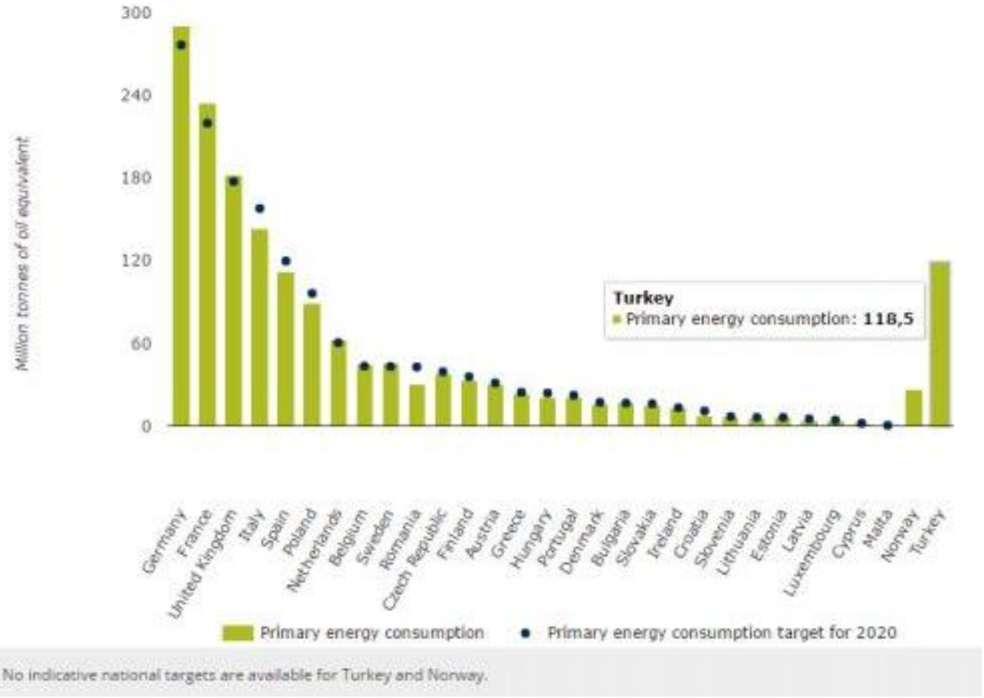


Figure 2: Turkey Primary Energy Consumption

Source: Global Energy Statistics, 2018

In addition, according to the European Environment Agency, although the fifth largest energy consuming countries among the EU countries, Turkey still does not have a national 2020 target (European Environment Agency, 2017).



Note: No indicative national targets are available for Turkey and Norway.

Figure 3: National Primary Energy Consumption and Indicative National Energy Efficiency Targets for 2020

Source: European Environment Agency, 2017

The government intends to reduce this dependence by planning investments in natural gas, electricity and nuclear energy infrastructure. However, approximately 40% of all energy consumption in Turkey is responsible for the building sector (EIA, 2014). As the building industry has a great potential for saving energy, it seems inevitable to improve building energy performance. It is important to adapt to optimum cost levels of minimum energy performance requirements, as required by European Union directives and regulations.

Turkey, as a candidate to EU and a signed to Kyoto Protocol, has to follow the directives. In this context, Turkey has published "Building Energy Efficiency Regulation"(Ministry of Environment and Urbanization, 2008). In accordance with this regulation, the building energy performance Bep-Tr was developed and published in 2010 for the purpose of certifying all buildings (Ministry of Environment and Urbanization, 2010).

2.2. The Cost-Optimality

Energy is one of the most important issues that interest all nations and increase consumption continuously. The buildings are located in the center of this energy consumption. They are responsible for about 40% of final energy consumption (European Commission, 2016). Since the late 1990s, the European Commission has implemented serious action plans to improve energy efficiency (European Commission, 2017b). In accordance with these action plans, Energy Performance Directive in Buildings (EPBD) in 2002 has been published. According to the EPBD, all EU countries have to determine the minimum energy performance levels at the buildings and certify the buildings according to their energy performance levels (EU, 2002). European Union (EU) Energy Performance Directive of Buildings (EPBD) recast was released on 2010 setting the cost optimal terms for buildings. By 2020, the EU had forced member states to adapt to new constructed building legislations (EU, 2010). According to the Energy Performance Directive of Buildings, minimum energy performance requirements for buildings or building units must be set with a view to achieving cost-optimal levels. (EU, 2010). As a response to this aim, member states should take the necessary measures to ensure that minimum energy performance requirements are set for building elements that form part of the building envelope and that have a significant impact on the energy performance of the building envelope when they are replaced or retrofitted, with a view to achieving cost-optimal levels (EPBD Art. 4.1 and also in Recital 14). Cost optimality (Cost-optimal levels) is defined as the energy performance level which leads to the lowest cost during the estimated economic lifecycle in Article 2 (14) of the Directive. It is a methodology that the lowest overall cost indicates the cost optimal level.

Cost-optimal levels are defined as the energy performance level which leads to the lowest cost during the estimated economic lifecycle in Article 2 (14) of the Directive.

The economic life cycle has been identified 30-year for residential buildings. When determining the cost of a building's 30-year life cycle, it is necessary to specify all costs with a net present value. Building life cycle cost include investment cost, operational and maintenance cost and disposal cost. During the design phase, LCC can be used to identify the cost-optimal design.

The concept of cost optimality has entered the literature with the 2010 EPDB recast. Prior to that, in most studies on energy efficiency, the economic evaluations was neglected or became of secondary importance (Al-Homoud, 2001; Crawley *et al.*, 2008; Gustavsson & Joelsson, 2010; Lam *et al.*, 2010; J. A. White & Reichmuth, 1996). Besides, while some studies took into account the initial investment cost (Azari, 2014), some only calculated the total net present value (Verbeeck & Hens, 2010).

Since the EPBD recast, various applications related to cost-optimal analysis have been carried out by academic research institutions (Ascione *et al.*, 2015; Barthelmes *et al.*, 2014; Becchio *et al.*, 2015; Corrado *et al.*, 2014; Ferrara *et al.*, 2014; Ganiç & Yılmaz, 2014; Hamdy *et al.*, 2013; Kurnitski *et al.*, 2011; Monetti, 2015; Pikas *et al.*, 2014) , as well as by the EU and national bodies (Boermans *et al.*, 2011; BPIE, 2013).

Studies carried out by academic research institutions have concentrated on different climatic conditions and different types of buildings. Pikas *et al.* (2014) examined the cost-optimal methodology for different types of buildings in terms of their window sizes according to Estonian legislation, using the IDA-ICE 4.5 model and they calculated the financial gap and made suggestions. Brinks *et al.* (2016) explored nearly zero energy levels of high industrial buildings using the TRNSYS 17 model according to German requirements. It has been dealt with in terms of airtightness, thermal bridges, and floor slabs of industrial buildings, and has identified cost-optimal overall opaque U-values. Tsalikis and Martinopoulos (2015) studied solar potential regarding photovoltaic and solar thermal utilization for housing in four different cities in Greece using software program. They also calculated net present values and payback periods for each investment alternatives. Becchio *et al.* (2015) focused electric systems of the building to provide the cost-optimality for a new single family house in Italy by means of energy simulation software Energy Plus™. They proposed only three system configurations for a single-family house. Abela *et al.* (2016) compared the existing building energy performance certification systems (EPC) in Mediterranean countries such as Malta, Italy, Greece and Cyprus using the dynamic simulation software IES-VE. These studies have offered only a few suggestions for the building to be cost-optimal. In other words, they do not guarantee the most optimal solution proposal. Apart from that, it was studied in order to get a closer to the most optimal option which combines different methodologies with cost-optimal methodology. Zavadskas *et al.* (2017) combined the cost-optimal methodology with other methodology that is the Multi Attribute Decision Making (MADM) to reach closest to the optimal alternative. Ferrara *et al.* (2016) took optimization together with cost-optimal methodology for building envelopes and energy systems in two different climates using the TRNSYS dynamic building simulation program. Lindberg *et al.* (2016) investigated cost-optimal solutions with using Mixed Integer Linear (MILP) optimization model for the energy system design in Germany. Seljom *et al.* (2017) analyzed how a comprehensive implementation of net zero energy buildings (ZEB) affects cost-optimal investments of up to 2050 in the Scandinavian energy system by means of a stochastic TIMES model which is a bottom-up optimization model. Ascione *et al.* (2015) aimed to combine building energy performance simulations and optimization techniques with nearly zero energy building design by means of combination of IDA-ICE, Energy Plus™ and MATLAB® in order to identify the cost-optimal solution in Mediterranean climate conditions. However, in this study, only 80 cases can be generated as alternatives.

Apart from studies on how to implement a cost-effective approach, this concept is used as a tool to examine the energy performance of structures and the influence of one or more construction technologies on the structure (Fokaides & Papadopoulos, 2014; Teodoriu *et al.*, 2014).

Cost-optimality approach has also been used to investigate the following areas

- Determination of strategies and policies for building construction site (Brandão de Vasconcelos *et al.*, 2016)
- Improvement of building design optimization methodologies (Ferrara *et al.*, 2014; Hamdy *et al.*, 2016)
- Comparison between design variables (Ferrara *et al.*, 2016)

Black box model methods are used in most of the studies where cost optimality approach has been applied. In the black box approach, internal structure or processing and the knowledge about inputs, outputs, and the relationship between them cannot be observed. Following programs are utilized in the studies:

- Energy Plus™ (Ascione *et al.*, 2015; Aste *et al.*, 2013; Becchio *et al.*, 2015; Brandão de Vasconcelos *et al.*, 2016),
- IDA ICE (Arumägi & Kalamees, 2014; Niemelä *et al.*, 2017; Pikas *et al.*, 2014),
- TRNSYS (Brinks *et al.*, 2016; Chardon *et al.*, 2016; Ferrara *et al.*, 2016; Penna *et al.*, 2015).

In Turkey, there exist a few numbers of studies which discussed the cost optimal methodology. Yılmaz *et al.* (2013) focused on solar thermal and solar power systems integrated to its roofs in the framework of EPBD to provide comfortable indoor environment to the occupants by means of simulation model. Ganiç and Yılmaz (2014) investigated an office building case study in Turkey focusing on the national parameters using the EPBD methodology by means of Energy Plus™ simulation software with Legacy Open Studio®. Ashrafian *et al.* (2016) focused on the affordable refurbishment in three different cities of Turkey in terms of different envelope properties using Energy Plus™ software. Kalaycıoğlu and Yılmaz (2017) also analyzed several types of buildings in the EPBD methodology framework at district scale using Design Builder software.

Cost optimality and energy efficiency measurement in building are the most important concepts in order to provide sustainability, social equity, protect environment completely and saving energy. To ensure social and economic well-being, these must be a political, economic and environmental strategy. These important concepts can be measured simultaneously by means of life cycle thinking methods. Life cycle costing which is one of these methods has been utilized in a sustainability context for buildings (BS ISO 15686-5, 2012).

2.3. Life Cycle Costing

Sustainability is on the international agenda and gives direction to the construction sector. Sustainability covers the three pillars: economic, social and environmental. To assess the building holistically in terms of sustainability, its entire life cycle has to be taken into consideration. In this section, life cycle costing as a part of sustainability assessment is investigated.

LCC can be defined as the method for assessing the economic value of decisions of a design project. Basically, LCC is gate-to-grave costs. It encompasses all costs of investment, operational, maintenance and disposal. Life cycle cost analysis (LCC) is a method to estimate the total ownership costs (Office of Government Commerce (OGC), 2003).

A key element in LCC is an economic assessment using equivalent dollars. Kirk & Dell'isola (1995) summarized LCC as an economic assessment of design alternatives, considering all significant costs of ownership over the economic life of each alternative, expressed in equivalent money. In 1972, The U.S. Department of Health, Education, and Welfare defined LCC as the systematic consideration of cost, time and quality.

It has several definitions but the most useful one is that:

> *The life cycle cost of an item is the sum of all funds expended in support of the item from its conception and fabrication through its operation to the end of its useful life (White & Ostwald, 1976).*

In the construction sector, lifecycle costing is used to measure the quantity of whole buildings, systems, or building components and materials costs and observing the happened all the way through the life cycle (Lindholm & Suomala, 2005; Woodward, 1997)

The technique can also be used to inform designers and clients and assist decision making for building investment projects (Flanagan *et al.*, 1987; Glick & Guggemos, 2010; Morrissey & Horne, 2011; Sterner, 2002).

Generally, LCC can be specified during the early concept development and design phase of any project (United Nation Environment Programme (UNEP), 2004). Therefore, the technique is helpful for predicting the total cost of building in the early phase (Bogenstätter, 2000; Pulakka & Sarja, 1999). It can also be enabled to evaluate financial benefits of energy efficiency measures for use in the building (Moore *et al.*, 2010; Morrissey & Horne, 2011).

2.3.1. Historical Development of LCC

In the construction sector, Stone (1983) first used the term 'costs in use' in the UK. According to Bird (1986), the first building application of the LCC was performed in the late 1950s. This demonstrates a shift from an existing concern with capital costs to the consideration of the results, in terms of operational costs. Although significant effort used to support and explain the concept, there is no desired number of applications due to general skepticism about adopting the LCC approach. In early 1960s , LCC was not yet spread as a methodology (Hoogmartens *et al.*, 2014). In contrast, in USA economic evaluation methods have been used extensively for water resource investments (Goh & Sun, 2015). However, LCC was firstly designed in the mid-1960s for procurement purposes in the U.S. Department of Defense (Epstein, 1996; White & Ostwald, 1976). The 1973 energy crisis raised awareness for the energy. This created a strong interest in LCC in the construction sector (Marshall, 1987). Since the 1980s, most of the US government agencies and many private owners required to use formal life-cycle evaluation methods to compare and assess alternative energy in building design options (Goh & Sun, 2015). At the same years, LCC performance planning needs to emerge in Australia. Bromilow & Pawsey (1987) studied on LCC performance theory launched in the Commonwealth Scientific and Industrial Research Organization (CSIRO), Division of Building Research, the National Committee on Rationalized Building (NCRB), the NCRB Facilities Management Sub-committee, and the Australian Vice-Chancellors' Working Group on Building Management. France familiarized the Life Cycle Costing concept in the 1970s with the first studies associated with building cost (Perret & Jouvent,1995). In 2008, the Building Cost Information Service (BCIS) prepared a practical guide on the application of LCC in the UK. Then the guide was accepted by the International Organization for Standardization (ISO) and entered into force in the UK (BCIS, 2008). Afterwards, the concept is most widely used in the military sector and construction industry. The public sector has been the organizer related to the life-cycle costing calculations. LCC assists to recent trends including operational staff effectiveness (re-engineering), facility obsolescence, sustainability, total quality management (TQM), and value engineering (VE).

When analyzing developments in the terminology of LCC, according to Ferry *et al.* (1999), the first used term 'costs-in-use' is now obsolete. The term "life-cycle costing" is used to analyze and estimate both capital and running costs.

2.3.2. LCC Purposes

Life cycle costing has been originally developed to assist procurement purposes to be used from a client’s perspective. Most of the LCC methods are designed to be utilized to help design decision-making. However, none of them is used from a client’s perspective (Fabrycky & Blanchard, 1991; Woodward, 1997). Dunk (2004) discusses LCC from a point of view of a manufacturer perspective. Barringer & Weber (1996) present a useful frame of reference detailing Life Cycle Costing purposes:

- ***Affordability studies****- measure the impact of a system or project’s LCC on long-term budgets and operating results.*
- ***Source selection studies****-compare estimated LCC among competing systems or suppliers of goods and services.*
- ***Design trade-offs****- influence design aspects of plants and equipment that directly impact LCC.*
- ***Repair level analysis****-quantify maintenance demands and costs rather than using rules of thumb such as …maintenance costs ought to be less than _? _% of the capital cost of the equipment.*
- ***Warranty and repair costs****-suppliers of goods and services along with end-users need to understand the cost of early failures in equipment selection and use.*
- ***Suppliers sales strategies****-can merge specific equipment grades with general operating experience and end-user failure rates using LCC to sell for best benefits rather than just selling on the attributes of low, first cost.*

Also used in different phases of the building's life cycle, the LCC can be utilized for making strategic decisions about building materials and systems, for decisions to be made between different options, for selecting correct and precise solution to the problem related to the building and for optimization.

2.3.3. Cost Components of LCC

LCC is an estimation of the future costs (Korpi & Ala-Risku, 2008). Purpose of the lifecycle costing is to supply a framework for finding the total cost with an intention of reducing it (Fabrycky & Blanchard, 1991). The total cost includes investment cost (construction cost), operational and maintenance costs, and end-of-life costs (disposal cost).

- **Investment (construction) cost:**

The cost is referred to as initial, first or project cost which is divided into two parts- hard and soft cost. While hard cost includes labor, equipment, materials, furnishings, *etc.*, soft cost contains design and permit fees *etc.* Investment costs include things construction facilities, manufacturing, logistic support requirements *etc.* (Fabrycky& Blanchard, 1991).

- **Operations and Maintenance Costs:**

The cost covers consumer/user operations of the building. Operations and maintenance costs contain costs for routine, preventive, and corrective maintenance. In another word, it refers to the costs that incurred to maintain building systems running properly. The costs include utility costs, service cost, maintenance activities *etc.* (Fabrycky & Blanchard, 1991). This part is the most important portion of the total cost and but are the hardest to predict (Asiedu & Gu, 1998). According to US government records, the cost may be greater than the first cost by as much as ten times (Wilson, 1986).

The costs should be estimated with the same rigor as production and construction cost. It is usually a good practice to estimate this cost using an activity-based cost approach and in terms of annual costs (US DOE, 2014). Generally, this cost constitutes a majority of the total cost.

- **End-of-Life Costs (Disposal Cost):**

The cost is referred to as disposal cost at the end of its lifecycle period. The costs are often ignored in its early phases. The cost can be calculated using a variety of methodologies like other costs. According to U.S. Department of Energy (2014), one of the best methods for predicting final disposal cost is to understand and use historical costs for similar activities. It is a critical point that revenue from the reuse of the end of life materials affects total LLC. However, this is very difficult to calculate.

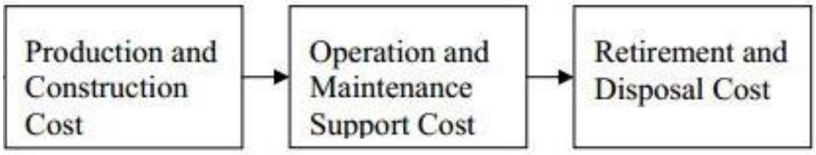


Figure 4: Cost Breakdown Structure

Source: Fabrycky & Blanchard, 1991

2.3.4. Parameters Associated with LCC

- **Inflation:**

Inflation can be described as general increase in prices of goods and services over a period of time by Kirk and Dell Isola (1995). Basically, life cycle cost estimates the future cost of service, product or building. Hence inflation rate is an important thing in life cycle costing. It strongly affects the result of LCC.

- **Life of material:**

Life of material should be considered the material economic life. The economic life is a period of time during which an improvement has value in excess of its salvage value (Kirk & Dell’isola, 1995).

- **Discount rate:**

The discount rate is referred as to the time value of money. The rate is a highly important factor in economic evaluations. It needs to be required for in the LCC calculations (Fabrycky & Blanchard, 1991). It can have a significant effect on the result. It can be defined as to calculate the present value of future cash flows.

It is very important that all cost elements used are brought in the same period over time to predict the current value of the alternative and to be able to make a comparison. Figure 5 represents a cash flow diagram over the lifecycle period.

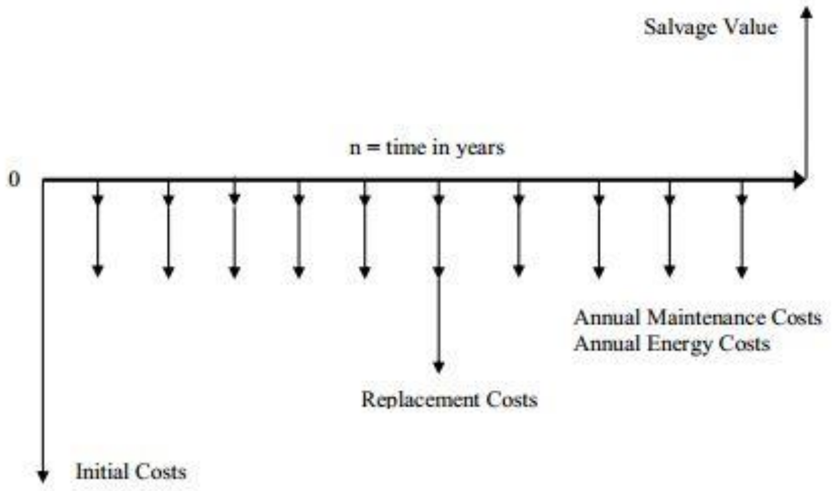


Figure 5: Cash Flow Diagram

Source: Kirk & Dell'isola, 1995

2.3.5. Related Studies

LCC can be defined as the method for assessing the economic value of decisions of a design project. Basically, LCC is gate to-grave costs. Life cycle costing for buildings is usually taken as total cost. This total cost includes annual operating, maintenance and disposal costs (Levander *et al.,* 2009; Sterner, 2002; Reddy *et al.,* 2015).

In the 1960s, there were few studies on the life-cycle cost approach to making economic assessments over the life of all costs associated with a project investment (Grant & Ireson, 1960). Even in the 1980s, the situation was the nearly same (Flanagan, 1984). After that years, studies on assessing the total LCCs of the buildings have increased (Bird, 1986; Bishop, 1984; Johnson *et al.*, 1987; Marshall, 1987).

In 1986, Bird (1986) suggests a broader view on LCC. According to him, the aims of the method are not just reducing the running cost or total cost:

> *to enable clients and building users to know how to obtain a value for money in their own terms, by knowing what these costs are likely to be and whether the performance obtained warrants particular levels of expenditure* (Bird, 1986) (p. 281).

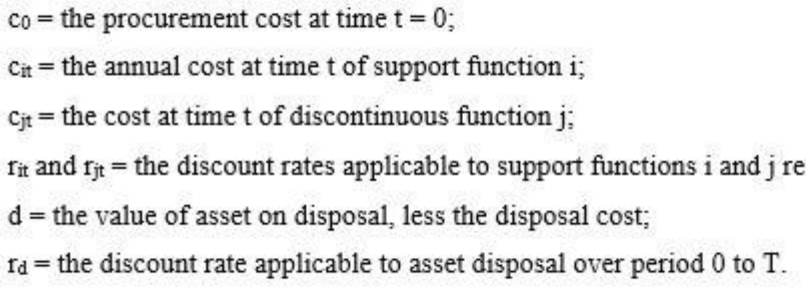
When analyzing lifecycle costing literature, it is possible that life-cycle cost can be classified in terms of the scope of the applied building (building level or component level), taking environmental impact into account (environmental or traditional), being used with any post-processing tool (optimization) or ultimate purpose (affordability, inform the client *etc.*).

- **In terms of traditional applications:**

In term of traditional applications which only consider the cost and ignore energy consumption and environmental concerns, Bromilow and Pawsey (1987) studied lifecycle costing performance theories in the Commonwealth Scientific and Industrial Research Organization (CSIRO) Division of Building Research, the National Committee on Rationalized Building (NCRB), the NCRB Facilities Management Sub-committee, and the Australian Vice-Chancellors' Working Group on Building Management. A simple mathematical model has been developed to calculate the long-running cost of Australian university buildings. The mathematical models simulate the lifecycle pattern of a building. The model constituted of a mathematical equation that is as follow (Bromilow & Pawsey, 1987).

$$NPV : c_o + \sum_{i}^{n} \sum_{t=1}^{T} c_{it} \left(1 + r_{it}\right)^{-t} + \sum \sum c_{jt\left(1+r_{jt-1}\right)} - d \left(1 - r_d\right)^{-T}$$

Where



c_0 = the procurement cost at time t = 0;
c_{it} = the annual cost at time t of support function i;
c_{jt} = the cost at time t of discontinuous function j;
r_{it} and r_{jt} = the discount rates applicable to support functions i and j respectively;
d = the value of asset on disposal, less the disposal cost;
r_d = the discount rate applicable to asset disposal over period 0 to T.

Most of the costs are classified as continuous costs like annual cost (*i.e.* maintenance, energy, cleaning) and dis-continuous costs *i.e.* replacement of building components. Bromilow & Pawsey (1987) estimated the operational cost using historical data. However, Flanagan *et al.* (1987) in the traditional approach as a possible improvement, suggested that a risk management system should be included in this technique considering both the risk and uncertainty. According to them, the LCC approach deals with the future, and in the future, it could not be known clearly. For this reason, it was stated that applying probability and sensitivity analysis to life-cycle costing can give more accurate results (Flanagan *et al.*, 1987). In the same years, building economic methods began commonly used in the US to conduct the analysis of building operational costs. Marshall (1987) investigated that the effects of acid rain on buildings and cost-effectiveness of automatic sprinkler systems. The importance of the study is that LCC was applied several applications to real-world problems.

Al-Hajj & Horner (1998a) developed a mathematical equation that would facilitate estimating total operating and maintenance costs. The equation is as follow (Al-Hajj & Horner, 1998b, p.).

$$T_c = \frac{1}{CMF} \sum_{i=1}^{n} CSI_i$$

T_c is the total cost,

CMF is the cost model factor (the ratio of the cost of the cost-significant items to the total cost),

CSI_i is the cost of the i_{th} cost significant item (any item whose cost exceeds the mean)

n is a total number of cost significant items.

In this model, they have dealt with important items only in terms of cost. As a result of this study, to facilitate the data collection process, the operational and maintenance costs of a typical building were found to be about 1/6 of all other costs. In this study, running cost and the total cost is considered as equivalent. The model is described in more detail below.

$$R_c = \frac{1}{\text{CMF}} \times \sum_{i=1}^{n} [(c_1 + c_2) + (e_1 + e_2 + e_3) + (a_1 + a_2) + (o_1 + o_2) + (m_1 + m_2)]_i$$

R_c is the total running cost
c_1 is the expenditure on internal cleaning,
c_2 is laundry,
e_1 is gas,
e_2 is electricity,
e_3 is fuel oil,

a_1 is management fees,
a_2 is porterage (security),
o_1 is rated,
o_2 is insurance,
m_1 is internal decoration,
m_2 is roof repair

Kirkham *et al.* (2002) examined the facility management costs of 450 hospital buildings. They propose a new method to calculate the LCC using the stochastic modeling method. However, this modeling approach is not a very appropriate method for general use because it is very complicated. Cole and Sterner (2000) emphasize the benefits of LCC concept and provision for a more extensive view of costs. Minami (2004) evaluated the improvement and repair work costs of Buildings of Post Offices in Japan by adopting a whole-life cost approach. Most important point in the study is on the relationship between the age of the buildings and repair work. For example, the repair and improvement cost 35 to 40 years after a building has been completed. For buildings, 60 to 70 years old the repair and improvement costs were not so high. Besides overall cost reduction was analyzed by extending the life of the building. Minami (2004) stated that the total initial and operating costs can reduce increasing longevity. Reidy *et al.* (2005) investigated Stanford University Science Buildings and evaluate the cost-effectiveness of project design decisions with Building Life Cycle Cost Program (BLCC). In the study, building total lifetime was accepted as 30 years and the discount rate was accepted as 4.4%. The study result is that the present value of usage stage of the building is nearly as great as the initial project costs.

- **In terms of Environmental applications:**

In terms of environmental applications, in 1996, the life-cycle cost approach was combined with environmental concerns (Epstein, 1996). Aye *et al.* (2000) demonstrated a case study of a high-performance commercial office building in terms of environment in Melbourne, Australia. They analyze construction options by using standard LCC methodology. The options are:

- to renovate the existing building,
- buy an alternative building and renovate,
- buy a development site and construct a new building.

Importance of the study is the use of standard lifecycle costing methods in decision-making tool. Bartlett & Howard (2000) show that, when considered the environmental impacts and total lifecycle costs of buildings together, the result will be sustainable and long-term for both the business and the environment, on account of the savings from energy consumption can repay the capital investment and generate long-term returns. According to Bogenstatter (2000), LCC has a great potential. Early stages of the design processes are very critical phases to take a decision related to critical issues which are construction and operating costs, Bogenstatter (2000) stated that ecological and economic objectives perfectly complement each other to achieve sustainability. He describes ecological targets as broader than environmental metrics. Performance requirements can include direct and indirect effects on the environment, for example, the conservation or development of natural resources and surrounding ecosystems (Bogenstätter, 2000). Gluch & Baumann (2004) studied the practical usefulness of the lifecycle costing in strategic decisions. To reduce confusion because of the variety of terms and meanings, they described some critical issues as critical for the LCC's ease of use which are the reliability and availability of environmental data, the perceived advantages of using Lifecycle costing in investment decisions and an understanding of methods and conceptual definitions (Gluch & Baumann, 2004). The increasing use of LCC facilitated the adoption as a valuable approach. It is developed some strategies to reconcile theory and practice of LCC. Cole & Sterner (2000) stated that reliance should be instilled in both the design team and the client about the value of LCC to reach high-performance aim for green buildings. The usage of LCC becomes perceiving as a strategic choice. Similarly, Sterner (2002) reported that the interest in using LCC approaches increased and real applications would encourage usage of LCC. Hence quality, accessibility of cost and the confidence in the result should be improved (Sterner, 2002). McLeod & Fay (2010) investigated the cost-effectiveness of thermal performance measures. In their study, the discount rate is not specified. However, they only took into account the building investment cost, others of life cycle cost of the buildings (*i.e.* operational and maintenance costs) are ignored. König and De Cristofaro (2012) proposed a building certification system that is included in the life cycle cost approach. This system calculates both cost of the building and environmental impact. In this study, calculation methods are computed through BNB / DGNB program. Morrissey& Horne (2011) applied a thermal modeling approach within an LCC framework for a housing. They used 3.5% as a discount rate for over 0–30 years old building; 3% as a discount rate for over 30–70 years old building. However, they only took into account the operational cost of the building. Their study result is that energy-efficient building designs are the most cost-effective. Sayed and Sawant (2015) evaluated the economic feasibility of six green components for a case project placed in Mumbai(suburban location in India). The green components were described as monocrystalline solar photovoltaic panels, evacuated tube collectors type solar water heater, solar street lights, energy efficient compact fluorescent lamp, T5 fluorescent tubes luminaries, Nisargruna type bio-methanation plants. In the study, 8% as a discount rate for 25 years was used. In 2016, Stephan and Stephan (2016) assessed total life-cycle energy demand of residential buildings in Sehaileh, Lebanon, through a software program (DEROB-LTH). They used 12.2% as a discount rate for 50 years old building. LCC calculations are important for educational buildings in terms of energy efficiency. Kale *et al.* (2016) compared life-cycle costs of two educational buildings in terms of energy efficient approach using solar power panels.

In construction projects, Life Cycle Costing calculations can be performed at the whole building or component level (Gundes, 2016). At the building component level, the concept of Life Cycle Costing was implemented to reduce CO2 emissions through whole-life cost analysis in the UK housing sector (Pellegrini-Masini *et al.*, 2010). Pellegrini-Masini *et al.*(2010) investigate the total lifetime costs of three cases of energy demand reduction technologies over a 25 years period (2005–2030) for housing stock in the UK. Interventions are classified as comprehensive, complete and limited related to improving building fabric and ventilation systems which meet to target 50% reduction in CO_2 emissions by 2030. In a similar way Wong *et al.*(2010) research LCC as a method to evaluate the economic feasibility of using transparent and conventional insulation façade systems for office buildings in the United Kingdom. Facades are compared with each other, in terms of energy and cost-performance. The results demonstrate Life cycle costing method can be used effectively to assess the economic feasibility of the low carbon technologies *i.e.* TIfaçade (Transparent insulation Facade) (Wong *et al.*, 2010). Similarly, Real (2010) investigate façade solutions in terms of their life cycle costing. In the study, total lifetime is 25 and 50 years and 6% is applied as the discount rate.

- **In terms of using any post-processing tool**

In terms of using any post-processing tool, in the building sector, the studies about using together LCC and optimization as a decision-support tool are very few. Lugmaier (2000) proposes to describe building energy efficiency measures with the aid of computer program (Vinsim, TSBI3, Soldia). He uses different building energy simulations and optimization programs. According to Al Homoud (2001), the building energy can be optimized by means of computer-aided building energy simulation and optimization techniques. Coley and Schukat, (2002) state that computer programs can be used to minimize the heat loss of a building. Similarly, there are some studies in order to optimize a building's energy by means of computer-aided building energy simulation and optimization techniques (Miller, 1995; Nielsen *et al.*, 2001; Wetter, 2009). Marszal and Heiselberg (2011) aim to determine the cost-optimal zero housing. The study proposed to optimize them by calculating the life cycle cost of zero-energy buildings. The study includes an only high-tech component such as Photovoltaic, Windmill then optimizes life-cycle costs according to alternatives of the component. This study is done within the scope of a large project and the calculations about operational and maintenance cost of the building for this study are provided from this project. Heralova (2014) studied life cycle costing analyzing as a decision support system and aims to find the most suitable in term of economical among two alternatives. In this study, a calculation of operational and maintenance cost of the building is computed through Buildpass program. When analyzing the literature, the combination of life cycle cost and optimization is mostly at the building component level. These studies are limited to the finding of optimum insulation thickness (Çomaklı & Yüksel, 2003; Hasan, 1999; Sisman *et al.*, 2007; Yildiz *et al.*, 2008).

- **In terms of ultimate purpose**

LCC has been utilized for varies disciplines and area such as affordability, inform the clients cost optimality in the construction sector. According to several authors, the lifecycle costing approach is used to inform clients and designers regarding different investment scenarios (Glick& Guggemos, 2010; Mithraratne, 2001; Morrissey &Horne,2011; Sterner, 2002). The LCC has also been utilized to evaluate the financial advantages of housing energy efficiency measures (Belusko & O'Leary, 2010; Moore *et al.*, 2010; Morrissey & Horne, 2011). The LCC approach is used for decision making by some authors (Korpi & Ala-Risku, 2008; Mithraratne & Vale, 2004), for optimization of the building (Bakis *et al.*, 2003; Heralova, 2014) for affordability studies (Udawattha & Halwatura, 2017)

Smith (2010) study life cycle costing to evaluate housing affordability with the aid of a computer program. Udawattha and Halwatura (2017) draw attention to the significance of energy consumption in affordable houses. The study evaluates the environmental sustainability and the life-cycle costing of different walling materials. The operational cost data of the wall types are provided by the computer simulation model.

2.3.6. Difficulties of Implementation of the LCC

From an academic perspective, LCC is a domain of great potential to achieve the framework for reaching sustainable development. On the other hand, there exist several critical, controversial discussion topics regarding the use of the method. Johnson *et al.* (1987) state one of the difficulties that subjective factors were dominant in the management decisions and facility design, even for some operational decisions. Hence, the significance of qualitative data come to fore so that life cycle costing principles are effectively implemented. Johnson *et al.* (1987) highlight a limitation regarding implementing the traditional LCC procedures because many of these factors which are used are difficult to foresee and hard to fit into mathematical analyses. The problem leads to decrease the effective use of lifecycle cost analysis because of dominating noneconomic qualitative policy considerations in decisions (Johnson *et al.*, 1987). Other difficulties in the effective use of lifecycle costing methods are difficulties of reaching adequate and convenient data and the lack of consensus on the basis of calculations (Bird, 1986). Schade (2007) expressed that different data affect the LCC in different stages of the life cycle. Cost data, physical data, occupancy data, quality data, performance data are required data categories for LCC.

Difficulties associated with problems of the variability of cost data; uncertainty, collecting cost and performance data for buildings are discussed by Marshall (1987) and Flanagan (1984).

Cole and Sterner (2000) describe the combination of large amounts of hard and soft data as methodological problems and limitations. This can lead to inaccuracy caused by future extrapolation. The problem may also lead to the lack of universal methods and useful software in standard formats to increase adoption and usage. This can limit the implementation of LCC based on the different characteristics of the building process. Sterner (2000) implies that access to reliable data as an input is very important in the LCC process and affects highly influential its outcome.

2.4. Criticism of Literature

The literature on energy efficiency has gained popularity after the 1973/74 oil crisis, although the rules and regulations governing the construction sector are based on very old times. After the Kyoto Protocol, awareness has grown even further, and serious action plans have been put into practice by the end of the 1990s. In 2010, the concept of cost optimality with the recast EBPD has entered the literature (EU, 2010). With this concept, the main axis in energy efficiency studies is not only energy saving but also optimization of cost and energy. Prior to the cost optimality, studies have mostly focused only on energy saving achievements (Azari, 2014; Gustavsson & Joelsson, 2010) and generally, in economic calculations, only the initial cost was taken into account, usage cost was ignored (Dolmans, 2011). After the publication of the recast EPDB Directive (EU, 2010), in economic calculations, the life cycle costing including pre-usage, usage and end of the usage costs began to be taken into account (Ascione *et al.*, 2015; Barthelmes *et al.*, 2014; Becchio *et al.*, 2015; Corrado *et al.*, 2014; Ferrara *et al.*, 2014; Ganiç & Yılmaz, 2014; Hamdy *et al.*, 2013; Kurnitski *et al.*, 2011; Monetti, 2015; Pikas *et al.*, 2014). However, although the studies take into account the entire life-cycle costs of the building, they calculate the building investment cost using the unit prices to construct the whole building based on typology and function. These costs are a general template and give the same unit price for every building in that building class even if the materials and/or systems are different.

Furthermore, in the literature some studies focus on specific parts of the building (*e.g* window, wall, insulation) and only make improvements on those parts (Becchio *et al.*, 2015; Ferrara *et al.*, 2016; Pikas *et al.*, 2014; Tsalikis & Martinopoulos, 2015). However, buildings should be considered as a whole in energy calculations and suggestions for all necessary systems should be made to achieve cost optimum level.

While energy efficiency is a globally important term, its applications and measures are closely related to the local scale. Optimal design solutions, from both energy and cost point of view, are highly influenced by local availability of materials, their costs and other local dynamics. The studies on the cost optimality ignore these important issues. In addition, the studies use black box model to implement the EPDB methodology. Black-box models has focused on a general framework and they are not constructed for a specific country. Therefore, they are not dominated by a majority of local dynamics (*e.g.* costs, availability of materials / systems) in certain countries because it is used in many countries. Besides, they require large amounts of training and may not always reflect what is desired. Therefore, models should be constructed for specific purposes, taking into account the local dynamics of that country, using specific methodologies and standards.

Another problem with the literature on cost optimality is that they offer a few applications for reducing the primary and final energy used on the building, and it does not guarantee the most optimum design options. In addition, finding the most optimal option requires significant effort and experience to make the right decisions. Hence the cost optimality method should be considered as a complex optimization problem rather than offering few alternatives to improve the reference building (Ascione *et al.*, 2015; Kalaycıoğlu & Yılmaz, 2017; Lindberg *et al.,* 2016). The main reason for the limitations in these studies are that the methodologies are black-box. Therefore, the solutions proposed are limited to recommendations of the program user.

Cost optimality and energy efficiency measurement can be measured simultaneously by means of life cycle thinking methods. Life cycle costing which is one of these methods that has been utilized in a sustainability context for buildings. Many publications were found related to LCC. The most of them were published in 1984, 1986 and 1987. After 1973, energy crisis raised awareness for the energy. This created a strong interest in lifecycle costing method. Some of the publications include a mathematical description of the concept implemented. Others were relevant to the buildings in the context of environmental awareness. However, there is increasing trend of life cycle costing methods on implemented to research on building in this context. According to publications associated with LCC, the lifespan of buildings can be classified three types as less than 30 years, between 30 and 50 years and more than 50 years. It is possible to gather studies under four headings as the scope of the applied building (building level or component level), taking environmental impact into account (environmental or traditional), being used with any post-processing tool (optimization) or ultimate purpose (affordability, inform the client *etc.*). When analyzing the headings, the absence of a transparent, systematic LCC-based decision support system is noticed. Moreover, there is no study bringing together optimization and LCC with cost optimality transparently. There is a clear gap in this issue.

Turkey, as a candidate to EU and a signed to Kyoto Protocol, has to follow the energy efficiency directives. However, there exist a few numbers of studies which discussed the cost optimal methodology. All of the studies use black box models that its internal structure or processing and the knowledge about its inputs, outputs, and the relationship between them cannot be observed. In addition, the models may not always reflect what is desired such as graphs, diagrams, charts. Furthermore, since these studies are not integrated with optimization methods, they can offer a limited number of suggestions and do not guarantee the most optimal option.

CHAPTER 3

MATERIAL AND METHOD

This study aims to develop an LCC-based decision support tool which life cycle costing and optimization have been successfully combined in order to jointly provide cost optimization of energy efficient design and refurbishment. The DST has a transparent computable, measurable structure and calculates nearly one-million alternatives. The objective of the tool is to provide the most optimal value of materials and systems.

In the chapter, the computational background of the decision-support tool can be described. The decision support tool consists of two parts.

- LCC-based model
- Optimization part

LCC-based model, the first part of the developed the decision support tool, is a program that finds total LCC of buildings under the specific design conditions and project-specific boundary conditions. The second part of the decision-support tool, the optimization part, tries to calculate all linear dependent variables and decide afterward which set of solution is the best.

The model has divided the building into components (*e.g.* wall window). Each component contains some alternatives which consist of the materials/methods widely used in the construction sector in Turkey. They are expressed by a mathematical equation. As a result, the model was developed that calculated the total lifecycle cost of the housing as a whole. The calculations are gathered from legislation (if any) and/or literature specific to Turkey. The mathematical equations are selected according to data availability in Turkey. Then, data sets including design variables are created and framework conditions such as climate, building geometry, interest rate and energy prices are designated. Then, a combined LCC-based-optimization is created to find the optimum values of the design variables by combining the life cycle cost-based model with the optimization algorithms. The model generates an output for each input. Optimization part calculates all of the results one by one and this process is repeated until the minimum lifecycle cost is reached. The output of the decision support tool is the most economical design under the specific design conditions and by given design options. In addition, the tool also provides the amount of energy consumed.

3.1. The Decision-Support Tool

In the DST, the building is considered as building parts. The variables are also widely used in the construction sector in Turkey. The decision support tool calculates LCC by considering external wall types, internal wall types, insulation material, insulation thickness, window types, and window glass types, number of floors, orientation possibilities, heating systems, fuel types, and hot water systems. The decision support tool structure is designated in Figure 6 and Figure 7.

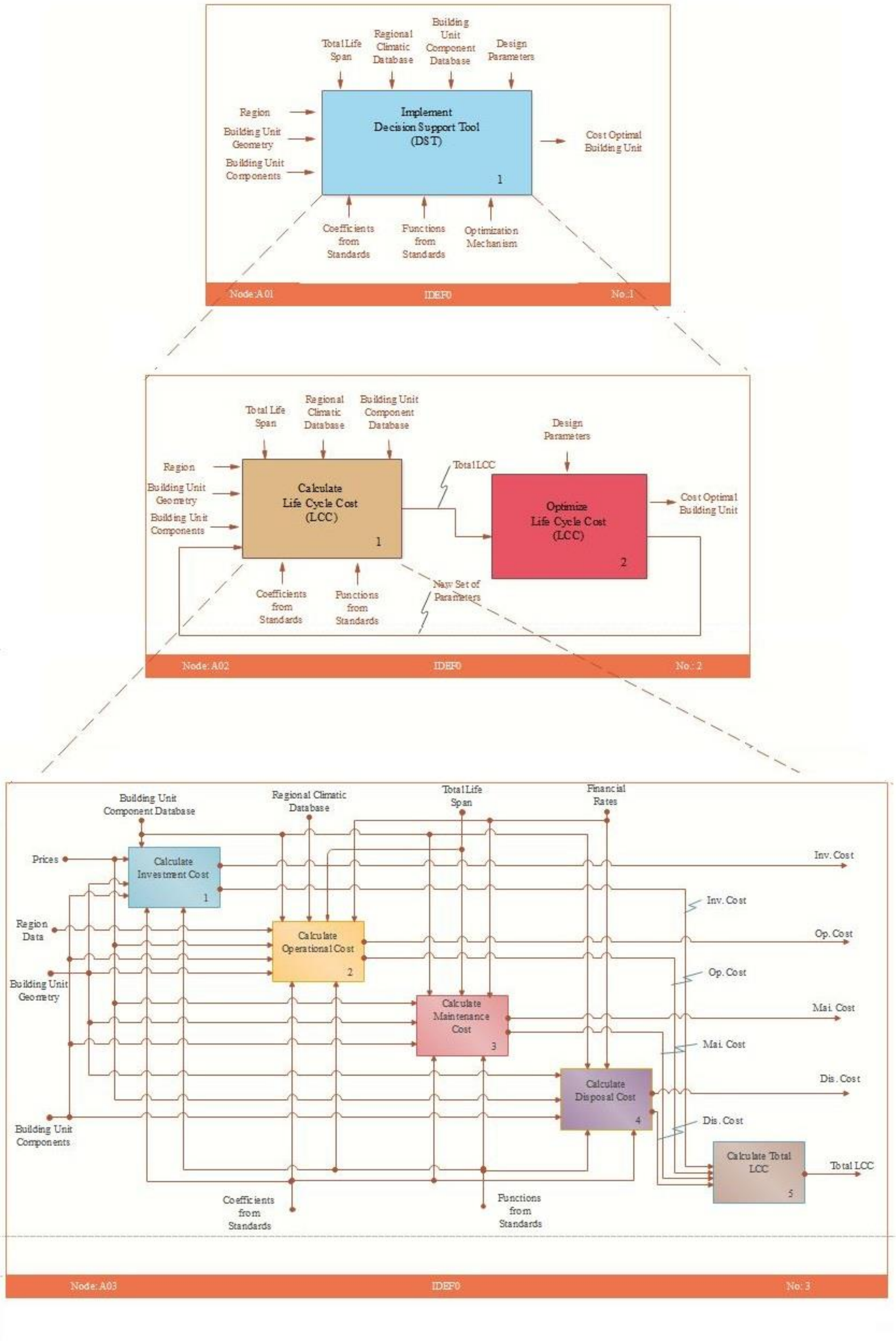


Figure 6: The Decision Support Tool-Process Model (IDEF0)

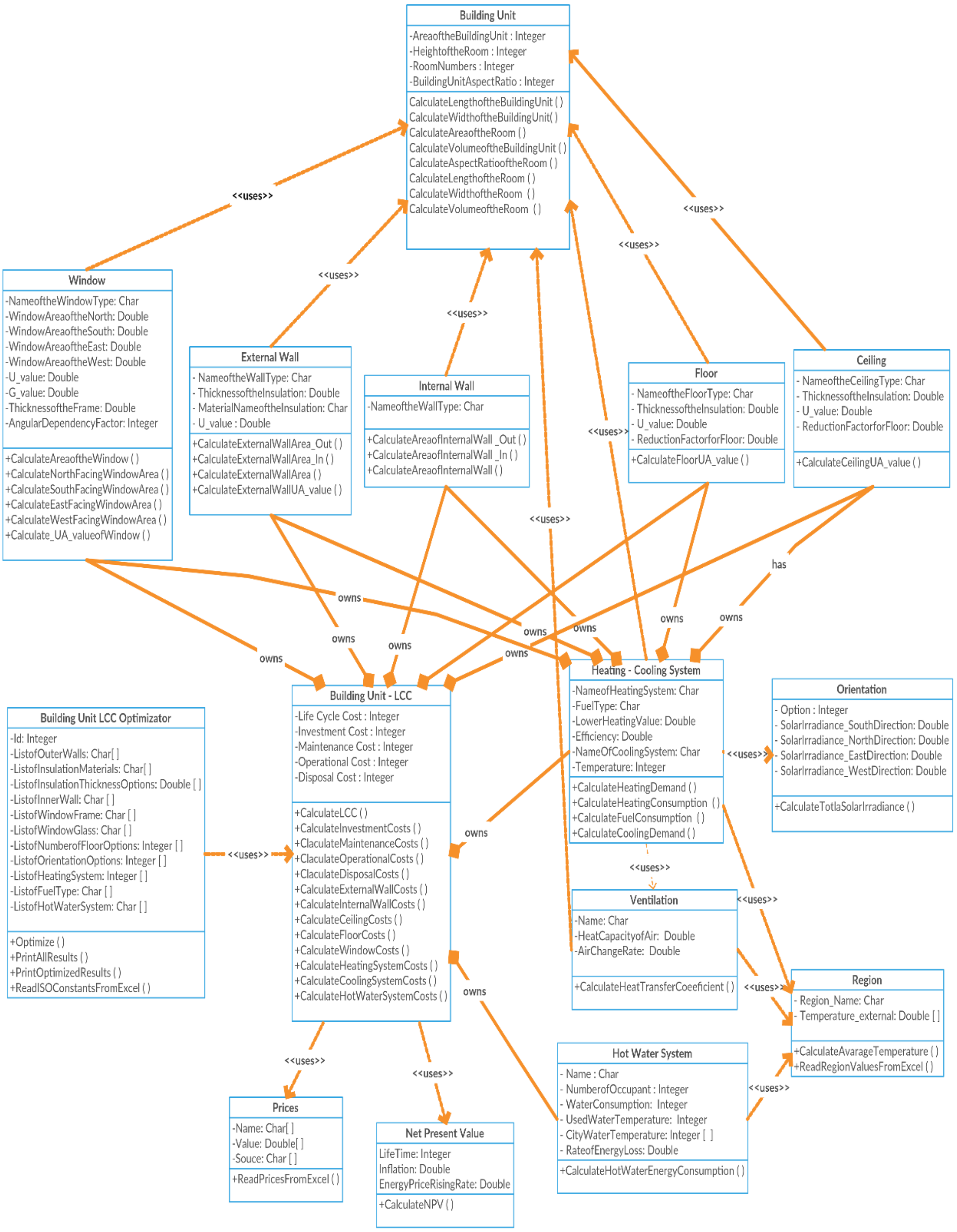


Figure 7: The Decision Support Tool-Data Model (UML)

The model uses the monthly method, known as quasi-steady state method taking into account variations in external temperature and solar radiation. Mathematical equations used in the decision support tool are based on scientific articles, “Energy Performance of Buildings Directive”, “Building Energy Performance Regulation” and the related standards specific to Turkey and life cycle cost, cost-optimal and energy literature.

A comprehensive literature review was conducted while the model was being constructed. In order to create the background of the calculations, the documents and standards in the legislation in force have been completely analyzed. The most important of them for the building is that “Directive 2002/91/EC on Energy Performance in Buildings (EPBD)” and “Building Energy Performance Regulation” is the top-level document in the evaluation of building energy performance. The overview of the EPBD standards are as follows.

Table 1: Overview of the EPBD Standards

GENERAL	
TR 15615	Explanation of the general relationship between various European Standards and the Energy Performance of Buildings Directive (EPBD) - Umbrella document
EN 15217	Energy performance of buildings – Methods for expressing energy performance and for the energy certification of buildings
EN 15603	Energy performance of buildings. Overall energy use and definition of energy ratings
GROUP OF HEATING SYSTEM STANDARDS	
EN 15316-1	Heating systems in buildings - Methods for calculation of system energy requirements and system efficiencies - Part 1: General
EN 15316-2.1	Heating systems in buildings — Method for calculation of system energy requirements and system efficiencies — Part 2-1: Space heating emission systems
EN 15316-2.3	Space heating distribution systems
EN 15316- 3	Heating systems in buildings — Method for calculation of system energy requirements and system efficiencies
EN 15316-3.1	Domestic hot water systems, characterization of needs
EN 15316-3.2	Domestic hot water systems, distribution
EN 15316-3.3	Domestic hot water systems, generation
EN 15316- 4	Heating systems in buildings Method for calculation of system energy requirements and system efficiencies
EN 15316-4.1	Space heating generation systems, combustion systems
EN 15316-4.2	Space heating generation systems, heat pump systems
EN 15316-4.3	Heat generation systems, thermal solar and photovoltaic systems
EN 15316-4.4	Heat generation systems, building-integrated cogeneration systems

Table 1 (continued)

EN 15316-4.5	Space heating generation systems- District heating and cooling, Module
EN 15316-4.6	Heat generation systems, photovoltaic systems
EN 15316-4.7	Space heating generation systems, biomass combustion systems
GROUP OF VENTILATION AND COOLING SYSTEM STANDARDS	
EN 15242	Ventilation for buildings — Calculation methods for the determination of air flow rates in buildings including infiltration
EN15241	Ventilation for buildings – Calculation methods for energy losses due to ventilation and infiltration in commercial buildings
EN13779	Ventilation for non-residential buildings — Performance requirements for ventilation and room-conditioning systems
EN 15243	Ventilation for buildings — Calculation of room temperatures and of load and energy for buildings with room conditioning systems
GROUP OF CALCULATION STANDARDS	
EN-ISO 13790	Energy performance of buildings Calculation of energy use for space heating and cooling
EN-15255	Thermal performance of buildings - Sensible room cooling load calculation - General criteria and validation procedures
EN-15265	Thermal performance of buildings - Calculation of energy needs for space heating and cooling using dynamic methods - General criteria and validation procedures
EN-ISO 13791	Thermal performance of buildings -- Calculation of internal temperatures of a room in summer without mechanical cooling -- General criteria and validation procedures

Table 1 (continued)

EN-ISO 13792	Thermal performance of buildings -- Calculation of internal temperatures of a room in summer without mechanical cooling -- Simplified methods
GROUP OF SUPPORTING STANDARDS	
EN 15193	Energy performance of buildings — Energy requirements for lighting
EN 15232	Energy performance of buildings – Impact of Building Automation, Controls and Building Management
EN 15377	Design of embedded water-based surface heating and cooling systems
EN 15377-1	Determination of the design heating and cooling capacity
EN 15377-2	Design, dimensioning and installation
EN 15377-3	Optimizing for use of renewable energy sources
EN 15459	Economic evaluation procedure for energy systems in buildings. Calculation procedures
EN 15251	Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics

The mathematical equations and assumptions used in the LCC-based decision support tool are compiled from the related standards, documents, and scientific articles.

The study proposed DST including multi-actor collaboration. There exist three main actors which are designer, policy/decision maker, contractor. While each phase of the DST is important to inform policy makers and decision makers and ensuring sustainability, DST guides the designer on how to improve the design and the contractor is only interested in the pre-use phase and the phase informs the contractor about the investment cost of the building.

3.1.1. Life Cycle Costing Based Model

Life cycle costing-based model contains three main parts:

-The first part of pre-usage phase known as initial cost including construction costs. Construction costs can be defined as the sum of the quantities. Such quantities are labor, material, machines *etc*. The construction costs comprise the initial (investment) cost.

-The second part is usage phase including operational and maintenance costs. The operational costs are directly linked to operating the building such as energy, water usage. The calculation of operational costs are frequently calculated per m^2 and annually. In this calculation, future costs are converted to a present cost value. The maintenance costs are the sum of the costs required to maintain a building under good working conditions such as repairs, renewals. The costs occur at specific time intervals and these costs are increasing as the lifespan of the buildings increases.

-The post usage phase includes two part; disposal cost and salvage value. The disposal cost refers to the cost of building demolition.The salvage value represents the revenue from the sale of recycled materials after the building has been demolished. Because of the fact that the use of discounting, the cost is a very small percentage of building total cost.

Figure 8: LCC Model

The discount rate is a critical component in LCC. It represents the time value of money. It is used with the inflation rate in the calculation of present value. Inflation rate can be described as a general increase rate in the price of goods or services without any increase in their prices.

A general formula that could be used to calculate LCC is as follows.

$$LCC = IC_0 + \sum_{t=0}^{N} OC\,.PV_{sum} + \sum_{t=0}^{N} MC\,.PV_{sum} + D.PV \qquad \text{Equation 1}$$

Where

$$PV_{sum} = \frac{(1+r)^t - 1}{r(1+r)^t} \qquad \text{Equation 2}$$

and

$$PV = \frac{1}{(1+r)^t} \qquad \text{Equation 3}$$

IC_0	is initial costs consists of construction cost
OC	is operation costs including annual costs (*i.e.* energy)
MC	is maintenance cost including annual costs (*i.e.* costs for replacement)
DC	is disposal cost
PV	is present value
N	is length of study (year)
t	is time variable
r	is discount rate

LCC calculation results are not always accurate because estimates are made regarding the future based on what is known today. Most of the literature about LCC suggests sensitivity analysis to minimize the uncertainty (Flanagan, 1984; Flanagan *et al.*, 1987; Kirk & Dell'isola, 1995; Sterner, 2000). Sensitivity analysis describes the effect of a change in a single parameter value in a project.

In the thesis, the building is considered as a sum of the building components (*i.e.* wall, floor, ceiling) and the effects on each life-cycle cost phase, of each building component, will be calculated to determine pre-usage phase cost. The building elements to be used in the pre-usage phase have been determined as delphi questionnaire (see Appendix IV).

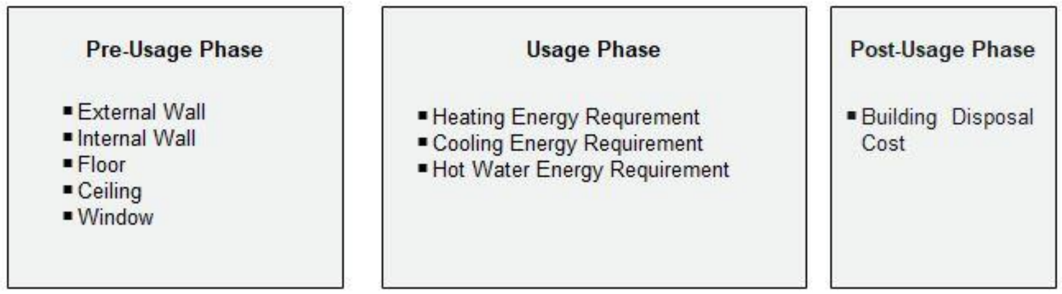
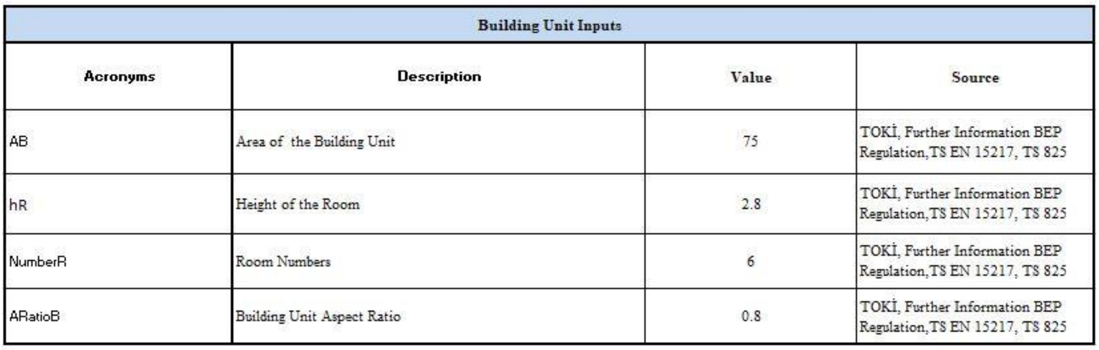


Figure 9: LCC Model-Detail

3.1.1.1. General Information About Building Geometry

The size and geometry of the building have a great effect on the building energy consumption. It is strongly associated with the amount of material used. However, these calculations are quite complex and vary for each house. Therefore, they have been tried to be simplified. The data obtained from this section is vital in the other parts where the building cost will be calculated over its lifetime. The part is designed to be easy-to-use as it is in other parts of the model. This part includes the sources used to construct the model. In this model, input area regarding building geometry is as follows.



Building Unit Inputs			
Acronyms	Description	Value	Source
AB	Area of the Building Unit	75	TOKİ, Further Information BEP Regulation,TS EN 15217, TS 825
hR	Height of the Room	2.8	TOKİ, Further Information BEP Regulation,TS EN 15217, TS 825
NumberR	Room Numbers	6	TOKİ, Further Information BEP Regulation,TS EN 15217, TS 825
ARatioB	Building Unit Aspect Ratio	0.8	TOKİ, Further Information BEP Regulation,TS EN 15217, TS 825

Figure 10: Building Geometry Input Area

One of the things to take into consideration is the number of the rooms. In this model, every space like a bathroom, WC, kitchen *etc.* is accepted as a room. In calculations about the rooms, all rooms are calculated to be the same size, but in-wall calculations where using room sizes as data, the result is the same as those in plans with different room sizes. Another thing is building aspect ratio that affects the geometry of a building. The building aspect ratio has divided the length of the building by its width. The designer will enter inputs in the “value” column. The model will calculate other values needed to determine the building lifecycle cost depending on the input of the designer. These values are the building unit length, the building unit width, the area of the room, the volume of the building unit, the aspect ratio of the room, the room length, the room width, the room volume.

The length of the building unit:

$$L_B = \sqrt{A_B . ARatio_B} \qquad \text{(m) Equation 4}$$

$A_{B.}$:Area of building unit

$ARatio_B$:Building unit aspect ratio

The width of the building unit:

$$W_B = \sqrt{\frac{A_B}{ARatio_B}} \qquad \text{(m) Equation 5}$$

A_B.:Area of building unit

$ARatio_B$:Building unit aspect ratio

The area of the room:

$$A_R = \frac{A_B}{Number_R} \qquad (\text{m}^2) \text{ Equation 6}$$

A_B.:Area of building unit

$Number_R$:Room number

The volume of the building unit:

$$V_B = h_R . A_B \qquad (\text{m}^3) \text{ Equation 7}$$

h_R: Room height

A_B.:Area of building unit

The aspect ratio of the room:

$$ARatio_R = ARatio_B . \frac{4}{Number_R} \qquad \text{Equation 8}$$

$ARatio_B$:Building unit aspect ratio

$Number_R$:Room number

The length of the room:

$$L_R = \sqrt{ARatio_R . A_R} \qquad \text{(m) Equation 9}$$

$ARatio_R$: Room aspect ratio

A_R: Room Area

The room width:

$$W_R = \sqrt{\frac{A_R}{ARatio_R}} \qquad \text{(m) Equation 10}$$

$ARatio_R$: Room aspect ratio

A_R: Room Area

The volume of the room:

$$V \quad = h_R . A_R \qquad \text{(m}^3\text{) Equation 11}$$

h_R: Room height

A_R: Room Area

This section of the model also contains total life cycle time, the region where the building is located, information on building floor number, indoor climate determined in order to provide a suitable climate for the occupants live in.

Total life time Input			
Acronyms	**Description**	**Value**	**Source**
totalLC	total life cycle time	30	Scientific Articles

Figure 11: Total Life Cycle Time Input Area

The dataset created in this section is based on the 30-year time frame used in mortgage applications all over the world. The designer can change this part according to the life cycle the designer wants to calculate.

According to TS 825, thermally Turkey's geography is divided into four regions. These regions are determined according to climatic conditions.

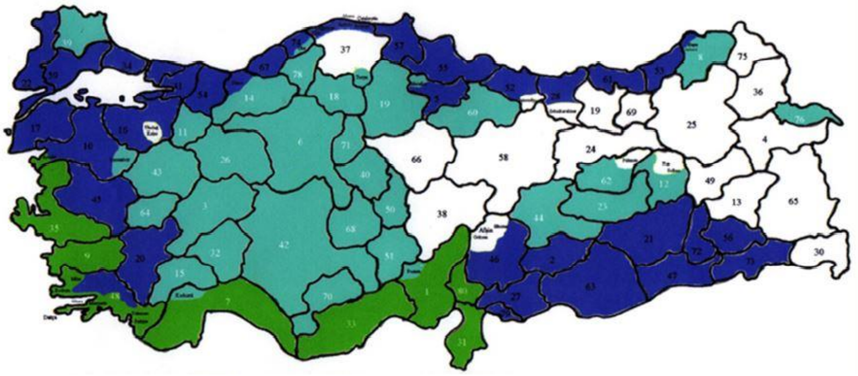
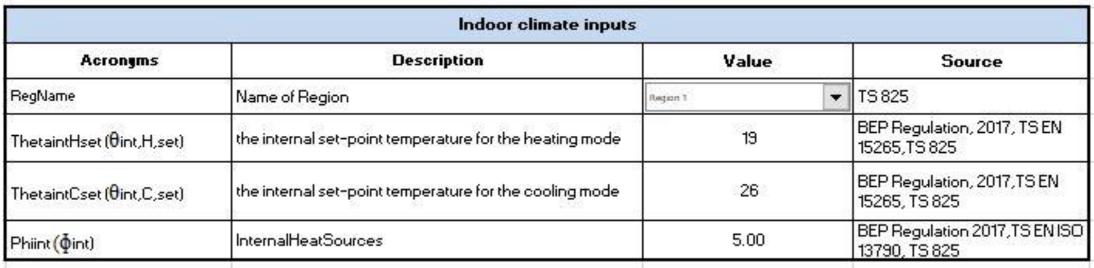


Figure 12: Regions

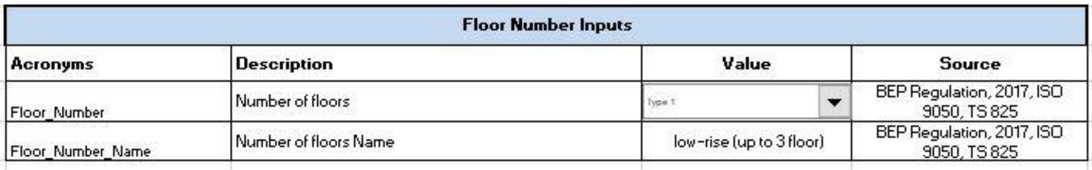
Since the temperature of each region is different, the calculation of life-cycle cost could be different in the housing to be constructed there. Therefore, in the model, it is necessary to determine in which region the housing cost is to be calculated and that region must be selected in the model. It also comes as default in the model at optimum internal temperatures from the standard. According to TS 825 and BEP regulation, the internal gain is accepted as 10 W/m^2 for residential buildings and 10 W/m^2 for office buildings. The model fills in this area automatically. Figure 15 shows “Indoor Climate Inputs” area.



Indoor climate inputs			
Acronyms	Description	Value	Source
RegName	Name of Region	Region 1	TS 825
ThetaintHset (θint,H,set)	the internal set-point temperature for the heating mode	19	BEP Regulation, 2017, TS EN 15265,TS 825
ThetaintCset (θint,C,set)	the internal set-point temperature for the cooling mode	26	BEP Regulation, 2017,TS EN 15265, TS 825
Phiint (Φint)	InternalHeatSources	5.00	BEP Regulation 2017,TS EN ISO 13790, TS 825

Figure 13: Indoor Climate Inputs Area

In this section, the user must choose the number of floors of the apartment where the housing is located. Depending on the floors number selected, the amount of solar radiation will change, then the heating parameters will be affected.



Floor Number Inputs			
Acronyms	Description	Value	Source
Floor_Number	Number of floors	Type 1	BEP Regulation, 2017, ISO 9050, TS 825
Floor_Number_Name	Number of floors Name	low-rise (up to 3 floor)	BEP Regulation, 2017, ISO 9050, TS 825

Figure 14: Floor Number Inputs Area

3.1.1.2. Design Variables

In the decision support tool, alternatives for each building component have been identified. The alternatives are types of components frequently used in the construction sector in Turkey. Each alternative is quantified using the calculations in the standards and legislation. The decision support system has a transparent computable, measurable structure, so the designer can add as alternatives as desired.

-External Wall Types

The external wall has great influence on the building life-cycle cost by affecting its heating and cooling energy demand. The external wall has a significant influence on the initial investment cost and operational cost that incurred during the life cycle of the building. In Turkey, brick, reinforced concrete, pumice masonry unit and autoclaved aerated concrete is used as building material in exterior wall applications

(Aytaç & Aksoy, 2006; Çay, 2011; Deniz *et al.*, 2009; Fertelli, 2013; Gürel & Cingiz, 2000). This tool includes types of an exterior wall made of these materials as a wall type alternative.

Table 2: External Wall Types

Type	Name
Wall Type 1	Pumice Masonry Unit (BIMS Block)
Wall Type 2	Autoclaved Aerated Concrete Wall
Wall Type 3	Reinforced Concrete Wall
Wall Type 4	Brick Wall

-Internal Wall Types

The cost of the wall is an important factor in the investment cost of the housing. The tool consists of four types of internal wall type.

Table 3: Internal Wall Types

Type	Name
Wall Type 1	Brick Wall
Wall Type 2	Autoclaved Aerated Concrete Wall
Wall Type 3	Reinforced Concrete Wall
Wall Type 4	Pumice Masonry Unit (BIMS Block)

-Insulation Material Types

Thermal insulation is the most important aspect of policies developed depending on the concept of energy efficiency all over the world. One of the most important functions of the building is the providing of internal thermal comfort conditions. The insulation material is of utmost importance to achieve this. The most commonly used insulation materials in Turkey have expanded polystyrene insulation boards, extruded polystyrene insulation boards, rock wool, fiberglass (Çomaklı & Yüksel, 2003; Hasan, 1999; Sisman *et al.*, 2007; Yildiz *et al.*, 2008). Therefore, in the tool, these materials were included in the calculations as an alternative.

Table 4: Insulation Material Types

Type	**Name**
Insulation Material Type 1	Expanded Polystyrene Insulation Boards
Insulation Material Type 2	Extruded Polystyrene Insulation Boards
Insulation Material Type 3	Rock wool
Insulation Material Type 4	Fiberglass

-Insulation Material Thicknesses

As for the energy efficiency of the buildings, the thickness of the insulation material is at least as important as the insulation material. The use of insulation material in the right thickness is very important in terms of building energy efficiency. The fact that the insulation material is thicker than the optimum level increases the initial investment cost of the building, while if it is thin, it increases the operating cost of the building. Therefore, it is necessary to make the calculation of the thickness of the most optimum insulation material in the early design stage. In this thesis, ten different insulation material thicknesses were used, taking into account the studies done in this area in the literature (Çomaklı & Yüksel, 2003; Hasan, 1999; Sisman *et al.*, 2007; Yildiz *et al.*, 2008).

Table 5: Insulation Material Thicknesses

Type	Name
Insulation Thicknesses Type 1	0,01m
Insulation Thicknesses Type 2	0,02m
Insulation Thicknesses Type 3	0,03m
Insulation Thicknesses Type 4	0,04m
Insulation Thicknesses Type 5	0,05m
Insulation Thicknesses Type 6	0,06m
Insulation Thicknesses Type 7	0,07m
Insulation Thicknesses Type 8	0,08m
Insulation Thicknesses Type 9	0,09m
Insulation Thicknesses Type10	0,10m
Insulation Thicknesses Type11	0,11m
Insulation Thicknesses Type12	0,12m
Insulation Thicknesses Type13	0,13m
Insulation Thicknesses Type14	0,14m
Insulation Thicknesses Type15	0,15m
Insulation Thicknesses Type16	0,16m
Insulation Thicknesses Type17	0,17m
Insulation Thicknesses Type18	0,18m
Insulation Thicknesses Type19	0,19m
Insulation Thicknesses Type20	0,20m

-Frame of Window

When literature is examined, four kinds of window frames are widely used. They are PVC, Timber Aluminum, Heat-retaining Aluminum (Ayçam, 2006; Maçka, 2008).

Table 6: Window Frame Types

Type	Name
Type 1	PVC Frame
Type 2	Timber Frame
Type 3	Aluminum Frame
Type 4	Heat-retaining Aluminum Frame

-Glass of Window

In this thesis, three different window glass types were calculated.

Table 7: Window Glass Types

Type	Name
Type 1	Single glazing unit
Type 2	Double glazing unit
Type 3	Heat controlled double glazing unit (low-e)

-Number of floors

In this thesis, three different number of floor types were investigated.

Table 8: Number of Floor Types

Type	Name
Type 1	low-rise (up to 3 floor)
Type 2	high-rise (up to 10 floor)
Type 3	higher than 10 floors

-Orientation

Turkey has great solar energy potential. In Turkey, energy efficiency is a vital issue because of external dependency. The potential is an important opportunity to reduce Turkey's external dependency. Orientation among passive solar designs that are used to provide energy efficiency of buildings is the most important (Balcomb *et al.*, 1977; Capeluto, 2003; Givoni, 1991; Hoffman *et al.*, 1983; Morrissey *et al.*, 2011). Studies present that building orientation and shape affect the energy consumption of building (Gadomski, 1987; Jedrzejuk & Marks, 1994; Lin, 1981; Mingfang, 2002; Radford *et al.*, 1984). In this thesis, two different orientations were calculated.

Table 9: Orientation Possibilities

Type	**Name**
Orientation type 1	South-East Direction
Orientation type 2	North-West Direction

-Heating Systems Types

The type of heating system used is critical for energy efficiency in buildings. One of the things to be aware of when making this selection is the total cost of the heating system including operational cost. Therefore, this decision must be given in the first design phase.

Table 10: Heating System Types

Type	**Name**
Heating System type 1	Stand-alone Heating System
Heating System type 2	Central Heating System

-Fuel Types

In this thesis, three different fuel types were calculated.

Table 11: Fuel Types

Type	Name
Fuel type 1	Natural gas
Fuel type 2	Fuel Oil
Fuel type 3	Coal

-Hot Water Systems Types

Water consumption is very important in terms of efficient use of resources. Considerable savings can be achieved by reducing water consumption and choosing the right system. one of the important factors is to consider the total cost of the system, not just the investment cost. In this thesis, two different hot water systems were calculated.

Table 12: Hot Water System Types

Type	Name
Hot Water System type 1	Stand Alone Water Heater
Hot Water System type 2	Combi-boiler

According to these design variables, there exist one-million possibilities. The decision-making tool aims to find the optimum choices by evaluating each possibility under given design constraints.

3.1.1.3. Investment Cost

The building investment cost is described as construction cost in this thesis. The investment cost is of great significance for the total life-cycle cost. Since decisions taken at this phase have considerable effects on the building life-cycle cost. A small measure or a small change taken in this phase can lead to significant savings or wastes during the overall building life cycle cost. In this thesis, the building is considered as a sum of the building components (*i.e.* wall, floor, and ceiling) and the effects on each life-cycle cost phase, of each building component, will be calculated. The building components are as follows.

- Wall
    - External wall
    - Internal wall
- Floor
- Ceiling
- Window

-Wall

In this model, two different wall calculations are made as external wall and the internal wall. The reason for this division is that properties of the internal wall and external wall are different from each other. Different materials are used because the external walls are in contact with the external environment (*i.e.* insulation material). In addition, whereas the internal wall only affects the investment cost and disposal cost, the external wall has an effect on all three phases (investment, operational and disposal cost).

- ***External wall***

The external wall has great influence on building lifecycle cost by affecting its heating and cooling energy demand. The model offers two different external wall calculations for ease of calculation. These types are the external wall of the outer room and the internal wall of the outer room.

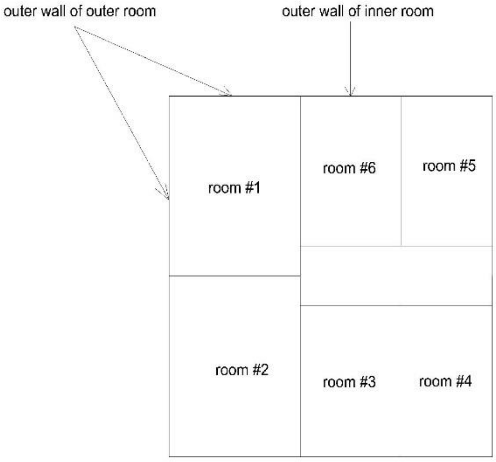


Figure 15: Sample Plan

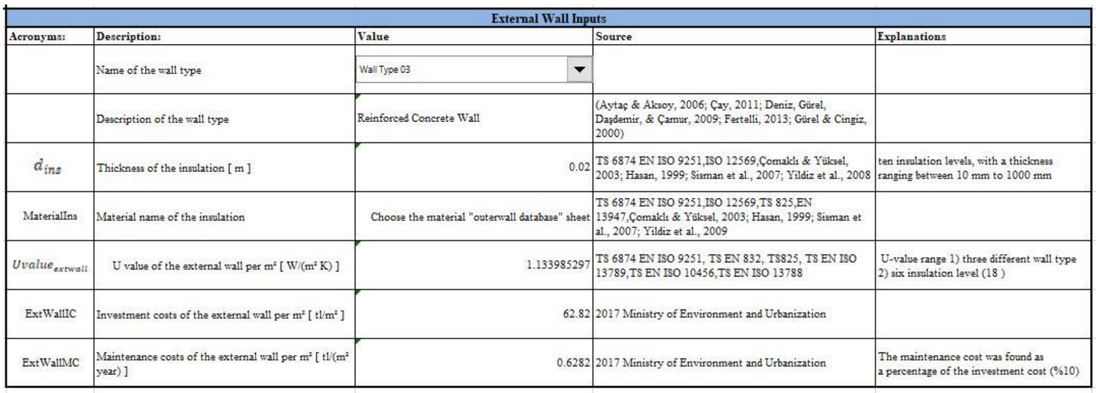
According to sample plan, the area of the external wall of the outer room is calculated as follows.

$Aout_{\mathrm{extwall}} = \mathrm{h_R}.(\mathrm{L_R} + \mathrm{W_R}).4$ (m^2) Equation 12

Area of external wall of inner room is calculated as below

$Ain_{extwall} = h_R.L_R.(Number_R - 4)$ (m^2) Equation 13

This model offers designer the possibility of easy way calculation of life-cycle costs of own choices. Figure 16 represents “External Wall Input” area.

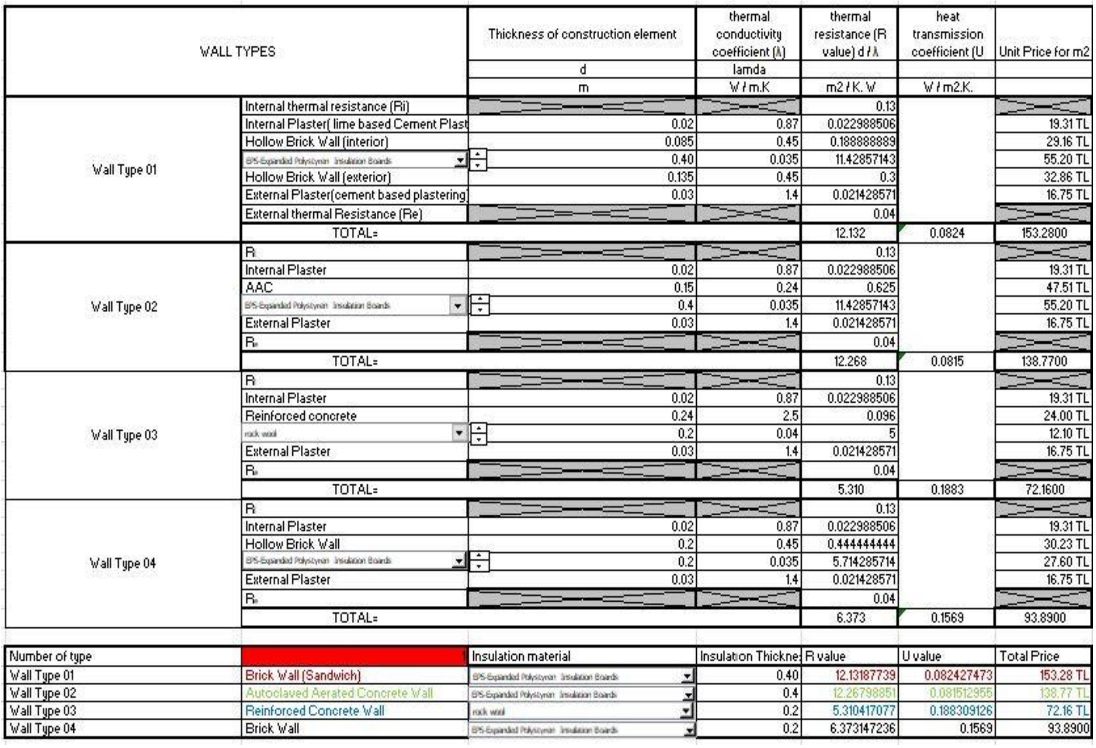


External Wall Inputs

Acronyms:	Description:	Value	Source	Explanations
	Name of the wall type	Wall Type 03		
	Description of the wall type	Reinforced Concrete Wall	(Aytaç & Aksoy, 2006; Çay, 2011; Deniz, Gürel, Daşdemir, & Çamur, 2009; Fertelli, 2013; Gürel & Cingiz, 2000)	
d_{ins}	Thickness of the insulation [m]	0.02	TS 6874 EN ISO 9251,ISO 12569,Çomaklı & Yüksel, 2003; Hasan, 1999; Sisman et al., 2007; Yildiz et al., 2008	ten insulation levels, with a thickness ranging between 10 mm to 1000 mm
MaterialIns	Material name of the insulation	Choose the material "outerwall database" sheet	TS 6874 EN ISO 9251,ISO 12569,TS 825,EN 13947,Çomaklı & Yüksel, 2003; Hasan, 1999; Sisman et al., 2007; Yildiz et al., 2009	
$Uvalue_{extwall}$	U value of the external wall per m² [W/(m² K)]	1.133985297	TS 6874 EN ISO 9251, TS EN 832, TS825, TS EN ISO 13789,TS EN ISO 10456,TS EN ISO 13788	U-value range 1) three different wall type 2) six insulation level (18)
ExtWallIC	Investment costs of the external wall per m² [tl/m²]	62.82	2017 Ministry of Environment and Urbanization	
ExtWallMC	Maintenance costs of the external wall per m² [tl/(m² year)]	0.6282	2017 Ministry of Environment and Urbanization	The maintenance cost was found as a percentage of the investment cost (%10)

Figure 16: External Wall Input Area

In this area, the designer chooses only wall type, the thickness of insulation and thickness of the material. Then U value, investment cost and maintenance cost of the chosen wall type will be calculated automatically. The data in this excel page comes from the following page. The sheet was created by the author, derived from unit prices of the Ministry of Environment and Urbanism and from calculations in standards and regulations.



WALL TYPES		Thickness of construction element	thermal conductivity coefficient (λ)	thermal resistance (R value) d / λ	heat transmission coefficient (U	Unit Price for m2
		d	lamda			
		m	W / m.K	m2 / K. W	W / m2.K.	
Wall Type 01	Internal thermal resistance (Ri)			0.13		
	Internal Plaster(lime based Cement Plast	0.02	0.87	0.022988506		19.31 TL
	Hollow Brick Wall (interior)	0.085	0.45	0.188888889		29.16 TL
	EPS-Expanded Polystyren Insulation Boards	0.40	0.035	11.42857143		55.20 TL
	Hollow Brick Wall (exterior)	0.135	0.45	0.3		32.86 TL
	External Plaster(cement based plastering)	0.03	1.4	0.021428571		16.75 TL
	External thermal Resistance (Re)			0.04		
	TOTAL=			12.132	0.0824	153.2800
Wall Type 02	Ri			0.13		
	Internal Plaster	0.02	0.87	0.022988506		19.31 TL
	AAC	0.15	0.24	0.625		47.51 TL
	EPS-Expanded Polystyren Insulation Boards	0.4	0.035	11.42857143		55.20 TL
	External Plaster	0.03	1.4	0.021428571		16.75 TL
	Re			0.04		
	TOTAL=			12.268	0.0815	138.7700
Wall Type 03	Ri			0.13		
	Internal Plaster	0.02	0.87	0.022988506		19.31 TL
	Reinforced concrete	0.24	2.5	0.096		24.00 TL
	rock wool	0.2	0.04	5		12.10 TL
	External Plaster	0.03	1.4	0.021428571		16.75 TL
	Re			0.04		
	TOTAL=			5.310	0.1883	72.1600
Wall Type 04	Ri			0.13		
	Internal Plaster	0.02	0.87	0.022988506		19.31 TL
	Hollow Brick Wall	0.2	0.45	0.444444444		30.23 TL
	EPS-Expanded Polystyren Insulation Boards	0.2	0.035	5.714285714		27.60 TL
	External Plaster	0.03	1.4	0.021428571		16.75 TL
	Re			0.04		
	TOTAL=			6.373	0.1569	93.8900

Number of type		Insulation material	Insulation Thickne	R value	U value	Total Price
Wall Type 01	Brick Wall (Sandwich)	EPS-Expanded Polystyren Insulation Boards	0.40	12.13187739	0.082427473	153.28 TL
Wall Type 02	Autoclaved Aerated Concrete Wall	EPS-Expanded Polystyren Insulation Boards	0.4	12.26798851	0.081512955	138.77 TL
Wall Type 03	Reinforced Concrete Wall	rock wool	0.2	5.310417077	0.188309126	72.16 TL
Wall Type 04	Brick Wall	EPS-Expanded Polystyren Insulation Boards	0.2	6.373147236	0.1569	93.8900

Figure 17: External Wall Type Dataset Sheet

The value of thermal resistance and thermal transmittance are determined in TS 825. Thermal resistance also identified as R-value is the ability of a material to resist the flow of heat. It depends on the materials thickness and the conductivity of the materials used. R-value can be expressed as:

$$R = \frac{d}{\lambda_h} \qquad (m^2.K/W) \text{ Equation 14}$$

d is the thickness of the materials

λ_h is the conductivity of the materials used

For multi-layer structural elements, thermal resistance is calculated by using individual structural element thicknesses and the thermal conductivity values of these structural elements shown in Equation 15.

$$R = \frac{d_1}{\lambda_{h1}} + \frac{d_2}{\lambda_{h2}} + \cdots . + \frac{d_n}{\lambda_{hn}} \qquad (m^2.K/W) \text{ Equation 15}$$

Thermal transmittance also identified as U-value is a significant concept in building design. It represents the rate of transfer of heat between two spaces with different temperatures through one square meter of a building element. According to TS 825 and BEP Regulation the calculation of thermal transmittance is as follows:

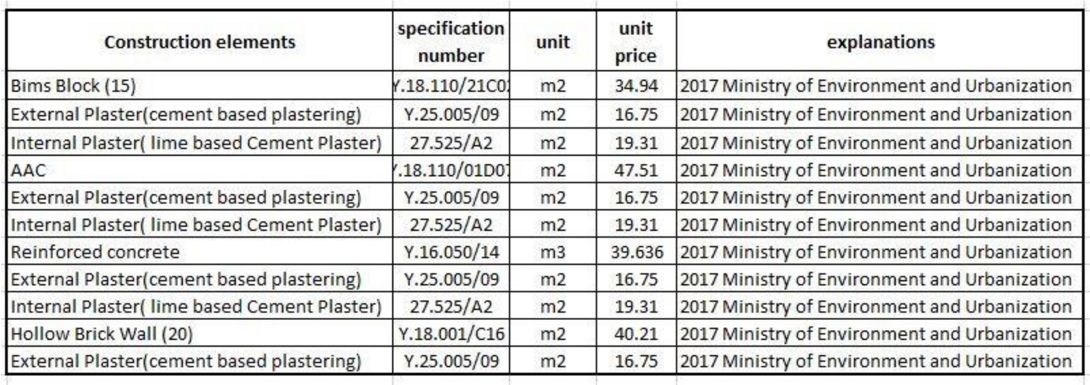
$$U = \frac{1}{R_{si}+R_m+R_{se}} \qquad (W/\ m^2.K) \text{ Equation 16}$$

R_{si} is the surface resistance of internal surface

R_{se} is the surface resistance of the external surface

The surface resistance of the external and internal surface is determined in TS 825, TS EN ISO 13789 and BEP Regulation.

Each material is assigned a corresponding item number, and the price of 2017 published by the Ministry of Environment and Urbanism has been used according to the corresponding item number.



Construction elements	specification number	unit	unit price	explanations
Bims Block (15)	Y.18.110/21C0	m2	34.94	2017 Ministry of Environment and Urbanization
External Plaster(cement based plastering)	Y.25.005/09	m2	16.75	2017 Ministry of Environment and Urbanization
Internal Plaster(lime based Cement Plaster)	27.525/A2	m2	19.31	2017 Ministry of Environment and Urbanization
AAC	.18.110/01D0	m2	47.51	2017 Ministry of Environment and Urbanization
External Plaster(cement based plastering)	Y.25.005/09	m2	16.75	2017 Ministry of Environment and Urbanization
Internal Plaster(lime based Cement Plaster)	27.525/A2	m2	19.31	2017 Ministry of Environment and Urbanization
Reinforced concrete	Y.16.050/14	m3	39.636	2017 Ministry of Environment and Urbanization
External Plaster(cement based plastering)	Y.25.005/09	m2	16.75	2017 Ministry of Environment and Urbanization
Internal Plaster(lime based Cement Plaster)	27.525/A2	m2	19.31	2017 Ministry of Environment and Urbanization
Hollow Brick Wall (20)	Y.18.001/C16	m2	40.21	2017 Ministry of Environment and Urbanization
External Plaster(cement based plastering)	Y.25.005/09	m2	16.75	2017 Ministry of Environment and Urbanization

Figure 18: Sample Specification Number and Unit Price Sheet

In the light of this information, the following calculations are made automatically by the model according to the wall type, insulation thickness and insulation material selected by the designer.

Total external wall area:

$$A_{extwall} = (Aout_{extwall} + Ain_{extwall}) - A_W$$ (m^2) Equation 17

U value of external wall:

$$Uvalue_{extwall} = \frac{1}{R_{si}+R_1+\cdots+R_{se}}$$ (W/m^2. K) Equation 18

UA value of Total External wall area:

$$UAvalue_{extwall} = Uvalue_{extwall}.A_{extwall}$$ (W/K) Equation 19

$Uvalue_{extwall}$: U value of external wall

Investment costs external wall:

$$TotalExtWallIC = ExtWallIC.A_{extwall}$$ (TL) Equation 20

Maintenance costs external wall:

$$TotalExtWallMC = ExtWallMC.A_{extwall}$$ (TL/year)Equation21

- ***Internal wall***

For the internal wall, there exist two different calculations in terms of ease of calculation and compliance with each project. In this internal wall calculation, as in the calculation of the external wall, the area of the internal wall is divided into inner and outer room wall area.

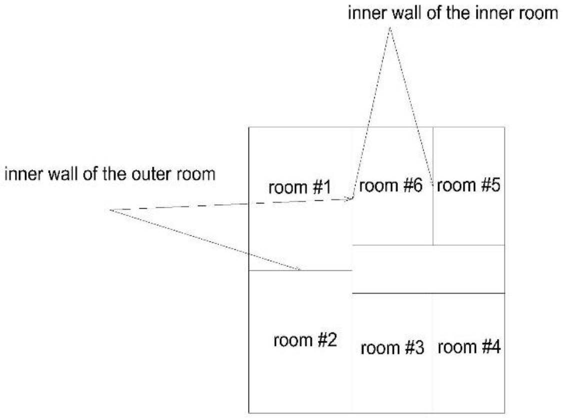


Figure 19: Sample Plan

The internal wall of an outer room calculation is expressed as follows.

$$Aout_{intwall} = h_R.(L_R + W_R).0{,}5.4 \quad (m^2) \text{ Equation 22}$$

h_R: Room height

L_R: Room length

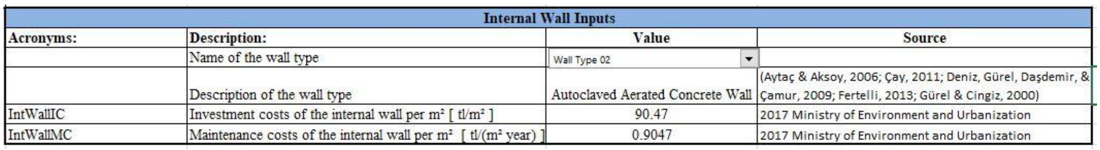
W_R: Room width

In the internal wall of an outer room calculation, a reduction factor of 0,5 is used because two rooms share an internal wall.

The internal wall of an inner room is calculated as follows.

$Ain_{intwall} = h_R . L_R . (Number_R - 4)$ (m^2) Equation 23

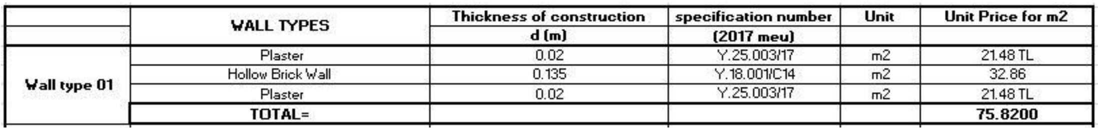
"Internal Wall Input" area in the model are shown in Figure 20.



Internal Wall Inputs			
Acronyms:	Description:	Value	Source
	Name of the wall type	Wall Type 02 ▾	
	Description of the wall type	Autoclaved Aerated Concrete Wall	(Aytaç & Aksoy, 2006; Çay, 2011; Deniz, Gürel, Daşdemir, & Çamur, 2009; Fertelli, 2013; Gürel & Cingiz, 2000)
IntWallIC	Investment costs of the internal wall per m² [tl/m²]	90.47	2017 Ministry of Environment and Urbanization
IntWallMC	Maintenance costs of the internal wall per m² [tl/(m² year)]	0.9047	2017 Ministry of Environment and Urbanization

Figure 20: Internal Wall Inputs

In this area, the designer chooses only internal wall type. Afterward, investment cost and maintenance cost of the chosen wall type will be calculated automatically. The data in this excel page comes from the following page (Figure 21). The author, derived from unit prices of the Ministry of Environment and Urbanism, created the sheet.



	WALL TYPES	Thickness of construction	specification number	Unit	Unit Price for m2
		d (m)	(2017 meu)		
Wall type 01	Plaster	0.02	Y.25.003/17	m2	21.48 TL
	Hollow Brick Wall	0.135	Y.18.001/C14	m2	32.86
	Plaster	0.02	Y.25.003/17	m2	21.48 TL
	TOTAL=				75.8200

Figure 21: Internal Wall Type Dataset Sheet (Sample)

The investment cost also includes labor cost. In the internal wall calculations, after the designer selects internal wall type, the model automatically performs the following calculations.

Internal Wall Area:

$A_{intwall} = \mathrm{Aout}_{intwall} + \mathrm{Ain}_{intwall}$ (m^2) Equation 24

Internal Wall Investment Cost:

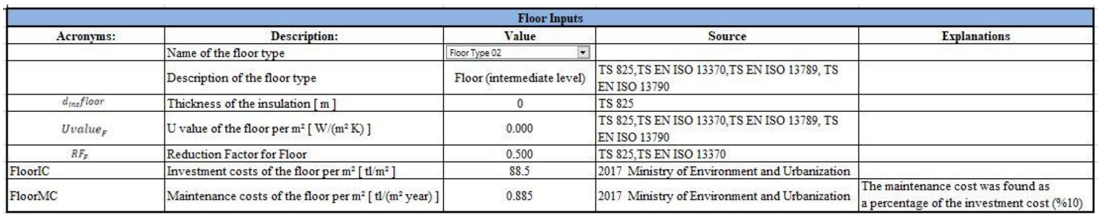
$\mathrm{TotalIntWallIC} = \mathrm{IntWallIC} . A_{intwall}$ (TL) Equation 25

Internal Wall Maintenance Cost:

$$\text{TotalIntWallMC} = \text{IntWallMC}.A_{intwall} \qquad \text{(TL/year) Equation 26}$$

-Floor

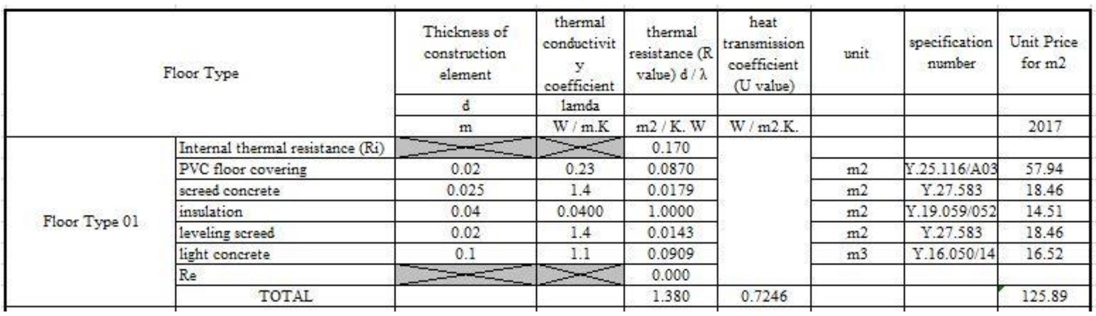
The floor is a crucial part of a building. It also has a considerable effect on the life-cycle cost of the building. There exist three different types of floor in this model. These floor types are a basement, intermediate level, and upper level. The main reason for this classification is the use of materials. Because, if the floor is connected the ground, it is necessary to use insulation materials because heat can be lost through the floor. This affects both the cost and the U and R values of the floor when compared to the intermediate and upper floor. In this model, If the housing is in the middle of the upper floor, U value and R-value are not calculated. Then, they are not included in calculations for heating and cooling.



Floor Inputs				
Acronyms:	**Description:**	**Value**	**Source**	**Explanations**
	Name of the floor type	Floor Type 02		
	Description of the floor type	Floor (intermediate level)	TS 825,TS EN ISO 13370,TS EN ISO 13789, TS EN ISO 13790	
$d_{ins}floor$	Thickness of the insulation [m]	0	TS 825	
$Uvalue_F$	U value of the floor per m² [W/(m² K)]	0.000	TS 825,TS EN ISO 13370,TS EN ISO 13789, TS EN ISO 13790	
RF_F	Reduction Factor for Floor	0.500	TS 825,TS EN ISO 13370	
FloorIC	Investment costs of the floor per m² [tl/m²]	88.5	2017 Ministry of Environment and Urbanization	
FloorMC	Maintenance costs of the floor per m² [tl/(m² year)]	0.885	2017 Ministry of Environment and Urbanization	The maintenance cost was found as a percentage of the investment cost (%10)

Figure 22: Floor Inputs

In this section, the designer just selects the floor types defined as a basement, intermediate level, and upper level. following the selection of the floor type, Other values will be automatically completed by the model. The data in this excel page comes from the following page (Figure 23). The sheet was created by the author, derived from unit prices of the Ministry of Environment and Urbanism and from calculations in standards and regulations. The value of thermal resistance and thermal transmittance are calculated as determined in “TS 825”, “TS EN ISO 13370”, “TS EN ISO 13789”, “TS EN ISO 1379”.



Floor Type		Thickness of construction element	thermal conductivity coefficient	thermal resistance (R value) d / λ	heat transmission coefficient (U value)	unit	specification number	Unit Price for m2
		d	lamda					
		m	W / m.K	m2 / K. W	W / m2.K.			2017
Floor Type 01	Internal thermal resistance (Ri)			0.170				
	PVC floor covering	0.02	0.23	0.0870		m2	Y.25.116/A03	57.94
	screed concrete	0.025	1.4	0.0179		m2	Y.27.583	18.46
	insulation	0.04	0.0400	1.0000		m2	Y.19.059/052	14.51
	leveling screed	0.02	1.4	0.0143		m2	Y.27.583	18.46
	light concrete	0.1	1.1	0.0909		m3	Y.16.050/14	16.52
	Re			0.000				
	TOTAL			1.380	0.7246			125.89

Figure 23: Sample Floor Input Database Sheet

In the floor calculations, after the designer chooses floor type, the model automatically performs the following calculations.

Floor U value:

$$Uvalue_F = \frac{1}{R_i + R_1 + \cdots + R_e}$$ (W / m^2.K) Equation 27

Floor UA value:

$$UAvalue_F = Uvalue_F . A_R . RF_F$$ (W/K) Equation 28

Floor Investment Cost for Room:

$$RoomFloorIC = FloorIC . A_R$$ (TL) Equation 29

Floor Maintenance Cost for Room:

$$FloorMC = FloorMC . A_R$$ (TL/year) Equation 30

Total Floor Investment Cost:

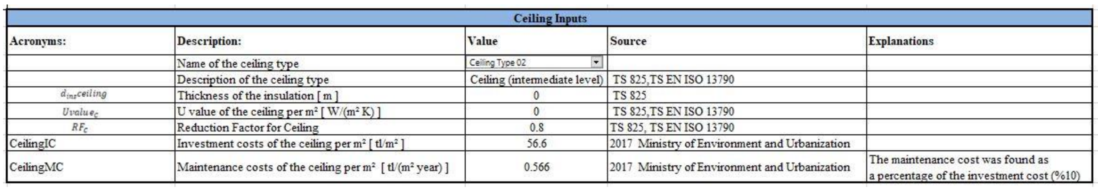
$$TotalFloorIC = RoomFloorIC . Number_R$$ (TL) Equation 31

Total Floor Maintenance Cost:

$$TotalFloorMC = RoomFloorMC.Number_R \qquad \text{(TL/year) Equation 32}$$

-Ceiling

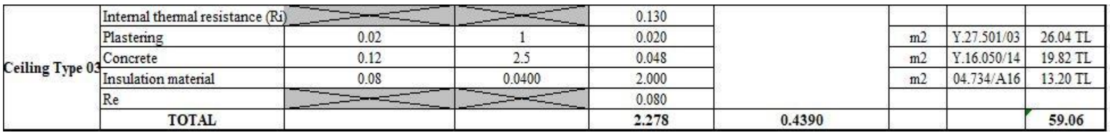
The ceiling has a great impact on the building lifecycle cost due to heat losses from buildings occur through the ceiling. There exist three different types of the ceiling in this model. These ceiling types are a basement, intermediate level, and upper level. The main reason for this classification is the use of materials. Because, if the ceiling is connected the roof, it is necessary to use insulation materials because heat will be lost through the ceiling. This affects both the cost and the U and R values of the ceiling when compared to the basement and intermediate level floor. In this model, if the housing is in the basement or the middle floor, U value and R-value are not calculated. Then, they are not included in calculations for heating and cooling.



Ceiling Inputs				
Acronyms:	**Description:**	**Value**	**Source**	**Explanations**
	Name of the ceiling type	Ceiling Type 02		
	Description of the ceiling type	Ceiling (intermediate level)	TS 825,TS EN ISO 13790	
$d_{ins}ceiling$	Thickness of the insulation [m]	0	TS 825	
$Uvalue_C$	U value of the ceiling per m² [W/(m² K)]	0	TS 825,TS EN ISO 13790	
RF_C	Reduction Factor for Ceiling	0.8	TS 825, TS EN ISO 13790	
CeilingIC	Investment costs of the ceiling per m² [tl/m²]	56.6	2017 Ministry of Environment and Urbanization	
CeilingMC	Maintenance costs of the ceiling per m² [tl/(m² year)]	0.566	2017 Ministry of Environment and Urbanization	The maintenance cost was found as a percentage of the investment cost (%10)

Figure 24: Ceiling Input Area

In this area, the designer just selects the ceiling types defined as a basement, intermediate level, and upper level. After the selection of the ceiling type, other values will be automatically completed by the model. The data in this excel page comes from the following page (Figure 25). The sheet was created by the author, derived from unit prices of the Ministry of Environment and Urbanism and from calculations in standards and regulations. The value of thermal resistance and thermal transmittance are calculated as determined in “TS 825” and “TS EN ISO 13790”.



Ceiling Type 03	Internal thermal resistance (Ri)			0.130				
	Plastering	0.02	1	0.020		m2	Y.27.501/03	26.04 TL
	Concrete	0.12	2.5	0.048		m2	Y.16.050/14	19.82 TL
	Insulation material	0.08	0.0400	2.000		m2	04.734/A16	13.20 TL
	Re			0.080				
	TOTAL			**2.278**	**0.4390**			**59.06**

Figure 25: Sample Floor Input Database Sheet

In the ceiling calculations, after the designer chooses one of the ceiling types, the model automatically performs the following calculations.

Ceiling U value:

$$Uvalue_C = \frac{1}{R_i + R_1 + \cdots + R_e} \qquad \text{(W / m2.K) Equation 33}$$

Ceiling UA value:

$$UAvalue_C = Uvalue_C . A_R . RF_C \qquad \text{(W/K) Equation 34}$$

Ceiling Investment Cost for Room:

$$RoomCeilingIC = Ceiling\text{IC}. A_R \qquad \text{(tl) Equation 35}$$

Ceiling Maintenance Cost for Room:

$$CeilingMC = Ceiling\text{MC}. A_R \qquad \text{(tl/year) Equation 36}$$

Ceiling Investment Cost:

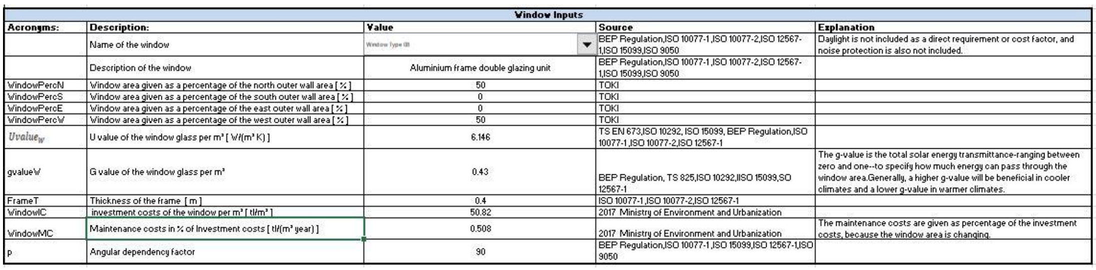
$$ToalCeilingIC = RoomCeilingIC. Number_R \qquad \text{(tl) Equation 37}$$

Ceiling Maintenance Cost:

$$TotalCeilingMC = RoomCeilingMC.Number_R \qquad \text{(tl/year) Equation 38}$$

-*Window*

The window is one of the most significant building elements. It influences almost all the comfort variables and also affects the life-cycle cost of the building. Windows transmit heat through its glass and frame. However, it causes heat loss according to the performance of a window and at the same time, it has heat gain through solar energy transmission. Therefore, the window is crucial to the building energy efficiency. In this model, window and orientation are in bidirectional interaction. According to the orientation of the building, heat gain through solar energy transmission could be calculated. This model suggests window input area shown in Figure 26.



Window Inputs

Acronyms:	Description:	Value	Source	Explanation
	Name of the window	Window Type (8)	BEP Regulation,ISO 10077-1 ,ISO 10077-2,ISO 12567-1,ISO 15099,ISO 9050	Daylight is not included as a direct requirement or cost factor, and noise protection is also not included.
	Description of the window	Aluminium frame double glazing unit	BEP Regulation,ISO 10077-1 ,ISO 10077-2,ISO 12567-1,ISO 15099,ISO 9050	
WindowPercN	Window area given as a percentage of the north outer wall area [%]	50	TOKI	
WindowPercS	Window area given as a percentage of the south outer wall area [%]	0	TOKI	
WindowPercE	Window area given as a percentage of the east outer wall area [%]	0	TOKI	
WindowPercW	Window area given as a percentage of the west outer wall area [%]	50	TOKI	
$Uvalue_W$	U value of the window glass per m² [W/(m² K)]	6.146	TS EN 673,ISO 10292, ISO 15099, BEP Regulation,ISO 10077-1 ,ISO 10077-2,ISO 12567-1	
gvalueW	G value of the window glass per m²	0.43	BEP Regulation, TS 825,ISO 10292,IISO 15099,SO 12567-1	The g-value is the total solar energy transmittance-ranging between zero and one--to specify how much energy can pass through the window area.Generally, a higher g-value will be beneficial in cooler climates and a lower g-value in warmer climates.
FrameT	Thickness of the frame [m]	0.4	ISO 10077-1 ,ISO 10077-2,ISO 12567-1	
WindowIC	investment costs of the window per m² [tl/m²]	50.82	2017 Ministry of Environment and Urbanization	
WindowMC	Maintenance costs in % of Investment costs [tl/(m² year)]	0.508	2017 Ministry of Environment and Urbanization	The maintenance costs are given as percentage of the investment costs, because the window area is changing.
p	Angular dependency factor	90	BEP Regulation,ISO 10077-1 ,ISO 15099,ISO 12567-1,ISO 9050	

Figure 26: Window Inputs

In this area, the designer selects one of the window types. Then, the designer enters the window percentages located on the facades of the building (north, south, east, west façade). Afterward, the model calculates window U value, g value, investment cost, and maintenance cost automatically. The data in this excel page comes from the "window database sheet" in the model. The sheet was created by the author, derived from unit prices of the Ministry of Environment and Urbanism and from calculations in standards and regulations. The value of thermal resistance and thermal transmittance are calculated as determining in TS 825 and TS EN 673. The g- value is another important value for windows. The g-value is the total solar energy transmission and varies from zero to one. If this value is close to zero, it means that the lower solar energy can pass through glass and if it is close to one, it means that the higher solar energy can pass. In the window calculations, after the designer chooses one of the window types, the model automatically performs the following calculations.

Area of the window:

$$A_W = A_{W,S} + A_{W,N} + A_{W,E} + A_{W,W} \qquad (\text{m}^2) \text{ Equation 39}$$

North facing window area (according to building orientation):

$$A_{W,N} = \frac{WindowPercN}{100}.W_B.h_R \qquad (\text{m}^2) \text{ Equation 40}$$

South facing window area (according to building orientation):

$$A_{W,S} = \frac{WindowPercS}{100}.W_B.h_R \qquad (\text{m}^2) \text{ Equation 41}$$

East facing window area (according to building orientation):

$$A_{W,E} = \frac{WindowPercE}{100}.L_B.h_R \qquad (\text{m}^2) \text{ Equation 42}$$

West facing window area (according to building orientation):

$$A_{W,W} = \frac{WindowPercW}{100}.L_B.h_R \qquad (\text{m}^2) \text{ Equation 43}$$

Window UA value:

$UAvalue_W = Uvalue_W . A_W$ (W/K) Equation 44

Window Investment Cost:

$TotalWindowIC = WindowIC . A_W$ (tl) Equation 45

Window Maintenance Cost:

$TotalWindowMC = WindowMC . A_W$ (tl/year) Equation 46

3.1.1.4. Operational Cost

The building operational cost can be described as the sum of the costs incurred during the usage phase. When analyzing the literature, it is clear that operating costs of the housing have a considerable percentage among the other costs of the housing (Mithraratne & Vale, 2004; Pellegrini-Masini *et al.*, 2010; Wong *et al.*, 2010). In this thesis, the operational cost is examined in terms of energy.

-Theoretical background of Heating and Cooling Energy Needs Calculations

Energy demand in Turkey has been rising rapidly in recent years. Particularly, residential energy demand has a big share in total energy demand. Heating and cooling play a substantial role in the residential energy demand. In Turkey, the heating and cooling constitute approximately 75% of the energy consumption in the buildings (UNDP, 2010). Residential energy demand is based on building material thermal characteristics, internal air temperature, orientation, and local climate *etc.* (Runming Yao & Steemers, 2005). Calculating energy demand is a complicated issue due to the following factors (Swan & Ugursal, 2009):

- The sector encompasses a wide variety of structure sizes, geometries, and thermal envelope materials.
- Occupant behavior varies widely and can impact energy consumption by as much as 100% for a given dwelling.

- Privacy issues limit the successful collection or distribution of energy data related to individual households.

According to ISO standards (2008), the calculation steps are defined as follows.

1) Choose the type of calculation method.
2) Define the boundaries of the total of conditioned spaces and the unconditioned spaces.
3) If required, define the boundaries of the different calculation zones
4) Define the indoor conditions for the calculations and the external climatic and other environmental data inputs.
5) Calculate, per period and building zone, the energy needs for heating, and the energy need for cooling.
6) Combine the results for different periods and different zones serviced by the same systems and calculate the energy use for heating and for cooling taking into account the dissipated heat of the heating and cooling systems
7) Calculate the operational length of the heating and cooling season
8) Depending on the application and type of building (to be decided nationally), it may be required to perform the calculation of the energy need for heating and cooling in multiple steps, for instance, to account for interactions between the building and the system, or between adjacent zones.

As pointed out in ISO standards, there are two main calculation methods of heating-cooling energy needs. First one is quasi-steady state methods. These methods are calculated the heat balance for long enough time to disregard heat stored or released. The long enough time is generally one month or a whole season. The second calculation method is dynamic method. Unlike quasi-steady state methods, the methods are calculated the heat balance with short periods generally one hour and the heat stored or released are taking into consideration. Both methods have advantages and disadvantages against each other. The simple hourly method known as dynamic method constitute hourly patterns by comparing hourly changes in buildings, external climatic conditions, and building systems. Due to the fact that the method results are derived from direct calculations, the user cannot predict for subsequent calculations by monthly or annual correlation coefficients. However, the monthly method, known as quasi-steady state method uses correlation coefficients. The coefficients are defined in TS EN ISO 13790. Moreover, this method provides more reliable and precise results for calculations annually unlike the simple hourly known as a dynamic method(TS ISO 13790,2008).

TS EN ISO-13790 (2008) investigates the validity of the monthly calculation method according to EN 15265 which specifies a set of assumptions, requirements and validation tests. The buildings' annual energy requirements located in three different European cities (Paris, Stockholm, and Rome) in the test cases are determined using the monthly method. The results are compared with the simple hourly method results. The results of the comparison show that the deviations of the results of "the monthly method" are lower than "the simple hourly method" (TS EN ISO 13790, 2008). Moreover, the climate data and the hourly patterns in using a simple hourly calculation method, are not public domain. In Turkey, a monthly calculation method has been suggested as a national evaluation tool of Turkey by TS825. The tool uses the climatic data for a representative meteorological year and a resultant temperature (known as an operative temperature) as a set temperature with monthly patterns. It also uses for several cities' typical meteorological years.

In the LCC-based model, the use of the monthly calculation method is the reason for the preference for the following reasons:

- The number of calculation steps compared to the simple hourly method
- The availability of "convergence coefficients"
- The comparability of following calculations in annual and monthly assessments
- The lack of data on hourly use patterns in public domain
- The accessibility of monthly method data
- The difficulties in obtaining hourly climate data

In literature, quasi-steady state method is widely used (Al-Homoud, 2001, p.; Atmaca, 2016; Çomaklı & Yüksel, 2003; Durmayaz *et al.*, 2000; Garcia-Hansen *et al.*, 2002; Hasan, 1999; Holman, 1997; Schlueter & Thesseling, 2009; Sisman *et al.*, 2007; J. A. White & Reichmuth, 1996; Yildiz *et al.*, 2008).

When analyzing the calculation of energy required for cooling and heating used in the literature, it is seen that all of them are derived from the "TS EN ISO 13790", "TS825" and the "BEP-TR Regulation".

The energy requirement for space heating corresponds to the difference between the "total heat transfer" ($\mathrm{Q_{H,ht}}$) and the "total heat gains" ($\mathrm{Q_{H,gn}}$) corrected by "the dimensionless gain utilization factor". It is calculated as:

$$Q_{H,nd} = Q_{H,ht} - \eta_{H,gn} . Q_{H,gn} \qquad \text{(MJ) Equation 47}$$

In the formula, H refers to heating and $Q_{H,nd}$ must be equal or greater than zero.

$Q_{H,nd}$ is the building energy need for heating, in MJ

$Q_{H,ht}$ is the total heat transfer for the heating mode

$\eta_{H,gn}$ is the dimensionless gain utilization factor

$Q_{H,gn}$ are the total heat gains for the heating mode

- ***Heat losses***

In a building, there exist two type heat transfers; "transmission" ($\mathrm{Q_{tr}}$) and "ventilation" ($\mathrm{Q_{ve}}$). The total heat transfer is equal to the sum of the heat transfer through the ventilation and transmission calculated for each month. The overall heat transfer ($\mathrm{Q_{H,ht}}$) is calculated as:

$$Q_{H,ht} = Q_{tr} + Q_{ve} \qquad \text{(MJ) Equation 48}$$

The heat transfer by transmission for heating mode equals to multiply the total heat transfer coefficient (H_{tr}) by the temperature difference between the internal set point ($\theta_{int,H,set}$) and the external environment (θ_{e}) for the heating duration of each month. The heat transfer by transmission is computed as follows:

For heating:

$$Q_{tr} = \left[H_{tr}\left(\theta_{int,H,set} - \theta_{e}\right)\right]t \qquad \text{(MJ) Equation 49}$$

For cooling:

$$Q_{tr} = \left[H_{tr}\left(\theta_{e} - \theta_{int,C,set}\right)\right]t \qquad \text{(MJ) Equation 50}$$

H_{tr} is the overall heat transfer coefficient
$\theta_{int,H,set}$ is the internal set-point temperature for the heating mode
$\theta_{int,C,set}$ is the internal set-point temperature for the cooling mode
θ_{e} is the external temperature

In the “BEP-TR Regulation” and “TS EN ISO 13790”, the internal set point temperature($\theta_{int,set}$) for the heating mode is determined as 20°C and for the cooling mode at 26°C. Therefore, in the decision support tool, these temperatures are accepted.

Similar to the calculation of the overall heat transfer by transmission, the total heat transfer by ventilation is computed as:

For heating:

$$Q_{ve} = H_{tr}\left(\theta_{int,H,set} - \theta_{e}\right)t \qquad \text{(MJ) Equation 51}$$

For cooling:

$$Q_{ve} = H_{tr}\left(\theta_{\ e} - \theta_{\ int,C,set}\right)t \qquad \text{(MJ) Equation 52}$$

- ***Heat Transmission Coefficients***

The heat transmission could be divided into four. They are *"from conditioned spaces to the external environment"*, *"to the ground"*, *"through unconditioned spaces"*, and *"to unconditioned buildings"*. The total heat transmission coefficient by transmission is equal to the sum of all. According to TS EN ISO 13789, the coefficients for each transparent (*i.e.* window) and opaque (*i.e.* wall) elements in a building are calculated. Total heat transfer coefficient by transmission is represented as follows:

$$H_{tr} = H_D + H_G + H_U + H_A \qquad \text{(W/K) Equation 53}$$

H_D is the direct heat transfer by transmission to the external environment

H_G is heat transfer by transmission to the ground

H_U is heat transfer by transmission to unconditioned spaces

H_A is heat transfer by transmission to adjacent buildings

The direct transmission is the heat transfer depending on the temperature differences between the indoor environment and the outdoor environment through the building elements. When calculating direct transmission, the properties of the building elements are important. The direct transmission coefficient is computed by multiplying the building element area by its U-value (thermal transmittance).

$$H_D = \sum A_i\, U_i \qquad \text{(W/K) Equation 54}$$

H_G, H_U, H_A are calculated the same equations shown as Equation 54. Distinctly, an adjustment factor is used. *"Heat transfer by transmission to the ground"*, *"heat* *transfer by transmission to unconditioned spaces"* and *"heat transfer by transmission to adjacent buildings"* are calculated as follows:

$$H_X = b_{tr}.\sum A_i\, U_i \qquad \text{(W/K) Equation 55}$$

$H_X$represents H_G, H_U, H_A.

There exists a different adjustment factor calculation for each condition. These calculations are defined in the "BEP-TR Regulation", "TS EN ISO 13370" and "TS EN ISO 13789".

○ ***U-value (Thermal transmittance) and R-value (Thermal resistance)***

Thermal resistance also defined as R-value is the ability of a material to resist the flow of heat. It is based on the material thickness and the conductivity of the materials used. Thermal resistance can be expressed as:

$$\mathrm{R} = \frac{d}{\lambda_\mathrm{h}} \qquad (\mathrm{m}^2.\mathrm{K/W}) \text{ Equation 56}$$

d is the thickness of the materials

$\lambda_\mathrm{h}$is the conductivity of the materials used

For multi-layer structural elements, thermal resistance is calculated by using individual structural element thicknesses and the thermal conductivity values of these structural elements shown in Equation 57.

$$\mathrm{R} = \frac{d_1}{\lambda_{h1}} + \frac{d_2}{\lambda_{h2}} + \cdots . + \frac{d_n}{\lambda_{hn}} \qquad (\mathrm{m}^2.\mathrm{K/W}) \text{ Equation 57}$$

Thermal transmittance also defined as U-value is a significant concept in building design. It represents the rate of transfer of heat between two spaces with different temperatures through one square meter of a building element. According to “TS825”, “TS EN ISO 13790”, the calculation of thermal transmittance is as follows:

$$\mathrm{U} = \frac{1}{R_{si}+R_m+R_{se}} \qquad (\mathrm{W/m^2.K}) \text{ Equation 58}$$

“R_{si} is the surface resistance of the internal surface

R_{se} is the surface resistance of the external surface”

The surface resistance of the external and internal surface is determined in “TS 825”, “TS EN ISO 13790” and “BEP-TR Regulation”.

○ ***Ventilation Heat Transfer Coefficients***

The buildings perform heat transfer in two ways. The first one is transmission heat transfer (explained at “Heat Transmission Coefficients”). The second one is ventilation heat transmission calculated as Equation 59. The ventilation heat transfer coefficient is multiplying the air-flow rate by the conditioned/unconditioned space by the air heat capacity of per volume.

$$H_{ve} = \rho . c . q \qquad (\mathrm{W/K}) \text{ Equation 59}$$

$\rho . c$ is the heat capacity of air per volume

q is the airflow rate

The air heat capacity per volume is determined as 0.33 W.h./ (m^3.K) or 1200 Joule/(m^3.K) according to "TS EN ISO 13790". The airflow rate relies on multiplying the air change rate by the zone volume and as shown in Equation 60.

$$q = V_B . n_h \quad \text{(m}^3\text{/h) Equation 60}$$

Therefore, the ventilation heat transfer coefficient can be calculated as follows:

$$H_{ve} = \rho . c . n_h . V_B \quad \text{(W/K) Equation 61}$$

- ***Heat gains***

There are two types of heat gains; solar gains and internal gains. Total heat gains are calculated as the sum of the internal heat gains (Q_{int}) and the solar heat gains (Q_{sol}). Heat gains are the same for both cooling and heating modes because of not depending on the setpoint temperatures for heating and cooling modes.

$$Q_{gn} = Q_{int} + Q_{sol} \quad \text{(MJ) Equation 62}$$

The total heat gain can be specified according to the internal heat sources and solar heat source during the month considered.

From internal heat gain:

$$\mathrm{Q_{int}} = \phi_{\mathrm{int,.mn}} . \mathrm{t} \quad \text{(MJ) Equation 63}$$

From solar heat gain:

$$Q_{sol} = \phi_{sol,.mn} . \mathrm{t} \quad \text{(MJ) Equation 64}$$

When all brought together, the final equations of energy requirements for space heating and cooling are as follows:

For Heating:

$$Q_{H,nd} = \left[(H_{tr} + H_{ve})\left(\theta_{int,H,set} - \theta_{e}\right) - \eta_{H,gn}(\phi_{int} + \phi_{sol})\right]t \quad \text{(MJ) Equation 65}$$

For Cooling:

$$Q_{C,nd} = [(\phi_{int} + \phi_{sol}) - \eta_{C,Is}\left[(H_{tr} + H_{ve})\left(\theta_{e} - \theta_{int,C,set}\right)\right]t \quad \text{(MJ) Equation 66}$$

- ***Heat Flow Rate from Internal Heat Sources***

The first heat gain comes from the internal heat sources. The “BEP-TR Regulation” and the “TS EN ISO 13790” standard are used together to calculate the time-averaged heat-flow rate of internal heat sources in a building. The internal heat gains are calculated as shown in Equation 67.

$$\phi_{\mathrm{int}} = \phi_{\mathrm{int,.sen,D}} + \phi_{\mathrm{int,.sen,M}} + \phi_{\mathrm{int,.App,lat}} + \phi_{\mathrm{int,.Occ,lat}} + \phi_{\mathrm{int,.W}} + \phi_{\mathrm{int,.lg}}$$

(W) Equation 67

ϕ_{int} is the time-averaged heat flow rate from internal heat sources
$\phi_{int,sen,D}$ is heated from the other spaces

$\phi_{int,sen,M}$ is heated from the living room and kitchen

$\phi_{int,App,lat}$ is dissipated heat from appliances
$\phi_{int,Occ,lat}$ is metabolic heat from the occupants

$\phi_{int,W}$ is hot water use

$\phi_{int,lg}$ is lighting devices

According to BEP-TR Regulation, internal heat gain calculations are as follows

- Sensible heat gains from occupants and living spaces [W]:

$$A_f = A_{f,D} + A_{f,M}$$ (m2)Equation 68

$A_{f,D}$ is floor area excluding kitchen and living room

$A_{f,M}$ is floor area of kitchen and living room

$$\phi_{int,.sen,M} = A_{f,.M} \cdot \phi_{int,.sen,M,unit}$$ (W) Equation 69

$$\phi_{int,.sen,D} = A_{f,.D} \cdot \phi_{int,.sen,D,.unit}$$ (W) Equation 70

$$\phi_{\mathrm{int,.sen}} = \phi_{\mathrm{int,.sen,M}} + \phi_{\mathrm{int,.sen,D}}$$ (W) Equation 71

- Heat gains from hot water use:

$$\phi_{int,.W} = 25 + \left(15.Number_{occupant}\right)$$ (W) Equation 72

- Lateral heat gains from appliances:

$$\phi_{int,.App,lat} = \phi_{int,.App,lat,M} + \phi_{int,.App,lat,D}$$ (W) Equation 73

Heated from the living room and kitchen appliances:

$$\phi_{int,.App,.lat,M,unit} = \frac{\phi_{int,.App,.sen,M,unit}}{0.77} - \phi_{int,App,.sen,M,.unit}$$ (W/m2) Equation 74

$$\phi_{int,App,.lat,M} = A_{f,M} \cdot \phi_{int,.App,.sen,M,unit}$$ (W) Equation 75

Heated from the other spaces appliances:

$$\phi_{int,App,lat,D,unit} = \frac{\phi_{int,App,sen,D,unit}}{0.77} - \phi_{int,App,sen,D,unit}$$ (W/m2) Equation 76

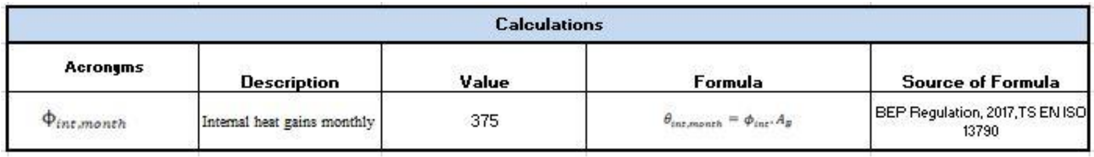
$$\phi_{int,.App,.lat,D} = A_{f,D} \cdot \phi_{int,.App,.sen,D,unit}$$ (W) Equation 77

Metabolic gains form occupants:

$\phi_{\text{int,..Oc,lat,unit}} = 55$ (W/person) Equation 78

$\phi_{int.,Oc,.sen,.unit} = 75$ (W/person) Equation 79

In the standard, this information is given for one m^2. The model calculated the value for the whole building. The internal heat sources calculation for the building is expressed as follows.



Calculations				
Acronyms	Description	Value	Formula	Source of Formula
$\phi_{int,month}$	Internal heat gains monthly	375	$\theta_{int,month} = \phi_{int} \cdot A_g$	BEP Regulation, 2017,TS EN ISO 13790

Figure 27: Internal Heat Gain Calculation for Whole Building

○ *Heat Flow-Rate from a Solar Heat Source*

The second heat gain comes from the solar heat source. Turkey is located on between latitudes 36–42^o N and longitudes 26–45^o E in the northern hemisphere. Turkey is in the solar belt and has an average sunshine-duration of 2610 hour per year. The average annual temperature 18-20 ° C on the southern coast, 14-16° C on the west and fluctuates between 4-18 ° C in the middle. Annually, average solar radiation is 3.6kW h / m2 day and overall radiation period is approximately 2610 hours (Sözen & Arcaklioğlu, 2005). Therefore, Turkey has great solar energy potential. In Turkey, energy efficiency is a vital issue because of external dependency. The potential is an important opportunity to reduce Turkey's external dependency. Orientation among passive solar designs that are used to provide building energy efficiency is the most important (Balcomb *et al.*, 1977; Capeluto, 2003; Givoni, 1991; Hoffman *et al.*, 1983; Morrissey *et al.*, 2011). Studies present that orientation and shape of the building affect the energy consumption of building (Gadomski, 1987; Jedrzejuk & Marks, 1994; Lin, 1981; Mingfang, 2002; Radford *et al.*, 1984). Decisions made in the design phase for buildings have long-term results especially for the environment and the energy consumption (Ryghaug & Sørensen, 2009). Before a building design really begins, planners take decisions that significantly affect the direction of a building. These decisions are based on many factors except energy consumption such as connecting roads, drainage patterns. However, the orientation of the building affects energy use considerably in a moderate way well-insulated house, without any other passive items or controls. Properly orienting housing effectively reduce energy use and can be simple and inexpensive to achieve if it is planned early (Andersson *et al.*, 1985).

Optimum oriented of a building significantly increases energy savings. At table 3, the heating and cooling energy savings resulting from rotating a model of a building by 30 °, 45 ° and 60 ° relative to the south axis are presented (US Air Force, n.d.). The greatest energy saving was achieved when the longest walls were turned 30% in the south.

Shaviv (1981) discussed the effect of the building glazing surface orientation on energy consumption. She found that the main glazing surface should be oriented to the south to provide significant energy saving.

Optimal building orientation provides benefits as follows (Pacheco *et al.*, 2012);

- *It is a low-cost measure that is applicable in the initial stages of project design.*
- *It reduces the energy demand.*
- *It reduces the use of more sophisticated passive systems.*
- *It increases the performance of other complex passive techniques.*
- *It increases the quantity of daylight, reduces the energy demand for artificial light, and contributes less to the internal heating load of the building.*
- *It improves the performance of solar collectors.*

Solar radiation data is essential to determine optimum orientation to reduce housing energy demand. It is the most contributor to heat gain arising from received on walls or transmission through windows. It is very significant to understand the characteristics of exposure to sunlight in different geometric shapes and orientations for energy saving and daylighting conditions.

Solar heat gain is important to determine building orientation. To calculate solar heat gain received on walls and through windows, studies use black box method. Simple and effective models are essential to deciding building orientation. Detailed physical models are time-consuming, require a lot of data and need a large number of parameters as an input (Nielsen *et al.*, 2001; Wang & Xu, 2006). Then, they may not always reflect the real situations. The calibration process of detailed physical models such as Energy Plus and DOE-2 *etc.* is a great challenge (Wang & Xu, 2006). The study aims to investigate white box methods and then adapt the most available one to Turkey.

It is possible to divide the studies about orientation into two parts; black box methods and white box methods. The black box method is defined in this study as follows; inputs and outputs can be just viewed without any knowledge of its internal functioning. In other words, researchers don't know which variable is the most/least important, how the function is progressing. On the contrary, white box method is a system in which the inner variables or logic are available for examination. To put it another way, the method is referred as a transparent box, glass box.

-Black box methods of solar gain

In building design, environmental conditions, solar energy, and climate should be considered. Lin (1981) determined that the shape of the building affects energy consumption similar to building orientation. Solar radiation that building is exposed to is one of the main factors. The greater the external surface of the building in cold regions, the more energy can be used for heating, the optimal form of the building should be at the minimum external surface. Andersson *et al.* (1985) presented that the east and west orientations generate a higher total load (heating and cooling) than the south and north orientation with computer program BLAST. Gadomski (1987) showed that optimum dimension for a rectangular plan with minimum heat requirement per m3 of volume. He did not take into consideration heat gain obtained because of insulation. Jedrzejuk and Marks (1994) discussed multi-criteria optimization problem for the building. While the minimum construction costs and the minimum yearly running costs were optimization criteria, lengths, height, angles, window sizes and thermal resistance were decision variables.

Littlefair (2001) discussed effective ways to provide solar gain in obstructed situations for housing with the computer program TOWNSCOPE. This study offers strategies for outside environment to ensure good access to daylight and solar radiation. According to him, most recommended building orientation is 20–30◦ to the south.

Florides *et al.* (2002) investigated the relationship between building orientation and shape in terms of their cost-effectiveness with using TRNSYS computer program. They found that regarding orientation while for a symmetrical house, the best position is to face the four cardinal points, for an elongated house, its long side facing south provide energy efficiency. In addition, the eastern orientation of the building surface has the biggest load contribution to the heating energy demand.

Chwieduk and Bogdanska (2004) studied building elements that received solar radiations with inclinations and azimuth angles to give recommendations for architects. To determine amount of solar radiation, they use two model; the isotropic diffuse sky model (Hottel–Woertz–Liu–Jordan model)(Liu & Jordan, 1963), and the anisotropic sky model of HDKR (Hay–Davies–Klucher–Reindl) (Reindl *et al.*, 1990). They try to describe most suitable parameters to design the orientation and inclination of building walls and roofs. According to the study, angles between -15 ° and 45 ° give good results, but to maximize solar energy gain throughout the year angle between the azimuth angle and the incident surface should be 15 ° (Chwieduk & Bogdanska, 2004).

Ling *et al.* (2007) studied the impact of solar radiation on high-rise building vertical surfaces with ECOTECT simulation programs in hot humid climate. They determined two shapes (vertical and square), three W/L ratio (1:1, 1:1, 7, 1:3) and four design days (21 March, 21 June, 21 September and 21 December). They concluded that circular shape with W/L ratio 1:1 is optimum shape to receive lowest solar radiation and the highest level of solar radiation is received on the eastern wall.

Morrissey *et al.* (2011) found that small houses were more flexible to change in orientation in terms of performance with BESTEST program. This implication is important to housing affordability because small houses can be expected to show relatively higher affordability performance than larger houses.

-*White box methods of solar gain*

Building orientation should be made according to the climate. Solar incident angle is one of the most important things to calculate solar radiation that building is exposed to. In many climates, in winter situation, and in summer situation are at 90^o to each other. At that case, building orientation is calculated as the number of degree hours above the base temperature in summer period compared to the degree hours below it in the winter period (Olgyay, 1963; Wigginton, 1996).

Life cycle energy consumption is related to orientation changing, insulation levels and materials of floors and exterior walls. According to Bekkouche *et al.* (2013), a slight change in the interior temperature was observed with a change of the building orientation to 45° towards the west or 45 towards the east. For this reason, they recommend changing the orientation angle by 90 °.

Gupta and Ralegaonkar (2004) optimized the orientation of a building for various building shape factors in order to reduce the sunlight received during the summer months and to bring it to the top in the winter. The total energy gets from this radiation is calculated by applying as follows.

$$E = A \times \int_{\omega_1}^{\omega_2} (0.834 \times H) \times \left(\frac{\cos\ i}{\cos\ \theta_Z}\right) d\omega$$

(W) Equation 80

A: the surface area;

H: the monthly mean daily global radiation on a horizontal surface;

I: the incidence angle;

d_{ω}: the hour angle at sunrise or sunset;

θ_Z: the zenith angle or polar angle.

Yao *et al.* (2000) studied the performance of window design with a simplified method. The method stimulates energy and overheating performance of windows and is proper for architects and engineers at the design stage, even if less data is available. In this study, the hourly solar heat gain through windows has been calculated as follows;

$Solar = I.T_s.F_{shading}.A_{glaze}$ (W) Equation 81

$Solar$ is the total solar gain entering the room

I is the hourly total solar irradiance falling on the whole plane

T_s is the solar transmittance

$F_{shading}$ is the shading device factor

A_{glaze} is the area of the glazing

Aksoy and Inalli (2006) investigate impact building shape and orientation position on heating demand. They used buildings having a shape factor of 1/1, 2/1 and 1/2 with heating insulation and without heating insulation on the façade. These buildings are placed at the azimuth angle between 0 and 90 °. Aksoy and Inalli (2006) concluded that the most appropriate orientation position is provided when the longest walls were oriented toward the South. They also concluded that heating energy saving rate reached up to 36% when combining shape factor, orientation, and heating insulation. The total solar radiation is calculated by the following formula. Actually, the formula was used first time by Duffie and Beckham (1991).

$$I = R_{\mathrm{d}} I_{\mathrm{d}} + I_{\mathrm{y}} \frac{1+\cos\beta}{2} + I_{\mathrm{a}} p \frac{1-\cos\beta}{2}$$

(W/m^2) Equation 82

I: total solar radiation (W/m^2)

R_d: ratio of direct radiation on the horizontal and tilted surface

I_d: direct radiation on horizontal surface (W/m^2)

I_y: diffuse radiation on horizontal surface (W/m^2)

I_a: instantaneous radiation on the horizontal surface

ρ : density (kg/m^3)

β: the angle between the horizontal plane and an inclined surface,

The R_d parameter is calculated by the following equation:

$$R_{\mathrm{d}} = \frac{\cos\delta \sin\varphi \cos\gamma \cos w + \cos\delta \sin\gamma \sin w - \sin\delta \cos\varphi \cos\gamma}{\cos\varphi \cos\delta \cos w + \sin\varphi \sin\delta}.$$

Equation 83

δ: the declination angle

ϕ: latitude angle

w: hour angle

γ : azimuth angle (surface orientation angle)

Taking the studies about solar radiation a step further, Nielsen *et al.* (2001) make it easier to compare the energy performance of different windows based on orientation, tilt, g value, and U value. Energy performance is indicated by the net energy gain given as solar energy gain minus heat loss. Net energy gain of window or glazing relies on the thermal transmittance (the U-value) and the total solar energy transmittance (the g-value).

$$Q_{\mathrm{solar}} = g \cdot \left[\sum \left(q_{\mathrm{dir}} \cdot \left(1 - \tan^{p}(i/2)\right) \cdot \Delta t\right) + \sum \left(\left(q_{\mathrm{dif}} + q_{\mathrm{ref}}\right) \cdot f \cdot \Delta t\right)\right]$$

(MJ) Equation 84

$$Q_{\mathrm{loss}} = U \cdot \sum (20 - t_{\mathrm{u}}) \cdot \Delta t$$

(MJ) Equation 85

The climate has an important place in the building's energy consumption according to the building's average temperature and the amount of solar radiation that it is exposed to. The climate-linked building orientation also determines the amount of energy used for heating, cooling, and lighting. Therefore, it contributes to not only operating energy of a building but also the embodied energy. The solar heat acquired by solar radiation in a building depends on the following factors (MacMullan, 1992).:

- *The geographical latitude of the site, which determines the height of the sun in the sky.*
- *The orientation of the building on the site, such as whether rooms are facing north or south.*
- *The season of the year, which also affects the height of the sun in the sky.*
- *The local cloud conditions, which can block solar radiation.*
- *The angles between the sun and the building surfaces, because maximum gain occurs when surfaces are at right angles to the rays of the sun.*
- *The nature of the window glass and whether it absorbs or reflects any radiation.*

- *The nature of the roof and walls, because heavyweight materials behave differently to lightweight materials*

In the literature, some of the calculations were computed through black-box methods such as TOWNSCOPE, TRNSYS, HDKR *etc.* The other calculations named as white box methods were derived from ISO standards.

According to "TS EN ISO 13790" and "BEP-TR Regulation", Heat-Flow Rate from a Solar Heat Source is as follows.

$$\Phi_{sol} = \left(F_{sh,ob}.A_{sol}.I_{sol}\right) - \left(F_r.\Phi_r\right) \qquad \text{(W) Equation 86}$$

ϕ_{sol} is the heat flow rate of solar gains,

$F_{sh,ob}$ is the shading reduction factor for external obstacles

A_{sol} is the effective surface solar collection area

I_{sol} is solar irradiance

F_r is the form factor between the building element and the sky

ϕ_r is the extra heat flow due to thermal radiation to the sky from each building element.

In this model, the values of solar irradiance are taken from "TS 825". The form factor between the building element and the sky is adopted as 1 for horizontal building elements according to the "BEP-TR Regulation". The extra heat flow due to thermal radiation to the sky from each building element is as shown in equation 87.

$$\phi_r = R_{se}.U_{op}.A_{op}.h_r.\Delta\theta_{er} \qquad \text{(W) Equation 87}$$

R_{se} is external surface resistance

U_{op} is thermal transmittance

A_{op} is area of the opaque building element

h_r is the external radiative heat transfer coefficient

$\Delta\theta_{er}$ is the average difference between the external air temperature and the apparent sky temperature

The average difference between the external air temperature and the apparent sky temperature is accepted as 1 for Turkey and the external radiative heat transfer coefficient is obtained from the BEP Regulation.

Solar gain can be gained on both opaque surfaces and transparent surfaces of buildings. As stated equation 86, the effective surface solar area is calculated shown in Equation 88.

$$A_{sol} = A_{sol,op} + A_{sol,gl} \qquad \text{(m2) Equation 88}$$

Opaque surfaces are computed as follows.

$$A_{sol,op} = \alpha_{sol,em}.R_{se}.U_{op}.A_{op} \qquad \text{(m2) Equation 89}$$

$\alpha_{sol,em}$ is the direct solar absorbance of external surfaces

R_{se} is the external surface resistance

U_{op} is thermal transmittance

A_{op} is the area of each opaque building element

Transparent surfaces are computed as follows.

$$A_{sol,gl} = F_{sh,gl}.gvalue.A_W.\left(1 - F_f\right) \qquad \text{(m2) Equation 90}$$

$F_{sh,gl}$ is the shading reduction factor for movable shading provisions

$gvalue$ is the total solar energy transmittance of the transparent part of the element

A_W is the window area

F_f is the frame area fraction

- ***Utilization Factors***

In the monthly heating and cooling energy requirement calculation method, heat losses and gains can be systematically calculated. However, utilization factors have very important roles in these calculations. The factor is dimensionless and computed as "TS EN ISO 13790". The utilization factor for heating:

- If $\gamma_H > 0$ and $\gamma_H \neq 1$

$$\eta_{H,gn} = \frac{1-\gamma_H^{\alpha,H+1}}{1-\gamma_H^{\alpha,H+1}} \qquad \text{Equation 91}$$

- If $\gamma_H = 1$

$$\eta_{H,gn} = \frac{\alpha_H}{\alpha_H+1} \qquad \text{Equation 92}$$

- If $\gamma_H < 0$

$$\eta_{H,gn} = \frac{1}{\gamma_H} \qquad \text{Equation 93}$$

The gain/loss ratio is as follows:

$$\gamma_H = \frac{Q_{H,gn}}{Q_{H,ht}} \qquad \text{Equation 94}$$

Numerical parameter in utilization factor:

$$\alpha_H = \alpha_{H,0} + \frac{\tau}{\tau_{H,0}} \qquad \text{Equation 95}$$

The utilization factor for cooling:

- If $\gamma_C > 0$ and $\gamma_C \neq 1$

$$\eta_{C,ls} = \frac{1-\gamma_C^{-\alpha,C+1}}{1-\gamma_C^{\alpha,C+1}} \qquad \text{Equation 96}$$

- If $\gamma_C = 1$

$$\eta_{C,ls} = \frac{\alpha_C}{\alpha_C} + 1 \qquad \text{Equation 97}$$

The gain/loss ratio is as follows:

$$\gamma_C = \frac{Q_{C,gn}}{Q_{C,ht}} \qquad \text{Equation 98}$$

Numerical parameter in utilization factor:

$$\alpha_C = \alpha_{C,0} + \frac{\tau}{\tau_{C,0}} \qquad \text{Equation 99}$$

The time constant determines the internal thermal inertia of the conditioned building/zone. The time constant is calculated for both heating and cooling. The time constant is calculated as follows.

$$\tau = \frac{\frac{c_m}{3600}}{H_{tr}+H_{ve}} \qquad \text{Equation 100}$$

c_m is The internal heat capacity of the building

BEP Regulation defines three types of the internal heat capacity of the building.

Table 13: Construction Types

Source: BEP Regulation, 2017

Construction	The internal heat capacity
Light construction	110,000 J/K
Medium construction	165,000 J/K
Heavy construction	260,000 J/K

The internal heat capacity of the building is determined according to the construction type of the building and the properties of the materials used. The calculation can be made according to “TS EN ISO 13786”.

-Calculation of Heating Energy Demand

The energy requirement for space heating corresponds to the difference between the total heat transfer and the total heat gains corrected by the dimensionless gain utilization factor. It is calculated as:

$$Q_{H,nd} = Q_{H,ht} - \eta_{H,gn} . Q_{H,gn} \qquad \text{(MJ)} \quad \text{Equation 101}$$

In the formula, H refers to heating and $Q_{H,nd}$ must be equals or greater than zero.

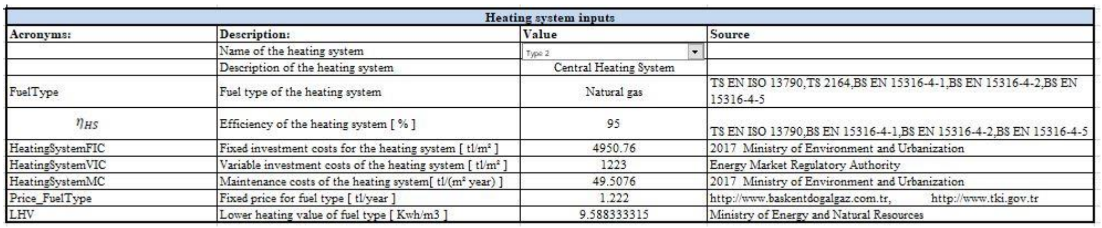
$Q_{H,nd}$ is the building energy need for heating, in MJ

$Q_{H,ht}$ is the total heat transfer for the heating mode

$\eta_{H,gn}$ is the dimensionless gain utilization factor

$Q_{H,gn}$ is the total heat gains for the heating mode

This model offers designer the possibility of easy way calculation of lifetime costs of own choices. “Heating system Inputs” section is represented in Figure 28.

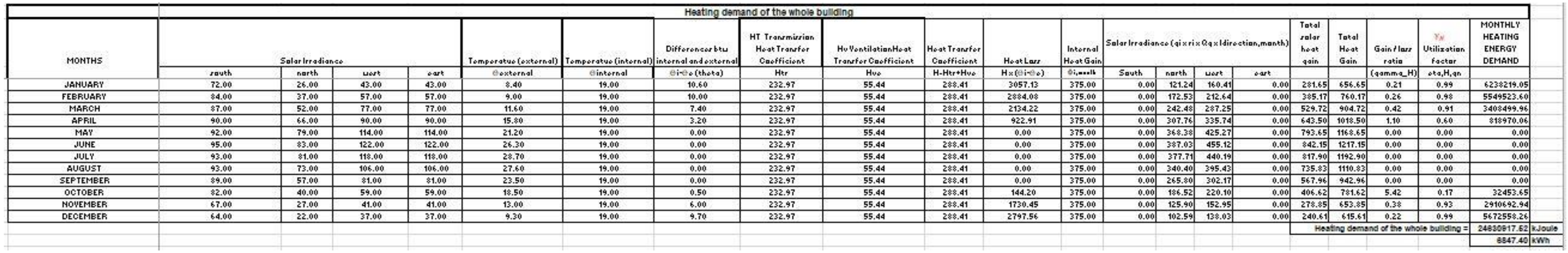


Heating system inputs

Acronyms:	Description:	Value	Source
	Name of the heating system	Type 2	
	Description of the heating system	Central Heating System	
FuelType	Fuel type of the heating system	Natural gas	TS EN ISO 13790,TS 2164,BS EN 15316-4-1,BS EN 15316-4-2,BS EN 15316-4-5
η_{HS}	Efficiency of the heating system [%]	95	TS EN ISO 13790,BS EN 15316-4-1,BS EN 15316-4-2,BS EN 15316-4-5
HeatingSystemFIC	Fixed investment costs for the heating system [tl/m^2]	4950.76	2017 Ministry of Environment and Urbanization
HeatingSystemVIC	Variable investment costs of the heating system [tl/m^2]	1223	Energy Market Regulatory Authority
HeatingSystemMC	Maintenance costs of the heating system[tl/(m^2 year)]	49.5076	2017 Ministry of Environment and Urbanization
Price_FuelType	Fixed price for fuel type [tl/year]	1.222	http://www.baskentdogalgaz.com.tr, http://www.tki.gov.tr
LHV	Lower heating value of fuel type [Kwh/m3]	9.588333315	Ministry of Energy and Natural Resources

Figure 28: Heating System Input Area

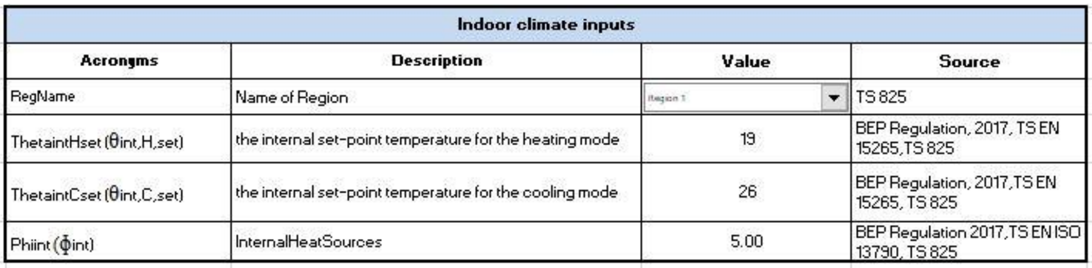
In this area, the designer selects only heating system types, then heating system investment cost, heating system maintenance cost, the heating demand of the whole building, heating consumption, fuel consumption yearly, cost of the fuel consumption yearly will be calculated automatically. The data in this excel page comes from the following page. The sheet was created by the author, derived from unit prices of the Ministry of Environment and Urbanism and from calculations in standards and regulations.



	Heating demand of the whole building																					
MONTHS	Solar Irradiance				Temperatue (external)	Temperatue (internal)	Differences btw internal and external	HT Transmission Heat Transfer Coefficient	Hv Ventilation Heat Transfer Coefficient	Heat Transfer Coefficient	Heat Loss	Internal Heat Gain	Solar Irradiance (qi x ri x Qq x Idirection,month)				Total solar heat gain	Total Heat Gain	Gain / loss ratio	Y_H Utilization factor	MONTHLY HEATING ENERGY DEMAND	
	south	north	west	east	Θexternal	Θinternal	Θi-Θe (theta)	Htr	Hve	H-Htr+Hve	H x (Θi-Θe)	Φi,mealk	South	north	west	east			(gamma_H)	eta,H,gn		
JANUARY	72.00	26.00	43.00	43.00	8.40	19.00	10.60	232.97	55.44	288.41	3057.13	375.00	0.00	121.24	160.41	0.00	281.65	656.65	0.21	0.99	6238219.05	
FEBRUARY	84.00	37.00	57.00	57.00	9.00	19.00	10.00	232.97	55.44	288.41	2884.08	375.00	0.00	172.53	212.64	0.00	385.17	760.17	0.26	0.98	5549523.60	
MARCH	87.00	52.00	77.00	77.00	11.60	19.00	7.40	232.97	55.44	288.41	2134.22	375.00	0.00	242.48	287.25	0.00	529.72	904.72	0.42	0.91	3408499.96	
APRIL	90.00	66.00	90.00	90.00	15.80	19.00	3.20	232.97	55.44	288.41	922.91	375.00	0.00	307.76	335.74	0.00	643.50	1018.50	1.10	0.60	818970.06	
MAY	92.00	79.00	114.00	114.00	21.20	19.00	0.00	232.97	55.44	288.41	0.00	375.00	0.00	368.38	425.27	0.00	793.65	1168.65	0.00	0.00	0.00	
JUNE	95.00	83.00	122.00	122.00	26.30	19.00	0.00	232.97	55.44	288.41	0.00	375.00	0.00	387.03	455.12	0.00	842.15	1217.15	0.00	0.00	0.00	
JULY	93.00	81.00	118.00	118.00	28.70	19.00	0.00	232.97	55.44	288.41	0.00	375.00	0.00	377.71	440.19	0.00	817.90	1192.90	0.00	0.00	0.00	
AUGUST	93.00	73.00	106.00	106.00	27.60	19.00	0.00	232.97	55.44	288.41	0.00	375.00	0.00	340.40	395.43	0.00	735.83	1110.83	0.00	0.00	0.00	
SEPTEMBER	89.00	57.00	81.00	81.00	23.50	19.00	0.00	232.97	55.44	288.41	0.00	375.00	0.00	265.80	302.17	0.00	567.96	942.96	0.00	0.00	0.00	
OCTOBER	82.00	40.00	59.00	59.00	18.50	19.00	0.50	232.97	55.44	288.41	144.20	375.00	0.00	186.52	220.10	0.00	406.62	781.62	5.42	0.17	32453.65	
NOVEMBER	67.00	27.00	41.00	41.00	13.00	19.00	6.00	232.97	55.44	288.41	1730.45	375.00	0.00	125.90	152.95	0.00	278.85	653.85	0.38	0.93	2910692.94	
DECEMBER	64.00	22.00	37.00	37.00	9.30	19.00	9.70	232.97	55.44	288.41	2797.56	375.00	0.00	102.59	138.03	0.00	240.61	615.61	0.22	0.99	5672558.26	
																	Heating demand of the whole building =				24630917.52	kJoule
																					6847.40	kWh

Figure 29: Heating System Dataset Sheet

The region where the housing is located is important for the heating demand calculation. The heating demand of the housing can increase or decrease according to the region. Therefore, it is necessary to select correctly the region information. Four types of climate regions have been identified in Turkey. In the model, Indoor climate area is followed as. “Indoor climate inputs” section is represented in Figure 30.



Indoor climate inputs			
Acronyms	**Description**	**Value**	**Source**
RegName	Name of Region	Region 1	TS 825
ThetaintHset (θint,H,set)	the internal set-point temperature for the heating mode	19	BEP Regulation, 2017, TS EN 15265,TS 825
ThetaintCset (θint,C,set)	the internal set-point temperature for the cooling mode	26	BEP Regulation, 2017,TS EN 15265, TS 825
Phiint (Φint)	InternalHeatSources	5.00	BEP Regulation 2017,TS EN ISO 13790, TS 825

Figure 30: Indoor Climate Input Area.

In the calculation of heating demand, there is a need for regional information to be entered by the designer. As shown Figure 30, the designer selects only region name, then the model calculates the heating demand of the whole building is calculated automatically. The data in this excel page comes from the following page. The sheet was created by the author, derived from calculations in standards and regulations.

	months		JANUARY	FEBRUARY	MARCH	APRİL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER	AVERAGE
Region 1	Temperature (external)	Θexternal	8.40	9.00	11.60	15.80	21.20	26.30	28.70	27.60	23.50	18.50	13.00	9.30	17.74
Region 2	Temperature (external)	Θexternal	2.90	4.40	7.30	12.80	18.00	22.50	24.90	24.30	19.90	14.10	8.50	3.80	13.62
Region 3	Temperature (external)	Θexternal	-0.30	0.10	4.10	10.10	14.40	18.50	21.70	21.20	17.20	11.60	5.60	2.60	10.57
Region 4	Temperature (external)	Θexternal	-5.40	-4.70	0.30	7.90	12.80	17.30	21.40	21.10	16.50	10.30	3.10	-2.80	8.15

Figure 31: Indoor Climate Dataset Sheet

Source: TS 825

In the calculation of the heating demand, the parameters mentioned in the previous sections (wall, ceiling, window, *etc.*) are required. The model was designed by considering this selection order. In the light of this information, the following calculations are made automatically by the model according to the region by the designer.

Heating System Investment Cost:

$$TotalHeatingSystemIC = HeatingSystemFIC + HeatingSystemVIC$$

(tl) Equation 102

Heating System Maintenance Cost:

$$TotalHeatingSystemMC = \frac{TotalHeatingSystemIC}{10}$$ (tl) Equation 103

Heating consumption:

$$Qsystem = \frac{HeatingDemand}{\eta_{HS}}$$ (kWh/year) Equation 104

Fuel consumption yearly

$$FuelCons = \frac{Qsystem}{LHV}$$ (m3 or kg) Equation 105

Cost of the Fuel consumption yearly

$$Cost_{FuelCons} = FuelCons.price_{fueltype}$$ (tl) Equation 106

-Calculation of Cooling Energy Demand

The energy requirement for space cooling corresponds to the difference between the total heat gains and the total heat transfer corrected by the dimensionless utilization factor for heat losses. It is calculated as:

$$Q_{C,.nd} = Q_{C,.gn} - \eta_{C,.Is}.Q_{C,.ht}$$ (MJ) Equation 107

In the formula, C refers to cooling and $Q_{C,\text{nd}}$ must be equals or greater than zero.

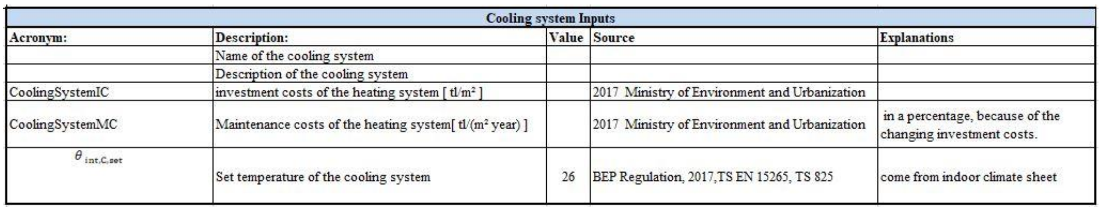
$Q_{C,\text{nd}}$ is the building energy need for cooling, in MJ;

$Q_{C,gn}$ are the total heat gains in the cooling mode

$\eta_{C,ls}$ is the dimensionless utilization factor for heat losses,

$Q_{C,ht}$ is the total heat transfer for the cooling mode

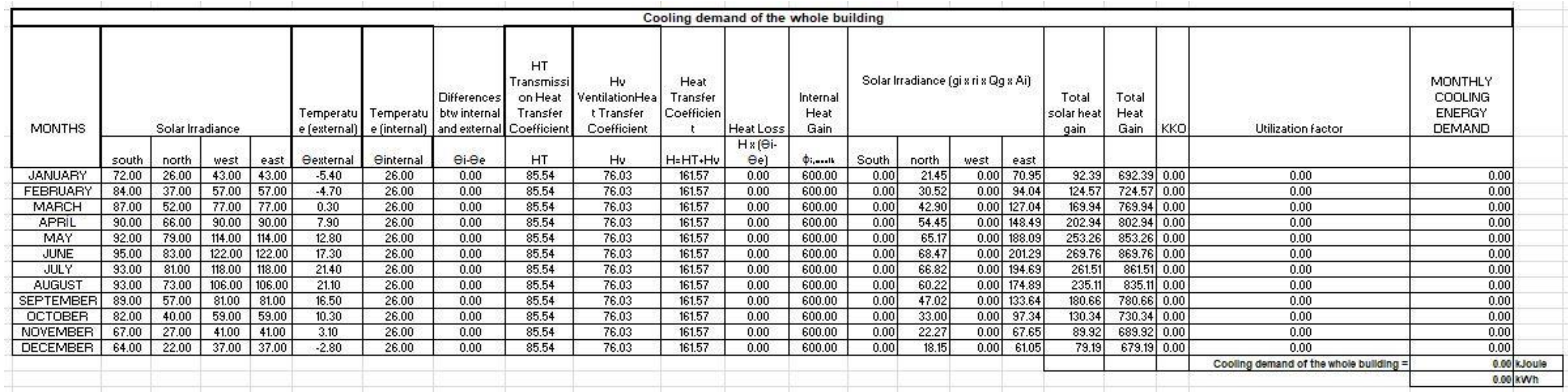
Figure 32 shows “Cooling system Input” area.



Cooling system Inputs				
Acronym:	**Description:**	**Value**	**Source**	**Explanations**
	Name of the cooling system			
	Description of the cooling system			
CoolingSystemIC	investment costs of the heating system [tl/m²]		2017 Ministry of Environment and Urbanization	
CoolingSystemMC	Maintenance costs of the heating system[tl/(m² year)]		2017 Ministry of Environment and Urbanization	in a percentage, because of the changing investment costs.
$\theta_{int,C,set}$	Set temperature of the cooling system	26	BEP Regulation, 2017,TS EN 15265, TS 825	come from indoor climate sheet

Figure 32: Cooling System Input Area

In this area, the designer selects only cooling system types, then cooling system investment cost, cooling system maintenance cost, cooling demand of the whole building, cooling electricity consumption will be calculated automatically. The data in this excel page comes from the following page. The sheet was created by the author, derived from unit prices of the Ministry of Environment and Urbanism and from calculations in standards and regulations.



Cooling demand of the whole building

MONTHS	Solar Irradiance				Temperature (external)	Temperature (internal)	Differences btw internal and external	HT Transmission Heat Transfer Coefficient	Hv VentilationHeat Transfer Coefficient	Heat Transfer Coefficient	Heat Loss	Internal Heat Gain	Solar Irradiance (gi x ri x Qg x Ai)				Total solar heat gain	Total Heat Gain	KKO	Utilization factor	MONTHLY COOLING ENERGY DEMAND	
	south	north	west	east	Θexternal	Θinternal	Θi-Θe	HT	Hv	H=HT+Hv	H x (Θi-Θe)	ϕi,…	South	north	west	east						
JANUARY	72.00	26.00	43.00	43.00	-5.40	26.00	0.00	85.54	76.03	161.57	0.00	600.00	0.00	21.45	0.00	70.95	92.39	692.39	0.00	0.00	0.00	
FEBRUARY	84.00	37.00	57.00	57.00	-4.70	26.00	0.00	85.54	76.03	161.57	0.00	600.00	0.00	30.52	0.00	94.04	124.57	724.57	0.00	0.00	0.00	
MARCH	87.00	52.00	77.00	77.00	0.30	26.00	0.00	85.54	76.03	161.57	0.00	600.00	0.00	42.90	0.00	127.04	169.94	769.94	0.00	0.00	0.00	
APRIL	90.00	66.00	90.00	90.00	7.90	26.00	0.00	85.54	76.03	161.57	0.00	600.00	0.00	54.45	0.00	148.49	202.94	802.94	0.00	0.00	0.00	
MAY	92.00	79.00	114.00	114.00	12.80	26.00	0.00	85.54	76.03	161.57	0.00	600.00	0.00	65.17	0.00	188.09	253.26	853.26	0.00	0.00	0.00	
JUNE	95.00	83.00	122.00	122.00	17.30	26.00	0.00	85.54	76.03	161.57	0.00	600.00	0.00	68.47	0.00	201.29	269.76	869.76	0.00	0.00	0.00	
JULY	93.00	81.00	118.00	118.00	21.40	26.00	0.00	85.54	76.03	161.57	0.00	600.00	0.00	66.82	0.00	194.69	261.51	861.51	0.00	0.00	0.00	
AUGUST	93.00	73.00	106.00	106.00	21.10	26.00	0.00	85.54	76.03	161.57	0.00	600.00	0.00	60.22	0.00	174.89	235.11	835.11	0.00	0.00	0.00	
SEPTEMBER	89.00	57.00	81.00	81.00	16.50	26.00	0.00	85.54	76.03	161.57	0.00	600.00	0.00	47.02	0.00	133.64	180.66	780.66	0.00	0.00	0.00	
OCTOBER	82.00	40.00	59.00	59.00	10.30	26.00	0.00	85.54	76.03	161.57	0.00	600.00	0.00	33.00	0.00	97.34	130.34	730.34	0.00	0.00	0.00	
NOVEMBER	67.00	27.00	41.00	41.00	3.10	26.00	0.00	85.54	76.03	161.57	0.00	600.00	0.00	22.27	0.00	67.65	89.92	689.92	0.00	0.00	0.00	
DECEMBER	64.00	22.00	37.00	37.00	-2.80	26.00	0.00	85.54	76.03	161.57	0.00	600.00	0.00	18.15	0.00	61.05	79.19	679.19	0.00	0.00	0.00	
																				Cooling demand of the whole building =	0.00	kJoule
																					0.00	kWh

Figure 33: Cooling System Dataset Sheet

The region where the housing is located is important for the cooling demand calculation. The cooling demand of the housing can increase or decrease according to the region. Therefore, it is necessary to select correctly the region information. In the calculation of cooling demand, there is a need for regional information to be entered by the designer. Then the model calculates the cooling demand of the whole building is calculated automatically.

In the calculation of the cooling demand, the parameters mentioned in the previous sections (wall, ceiling, window, *etc.*) are required. The model was designed by considering this selection order.

-Theoretical background of Hot Water (HW) Supply Energy Needs Calculations

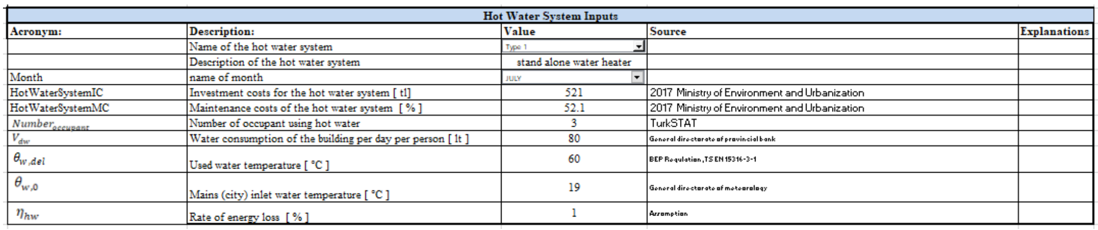
When determining the operational cost, it is also important for the energy needs for domestic hot water supply. To calculate the energy, need for hot water supply, water density, the water specific heat capacity and the volume of water used are required. In addition, the average monthly city water temperature and the average used water temperature are also important. The energy requirement for hot water supply is calculated as follows.

$$Q_{w,day} = \rho . c_w . V_{w,day} . \left(\theta_{w,del} - \theta_{w,0}\right) \qquad \text{(kWh)} \quad \text{Equation 108}$$

According to the “BEP-TR Regulation”, daily hot water consumption is defined as 45 liters for each person for multi-family houses. In addition, for each person for single-family houses, daily hot water consumption is determined as 60 liters. The regulation defines use water temperature as 60°C and supply (city) water temperature at 10°C. However, these values vary from city to city. The monthly detailed values are taken from the General Directorate of Meteorology. The model provides a transparent calculation method, so if the calculation is done for any province, its data can be loaded.

-Calculation of Hot Water (HW) Energy Demand

This model offers the “Hot Water Systems Input” sheet as follows.



Hot Water System Inputs				
Acronym:	**Description:**	**Value**	**Source**	**Explanations**
	Name of the hot water system	Type 1		
	Description of the hot water system	stand alone water heater		
Month	name of month	JULY		
HotWaterSystemIC	Investment costs for the hot water system [tl]	521	2017 Ministry of Environment and Urbanization	
HotWaterSystemMC	Maintenance costs of the hot water system [%]	52.1	2017 Ministry of Environment and Urbanization	
$Number_{occupant}$	Number of occupant using hot water	3	TurkSTAT	
V_{dw}	Water consumption of the building per day per person [lt]	80	General directorate of provincial bank	
$\theta_{w,del}$	Used water temperature [°C]	60	BEP Regulation ,TS EN 15316-3-1	
$\theta_{w,0}$	Mains (city) inlet water temperature [°C]	19	General directorate of meteorology	
η_{hw}	Rate of energy loss [%]	1	Assumption	

Figure 34: Hot Water Systems Input Sheet

In this area, the designer selects only hot water system types and enters the number occupant using hot water, then hot water system investment cost, hot water system maintenance cost, will be calculated automatically. The data in this excel page comes from the hot water database sheet in the model. The sheet was created by the author, derived from unit prices of the Ministry of Environment and Urbanism and from calculations in standards and regulations. In the hot water calculations, after the designer chooses one of the hot water systems types, the model automatically performs the following calculations.

Monthly Hot Water Energy Consumption

$$Q_{w,month} = Q_{w,day}.30 * 0.278 \qquad \text{(kWh) Equation 109}$$

Hot Water Energy Consumption Price

$$CostQ_{hw}1 = Q_{w,year}.price_{electricity} \qquad \text{(tl) Equation 110}$$

or

$$CostQ_{hw}2 = Q_{w,year}.\frac{price_{naturelgas}}{LHV_{naturalgas}} \qquad \text{(tl) Equation 111}$$

Monthly Water Consumption

$$V_{month} = \frac{Number_{occupant} . V_{dw} . 30}{1000} \qquad \text{(m3) Equation 112}$$

Yearly Water Consumption

$$V_{year} = V_{month} . 12 \qquad \text{(m3) Equation 113}$$

3.1.1.5. Maintenance Cost

Maintenance costs include regularly scheduled adjustments to preserve a building. It contains costs for routine, preventive, and corrective maintenance. In another word, it refers to the costs incurred to maintain building systems running properly (Woodward, 1997). The costs are defined as “occupancy cost” (Lutz *et al.*, 2006; Perera *et al.*, 1999; Thorbjoern, 1992). Maintenance costs are important for the calculation of the life cycle cost. However, any detailed information about the maintenance costs is not included in the standards and regulations in Turkey.

Maintenance costs for residential buildings represent approximately 1% of the investment cost (Bejrum, 1991; Bejrum, *et al.*, 1986; Johansson, & Öberg, 2001; Sterner, 2002) except for the maintenance costs of the systems and materials in the “Unit Prices Book” of 2017 published by Ministry of Environment and Urbanization and are defined as an equal series. For the simplification and generalization of the developed model and due to the lack of data about this issue in Turkey, the maintenance cost in this model was accepted as 1% of the investment cost.

3.1.1.6. Disposal Cost

The cost refers to as disposal cost at the end of its life cycle period. The costs are often ignored in its early phases. The disposal cost is important in environmental buildings and there exist serious financial impacts. However, as discounting is used, the effect on total cost of the building is minimal for traditional buildings (Abraham, & Dickinson, 1998; Sterner, 2002).

Just as in all developing countries, in terms of costs, every stage of the construction period is of great importance in Turkey. There are many studies in the literature on the topic of building disposal, but very few of these studies mention cost. The disposal cost of a building varies depending on many factors, from the quality and variety of the materials used in the building to the techniques used during construction and disposal. The disposal cost of building in the most general frame; site construction, preparation of demolition site, labor, equipment installation, machinery, transportation and disposal, storage of recoverable materials, legal permit costs and administrative costs (Coelho & de Brito, 2011).

In this model, the disposal cost calculation derived from unit prices of the General Directorate of Highways. The unit price covers one m^3 of the demolition of concrete construction, including loading at the construction site, unloading, all kinds of labor, tools and equipment expenses, contractor general expenses and profits.

3.1.1.7. Present Value

LCC is the sum of costs that incurred during the housing lifecycle period. However, most of the costs do not occur on this day. The present value method is used in LCC models to overcome this problem. This method takes into account the time value of money and makes the return equal to the market interest rate. In other words, future costs are reduced to "present value" (PV) using a reasonable discount rate for a lifetime. With this method, it is possible to determine the costs that occur for each year of housing at the current price. Therefore, the life cycle costs of different project alternatives could be compared. PV represents the total amount that needs to be reserved today to finance future spending. The Present Value formula can be shown as:

$$PV_{sum} = \frac{(1+r)^t - 1}{r(1+r)^t}$$ Equation 114

3.1.1.8. Assumptions and Limitations

LCC based model is the prediction of building future costs with today's data. When evaluating the literature, this method is generally implemented with black box methods. In this thesis, with transparent calculation methods, the original model is created. Life cycle costing model includes very complicated calculation method. Limitation and assumption in this model are set to enable calculations. Assumptions are as follows.

- The cost and energy required for the production of components in building materials are not included in this calculation.
- Salvage value is ignored due to the fact that the cost is a very small percentage of the building total cost.
- A 10% interest rate and 8% inflation rate were assumed.

3.1.2. Optimization of the LCC-Based Model

Optimization is the process of finding the optimal solution from given constraints and alternatives. It is a method to calculate a finite number of alternatives. It can be applied to all quantifiable problems. In general, an optimization problem aims to find the minimum/maximum values of a numerically determined parameter by changing design variables under the specific design conditions. The decision support tool aims to find the most appropriate building design by minimizing Life Cycle Costs (LCC) under given design constraints and by given design options. In this tool, optimization is considered as a minimizing of a quantified parameter.

According to Wetter (2000), the choice of an optimization method for a problem depends on the following aspects.

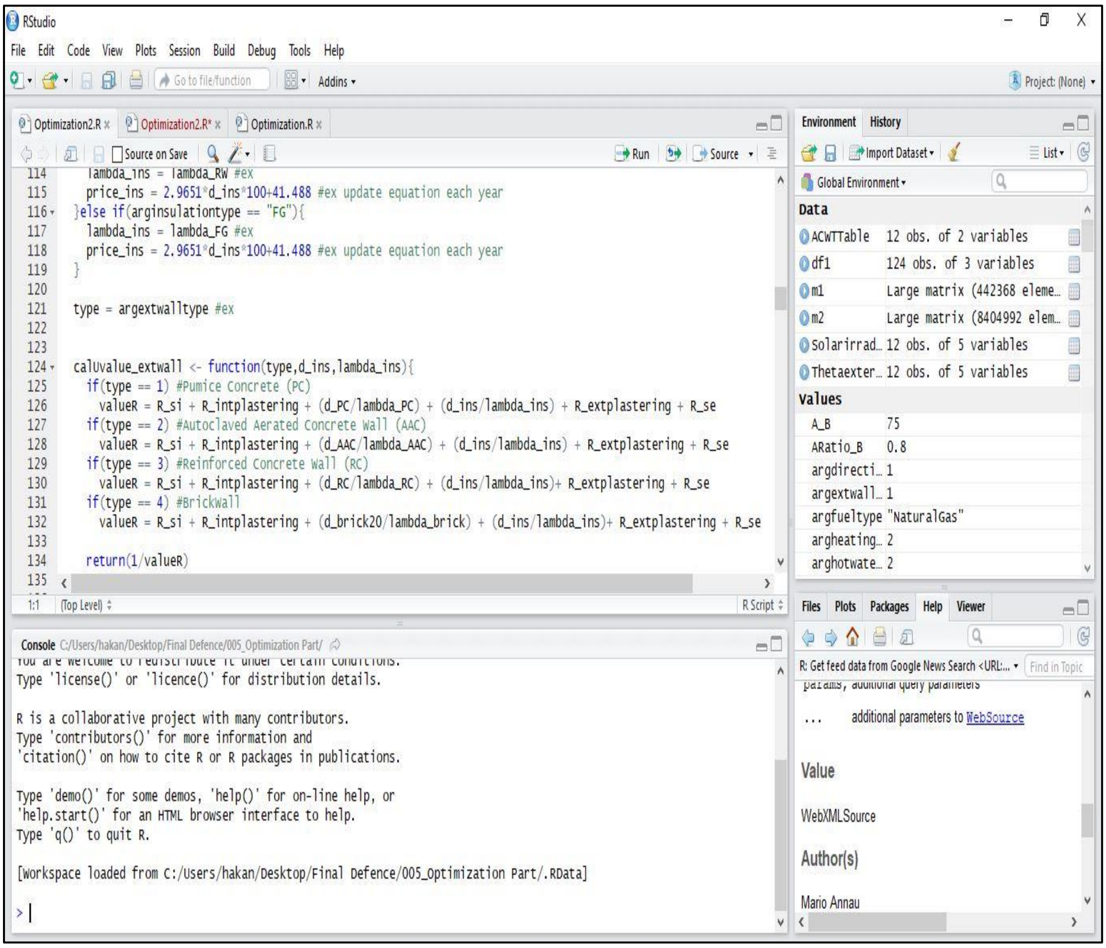
- structure of the objective function (linear, non-linear, convex, continuous, number of local minima, *etc*.)
- availability of analytic first and second order derivatives
- number of design variables
- design constraints

In this model, the optimization part is to consider all possible components as a single integrated problem. This problem is multi-purpose. This is because, while providing a comfortable environment for the households, it aims to minimize the amount of energy used and the cost targets at the same time. An optimization problem involves the variables and objectives of the problem. It is formulated by specifying these variables and objectives. The parameters to be used in the optimization parts are classified into two types.

- Fixed parameters
- Variable parameters

In this thesis, while fixed parameters are constant, variable parameters are called "design variables". The design variables are parameters used to find optimum values that give the best result in achieving objectives. The approach is to find optimal values of the design variables by combining the first part of the decision support system – LCC-based model- with the optimization algorithms.

In order to implement the decision support tool, it is necessary to work in harmony with each other in two parts. First of all, the lifecycle-based model will calculate the parameters of the building to be constructed, then all the possible results are written in the input files of the optimization program. Then, the optimization program starts. The whole process is repeated until all the possibilities are tested, and the lowest life-cycle cost is reached. This part offers designer the possibility of easy way calculation of life-cycle costs of own choices. Figure 35 represents "Main page of the second part-Optimization" area.



```
    lambda_ins = lambda_RW #ex
    price_ins = 2.9651*d_ins*100+41.488 #ex update equation each year
  }else if(arginsulationtype == "FG"){
    lambda_ins = lambda_FG #ex
    price_ins = 2.9651*d_ins*100+41.488 #ex update equation each year
  }

  type = argextwalltype #ex


  calUvalue_extwall <- function(type,d_ins,lambda_ins){
    if(type == 1) #Pumice Concrete (PC)
      valueR = R_si + R_intplastering + (d_PC/lambda_PC) + (d_ins/lambda_ins) + R_extplastering + R_se
    if(type == 2) #Autoclaved Aerated Concrete Wall (AAC)
      valueR = R_si + R_intplastering + (d_AAC/lambda_AAC) + (d_ins/lambda_ins) + R_extplastering + R_se
    if(type == 3) #Reinforced Concrete Wall (RC)
      valueR = R_si + R_intplastering + (d_RC/lambda_RC) + (d_ins/lambda_ins)+ R_extplastering + R_se
    if(type == 4) #BrickWall
      valueR = R_si + R_intplastering + (d_brick20/lambda_brick) + (d_ins/lambda_ins)+ R_extplastering + R_se

    return(1/valueR)
```

Console C:/Users/hakan/Desktop/Final Defence/005_Optimization Part/

```
You are welcome to redistribute it under certain conditions.
Type 'license()' or 'licence()' for distribution details.

R is a collaborative project with many contributors.
Type 'contributors()' for more information and
'citation()' on how to cite R or R packages in publications.

Type 'demo()' for some demos, 'help()' for on-line help, or
'help.start()' for an HTML browser interface to help.
Type 'q()' to quit R.

[Workspace loaded from C:/Users/hakan/Desktop/Final Defence/005_Optimization Part/.RData]

> 
```

Data

ACWTTable	12 obs. of 2 variables
df1	124 obs. of 3 variables
m1	Large matrix (442368 eleme…
m2	Large matrix (8404992 elem…
Solarirrad…	12 obs. of 5 variables
Thetaexter…	12 obs. of 5 variables

Values

A_B	75
ARatio_B	0.8
argdirecti…	1
argextwall…	1
argfueltype	"NaturalGas"
argheating…	2
arghotwate…	2

params, additional query parameters

...	additional parameters to WebSource

Value

WebXMLSource

Author(s)

Mario Annau

Figure 35: The Main Page of the Second Part-Optimization-

3.2. Validation

This study aims to develop a life-cycle costing-based decision support tool that can be used at all stages of the construction, especially in the preliminary design phase of the housing planning, starting from the concerns of sustainability and affordability in Turkey. Delphi Technique has been used for model validation in consultation with experts in the field of construction sector aimed at negotiating the proposed calculations. The Delphi technique, developed in the 1950s, is to make predictions about the future, to reveal expert opinions and to reach consensus (Terence *et al.*, 2000). For this reason, the model has been validated by referring to the views of the experts representing each dimension of the model selected from the construction sector, analyzing the agreements concerning the integration of the strategies proposed in the model. Three features of the Delphi technique stand out. These are anonymity, statistical analysis of group response, controlled feedback. In the Delphi technique, the most important thing is creating the group of experts. The technique is applied iterative administered to experts. After each application, the results are communicated to the participants. The process continues until convergence of opinion is reached.

The research was structured in 6 steps as shown in Figure 36.

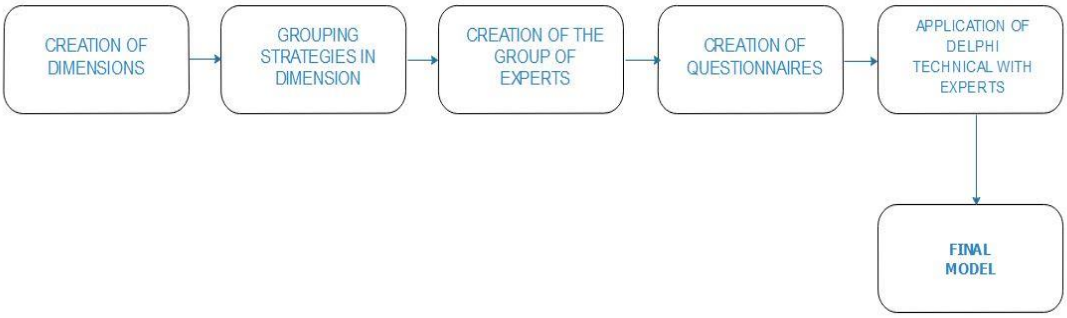


Figure 36: Delphi Research Structure

Source: adopted from Okoli & Pawlowski, 2004

A conceptual model was created that brings together the three dimensions of the LCC calculations in the construction sector, as shown in Table 14. Strategies related to the calculation of these dimensions have been established through literature.

Table 14: Dimension and Strategies

LCC Dimensions	Calculation Strategies
Pre-Usage Phase	Investment Cost
Usage Phase	Operational Cost Maintenance Cost
Post-Usage Phase	Disposal Cost

3.2.1. Information about the Experts

Each research session was consisted of thirteen experts. Selected experts should be qualified to reflect the views of the model. Experts have been selected among those who have had considerable views on the topic, which can provide a deep insight into the research in terms of experience and qualifications. All the experts have sufficient housing experience/knowledge. The information about the experts involved in the research is given in Table 15.

Table 15: Background Information of the Experts

	Affiliation	**Disciplines**	**Years of construction sector experience**
Expert 1	Implementation Department in TOKİ	Architect	12
Expert 2	Housing Development Projects and Research Department in TOKİ	Architect	18
Expert 3	Implementation Department in TOKİ	Civil Engineer	11
Expert 4	Real Estate Department in TOKİ	Civil Engineer	9
Expert 5	Implementation Department in TOKİ	Civil Engineer	7
Expert 6	Implementation Department in TOKİ	Civil Engineer	15
Expert 7	Housing Development Projects and Research Department in TOKİ	Civil Engineer	8
Expert 8	Housing Development Projects and Research Department in TOKİ	Architect	5
Expert 9	Implementation Department in TOKİ	Mechanical Engineer	9
Expert 10	Implementation Department in TOKİ	Civil Engineer	9
Expert 11	Implementation Department in TOKİ	Architect	11
Expert 12	Implementation Department in TOKİ	Mechanical Engineer	12
Expert 13	Implementation Department in TOKİ	Mechanical Engineer	10

All experts have rich hands-on experiences in the construction sector, hold senior management positions in their organizations and have been involved in the research activities in the construction sector.

3.2.2. Preliminary Interview

The research was conducted in a two-way; semi-structured interview and questionnaire. The aim of the semi-structured interview was to examine the current processes of the construction sector with regards to life cycle costing and to understand the experts' point of view in construction sector about the issue.

In the semi-structured face-to-face interviews, experts state that the most important process in construction projects is an economic decision-making process that helps to decide on new construction investments. They believe that this process must be designed accurately and precisely and emphasize the importance of considering local dynamics. Experts agree that this process will provide many benefits for both the government and the user. However, experts mentioned that a detailed work plan is not prepared at the beginning of each project and there is no defined economic decision analysis of the building which helps taking decisions on investments in new project. It also states that there is no process of how the material used will affect the energy of the building. In addition, they expressed that the choice of building materials depends mainly on low-cost and easily availability.

3.2.3. Questionnaire

The aim of the questionnaire is to determine the needs and usability of the DST in the construction sector. In the questionnaire, the selected experts in this study were consulted through a questionnaire containing 10 questions that would allow validation of the model revealed by the literature review (see Appendix IV). Experts were asked to provide feedback expressing their level of agreement with the questions. In the study, five-point Likert scale was used to analyze the opinions of the experts. Besides, experts were asked open-ended questions. Experts are also asked to identify problems and suggestions that have not been identified in the research until now.

3.2.4. Results

The purpose of this questionnaire is to collect the opinions of experts on the questions in Appendix IV. In this stage, questions were asked to each expert. Answers were requested to be sent to the researcher in an anonymous way. The consensus was evaluated by calculating the concordance coefficient proposed by Hurtado *et al.* (2013). According to Hurtado *et al.* (2013), the concordance coefficient is calculated by the mathematical expression of the total number of experts and the number of disagreeing experts. Accordingly, the concordance coefficient (Cc) is calculated as follows.

$$\mathrm{Cc} = (1 - \mathrm{Vn}/\mathrm{VT}).100$$

Vn: number of experts disagreeing
VT: total number of experts

-The First Round

In the research, there exist 9 scaled questions and 1 open-ended question. As result of the first round the concordance coefficients for each question are as follows.

Table 16: First Round Results

FIRST ROUND			
Question	**∑** **sum of experts' score**	**μ** **average score from experts**	**Cc** **coefficient of concordance of expert**
#1	44	3.38	76.92%.
#2	47	3.61	76.92%
#3	50	3.84	84.61%
#4	57	4.38	100%
#5	48	3.69	84,62%
#6	53	4.07	92.31%
#7	47	3.62	76.92%
#8	48	3.54	76.92%
#9	47	3.62	76.92%
#10	Open-Ended Question		

At the end of the first round the coefficient of concordance of each question were explained and the experts were asked to express their opinions about the questions. The answer given by the experts to each question is as follows.

Q1. The LCC based model makes a significant difference when applied in the design phase.

Some experts stated that in the design phase determining the all the costs of the building is very important in the housing sector. They pointed out that taking measures to reduce these costs is even more important especially in housing produced for the lower income group. Others expressed the opinion that the LCC-based model will not make a significant difference because it will not be used actively.

Q2. In the design stage, operational and maintenance costs of the building should be taken into consideration.

A large majority of experts state that these costs need to be taken into account. However, experts say that in the private sector, contractors will not take these costs into account to produce buildings cheaper.

Q3. It can be estimated the energy that the building will consume during its lifetime.

Some experts state that the energy that the building will consume during its lifetime can be predicted, but the existing energy programs are not used much because of the complex structures. Others expressed that they use the programs, but do not implement them in the projects they produce.

Q4. There is a connection between the material used and the energy consumption of the building.

All of the experts said that there is a connection between the material used and the energy consumption of the building.

Q5. It is possible to create the most economically advantageous building combination in its lifecycle period.

While some experts indicated that the most economically advantageous building combination in its lifecycle period cannot be created with existing programs, others expressed that it can be created, but that this is a very cumbersome and complex process.

Q6. In the early design phase, the high energy consumption of the building causes your design to change.

Most of the experts said that they would change their designs according to energy consumption of the building. Others claimed that these changes can lead to greatly increase the initial cost.

Q7. Using the LCC-based model in the design phase can help to reduce the energy consumption of the building.

Experts indicated that the LCC-based model will be very effective in reducing energy consumption. However, some experts claimed that people cannot use them effectively because its usage is complicated.

Q8. It is possible to reduce the total cost of the building by using an LCC-based model.

All experts stated that the investment cost of the building is very important indicator in the housing sector. However, operational cost and maintenance cost are often ignored by especially contractors. Some experts indicated that it is possible to reduce the total cost through this model. Others state that in Turkey, the total cost of the building is exactly incalculable because there are many variables such as material prices, inflation *etc.*

Q9. I would consider using the LCC-based model during the building design phase.

While many of the experts said they could use the model, others said they would not be able to use it because of reasons previously mentioned.

At the end of the discussion, the subjects that experts hesitate are explained in detail.

-The Second Round

In the second round, the results of the first round were anonymously sent to experts and explained. In almost all questions, an increase in the concordance level was observed. All coefficient of concordance was higher than 90%. As result of the second round the concordance coefficients for each question are as follows.

Table 17: Second Round Results

SECOND ROUND			
Question	**∑ sum of experts' score**	**μ average score from experts**	**Cc coefficient of concordance of expert**
#1	53	4.07	92.31%.
#2	54	4.15	84.62%.
#3	54	4.15	84.62%.
#4	60	4.62	100.00%
#5	51	3.92	92.31%
#6	57	4.38	92.31%.
#7	54	4.15	84.62%.
#8	53	4.07	84.62%.
#9	54	4.15	92.31%.
#10	Open-Ended Question		

At the end of the second round the coefficient of concordance of each question were explained and the experts were asked to express their opinions about the questions. The answer given by the experts to each question is as follows.

Q1. The LCC based model makes a significant difference when applied in the design phase.

All experts pointed out that LCC-based model can make a significant difference when applied in the design phase because the building's energy consumption and cost hotspots can be determined.

Q2. In the design stage, operational and maintenance costs of the building should be taken into consideration.

Experts state that these costs need to be taken into account. In private sector, if required arrangements are made, the contractors are also obliged to do. However, some experts were not sure whether these regulations would be made.

Q3. It can be estimated the energy that the building will consume during its lifetime.

Experts state that the energy that the building will consume during its lifetime can be estimated through user friendly software programs. However, they point out that existing software programs have very complicated structure. Therefore, they claimed that building energy consumption cannot be estimated.

Q4. There is a connection between the material used and the energy consumption of the building.

All of the experts said that there exists a connection between the material used and the energy consumption of the building.

Q5. It is possible to create the most economically advantageous building combination in its lifecycle period.

There is a consensus that the most economically advantageous building combination in its lifecycle period can be made with the decision support tool.

Q6. In the early design phase, the high energy consumption of the building causes your design to change.

In the first round some experts said that these changes can greatly increase the initial cost. At the end of the first round, initial cost increase rates and operational cost decrease rates were presented to experts. Experts reached a consensus about a small increase in initial costs can lead to significant savings during the building life cycle.

Q7. Using the LCC-based model in the design phase will help to reduce the energy consumption of the building.

In the first round some experts claimed that people cannot use them effectively because its usage is complicated. At the end of the first round, the decision support tool was explained in detail. It is stated that the DST has a transparent computable, measurable structure different from other black-box models. Then, the experts reached a consensus that it can be saved at a great rate from building energy consumption with the implementation of this DST.

Q8. It is possible to reduce the total cost of the building by using an LCC-based model.

In the first round some experts stated that in Turkey, the total cost of the building is exactly incalculable because there are many variables such as material prices, inflation. At the end of the first round, the decision support tool was explained in detail. It has been noted that the model takes all these variables into consideration while calculated building total cost.

Q9. I would consider using the LCC-based model during the building design phase.

Experts reached consensus that they could use the DST in the design phase.

-The Third Round

In the third and final round, the results of the second round were anonymously sent to experts and explained. The results of the third-round show that there is agreement among experts participating in the questionnaire. The model has not only been approved, but the model has also been revised with the help of an open-ended question. As result of the final round the concordance coefficients for each question are as follows.

Table 18: Third Round Results

THIRD ROUND			
Question	**∑ sum of experts' score**	**µ average score from experts**	**Cc coefficient of concordance of expert**
#1	61	4.69	100%.
#2	60	4.62	100%
#3	61	4.69	100%
#4	62	4.77	100%
#5	60	4.61	100%
#6	64	4,92	100%
#7	59	4.54	100%
#8	57	4.38	100%
#9	61	4.69	100%
#10	Open-Ended Question		

When the results of the rounds are analyzed, it can be seen that there is an increase in Cc in each round. The questions were the one reaching the highest Cc at third round (100% agreement). Thus, the model has been validated through experienced experts in the field.

The research including the semi-structured face-to-face interviews and the questionnaire found that an LCC-based DST is needed to determine how best to reduce a building life cycle cost to obtain a financially viable investment. Experts agreed that the DST would help reduce the total cost of a project by selecting the best alternative designs and components to minimize the cost over the entire life cycle of the project.

CHAPTER 4

IMPLEMENTATION OF THE DST

This chapter describes the implementation of the DST on the TOKI low-cost housing typology. It is given the general information of the low-cost housing produced for a better understanding housing sector. This chapter also includes DST implementation results and experts' opinions on the results.

The low-cost housing can be defined as low-profit housing by providing government subsidies and policy support to provide a decent housing for lower-income households. In the recent times, "low-cost housing" has been used as an alternative to term "affordable cost" housing (Gabriel *et al*,2005; Milligan *et al.*,2004). But, low-cost housing does not always mean affordable housing. Affordable housing, such as low-cost housing, is also produced for people who are unable to buy or rent housing under market conditions. However, the low-cost housing may not always be affordable when total life-cycle costs of the housing are calculated. In policies implemented especially in housing projects for the low-income groups, due to the fact that widely only initial cost is taken into account and maintenance and operating costs of housing are ignored, on the one hand, the housing producing for low-income groups after a while cannot be affordable, on the other hand it damages the sustainable environmental goals in terms of issues such as efficiently using energy, water, land, and other resources. In addition, for the reason that the allocated share for housing expenses increases in total income, one would have to allocate less money for food, health care, and other expenses. This can damage the social sustainability of the society. A housing project that appealed to the low-income group can contribute to a sustainable living by reducing maintenance and operational costs incurred throughout its life cycle. This is required a long-term analysis. Systematic, thorough methods and studies of integrated life cycle costing of housing options are needed. Current policies are the tendency to target construction costs of housing. However, it can have undesirable effects in the long term. Long-term policy perspectives are needed to provide lifetime housing affordability.

In Turkey, TOKI defines lower income groups as the maximum income level cannot exceed to 3200 ₺ (TOKI, 2016) or who have a “Green Card” or “receive salary within the meaning of the Law No. 2022205 or benefiting from the Social Aid and Solidarity Encouragement Fund within the meaning of the Law No 3294206” or “not having been dependent on any one of the social security institutions” (TOKI, 2010). According to this definition, there are even people who have no income in these houses built by TOKI. Lifetime affordability is more important especially for these people. Therefore, in this study, a low-income group was chosen.

One of the study aims is to contribute the housing policy in Turkey to produce lifetime affordable housing. It also informs policymakers and occupants in terms of the effectiveness of existing low-cost housing projects in the long-term maintenance and operational affordability.

4.1. Project Area

In the thesis, Ankara Mamak Kusunlar will be examined as a case study because of housing cost is very important for people living in this typology. The housings were produced by TOKI to provide housing for the low-income groups. The project area is located in Ankara, Mamak District, Kusunlar District.

Figure 37: Ankara Mamak Kusunlar Project Area Map

Kusunlar Project Area has located 17 km away from the city center of Ankara. There are no settlements in the vicinity of the Kusunlar Project Area. It is divided into regions with 1/25000 scale Başkent Master Development Plan approved on 16.02.2007.

According to Master Development Plan, the project area is located on the border of East and South Planning Area; It is located in the Eastern Planning Region. The eastern planning region, which includes TOKI project area, is defined as the most problematic and the most backward region in terms of physical thresholds and socioeconomic structure of the city. Accordingly, the "East Corridor" planning study in the context of the Samsun Road backbone aims to reduce social inequities in this region and to improve the region in a socio-spatial sense (Ankara Metropolitan Municipality, 2007).

The project area consists of the urban transformation projects. This area has been used for squatter housing owners who are within the scope of urban transformation projects in different regions of Ankara, but who are not entitled because they are not certified. Ankara Mamak Kusunlar Urban Transformation Project consists of 1374 houses in 27 apartment buildings. The buildings are 12, 13 and 14 stories. It has been completed by March 2014.

4.2. Building Geometry

The plan type, floor number, and area size of the case study are as follows.

Table 19: General Information about Mamak Kusunlar Urban Transformation Project

Plan Type	User Group	Number of floors	Area (Gross)	Number of apartments	Total housing unit number
B-1	Squatter housing owners who are not entitled because they are not certified	2B+Z+10N (5) 3B+Z+12N (11) B+Z+12N (11)	75,00m^2	27	1374

In the scope of the thesis study, B-1 plan type in the Mamak Kusunlar TOKI projects was chosen as a case study.

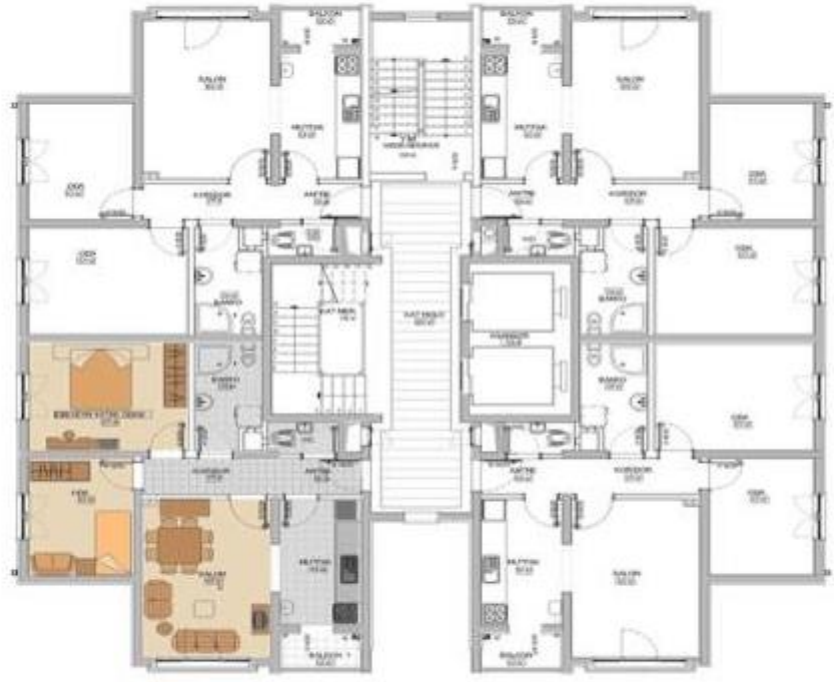


Figure 38: B-1 Plan Type

Source: TOKİ

The calculation will be made for single housing (B-1 plan type). The implementation of the model will be done on this case study.

4.3. Design Variables

External walls, insulation type and thickness;

The structural system of the building consists of concrete. Tunnel formwork system is used as a construction technique. For this reason, there exist two types of the opaque envelope that make up the exterior walls of the building. The physical properties of the external walls forming the building envelope are shown below.

Table 20: External Wall Properties

External Wall				
Material	**Thickness of construction element (d)**	**Thermal conductivity coefficient (λ)**	**specific heat (c)**	**Density (kg/m^3)**
External Plaster	0,03	1,4	840	1860
Reinforced concrete	0,24	2,5	1000	2300
Hollow Brick Wall	0,20	0,05	-	1200
Insulation Material (XPS)	0,05	0,030	1400	30
Internal Plaster	0,02	0,87	840	1600

Internal wall;

The physical properties of the internal wall are shown below.

Table 21: Internal Wall Properties

Internal Wall	
Material	Thickness of construction element (d)
Internal Plaster	0,02
Reinforced concrete	0,15
Internal Plaster	0,02

Window (glass and frame type);

The frames of the windows are made of PVC material and transparent clear glass is used as a transparent component. In the present case, the transparent component layer of the housing is 4 mm flat clear glass + 16 mm air space + 4 mm flat clear glass.

Ceiling;

In the model, the ceiling is considered as two types. Ceiling types vary according to which ceiling the housing is. The ceiling properties of the ground floor and intermediate floors are the same while the ceiling properties of the upper floor are different due to contact with the roof.

Table 22: Ceiling Properties-1

Ceiling-1				
Material	**Thickness of construction element (d)**	**Thermal conductivity coefficient (λ)**	**specific heat (c)**	**Density (kg/m^3)**
Plastering	0,02	1	840	1860
Screed concrete	0,025	1,4	1000	2300
Light Concrete	0,1	1,1	1000	2300

Table 23: Ceiling Properties-2

Ceiling-2				
Material	**Thickness of construction element (d)**	**Thermal conductivity coefficient (λ)**	**specific heat (c)**	**Density (kg/m^3)**
Plastering	0,02	1	840	1860
Reinforced concrete	0,12	2,5	1000	2300
Insulation material	0,08	0,04	1400	15

Floor;

In the model, the floor is considered as two types. The floor types vary according to which floor the housing is. The floor properties of the upper floor and intermediate floors are the same while the floor properties of the ground floor are different due to contact with the earth.

Table 24: Floor Properties-1

Floor-1				
Material	**Thickness of construction element (d)**	**Thermal conductivity coefficient (λ)**	**specific heat (c)**	**Density (kg/m^3)**
PVC floor covering	0.02	0.23	-	-
screed concrete	0.025	1.4	1000	1200
insulation	0.04	0.04	1400	15
leveling screed	0.02	1.4	1000	1200
light concrete	0.1	1.1	1000	1200

Table 25: Floor Properties-2

Floor-2				
Material	**Thickness of construction element (d)**	**Thermal conductivity coefficient (λ)**	**specific heat (c)**	**Density (kg/m^3)**
PVC floor covering	0.02	0.23	-	-
screed concrete	0.025	1.4	1000	1200
light concrete	0.1	1.1	1000	1200

Heating type and fuel type;

In the case study, Central Heating System is used as a heating type and natural gas is utilized as a fuel type.

Hot water system;

Two types of hot water types were identified in the model. They are stand-alone water heater and combi boiler. In the case study, combi boiler has been used in most of the housing. Therefore, in the study, combi boiler is evaluated as a hot water system type.

4.4. Finding Cost Optimal Solution with the DST

This study aims to develop an LCC-based decision support tool which life cycle costing and optimization have been successfully combined in order to jointly provide cost optimization of energy efficient design and refurbishment. The DST consists of two parts. The first part includes transparent box life cycle costing model which calculates life-cycle cost of housing for each variable separately. The second part of the tool is the optimization part which tries to calculate all linear dependent variables and decide afterward which set of solution is the best. The aim of the tool is to provide the most cost-optimal value of materials and system while presenting the life cycle cost of the building. The DST calculates nearly one million possibilities consisting of different combinations of design options. Among calculated one-million different hypothetical buildings, in order to determine a cost-optimal set of solution, the results of the LCC based model need to be optimized. An optimization tool that is perfectly compatible with the LCC-based model was constructed for this purpose. For this, each component expressed by a mathematical equation. The calculations are gathered from legislation (if any) and/or literature specific to Turkey. Then, data sets including design variables and constants are created and framework conditions such as climate, building geometry, interest rate and energy prices are designated. Then a "combined LCC-based-optimization” is created to find the optimum values of the design variables by combining the life cycle cost-based model with the optimization algorithms. The DST generates an output for each input. Optimization part calculates all results one by one and this process is repeated until the minimum lifecycle cost is reached. The output of the decision support tool is the most cost-optimal design under the specific design conditions and by given design options.

4.5. Comparison of Results

Among calculated one-million different hypothetical buildings, the comparison of the case study (Mamak Kusunlar) with the cost-optimal solution found with the help of the DST was made and the results are as follows. The results are based on a 30-year lifespan. It is assumed that all cases are located in the 3rd region in Turkey.

Table 26: Comparison of the Case Study and the Cost-Optimal Solution

Design Variable Name	**The case study**	**The cost-optimal solution**
External Wall Type	Reinforced Concrete (Mostly) Brick Wall	Pumice Masonry Unit
Internal Wall Type	Reinforced Concrete	Pumice Masonry Unit
Insulation Material Type	XPS	EPS
Insulation Thickness	0,05 m	0,13 m
Window Frame Type	PVC	Timber Frame
Window Glass Type	Double glazing unit	Double glazing unit (low-e)
Heating System Type	Central Heating	Central Heating
Used Fuel Type	Natural Gas	Natural Gas
Hot Water System Type	Combi Boiler	Combi Boiler
Life Cycle Cost (TL)	**117,832.90**	**106,613.75**

The pie charts of the case study and the cost-optimal solution life-cycle cost breakdown is as follows.

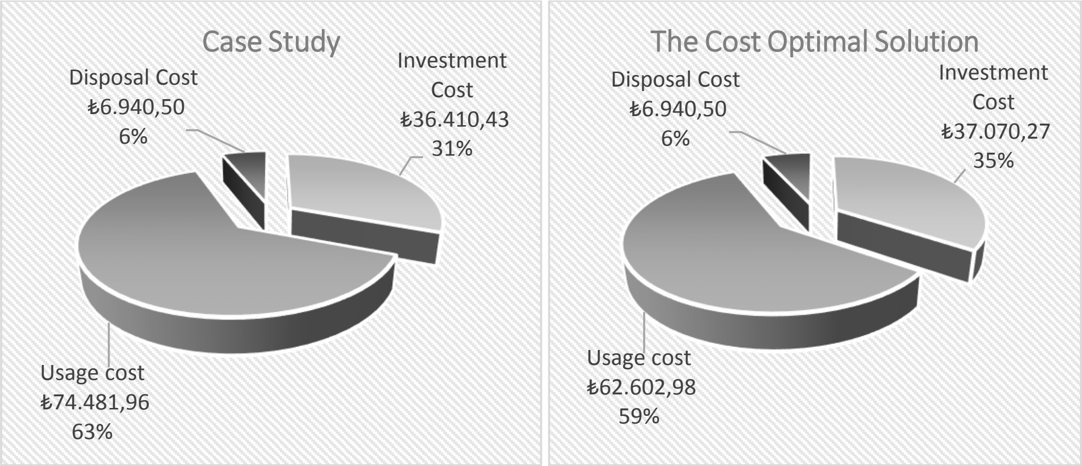


Figure 39: Life Cycle Cost Breakdown

For the case study, while the investment cost percentage is 31%, the usage cost (operational and maintenance costs) percentage of the case study is 63% of the total life-cycle cost. In addition, the disposal cost corresponds to 6%. For the cost optimal solution, according to chart, while the investment cost percentage is 35%, the usage cost (operational and maintenance costs) percentage of the case study is 59% of the total life-cycle cost. In addition, the disposal cost corresponds to 6%.

When analyzed regarding the comparison of the investment cost and usage cost (operational and maintenance costs), although the investment cost of the case-study is cheaper than the cost-optimal solution, the usage cost of the cost optimal solution is quite low. The cost-optimal solution provides the great majority of savings from usage cost (operational and maintenance costs). According to the results, the cost-optimal solution decreases the usage phase costs by 16% as it increases the investment costs only 1,8 % compared to case study.

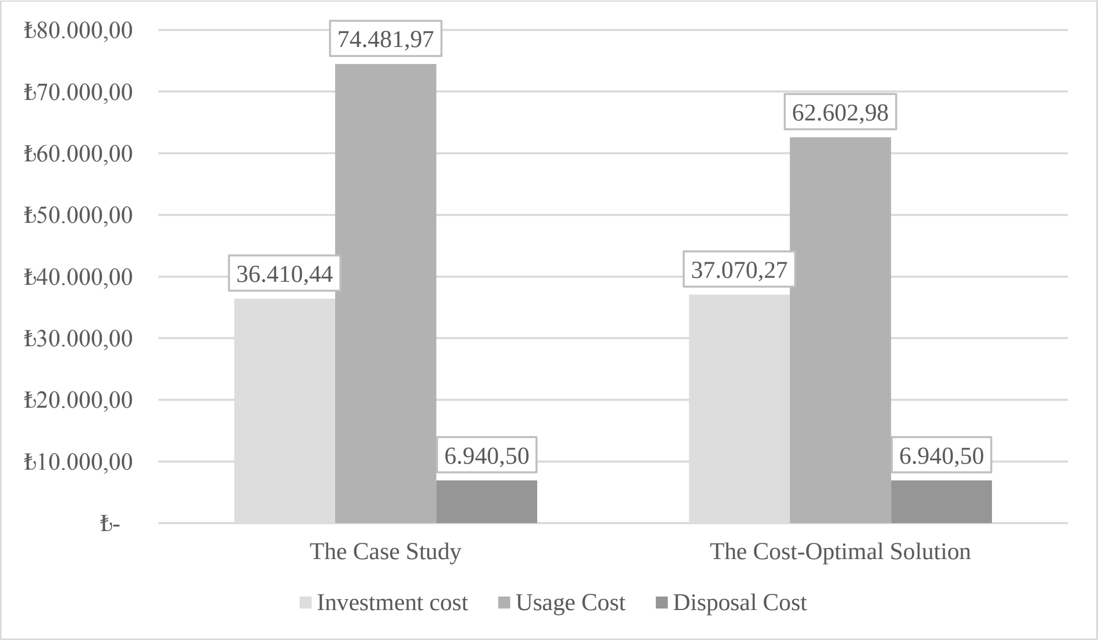


Figure 40: Comparison of the Case Study and the Cost-Optimal Solution

When compared the results of the case study and the cost optimal solution, while the total life-cycle cost of the cost-optimal solution is 117,832.90 TL, the cost optimal solution’s one is 106,613.75 TL. There exists 11,219.15 TL difference between the cost-optimal solution and the case study.

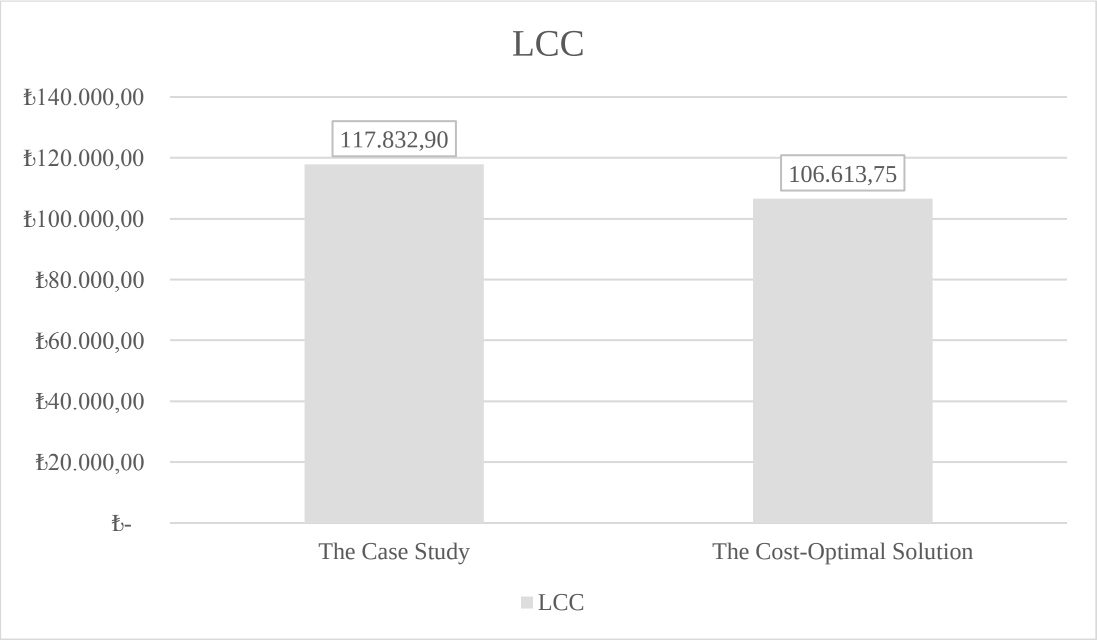


Figure 41: Comparison of the Case Study and the Cost-Optimal Solution in terms of LCC

When examined in terms of LCC and investment cost of all alternatives (nearly one-million), the cost optimal solution has minimum LCC. Figure 42 depicts the position of the cost optimum solution and case study among all alternatives.

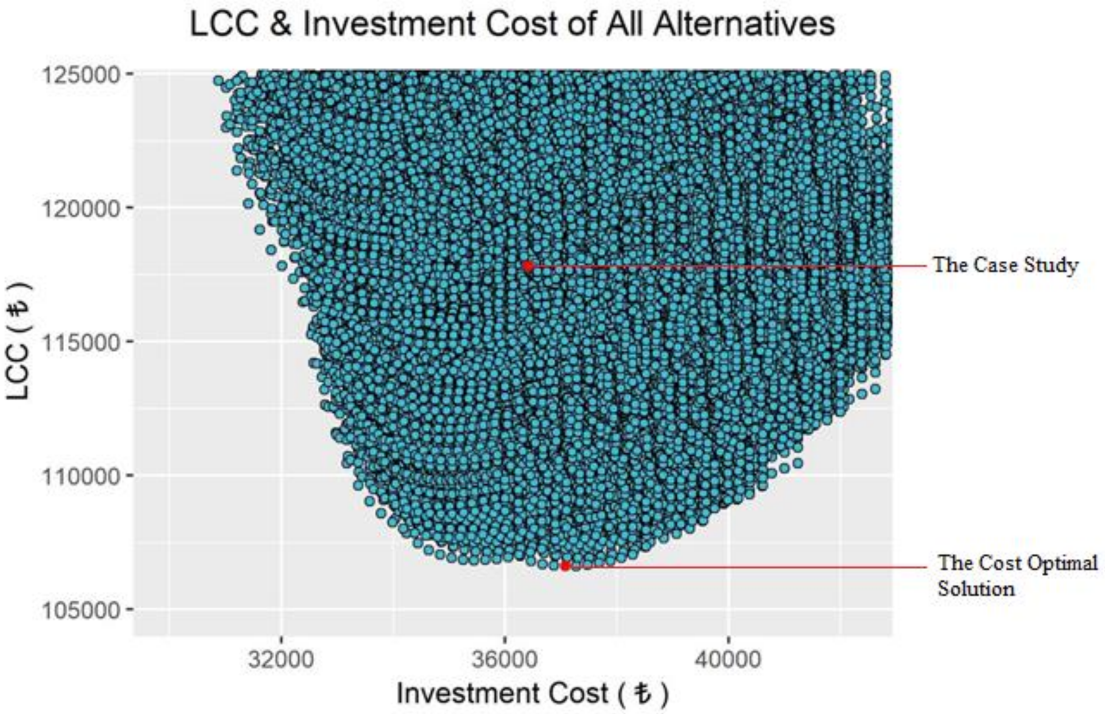


Figure 42: The Position of the Case Study and the Cost-Optimal Solution

Generally, the usage cost constitutes a majority of the total cost. This part is the most important portion of the total cost and but are the hardest to predict. When analyze of LCC and usage cost of all alternatives (nearly one-million), the cost-optimal solution has minimum LCC among other alternatives.

Figure 43 depicts the position of the cost-optimal solution and case study among all alternatives.

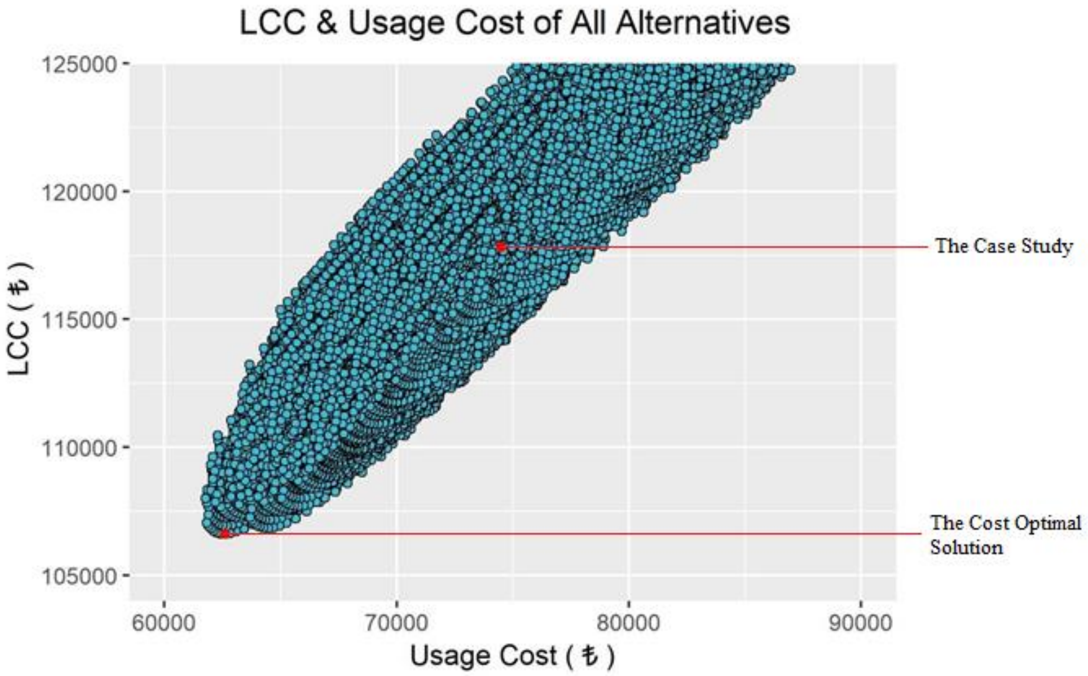


Figure 43: The Position of the Case Study and the Cost-Optimal Solution

Figure 44 depicts the position of the best-case scenario and case study among all alternatives. The energy consumption per m^2 of the cost optimal solution seems to be considerably lower than that of the case study.

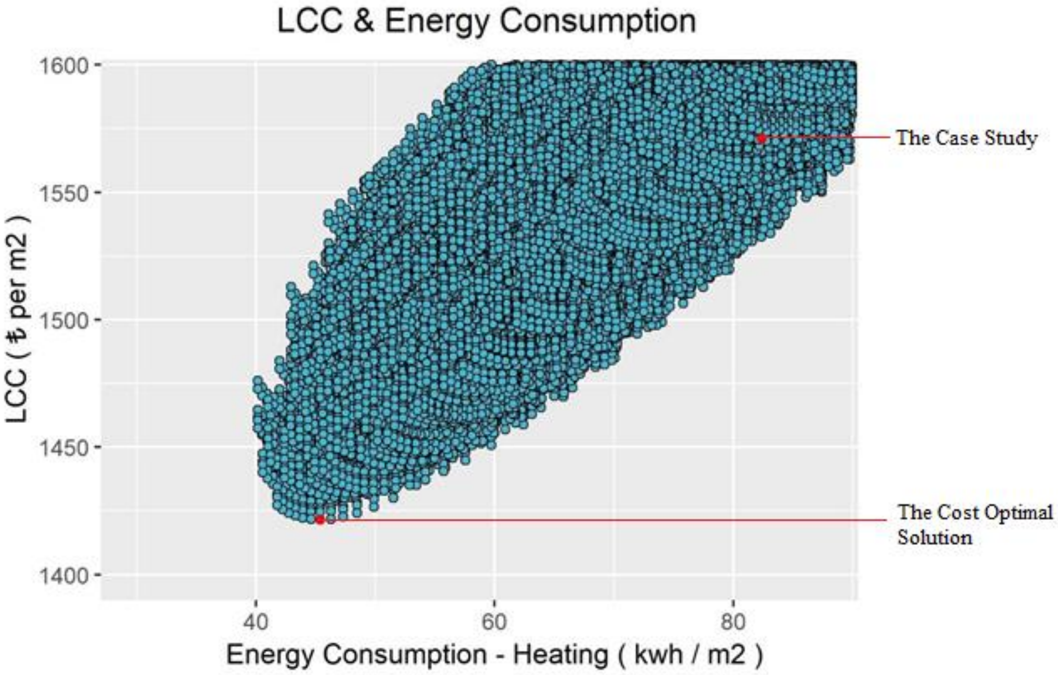


Figure 44: The Position of the Case Study and the Cost-Optimal Solution

When the study results in the 3rd region according to TSE 825 in the cost optimality literature are examined, Kalaycıoğlu and Yılmaz (2017) found that energy consumption per m^2 of reference case is 96.83 kwh/m^2 as energy consumption per m^2 of the cost optimal solution is 61.69 kWh/m^2 ; Ganiç and Yılmaz (2014) found that energy consumption per m^2 of reference case is 151.0 kWh/m^2 as energy consumption per m^2 of the cost optimal solution is 108.0 kWh/m^2.

With the decision support tool, the cost-optimal solution can be estimated in the planning stage and appropriate changes can be made and precautions can be taken. A small rise in the investment cost is accompanied by an important decrease in usage costs (operational and maintenance costs).

4.6. Scenario Analysis

In this phase, among calculated one-million different hypothetical buildings, the comparison of the case study with the most cost optimal solution and the other five scenarios. These five scenarios were chosen to reflect the effects of each variable on building energy performance among one-million hypothetical buildings.

The reference case is used as a basis to compare the energy and cost performance of the studied building. Reference building can be a real building, or it can be constituted virtually representing similar function, geometry and other relevant data of a cluster of buildings. This selected building should reflect the minimum requirements of the existing standards. As the standards differ for each country, reference buildings also vary. For example, according to American standard ASHRAE 90.1 (2007), there exist rules to define transparency ratio and orientation of the reference buildings. However, in Turkey there are only U-values in TS 825. Therefore, in order to be able to better interpret the scenario created, the reference case was determined in accordance with the mandatory national standard. The design parameters of the reference case are as follows.

Table 27: Reference Case Design Parameters

Design Variable Name	**Wall Type**	**Ins. Material**	**Ins. Thickness**	**Window Type**	**Heating System**	**Fuel Type**	**Hot-Water System Type**
Reference case	Reinforced Concrete	XPS	0.04 m	PVC Frame Single-glazing unit	Central Heating	Natural Gas	Stand-alone water heater

Energy performances of the seven scenarios were calculated as annual building (end-use) energy consumption and annual primary energy consumption (kWh/m^2 – year). The life cycle costing period has been set at 30 years for residential periods, as stated in the Regulation 244/2012. Table 28 gives a comparison of reference, cost optimal and five scenarios of residential building.

Table 28: Reference Building, Cost-Optimal Solution and Five Cases Comparison

	Investment Cost (TL)	Annual Energy Demand (Kwh)	Annual Energy Cost (TL)	Annual (TL)	Payback (year)
Reference Building	33,601.65	6,660.44	2,169.54		
The cost-optimal case	37,070.27	3,403.60	1,451.06	718	4.8
TOKI case (case study)	36,410.44	6,180.76	1,854,46	315	8.9
Scenario 01 **(improving only wall material)**	36,011.56	5,430.80	1,745.53	424	5.7
Scenario 02 **(improving only insulation material)**	35,849.07	6,583.33	1,912.94	257	8.8
Scenario 03 **(improving only insulation thickness**	38,286.93	4,550.00	1,617.59	552	8.5
Scenario 04 **(improving only window frame)**	36,464.03	5,928.31	1,817.79	352	8.1
Scenario 05 **(improving only window glass)**	36,516.73	5,676.68	1,781.24	388	7.5

According to the results, the cost optimal solution decreases the annual energy demand by 50 % as it increases the investment costs only 10 % compared to reference case. In addition, when the building's components are improved, the annual energy demand of the scenarios is as follows.

Table 29: Comparison Results

# Of Scenario	The Annual Energy Demand (Decreases)	The Investment Costs (Increases)
Scenario 01	18.46 %	6.69 %
Scenario 02	1.15 %	6.26 %
Scenario 03	31.68 %	12.23 %
Scenario 04	10.99 %	7.84 %
Scenario 05	14.77 %	7.98 %

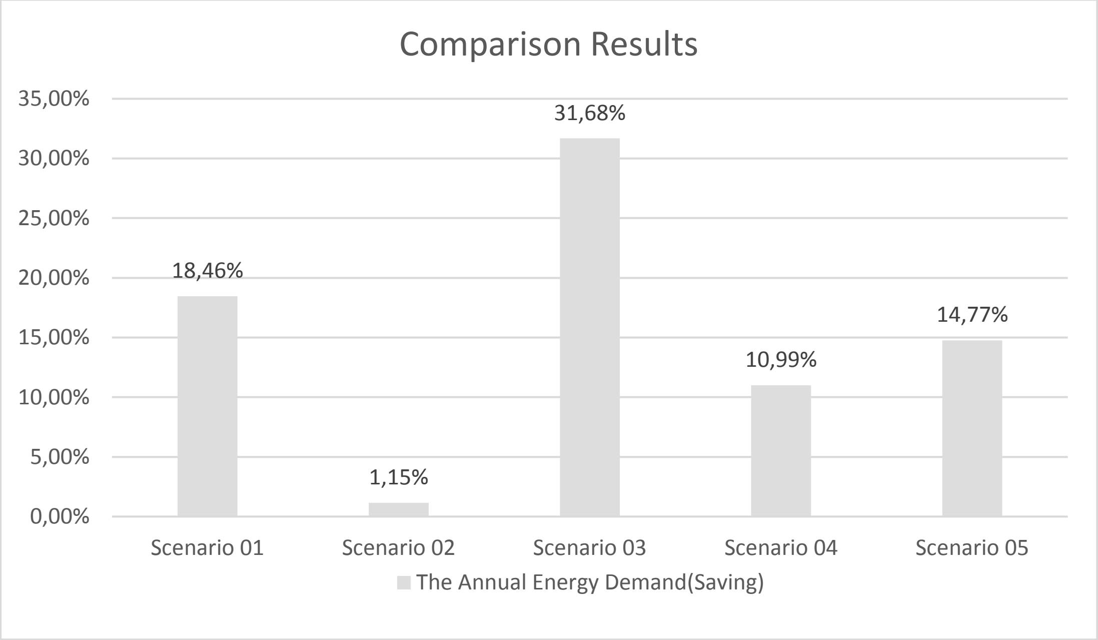


Figure 45: Comparison of the Annual Energy Demand and the Investment Cost

According to the result, the most effective component on life cycle energy consumption is insulation. However, at the same time, the component that increases the investment cost more than other scenarios, is also insulation.

One of the important methods used to analyze an investment is the payback period. The payback period represents the time length required to amortize the additional investment cost to the building by obtained energy saving. The payback period formula is as follows.

$PP = [C_I(A) - C_I(R)]/[C_E(R) - C_E(A)]$

PP : Payback period

$C_I(A)$: The investment cost of the analyzed alternative

$C_I(R)$: The investment cost of the reference case

$C_E(R)$: the annual energy cost of the reference case

$C_E(A)$: the annual energy cost of the alternative

The shorter the payback period for an investor, the better it is because it shows that the investment is profitable. Important point to discuss here, the cost-optimal case has the lowest payback periods, as the case study has the highest payback periods. Besides, each improvement to the case study shortens the payback period.

Table 30: Reference Building, Cost-Optimal Solution and Five Cases Comparison

	Investment Cost (TL)	**Usage Cost (TL)**	**LCC (TL)**
Reference Building	33,601.65	78,028.97	118,571.13
The cost-optimal case	37,070.27	62,602.98	106,613.76
TOKI case (case study)	36,410.44	74,481.96	117,832.91
Scenario 01 **(improving only wall)**	36,011.56	71,078.67	114,029.74
Scenario 02 **(improving only insulation type)**	35,849.07	76,046.45	118,836.02
Scenario 03 **(improving only insulation thickness**	38,286.93	68,009.86	113,237.30
Scenario 04 **(improving only window frame)**	36,464.03	73,399.97	116,804.50
Scenario 05 **(improving only window glass)**	36,516.73	72,321.24	115,778.47

According to the results, the cost optimal solution decreases the usage cost by 20 % as it increases the investment costs only 10 % compared to reference case. In addition, when the building's components are improved, the usage cost of the scenarios is as follows;

Table 31: Comparison of the Usage Cost and the Investment Cost

# Of Scenario	The Usage Cost (Decreases)	The Investment Cost (Increases)
Scenario 01	8.90 %	6.69 %
Scenario 02	2.54 %	6.26 %
Scenario 03	12.84 %	12.23 %
Scenario 04	5.93 %	7.84 %
Scenario 05	7.31 %	7.98 %

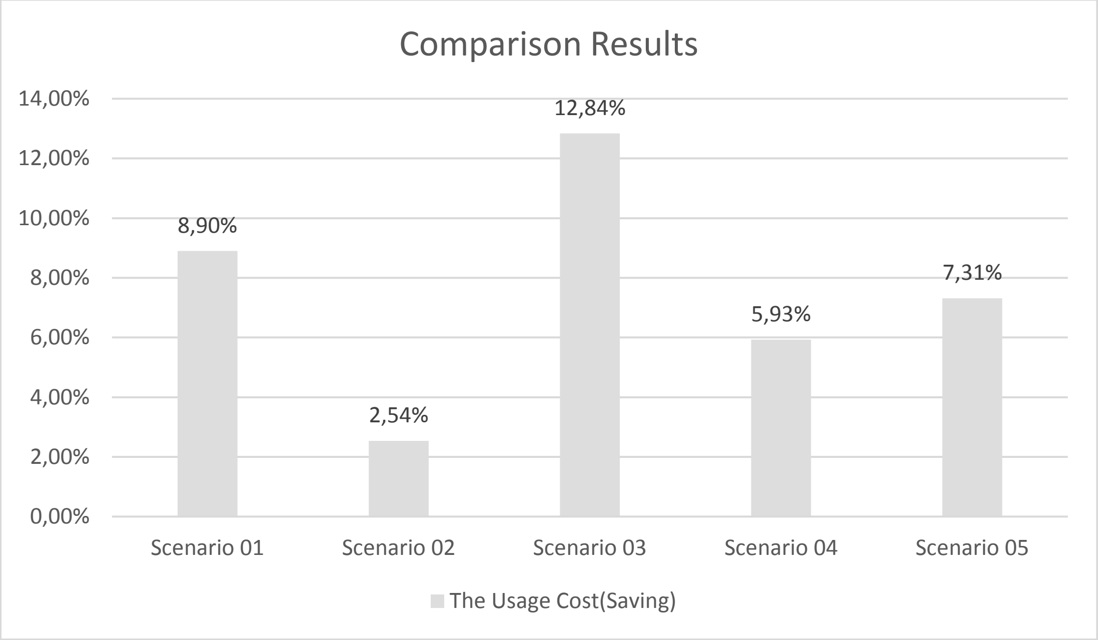


Figure 46: Comparison of the Usage Cost and the Investment Cost

According to the result, Scenario 03 decreases the usage cost more than other scenarios However, at the same time, it increases the investment cost more when compared to other scenarios.

4.7. Effects on Affordable Housing

In the housing literature, housing affordability is one of the most important topics. However, affordability is assessed as a short run indicator. In other words, only investment cost (construction cost) is taken into consideration. Operational/maintenance costs are often disregarded, so long-term affordability remains uncertain (Bogdon & Can, 1997; Burke & Ralston, 2004; Freeman & Soete, 1997; Gan & Hill, 2009; Linneman & Megbolugbe, 1992). Affordability can be generally defined as the ratio of household incomes to housing expenditures. However, in the affordability literature, "housing expenditures" are still under discussion. In this thesis, housing expenditures are discussed as total cost (maintenance and operational) incurred during the life cycle of the housing. Therefore, this thesis assesses the lifetime affordability of the housing.

The problem of housing affordability needs to be evaluated in terms of the energy efficiency measurements. Since, in definitions of housing affordability, crucial topics such as environmental and long-term economic sustainability of a housing are neglected (Mulliner *et al.,* 2013). A housing should be not only affordable but also environmentally and also long-term economically sustainable. Although in the short term, the terms of affordability as an economic sustainability and environmental sustainability are perceived as contradictory, in the long-term lifetime affordability and sustainability are complementary. This is required a long-term analysis. A balance between economic and environmental sustainability must be found. Thus, the sustainability and also cost optimal building is important to achieve affordability.

Buildings are responsible for approximately 40% of energy consumption (European Commission, 2017a). Most of this energy consumption comes from the energy that consume to keep buildings sufficient condition (*i.e.* operational and maintenance costs). However, in early design phase the costs including electricity, heating, water utilities *etc.* are ignored (Fankhauser & Tepic, 2007). Therefore, its lifetime housing affordability and energy demand is unclear.

The study aims to contribute the housing policy in Turkey to produce lifetime affordable housing. It also informs policymakers and occupants in terms of the effectiveness of existing low-cost housing projects in the long-term maintenance and operational affordability.

The proposed model has different objectives and target groups. In other words, the different parts of the model are important for different users and different purposes.

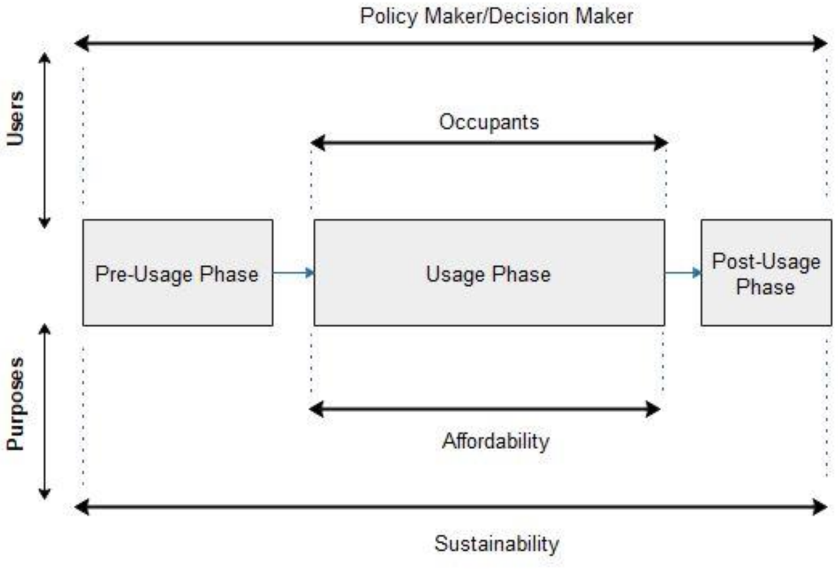


Figure 47: Model-Users and Purposes

While each phase is important to inform policy makers and decision makers and ensuring sustainability, only the "usage phase" provides information on the life-cycle cost of ownership and housing affordability. With this tool, the total cost of a housing can be estimated in the planning stage and appropriate changes can be made and precautions can be taken. Purchasers can get the information about housing expenses before getting the housing.

In the thesis, Ankara Mamak Kusunlar was examined as a case study. These housings were produced by TOKI directly to provide housing for the low-income groups. The DST is designed to calculate the total cost of building (investment cost, operational cost, maintenance cost, disposal cost *etc.*) for each specific building and find the most optimum solution in the design phase of the building over a 30 years period. The DST includes eleven types of design variables. These variables are the most widely used option in the construction sector in Turkey. There exist one million possibilities consisting of different combinations of these options. Among calculated one-million different hypothetical buildings, the case study (TOKİ Mamak Kusunlar) with the cost-optimal solution are compared.

When evaluated lifetime affordability, the operational and maintenance cost of the housing produced for lower income group by TOKI case is 74,481.9 TL for 30 years lifespan. The annual fee paid for the housing expenses (heating, cooling, hot water) is about 2,500 TL. While, in the cost-optimal solution, the annual fee paid for the housing expenses is nearly 2,000 TL. By implementing cost-optimal solution, approximately 20% of total housing expenses per year can be saved.

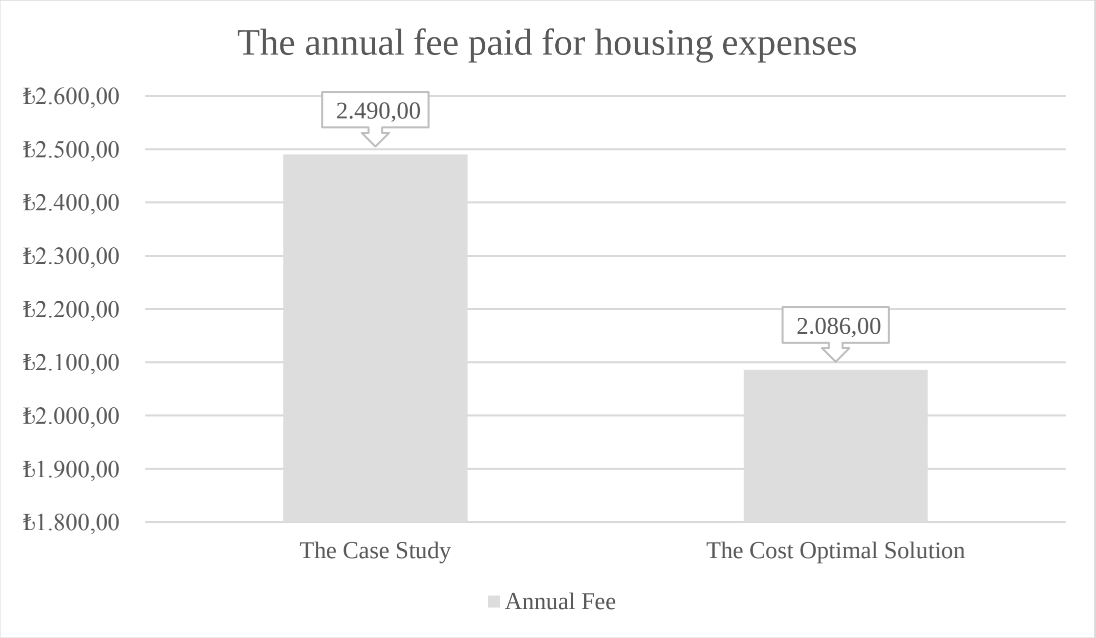


Figure 48: Comparison of the Annual Fees Paid for Housing Expenses

TOKI can define lower income groups as the maximum income level cannot exceed 3200 ₺ (TOKI, 2016). Nevertheless, most people residing in the low-cost housing produced by TOKI live below the minimum wage. According to Aslan & Güzey (Aslan & Güzey, 2015), only 7% of people residing in Mamak Karakusunlar TOKİ have income over 1000TL while the remaining 93% have income below 1000 TL. Therefore, a saving of about 500 TL per year is vital for these people. People would have to allocate less money for food, health care, and other expenses, because of that the allocated share for housing expenses increases in total income, this can damage the social sustainability of the society. According to TOKI's lower income group definition, there are even people who have no income in these houses built by TOKI. Lifetime affordability is more important especially for these people.

When evaluated life cycle cost breakdown, the operational and maintenance costs of a housing constructed according to the optimum parameters is less than the case study ones. A small rise in the investment cost is accompanied by an important decrease in operational and maintenance costs. That is, an increase of about 2% in the initial cost can provide a decrease of about 20% in the operational and maintenance costs. By increasing the initial cost by only 2%, annual savings of about 500 TL can be made.

4.8. Experts' Remarks on Implementation Results of the DST

The model has been validated by referring to the views of the experts representing each dimension of the DST selected from the construction sector, analyzing the agreements concerning the integration of the strategies proposed in the model (see 3.2 Validation). In addition to the validation, the implementation of the DST was carried out with these experts and they were asked to declare their opinion about implementation results. The experts in this section have been selected from the experts asked for a questionnaire to validate the DST due to the complex structure of the tool. Special attention was paid to the selected experts, to reflect the views of DST and to have a deep insight into the research in terms of experience and qualifications. Background information of the experts were given in Table 15.

After the implementation of the DST was carried out with the experts, in the discussion section, the implementation results were discussed through comparison of the case study and the cost-optimal solution, scenarios analysis and effects on affordable housing.

Comparison of the Case Study and the Cost-Optimal Solution

The comparison results of the case study and the cost-optimal solution were discussed with experts. The implementation results of the DST on a real case were found to be significant and interesting by experts. It is stated that in the design phase determining the energy consumption and total cost of the housing incurred in its life cycle period and identifying the hot spots that cause this cost and consumption can provide significant savings. They added that these data are very important in the construction sector.

Experts emphasized that the comparison of a real case and one-million hypothetic housing would not be possible with existing programs. They pointed out that many measures could be taken to reduce energy consumption and total cost and building performance could be improved to get closer to the cost-optimal solution in the current implementation. They also consensus that the ability of the DST to interactively demonstrate how a material or system that has been changed or added in a new structure or in the existing structure is affected the building life cycle cost by presenting the most optimal values would play an important role in the widespread use of the DST.

Scenario Analysis

The scenarios and results were discussed with experts. It was emphasized that the results of the scenarios are very striking, and they could not be determined without the help of a model. Experts said that the fact that they are known during the design phase will make a significant contribution to the construction sector. However, they did not make such evaluations in the current implementation and take measures only to reduce the investment cost. Among the scenarios, the most interesting scenario was 3. Experts found it remarkable that increasing the insulation thickness decreases the annual energy demand by about 30 % as it increases the investment costs only nearly 10 %.

It was stated that the ability of the DST to be tested one-million alternatives under different scenarios and to be calculated the 30-year building life cycle cost of the alternatives during refurbishment and early design phase are very useful. The 30-year energy cost calculated for each alternative design, compared to the building investment cost, was determined to provide significant savings in the energy consumption of the building. With this tool, it has also been shown mathematically that the issue of energy efficiency in the construction sector should be paid attention.

Effects on Affordable Housing

Effects of the results on affordable housing were discussed with experts. They pointed out that housing affordability is a social issue, it has never been addressed together with the issue of energy efficiency and cost-optimality based on technical calculation. In addition, they specified that the housing affordability is a new concept for Turkey and existing implementation takes into account the investment costs of the housing and ignore the other costs of the housing over incurred in its lifecycle period. They said that the DST makes it possible to approach the issue of housing affordability from a different perspective.

CHAPTER 5

CONCLUSIONS AND FURTHER WORK

5.1. Summary of the Research

Energy is an important issue for all nations because it is a vital input for socio-economic development and life-quality improvement. From the end of the Second World War, there has been a large increase in the demand for global energy. Providing increased energy supply and minimizing the environmental impacts related to increasing energy consumption are one of the greatest challenges in the twenty-first century. Buildings are surely responsible for a major part of the consumed energy. Hence, The Energy efficiency in buildings have been regarded as a key component to overcome this challenge. For this purpose, a variety of initiatives have been granted to reduce energy consumption in the buildings like the Directive 93/76/EEC, Directive 2004/8/EC, 2002/91/EC (EPDB). The directives did not include requirements or guidance regarding the level of ambition of the minimum energy performance levels. As a result of this uncertainty, each country has begun to set its own energy-saving level, ignoring their costs. Although energy-saving is an important criterion, it needs to be considered together with cost. Recast 36/EC/2010 has been published to prevent this problem. As a result of the directive, the concept of cost optimality has entered the literature (EU, 2010). However, there exist some gaps and problems in the implementation of this concept in the construction sector.

Firstly, the cost optimality concept suggests taking into account the life cycle of the building when calculating energy and cost. The life cycle costing including pre-usage, usage and end of the usage costs. However, in the literature, the unit prices to construct the whole building based on typology and function is used to calculate the investment cost instead of being calculated individually for each building. The calculation is a general template and is the same for every building in that building class even if the materials and/or systems are different.

Secondly, in the literature, some studies focus on specific parts of the building and only make improvements in these parts, rather than considering the building as a whole in energy calculations.

Thirdly, although optimal design solutions, from both energy and cost point of view, are highly influenced by local availability of materials, their costs and other local dynamics, these have not been considered in the studies. Furthermore, nearly all of the studies in the literature on EPDB methodology use black box models to implement the methodology. Black box models focused on a general framework and they are not constructed for a specific country. Therefore, they are not dominated by a majority of local dynamics in certain countries because it is used in many countries.

Finally, in the implementation of this methodology, studies offer few alternatives for reducing the primary and final energy used on the building, and it does not guarantee the most optimum design options. In addition, finding the most optimal option requires significant effort and experience to make the right decisions. The main reason for the limitations in these studies are that the methodologies are black-box. Therefore, the solutions proposed are limited to recommendations of the program user.

The new approach proposed in this study is to fill in the gaps and eliminate the problems in the literature. This study aims to develop an LCC-based decision support tool which life cycle costing and optimization have been successfully combined in order to provide jointly cost optimization of energy efficient design and refurbishment. The DST is designed to calculate the total cost of building (investment cost, operational cost, maintenance cost, disposal cost *etc.*) for each specific building and find the most optimum solution in the design phase of the building over a 30 years period. The DST includes eleven types of design variables. These variables are the most widely used option in the construction sector in Turkey. There exist one million possibilities consisting of different combinations of these options. In the thesis, Ankara Mamak Kusunlar was examined as a case study. These housings were produced by TOKI directly to provide housing for the low-income groups. According to results DST provides to save 50% of the building annual energy demand and 20 % of the building the usage cost.

5.2. Major Findings and Contributions

In construction sector, generally investment decisions are perceived as a short-term decision. This leads to significant problems in consuming energy and country economy in the long term. One of the important problems is that the building long-term cost and energy effectiveness of a project remains uncertain. To come up with this problem systematically, thorough methods and studies of integrated life cycle costing of building options are needed. With the proposed DST, it is aimed to fill the existing gaps and eliminate the problems. The DST can make a significant difference when applied in the design phase.

Energy efficiency in building are one of the most important concepts in order to construct the cost optimal building. Hence, in the early design stage, identifying the hot spots that make up the building's total energy consumption and taking precautions related to them are essential. The DST allows the designers to determine the energy demand during the building life cycle and to identify the hot spots of that energy demand and also to take precautions by changing design variables in the early design stage. With the implementation of this DST, it can be saved at a great rate from building energy consumption.

Energy-saving is one of the important pieces of the puzzle. However, rather than just thinking about energy saving, it is necessary to consider energy saving and investment cost together, because it is very difficult to achieve sustainability by ignoring the costs incurred in building life cycle period involved with energy efficiency investments. Decisions taken at the early design stage have considerable effects on the building life-cycle cost. The DST demonstrates that a small measure or a small change taken in this stage can lead to significant savings during the building life cycle.

In addition to the environmental and economic impacts of the DST, there are also social impacts. The DST evaluates whether the housings are really affordable and how to the housing contributes to the sustainable development. Implementation of the DST in housing can save a great deal of annual total housing expenditure. Therefore, people can allocate more money for food, health care, and other expenses, because of that the allocated share for housing expenses decreases in total income. This can provide the social sustainability of the society.

This study has many contributions to the construction sector. One of the important contributions of this study is that the DST allows to compare different alternatives and / or materials during early design stage. In this way, more conscious choices can be made in terms of housing, user and costs including operational costs. It also allows the improvement in energy efficiency can reach up to great percentage even with proper material and system selection. Secondly, the DST contributes to the development of more sustainable buildings. The DST can provide information on the lower operational costs of sustainable materials and installations in buildings, allowing more users, investors and developers to realize highly sustainable buildings. Thirdly, with DST, it is possible to map the risks of a building according to life cycle costs. This leads to the construction of better-thought-out buildings. Designed on the basis of the DST, the buildings are ready for the future because they reflect the needs of the users better, as the entire life cycle of the building is evaluated in the design phase.

5.3. Limitations of the Study

The DST aims to provide for the estimation of building future costs with today's data and finding the most cost-optimal solution. When evaluating the literature, this method is generally implemented with black box methods. In this thesis, with transparent calculation methods, the original model was constructed. Data used are enormous and complex and collecting the data takes a lot of time. Therefore, the building unit was chosen for the imptementation of the DST because it creates a more defined and concise field.

5.4. Recommendations for Further Work

In the decision support tool, alternatives for each building component have been identified. The alternatives are types of components frequently used in the construction sector in Turkey, but further research needs to be undertaken to identify new high-tech sustainable component/materials such as photovoltaic, solar panel. The designer can add as alternatives as desired because the decision support tool has a transparent computable, measurable structure. The new high-tech sustainable component/material may result in considerable savings from the operational-maintenance costs of the housing. Besides, this can provide information on the lower operational costs of sustainable materials and installations in buildings, allowing more users, investors and developers to realize highly sustainable buildings.

REFERENCES

AAbela, A., Hoxley, M., McGrath, P., & Goodhew, S. (2016). An investigation of the appropriateness of current methodologies for energy certification of Mediterranean housing. *Energy and Buildings*, *130*, 210–218. https://doi.org/10.1016/j.enbuild.2016.07.056

Abraham, D., & Dickinson, R. (1998). Disposal costs for environmentally regulated facilities: LCC approach. *Journal of Construction Engineering and Management*, *March/April*, 146-154.

Aksoy, U. T., & Inalli, M. (2006). Impacts of some building passive design parameters on heating demand for a cold region. *Building and Environment*, *41*(12), 1742–1754. https://doi.org/10.1016/j.buildenv.2005.07.011

Al-Hajj, A., & Horner, M. W. (1998a). Modelling the running costs of buildings. *Construction Management and Economics*, *16*(4), 459–470. https://doi.org/10.1080/014461998372231

Al-Homoud, M. S. (2001). Computer-aided building energy analysis techniques. *Building and Environment*, *36*(4), 421–433.

Andersson, B., Place, W., & Kammerud, R. (1985). The Impact of Building Orientation on Residential Heating and Cooling. *Energy and Buildings*, (8), 205–224.

Ankara Metropolitan Municipality (2007). Ankara Büyükşehir Belediyesi :: 2023 Başkent Ankara Nazım İmar Planı. Retrieved November 22, 2017, from http://www.ankara.bel.tr/ankara-buyuksehir-belediyesi-nazim-plan/

Arumägi, E., & Kalamees, T. (2014). Analysis of energy economic renovation for historic wooden apartment buildings in cold climates. *Applied Energy*, *115*, 540–548. https://doi.org/10.1016/j.apenergy.2013.10.041

Ascione, F., Bianco, N., De Stasio, C., Mauro, G. M., & Vanoli, G. P. (2015). A new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy performance. *Energy and Buildings, 88,* 78–90. https://doi.org/10.1016/j.enbuild.2014.11.058

Ashrafian, T., Yilmaz, A. Z., Corgnati, S. P., & Moazzen, N. (2016). Methodology to define cost-optimal level of architectural measures for energy efficient retrofits of existing detached residential buildings in Turkey. *Energy and Buildings*, *120,* 58–77. https://doi.org/10.1016/j.enbuild.2016.03.074

Asiedu, Y., & Gu, P. (1998). Product life cycle cost analysis: State of the art review. *International Journal of Production Research*, *36*(4), 883–908. https://doi.org/10.1080/002075498193444

Aslan, S., & Güzey, Ö. (2015). Karşılanabilir Konut" Sunumu: TOKİ Ankara Kusunlar Yoksul Grubu Konutları Örneği. *Journal of Ankara Studies*, *3*(1), 42–53.

Aste, N., Adhikari, R. S., & Manfren, M. (2013). Cost optimal analysis of heat pump technology adoption in residential reference buildings. *Renewable Energy*, *60*, 615–624. https://doi.org/10.1016/j.renene.2013.06.013

Atmaca, A. (2016). Life cycle assessment and cost analysis of residential buildings in south east of Turkey: part 1—review and methodology. *The International Journal of Life Cycle Assessment*, *21*(6), 831–846. https://doi.org/10.1007/s11367-016-1050-8

Ayçam, İ. (2006). *Türkiye Derece Gün Bölgelerinde Isıtma Gerektiren Dönem İçin Alçak KatlıKonut Binalarında Uygun Cam Tiplerinin Saptanmasına Yönelik Bir Yöntem* (Ph.D). Gazi University, Ankara.

Aydın, N. (2017). *Hammurabi Yasaları* (1st ed., Vol. 1). Ankara: Alfa Yayıncılık.

Aye, L., Bamford, N., Charters, B., & Robinson, J. (2000). Environmentally sustainable development: a life-cycle costing approach for a commercial office building in Melbourne, Australia. *Construction Management and Economics*, *18*(8), 927–934. https://doi.org/10.1080/014461900446885

Aytaç, A., & Aksoy, T. (2006). Enerji Tasarrufu İçin Diş Duvarlarda Optimum Yalitim Kalinliği ve Isitma Maliyeti İlişkisi. *Journal of Faculty Eng. Arch. Gazi Univ.*, *21*(4), 753–758.

Azari, R. (2014). Integrated energy and environmental life cycle assessment of office building envelopes. *Energy and Buildings*, *82*, 156–162. https://doi.org/10.1016/j.enbuild.2014.06.041

Bakis, N., Amaratunga, R. D. G., Kagioglou, M., & Aouad, G. (2003). An integrated environment for life cycle costing in construction. 20th CIB W78 Conference: IT in Construction, 2003, New Zealand.

Balcomb, J. D., Hedstrom, J. C., & McFarland, R. D. (1977). Simulation analysis of passive solar heated buildings—preliminary results. *Solar Energy*, *19*(3), 277–282.

Barringer, H. P., & Weber, D. P. (1996). Life Cycle Cost Tutorial. Presented at the Fifth International Conference on Process Plant Reliability, Houston, Texas.

Barthelmes, V., Becchio, C., Bottero, M., & Corgnati, S. (2014). The Influence of Energy Targets and Economic Concerns in Design Strategies for a Residential Nearly-Zero Energy Building. *Buildings*, *4*(4), 937–962. https://doi.org/10.3390/buildings4040937

BCIS (2008). *Standardised method of life cycle costing for construction procurement*. London, UK: The British Standards Institution.

Becchio, C., Dabbene, P., Fabrizio, E., Monetti, V., & Filippi, M. (2015). Cost optimality assessment of a single-family house: Building and technical systems solutions for the nZEB target. *Energy and Buildings*, *90*, 173–187. https://doi.org/10.1016/j.enbuild.2014.12.050

Bejrum, H. (1991). *Life-cycle economic appraisal for buildings and real estates*. Stockholm, Sweden.: Royal Institute of Technology.

Bejrum, H., Lundström, S., & Söderberg, B. (1986). *The economics of real estates in a long-term perspective, analysis of empirical data*. Stockholm, Sweden: Royal Institute of Technology.

Bekkouche, S., Benouaz, T., Cherier, M., Hamdani, M., Yaiche, M., & Khanniche, R. (2013). Influence of building orientation on internal temperature in saharan climates, building located in Ghardaïa region (Algeria). *Thermal Science*, *17*(2), 349–364. https://doi.org/10.2298/TSCI110121112B

Belusko, M., & O'Leary, T. (2010). Cost analyses of measures to improve residential energy ratings to 6 stars-playford North Development, South Australia. *Construction Economics and Building*, *10*(1/2), 36–47.

Bird, B. (1986). Costs-in-use, *5*(14), 281–285.

Bishop, D. (1984). Some reflections on life cycle costing. In J Brandon (Ed.), *Quality and profit in building design*. London: E. & F.N. Spon.

Boermans, T., Bettgenhauser, K., Hermelink, A., & Schimschar, S. (2011). *Cost-optimal Building Performance Requirements;* Stockholm, Sweden: European Council for an Energy Efficient Economy.

Bogdon, A., & Can, A. (1997). Indicators of local housing affordability: Comparative and spatial approaches, (25), 43–80.

Bogenstätter, U. (2000). Prediction and optimization of life-cycle costs in early design. *Building Research & Information*, *28*(5–6), 376–386. https://doi.org/10.1080/096132100418528

BPIE (2010). Cost-Optimality. Discussing Methodology and Challenges within the Recast Energy Performance of Buildings Directive; Brussels, Belgium.

BPIE (2013). *Building Performance Institute Europe, Implementing the cost-optimal methodology in EU countries. Lessons learned from three case studies*.

Brandão de Vasconcelos, A., Cabaço, A., Pinheiro, M. D., & Manso, A. (2016). The impact of building orientation and discount rates on a Portuguese reference building refurbishment decision. *Energy Policy, 91*, 329–340. https://doi.org/10.1016/j.enpol.2016.01.021

Brinks, P., Kornadt, O., & Oly, R. (2016). Development of concepts for cost-optimal nearly zero-energy buildings for the industrial steel building sector. *Applied Energy*, *173*, 343–354. https://doi.org/10.1016/j.apenergy.2016.04.007

Bromilow, F. J., & Pawsey, M. R. (1987). Life cycle cost of university buildings. *Construction Management and Economics*, *5*(4), S3–S22. https://doi.org/10.1080/01446193.1987.10462089

BS EN 15193 (2017). *Energy performance of buildings - Energy requirements for lighting*.

Burke, T., & Ralston, L. (2004). Measuring housing affordability. *AHURI Research and Policy Bulletin*, *45*. Retrieved from https://www.ahuri.edu.au/__data/assets/pdf_file/0016/2923/AHURI_RAP_Issue_45_Measuring_housing_affordability.pdf

Capeluto, I. G. (2003). Energy performance of the self-shading building envelope. *Energy and Buildings*, *35*(3), 327–336.

Çay, Y. (2011). Farklı Yapı Malzemeleri Kullanımında Isı Yalıtım Kalınlığının Enerji Tasarrufuna Etkileri. *Electronic Journal of Machine Technologies*, *8*(1), 47–56.

Chardon, S., Brangeon, B., Bozonnet, E., & Inard, C. (2016). Construction cost and energy performance of single-family houses: From integrated design to automated optimization. *Automation in Construction*, *70*, 1–13. https://doi.org/10.1016/j.autcon.2016.06.011

Chwieduk, D., & Bogdanska, B. (2004). Some recommendations for inclinations and orientations of building elements under solar radiation in Polish conditions. *Renewable Energy*, *29*(9), 1569–1581. https://doi.org/10.1016/j.renene.2003.12.018

Coelho, A., & de Brito, J. (2011). Economic analysis of conventional versus selective demolition—A case study. *Resources, Conservation and Recycling*, *55*(3), 382–392. https://doi.org/10.1016/j.resconrec.2010.11.003

Cole, R. J., & Sterner, E. (2000). Reconciling theory and practice of life-cycle costing. *Building Research & Information*, *28*(5–6), 368–375. https://doi.org/10.1080/096132100418519

Coley, D. A., & Schukat, S. (2002). Low-energy design: combining computer-based optimisation and human judgement. *Building and Environment*, *37*(12), 1241–1247.

Çomaklı, K., & Yüksel, B. (2003). Optimum insulation thickness of external walls for energy saving. *Applied Thermal Engineering*, (23), 473–479.

Corrado, V., Ballarini, I., & Paduos, S. (2014). Assessment of Cost-optimal Energy Performance Requirements for the Italian Residential Building Stock. *Energy Procedia*, *45*, 443–452. https://doi.org/10.1016/j.egypro.2014.01.048

Crawley, D. B., Hand, J. W., Kummert, M., & Griffith, B. T. (2008). Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*, *43*(4), 661–673. https://doi.org/10.1016/j.buildenv.2006.10.027

Deniz, E., Gürel, A. E., Daşdemir, A., & Çamur, D. (2009). Fuel consumption and influences of external wall optimum insulation thickness to owning cost of energy. *Technology*, *12*(4), 283–290.

DIN V 18599 (2011). *Energy Efficiency of Buildings - Calculation of the Net, Final and Primary Energy Demand for Heating, Cooling, Ventilation, Domestic Hot Water and Lighting. Parts 1-10, Beuth Verla*.

Dolmans, D. (2011). A change is going to come. A New Mandate: nearly zero energy buildings. *Eur. HVAC REHVA*, *6*(48), 34–37.

Duffle, J., & Beckman, W. A. (1991). *Solar Engineering of Thermal Processes* (2nd ed.). New York: John Wiley & Sons, Inc.

Dunk, A. S. (2004). Product life cycle cost analysis: the impact of customer profiling, competitive advantage, and quality of IS information. *Management Accounting Research*, *15*(4), 401–414. https://doi.org/10.1016/j.mar.2004.04.001

Durmayaz, A., Kadıoğlu, M., & Şen, Z. (2000). An application of the degree-hours method to estimate the residential heating energy requirement and fuel consumption in IstanbulKalorifer tesisatı proje hazırlama teknik esasları., *25*, 1245–1256.

EN 15217 (2007). *Energy performance of buildings – Methods for expressing energy performance and for energy certification of buildings*.

EN 15251 (2007). *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air 9 quality, thermal environment, lighting and acoustics]*.

EN 15459 (2008). *EN 15459, 2008, Energy performance of buildings - Economic evaluation procedure for energy systems in buildings*. Retrieved from http://www.cres.gr/greenbuilding/PDF/prend/set4/WI_29_TC-approval_version_prEN_15459_Data_requirements.pdf

EN ISO 13790 (2008). *Energy Performance of Buildings – Calculation of Energy Use for Space Heating and Cooling*.

Epstein, M. J. (1996). *Measuring corporate environmental performance: Best practices for costing and managing an effective environmental strategy*. Chicago: Irwin Professional Publishing.

EU (2002) *Directive of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings.*

EU (2010) *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)* (pp. 13–35). Retrieved from http://dx.doi.org/10.3000/17252555.L 2010.153.eng.

European Commission (1993). *Council Directive 93/76/EEC, 13 September 1993 to limit carbon-dioxide emissions by improving energy efficiency*.

European Commission (2003). *Directive 2002/91/EC, (2002), Directive of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings.*

European Commission (2016). EU Energy in Figures, Statistical Pocketbook.

European Commission (2017a). Buildings - Energy - European Commission. Retrieved July 25, 2018, from /energy/en/topics/energy-efficiency/buildings

European Commission (2017b). *Climate Strategies & Targets*. Retrieved from : http://ec.europa.eu/clima/policies/strategies en

European Council (2012). The Energy Efficiency Directive. Retrieved July 24, 2018, from https://www.eceee.org/policy-areas/EE-directive/

Fabrycky, W. J., & Blanchard, B. S. (1991). *Life-cycle cost and economic analysis*. Prentice Hall.

Ferrara, M., Fabrizio, E., Virgone, J., & Filippi, M. (2014). A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings. *Energy and Buildings*, *84*, 442–457. https://doi.org/10.1016/j.enbuild.2014.08.031

Ferrara, M., Fabrizio, E., Virgone, J., & Filippi, M. (2016). Energy systems in cost-optimized design of nearly zero-energy buildings. *Automation in Construction*, *70*, 109–127. https://doi.org/10.1016/j.autcon.2016.06.007

Ferry, D., Brandon, P., & Ferry, J. (1999). *Cost planning of buildings* (Vols. 1–7). Oxford: Blackwell Publishing.

Fertelli, A. (2013). Determination of optimum insulation thickness for different building walls in Turkey. *Transactions of FAMENA*, *37*(2), 103–113.

Flanagan, R. (1984). Life Cycle Costing- The Issues Involved (Vol. Vol. I). Presented at the Proceedings of the Third International Symposium on Building Economics, Canada, Ottawa: National Research Council.

Flanagan, R., Kendell, A., Norman, G., & Robinson, G. D. (1987). Life cycle costing and risk management. *Construction Management and Economics*, *5*(4), S53–S71. https://doi.org/10.1080/01446193.1987.10462093

Florides, G. A., Tassou, S. A., Kalogirou, S. A., & Wrobel, L. C. (2002). Measures used to lower building energy consumption and their cost effectiveness. *Applied Energy*, *73*(3), 299–328.

Fokaides, P. A., & Papadopoulos, A. M. (2014). Cost-optimal insulation thickness in dry and mesothermal climates: Existing models and their improvement. *Energy and Buildings*, *68*, 203–212. https://doi.org/10.1016/j.enbuild.2013.09.006

Freeman, C., & Soete, L. (1997). *The Economics of Industrial Innovation* (Vol. Third-Edition). Cambridge: MIT Press.

Gadomski, J. (1987). *Analysis of influence of the architectural concepts on heat loss in the buildings and some predictions of this field*. Warszawa: Institute of Buildings.

Gan, Q., & Hill, R. J. (2009). Measuring housing affordability: Looking beyond the median. *Journal of Housing Economics*, *18*(2), 115–125. https://doi.org/10.1016/j.jhe.2009.04.003

Ganiç, N., & Yılmaz, A. Z. (2014). Adaptation of the cost optimal level calculation method of Directive 2010/31/EU considering the influence of Turkish national factors. *Applied Energy*, *123*, 94–107. https://doi.org/10.1016/j.apenergy.2014.02.045

Garcia-Hansen, V., Esteves, A., & Pattini, A. (2002). Passive solar systems for heating, daylighting and ventilation for rooms without an equator-facing facade. *Renewable Energy*, *26*(1), 91–111.

Givoni, B. (1991). Characteristics, design implications, and applicability of passive solar heating systems for buildings. *Solar Energy*, *47*(6), 425–435.

Glick, S., & Guggemos, A. A. (2010). Life-cycle assessment and life-cycle cost as collaborative tools in residential heating system selection. *Journal of Green Building*, *5*(3), 107–115.

Gluch, P., & Baumann, H. (2004). The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. *Building and Environment*, *39*(5), 571–580. https://doi.org/10.1016/j.buildenv.2003.10.008

Goh, B. H., & Sun, Y. (2015). The development of life-cycle costing for buildings. *Building Research & Information*, 1–15. https://doi.org/10.1080/09613218.2014.993566

Grant, E., & Ireson, W. (1960). *Principles of engineering economy* (4th ed.). New York: Ronald Press.

Gundes, S. (2016). The Use of Life Cycle Techniques in the Assessment of Sustainability. *Procedia - Social and Behavioral Sciences*, *216*, 916–922. https://doi.org/10.1016/j.sbspro.2015.12.088

Gupta, R., & Ralegaonkar, R. (2004). Estimation of beam radiation for optimal orientation and shape decision of buildings in India. *Architectural Journal of Institution of Engineers*, (85), 27–32.

Gürel, A. E., & Cingiz, Z. (2000). Farklı dış duvar yapıları için optimum ısı yalıtım kalınlığı tespitinin ekonomik analizi. *SAÜ Fen Bilimleri Enstitüsü Dergisi*, *15*(1), 75–81.

Gustavsson, L., & Joelsson, A. (2010). Life cycle primary energy analysis of residential buildings. *Energy and Buildings*, *42*(2), 210–220. https://doi.org/10.1016/j.enbuild.2009.08.017

Hamdy, M., Hasan, A., & Siren, K. (2013). A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. *Energy and Buildings*, *56*, 189–203. https://doi.org/10.1016/j.enbuild.2012.08.023

Hamdy, M., Nguyen, A.-T., & Hensen, J. L. M. (2016). A performance comparison of multi-objective optimization algorithms for solving nearly-zero-energy-building design problems. *Energy and Buildings*, *121*, 57–71. https://doi.org/10.1016/j.enbuild.2016.03.035

Hasan, A. (1999). Optimizing insulation thickness for buildings using life cycle cost. *Applied Energy*, *63*(2), 115–124.

Heralova, R. S. (2014). Life Cycle Cost optimization within decision making on alternative designs. Retrieved from http://2015.creative-construction-conference.com/wp-content/uploads/2015/01/CCC2014_R_Schneiderova_Heralova.pdf

Hoffman, M., Rodan, K., Feldman, M., & Saposnik, D. S. (1983). Solar heating using common building elements as passive systems. *Solar Energy*, *30*(3), 275–287.

Holman, J. P. (1997). *Heat transfer*. New York: McGraw-Hill Companies.

Hoogmartens, R., Van Passel, S., Van Acker, K., & Dubois, M. (2014). Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. *Environmental Impact Assessment Review*, *48*, 27–33. https://doi.org/10.1016/j.eiar.2014.05.001

Hurtado, C. D., Correa, Z. C., & Cardona, Y. A. C. (2013). The role of a public university in a global environment: Networks and externalities of the R&D of the Cauca University. *Estudios Gerenciales*, *29*(129), 396–405. https://doi.org/10.1016/j.estger.2013.11.005

International Energy Agency. (2008). In support of the G8 Plan of Action. In IEA, *Deploying Renewables: Principles for Effective Policies* (pp. 15–198). OECD. https://doi.org/10.1787/9789264042216-1-en

ISO 13790 (2008). *Energy performance of buildings? Calculation of energy use for space heating and cooling.* Geneva, Switzerland: ISO.

Jedrzejuk, H., & Marks, W. (1994). Analysis of the influence of the service life and shape of buildings on the cost of their construction and maintenance, *3/4*(40), 507–518.

Johansson, C., & Öberg, M. (2001). Life cycle costs and affordability perspectives for multidwelling buildings in Sweden. In *Proceedings of second Nordic conference on construction economics and organization* (pp. 287–297). Gothenburg.

Johnson, R. E., Sherif, A., & Becker, F. D. (1987). Economics of university research laboratories — policy considerations. *Construction Management and Economics*, *5*(4), S31–S42. https://doi.org/10.1080/01446193.1987.10462091

Kalaycıoğlu, E., & Yılmaz, A. Z. (2017). A new approach for the application of nearly zero energy concept at district level to reach EPBD recast requirements through a case study in Turkey. *Energy and Buildings*, *152*, 680–700. https://doi.org/10.1016/j.enbuild.2017.07.040

Kale, N. N., Joshi, D., & Menon, R. (2016). Life cycle cost analysis of commercial buildings with energy efficient approach. *Perspectives in Science*, *8*, 452–454. https://doi.org/10.1016/j.pisc.2016.04.102

Kirk, S. J., & Dell'isola, A. (1995). *Life Cycle Costing for Design Professionals* (2nd ed.). New York: McGraw-Hill.

Kirkham, R. J., Boussabaine, A. H., & Awwad, B. H. (2002). Probability distributions of facilities management costs for whole life cycle costing in acute care NHS hospital buildings. *Construction Management and Economics*, *20*(3), 251–261. https://doi.org/10.1080/01446190110113701

König, H., & De Cristofaro, M. L. (2012). Benchmarks for life cycle costs and life cycle assessment of residential buildings. *Building Research & Information*, *40*(5), 558–580. https://doi.org/10.1080/09613218.2012.702017

Korpi, E., & Ala-Risku, T. (2008). Life cycle costing: a review of published case studies. *Managerial Auditing Journal*, *23*(3), 240–261.

Kurnitski, J., Allard, F., Braham, D., Goeders, G., Heiselberg, P., Jagemar, L., … Virta, M. (2011). How to define nearly net zero energy buildings nZEB, 7.

Lam, J. C., Wan, K. K. W., Wong, S. L., & Lam, T. N. T. (2010). Principal component analysis and long-term building energy simulation correlation. *Energy Conversion and Management*, *51*(1), 135–139. https://doi.org/10.1016/j.enconman.2009.09.004

Levander, E., Schade, J., & Stehn, L. (2009). Methodological and other uncertainties in life cycle costing. In *Performance Improvement in Construction Management* (pp. 233–246). Routledge. https://doi.org/10.4324/9780203876084

Lin, H. (1981). Building plane, form and orientation for energy saving. *Journal of Architecture*, (4), 37–41.

Lindberg, K. B., Fischer, D., Doorman, G., Korpås, M., & Sartori, I. (2016). Cost-optimal energy system design in Zero Energy Buildings with resulting grid impact: A case study of a German multi-family house. *Energy and Buildings*, *127*, 830–845. https://doi.org/10.1016/j.enbuild.2016.05.063

Lindholm, A., & Suomala, P. (2005). Present and Future of Life Cycle Costing: Reflections from Finnish Companies: A discussion, *2*(05), 282–293.

Ling, C. S., Ahmad, M. H., Ossen, D. R., & others. (2007). The effect of geometric shape and building orientation on minimising solar insolation on high-rise buildings in hot humid climate. *Journal of Construction in Developing Countries*, *12*(1), 27–38.

Linneman, P., & Megbolugbe, I. (1992). Housing affordability: Myth or reality, (29), 369–392.

Littlefair, P. (2001). Daylight, sunlight and solar gain in the urban environment. *Solar Energy*, *70*(3), 177–185.

Liu, B. Y., & Jordan, R. C. (1963). The long-term average performance of flat-plate solar-energy collectors: with design data for the US, its outlying possessions and Canada. *Solar Energy*, *7*(2), 53–74.

Lugmaier, A. (2000). Optimisation of Energy Efficiency Methods in Buildings regarding Life Cycle Costs.

Lutz, J., Lekov, A., Chan, P., Whitehead, C., Meyers, S., & Mcmahon, J. (2006). Life-cycle cost analysis of energy efficiency design options for residential furnaces and boilers. *Energy*, *31*(2–3), 311–329. https://doi.org/10.1016/j.energy.2005.02.002

Maçka, S. (2008). *TÜRKİYE İKLİM BÖLGELERİNE GÖRE ENERJİETKİN PENCERE TÜRLERİNİN BELİRLENMESİ* (Master Thesis). KARADENİZ TEKNİK ÜNİVERSİTESİ, Trabzon.

MacMullan, R. (1992). *Environmental Science in Building* (Third edition). London,Great Britain: MacMillan Press Ltd.

Marshall, H. E. (1987). Building economics in the United States. *Construction Management and Economics*, *5*(4), S43–S52. https://doi.org/10.1080/01446193.1987.10462092

Marszal, A. J., & Heiselberg, P. (2011). Life cycle cost analysis of a multi-storey residential Net Zero Energy Building in Denmark. *Energy*, *36*(9), 5600–5609. https://doi.org/10.1016/j.energy.2011.07.010

McLeod, P., & Fay, R. (2010). Costs of improving the thermal performance of houses in a cool-temperate climate. *Architectural Science Review*, *53*(3), 307–314. https://doi.org/10.3763/asre.2010.0022

Miller, G. A. (1995). WordNet: a lexical database for English. *Communications of the ACM*, *38*(11), 39–41.

Minami, K. (2004). Whole life appraisal of the repair and improvement work costs of Post Office buildings in Japan. *Construction Management and Economics*, *22*(3), 311–318. https://doi.org/10.1080/0144619032000108254

Mingfang, T. (2002). Solar control for buildings. *Building and Environment*, (37), 659–664.

Mithraratne, N. (2001). *Life cycle energy requirements of residential buildings in New Zealand.* (Ph.D). University of Auckland, New Zealand.

Mithraratne, N., & Vale, B. (2004). Life cycle analysis model for New Zealand houses. *Building and Environment*, *39*(4), 483–492.

Monetti, V. (2015). Scalable dynamic simulation-based methodology for the energy retrofit of existing buildings. https://doi.org/10.6092/polito/porto/2615480

Moore, M. T., Morrissey, J., & Horne, R. (2010). Cost benefit pathways to zero emission housing: Implications for household cash-flows in Melbourne. In *Proceedings in NZSSES transitions to sustainability conference. Auckland, New Zealand*. Retrieved from http://mams.rmit.edu.au/345b93ls3r5q.pdf

Morrissey, J., & Horne, R. E. (2011). Life cycle cost implications of energy efficiency measures in new residential buildings. *Energy and Buildings*, *43*(4), 915–924. https://doi.org/10.1016/j.enbuild.2010.12.013

Morrissey, J., Moore, T., & Horne, R. E. (2011). Affordable passive solar design in a temperate climate: An experiment in residential building orientation. *Renewable Energy*, *36*(2), 568–577. https://doi.org/10.1016/j.renene.2010.08.013

Nielsen, T. R., Duer, K., & Svendsen, S. (2001). Energy performance of glazings and windows. *Solar Energy*, *69*, 137–143.

Niemelä, T., Kosonen, R., & Jokisalo, J. (2017). Energy performance and environmental impact analysis of cost-optimal renovation solutions of large panel apartment buildings in Finland. *Sustainable Cities and Society, 32*, 9–30. https://doi.org/10.1016/j.scs.2017.02.017

Office of Government Commerce (OGC) (2003). *Achieving Excellence Guide 7: Whole-life Costing*. Retrieved from http://webarchive.nationalarchives.gov.uk/20110601212617/http://www.ogc.gov.uk/documents/CP0067AEGuide7.pdf

Okoli, C., & Pawlowski, S. D. (2004). The Delphi method as a research tool: an example, design considerations and applications. *Information & Management, 42*(1), 15–29. https://doi.org/10.1016/j.im.2003.11.002

Olgyay, V. (1963). *Design with Climate: Bioclimatic Approach to Architectural Regionalism*. Princeton, NJ.: Princeton University Press.

Pacheco, R., Ordóñez, J., & Martínez, G. (2012). Energy efficient design of building: A review. *Renewable and Sustainable Energy Reviews*, *16*(6), 3559–3573. https://doi.org/10.1016/j.rser.2012.03.045

Pellegrini-Masini, G., Bowles, G., Peacock, A. D., Ahadzi, M., & Banfill, P. F. G. (2010). Whole life costing of domestic energy demand reduction technologies: householder perspectives. *Construction Management and Economics*, *28*(3), 217–229. https://doi.org/10.1080/01446190903480027

Penna, P., Prada, A., Cappelletti, F., & Gasparella, A. (2015). Multi-objectives optimization of Energy Efficiency Measures in existing buildings. *Energy and Buildings*, *95*, 57–69. https://doi.org/10.1016/j.enbuild.2014.11.003

Perera, H. S. C., Nagarur, N., & Tabucanon, M. T. (1999). Component part standardization: A way to reduce the life-cycle costs of products. *International Journal of Production Economics*, *60*, 109–116.

Perret, P., & Jouvent, M. (1995). Guide de la maintenance des batiments. *External Uncertainty Factors and LCC: A Case Study*, *3*(37), 325–334.

Pikas, E., Thalfeldt, M., & Kurnitski, J. (2014). Cost optimal and nearly zero energy building solutions for office buildings. *Energy and Buildings*, *74*, 30–42. https://doi.org/10.1016/j.enbuild.2014.01.039

Pulakka, S., & Sarja, A. (1999). Life cycle cost design methods and tools. *Durability of Building Materials and Components*, *8*, 2715.

Radford, A., Gero, J., & Cruz, N. (1984). *Energy conservative in context of the use of multicriteria decision methods*. (M. Cowan, Ed.). Sydney: Pergamon Press.

Real, S. F. (2010). *Contribution of life cycle cost analysis to design sustainability in construction*. Masters dissertation in Civil Engineering, Department of Civil Engineering and Architecture-Instituto Superior Técnico-Technical University of Lisbon.

Reddy, V. R., Kurian, M., & Ardakanian, R. (2015). Life-cycle Cost Approach (LCCA): Framework and Concepts. In V. R. Reddy, M. Kurian, & R. Ardakanian, *Life-cycle Cost Approach for Management of Environmental Resources* (pp. 17–37). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-06287-7_2

Reidy, R., Davis, M., Coony, R., Gould, S., Mann, C., & Sewak, B. (2005). GUIDELINES FOR LIFE CYCLE COST ANALYSIS. Stanford University.

Reindl, D. T., Beckman, W. A., & Duffie, J. A. (1990). Evaluation of hourly tilted surface radiation models. *Solar Energy*, *45*(1), 9–17.

Ryghaug, M., & Sørensen, K. H. (2009). How energy efficiency fails in the building industry. *Energy Policy*, *37*(3), 984–991. https://doi.org/10.1016/j.enpol.2008.11.001

Sayed, S. S. M., & Sawant, P. H. (2015). Life-cycle cost and financial analysis of energy components in mass housing projects – A case project in sub-urban India. *International Journal of Sustainable Built Environment*, *4*(2), 202–221. https://doi.org/10.1016/j.ijsbe.2015.07.001

Schade, J. (2007). Life cycle cost calculation models for buildings. In *Nordic Conference on Construction Economics and Organsiation: 14/06/2007-15/06/2007* (pp. 321–329). Lule\a a tekniska universitet.

Schlueter, A., & Thesseling, F. (2009). Building information model based energy/exergy performance assessment in early design stages. *Automation in Construction*, *18*(2), 153–163. https://doi.org/10.1016/j.autcon.2008.07.003

Seljom, P., Lindberg, K. B., Tomasgard, A., Doorman, G., & Sartori, I. (2017). The impact of Zero Energy Buildings on the Scandinavian energy system. *Energy*, *118*, 284–296. https://doi.org/10.1016/j.energy.2016.12.008

Shaviv, E. (1981). The influence of the orientation of the main solar glazing on the total energy consumption of a building. *Solar Energy*, *26*(5), 453–454.

Sisman, N., Kahya, E., Aras, N., & Aras, H. (2007). Determination of optimum insulation thicknesses of the external walls and roof (ceiling) for Turkey’s different degree-day regions. *Energy Policy*, *35*(10), 5151–5155. https://doi.org/10.1016/j.enpol.2007.04.037

Smith, P. V. (2010). Life Cycle Costs & Housing Affordability Measurement. Retrieved from https://opus.lib.uts.edu.au/research/handle/10453/16598

Sözen, A., & Arcaklioğlu, E. (2005). Solar potential in Turkey. *Applied Energy*, *80*(1), 35–45. https://doi.org/10.1016/j.apenergy.2004.02.003

Stephan, A., & Stephan, L. (2016). Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. *Applied Energy*, *161*, 445–464. https://doi.org/10.1016/j.apenergy.2015.10.023

Sterner, E. (2000). Life-cycle costing and its use in the Swedish building sector. *Building Research & Information*, *28*(5–6), 387–393. https://doi.org/10.1080/096132100418537

Sterner, E. (2002). *Green procurement of building: estimation of life cycle cost and environmental impact.* Lulea University of Technology, Sweden.

Stone, P. (1983). *Building economy: Design, production and organisation – A synoptic view*. Oxford: Pergamon Press.

Swan, L. G., & Ugursal, V. I. (2009). Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews*, *13*(8), 1819–1835. https://doi.org/10.1016/j.rser.2008.09.033

Teodoriu, G., Balan, M., Şerbănoiu, I., & Verdeş, M. (2014). Cost-optimal Analysis of Performance Relation Thermal Insulation – Hydronic Heating System Applied to Romanian Residential Buildings. *Procedia Technology*, *12*, 583–590. https://doi.org/10.1016/j.protcy.2013.12.533

Terence, J., Wright, C., & Giovinazzo, R. (2000). *Delphi-a tool to support prospective planning*.

Thomas, S., Aydin, V., Kiyar, D. D., & Hafiz, A. (2015). Energy efficiency policies for buildings. *Wuppertal Institute for Climate, Environment and Energy*, 48.

Thorbjoern, M. (1992). *Building Economics for Architects.* Van Nostrand Reinhold.

TOKI (2010). *Konut Edinme Rehberi 2010*. Retrieved from http://www.toki.gov.tr/AppResources/UserFiles/files/KonutEdinmeRehberi.pdf

TOKI (2016). TOKİ | Toplu Konut İdaresi Başkanlığı. Retrieved January 18, 2016, from https://www.toki.gov.tr/

TS EN ISO 13790 (2008). Energy performance of buildings — Calculation of energy use for space heating and cooling. TSE.

Tsalikis, G., & Martinopoulos, G. (2015). Solar energy systems potential for nearly net zero energy residential buildings. *Solar Energy*, *115*, 743–756. https://doi.org/10.1016/j.solener.2015.03.037

Udawattha, C., & Halwatura, R. (2017). Life cycle cost of different Walling material used for affordable housing in tropics. *Case Studies in Construction Materials*, *7*, 15–29. https://doi.org/10.1016/j.cscm.2017.04.005

UNDP (2010). Promoting Energy Efficiency in Buildings.

UNFCCC (1997). Kyoto Protocol | UNFCCC. Retrieved July 24, 2018, from https://unfccc.int/process/the-kyoto-protocol

United Nation Environment Programme (UNEP) (2004). *Why Take a Life Cycle Approach?* France: UNEP.

US Air Force (n.d.). *Passive Solar Handbook Volume I, Introduction to passive solar concepts*. Retrieved from wbdg.org/ccb/AF/AFH/pshbk v1.pdf

US DOE (2014). *Life Cycle Cost Handbook Guidance for Life Cycle Cost Estimation and Analysis*. Washington, DC: U.S. Department of Energy Office of Acquisition and Project Management.

Verbeeck, G., & Hens, H. (2010). Life cycle inventory of buildings: A contribution analysis. *Building and Environment*, *45*(4), 964–967. https://doi.org/10.1016/j.buildenv.2009.10.003

Wang, S., & Xu, X. (2006). Simplified building model for transient thermal performance estimation using GA-based parameter identification. *International Journal of Thermal Sciences*, *45*(4), 419–432. https://doi.org/10.1016/j.ijthermalsci.2005.06.009

Wang, W., Zmeureanu, R., & Rivard, H. (2005). Applying multi-objective genetic algorithms in green building design optimization. *Building and Environment*, *40*(11), 1512–1525. https://doi.org/10.1016/j.buildenv.2004.11.017

Wetter, M. (2000). *GenOpt. Generic optimization Program* (Technical report). Berkeley, CA 94720, USA: Lawrence Berkeley National Laboratory. Retrieved from http://gundog.lbl.gov/GO/index.html

Wetter, M. (2009). Generic Optimization Program User Manual Version 3.0. 0. *Lawrence Berkeley National Laboratory*.

White, G. E., & Ostwald, P. (1976). The life cycle cost of an item is the sum of all funds expended in support of the item from its conception and fabrication through its operation to the end of its useful life, *57*(7), 39–42.

White, J. A., & Reichmuth, R. (1996). Simplified method for predicting building energy consumption using average monthly temperatures. In *Energy Conversion Engineering Conference, 1996. IECEC 96., Proceedings of the 31st Intersociety* (Vol. 3, pp. 1834–1839). IEEE. Retrieved from http://ieeexplore.ieee.org/abstract/document/553381/

Wigginton, M. (1996). *Glass in Architecture* (Phaidon Press). London.

Wilson, R. L. (1986). Operations and support cost model for new product concept development (pp. 128–131). Presented at the Proceedings of the 8th Annual Conference on Components and Industrial Engineering, Orlando, Florida.

Wong, I. L., Perera, S., & Eames, P. C. (2010). Goal directed life cycle costing as a method to evaluate the economic feasibility of office buildings with conventional and TI-façades. *Construction Management and Economics*, *28*(7), 715–735. https://doi.org/10.1080/01446191003753867

Woodward, D. G. (1997). Life cycle costing--theory, information acquisition and application. *Elsewer Science Ltd and IPMA*, *15*(6), 335–344.

Yao, R, Mcevoy, M., & Baker, N. (2000). A simplified thermal resistance network model for building thermal simulation. *Architecture Science Review*, (46), 225–232.

Yao, Runming, & Steemers, K. (2005). A method of formulating energy load profile for domestic buildings in the UK. *Energy and Buildings*, *37*(6), 663–671. https://doi.org/10.1016/j.enbuild.2004.09.007

Yildiz, A., Gurlek, G., Erkek, M., & Ozbalta, N. (2008). Economical and environmental analyses of thermal insulation thickness in buildings. *Journal of Thermal Science and Technology*, *28*(2), 25–34.

Yilmaz, A. Z., Akguc, A., Gali, G., & Aydın, B. (2013). A low cost-plus energy building in Istanbul. *The Rehva European HVAC Journal*, *3*(50), 63–65.

Zavadskas, E. K., Antucheviciene, J., Kalibatas, D., & Kalibatiene, D. (2017). Achieving Nearly Zero-Energy Buildings by applying multi-attribute assessment. *Energy and Buildings*, *143*, 162–172. https://doi.org/10.1016/j.enbuild.2017.03.037

APPENDICES

A. Studies on LCC

Summary of assumptions for the key input parameters applied to life-cycle costing (LCC) models

Author(s) (year)	Location	Assumed lifespan (years)	Assumed construction cost (as %of life-cycle cost)	Assumed running cost (as %of life-cycle cost)
Ive (2006)	UK	20	6%	94%
Mithraratne and Vale (2004)	NA	100	42%	58%
Pellegrini-Masini *et al.* (2010)	NA	25	16%	84%
Wong *et al.* (2010)	Malaysia	60	19%	81%
Tuhus-Dubrow and Krarti (2010)	US	60	34%	66%
Kshirsagar, El-Gafy, & Abdelhamid (2010)	NA	38	12%	88%
Wang,Wei, and Sun (2014)	NA	30	31%	69%

B. Equations

LIFE CYCLE COSTING			
Acronyms:	**Description:**	**Formula:**	**Source:**
LCC	Total Life Cycle Cost	$LCC = IC_0 + \sum_{t=0}^{N} OC \,.\, PV_{sum} + \sum_{t=0}^{N} MC \,.\, PV_{sum} + D.PV$	ISO 15686-5:2017
OC	Building Operational Cost	$OC = Cost_{FuelCons} + Cost_{cooling} + CostQ_{hw} + Cost_{DW}$	ISO 15686-5:2017
MC	Building Maintenance Cost	$MC = \sum (TotalExtWallMC + TotalIntWallMC + TotalFloorMC + TotalCeilingMC + TotalWindowMC + TotalHeatingSystemMC + TotalHotWaterMC)$	ISO 15686-5:2017
IC	Building Investment Cost	$IC = \sum (TotalExtWallIC + TotalIntWallIC + TotalFloorIC + TotalCeilingIC + TotalWindowIC + TotalHeatingSystemIC + TotalHotWaterIC)$	ISO 15686-5:2017
DC	Building Disposal Cost	$DC = price_{Disposal} * V_B$	ISO 15686-5:2017
PV_{sum}	Present Value factor for operational and maintenance costs	$PV_{sum} = \frac{(1+r)^t - 1}{r(1+r)^t}$	ISO 15686-5:2017
PV	Present Value factor for disposal cost	$PV = \frac{1}{(1+r)^t}$	ISO 15686-5:2017
BUILDING GEOMETRY			
Acronyms:	**Description:**	**Formula:**	**Source:**
L_B	Length of the Building	$L_B = \sqrt{A_B.ARatio_B}$	Building Geometry Calculations
W_B	Width of the Building:	$W_B = \sqrt{\frac{A_B}{ARatio_B}}$	Building Geometry Calculations
A_R	Area of the Room:	$A_R = \frac{A_B}{Number_R}$	Building Geometry Calculations

V_B	Volume of the Building:	$V_B = h_R . A_B$	Building Geometry Calculations
ARatio_R	Aspect ratio of the Room:	$\mathrm{ARatio}_R = \mathrm{ARatio}_B . \frac{4}{Number_R}$	Building Geometry Calculations
L_R	Length of the Room	$L_R = \sqrt{ARatio_R . A_R}$	Building Geometry Calculations
W_R	Width of the Room:	$W_R = \sqrt{\frac{A_R}{ARatio_R}}$	Building Geometry Calculations
V_R	Volume of the Room:	$V_R = h_R . A_R$	Building Geometry Calculations
TRANSPARENT SURFACES			
Acronyms:	**Description:**	**Formula:**	**Source:**
A_W	Area of the window [m^2]	$A_W = A_{W,S} + A_{W,N} + A_{W,E} + A_{W,W}$	Window Geometry Calculations
$A_{W,N}$	North facing window area [m^2] According to Orientation	$A_{W,N} = \frac{WindowPercN}{100} . W_B . h_R$ OR $A_{W,N} = \frac{WindowPercN}{100} . L_B . h_R$	Window Geometry Calculations
$A_{W,S}$	South facing window area [m^2] According to Orientation	$A_{W,S} = \frac{WindowPercS}{100} . W_B . h_R$ OR $A_{W,S} = \frac{WindowPercS}{100} . L_B . h_R$	Window Geometry Calculations
$A_{W,E}$	East facing window area [m^2] According to Orientation	$A_{W,E} = \frac{WindowPercE}{100} . W_B . h_R$ OR $A_{W,E} = \frac{WindowPercE}{100} . L_B . h_R$	Window Geometry Calculations
$A_{W,W}$	West facing window area [m^2] According to Orientation	$A_{W,W} = \frac{WindowPercW}{100} . W_B . h_R$ OR $A_{W,W} = \frac{WindowPercW}{100} . L_B . h_R$	Window Geometry Calculations
$\mathrm{UAvalue}_W$	UA of Window [W/K]	$\mathrm{UAvalue}_W = \mathrm{Uvalue}_W . A_W$	BEP Regulation, TS EN 673, ISO 10292, ISO 15099, ISO 10077-1, ISO 10077-2, ISO 12567-1, TS 825
TotalWindowIC	Investment Cost of Window [TL]	$\mathrm{TotalWindowIC} = \mathrm{WindowIC} . A_W$	2017 Ministry of Environment and Urbanization, General Directorate of Rural Services

TotalWindowMC	Maintenance Cost of Window [TL]	$\text{TotalWindowMC} = \text{WindowMC}.A_W$	2017 Ministry of Environment and Urbanization, General Directorate of Rural Services

OPAQUE SURFACES (EXTERNAL WALL)

Acronyms:	**Description:**	**Formula:**	**Source:**
R	thermal resistance (R value) [m2 / K. W]	$\text{R} = \frac{d}{\lambda_\text{h}}$	TS EN ISO 10456, TS 6874 EN ISO 9251, TS EN 832, TS825, TS EN ISO 13789, TS EN ISO 10456, TS EN ISO 13788
R	thermal resistance (R value) [m2 / K. W]	$\text{R} = \frac{d_1}{\lambda_{h1}} + \frac{d_2}{\lambda_{h2}} + \cdots . + \frac{d_n}{\lambda_{hn}}$	TS EN ISO 10456, TS 6874 EN ISO 9251, TS EN 832, TS825, TS EN ISO 13789, TS EN ISO 10456, TS EN ISO 13788
R	thermal resistance (R value) [m2 / K. W]	$\text{R} = R_{si} + \text{R}_1 + \cdots + R_{se}$	TS EN ISO 10456, TS 6874 EN ISO 9251, TS EN 832, TS825, TS EN ISO 13789, TS EN ISO 10456, TS EN ISO 13788
Uvalue	thermal transmittance W/ m^2.K	$U = \frac{1}{R_{si} + R + R_{se}}$	TS EN ISO 10456, TS 6874 EN ISO 9251, TS EN 832, TS825, TS EN ISO 13789, TS EN ISO 10456, TS EN ISO 13788
$\text{Uvalue}_{extwall}$	heat transmission coefficient (U value) [W / m2.K.]	$\text{Uvalue}_{extwall} = \frac{1}{R_{si} + R_1 + \cdots + R_{se}}$	TS EN ISO 10456, TS 6874 EN ISO 9251, TS EN 832, TS825, TS EN ISO 13789, TS EN ISO 10456, TS EN ISO 1378
$\text{Aout}_{extwall}$	Area of the external wall(out) [m²]	$\text{Aout}_{\text{extwall}} = \text{h}_\text{R}.(\text{L}_\text{R} + \text{W}_\text{R}).4$	Wall Calculations
$\text{Ain}_{extwall}$	Area of the external wall(in) [m²]	$\text{Ain}_{extwall} = h_R.L_R.(Number_R - 4)$	Wall Calculations
$A_{extwall}$	Area of the external wall(in)	$A_{extwall} = (Aout_{extwall} + Ain_{extwall}) - A_W$	Wall Calculations
ExtWallMC	Maintenance costs of the external wall per m²	$\text{ExtWallMC} = \frac{ExtWallIC}{10}$	2017 Ministry of Environment and Urbanization,

ExtWallIC_1	Investment costs of the external wall per m² [tl/m²] for Wall type 1	$ExtWallIC_1 = price_{intplastering} + price_{PC} + price_{ins} + price_{extplastering}$	2017 Ministry of Environment and Urbanization,
ExtWallIC_2	Investment costs of the external wall per m² [tl/m²] for Wall type 2	$\text{ExtWall}IC_2 = \text{price}_{intplastering} + \text{price}_{AAC} + \text{price}_{ins} + \text{price}_{extplastering}$	2017 Ministry of Environment and Urbanization,
ExtWallIC_3	Investment costs of the external wall per m² [tl/m²] for Wall type 3	$\text{ExtWall}IC_3 = \text{price}_{intplastering} + \text{price}_{RC} + \text{price}_{ins} + \text{price}_{extplastering}$	2017 Ministry of Environment and Urbanization,
ExtWallIC_4	Investment costs of the external wall per m² [tl/m²] for Wall type 4	$\text{ExtWall}IC_4 = \text{price}_{intplastering} + \text{price}_{brick20} + \text{price}_{ins} + \text{price}_{extplastering}$	2017 Ministry of Environment and Urbanization,
TotalExtWallIC	Investment cost of External wall [tl/year]	$\text{TotalExtWallIC} = \text{ExtWallIC}.A_{extwall}$	2017 Ministry of Environment and Urbanization,
TotalExtWallMC	Maintenance cost of External wall [tl/year]	$\text{TotalExtWallMC} = \text{ExtWallMC}.A_{extwall}$	2017 Ministry of Environment and Urbanization,
$\text{UAvalue}_{extwall}$	External wall UA value [W/K]	$\text{UAvalue}_{extwall} = \text{Uvalue}_{extwall}.A_{extwall}$	BEP Regulation 2017, TS 825, EN 13947
$\text{price}_{ins}\text{EPS}$	price of EPS in 2017	$price_{ins}EPS = = 1.5217.d_{ins}.100 + 35.861$	2017 Ministry of Environment and Urbanization, Regression analysis
$\text{price}_{ins}\text{XPS}$	price of XPS in 2017	$price_{ins}XPS = 2.7546.d_{ins}.100 + 35.865$	2017 Ministry of Environment and Urbanization, Regression analysis
OPAQUE SURFACES (INTERNAL WALL)			
Acronyms:	**Description:**	**Formula:**	**Source:**
$\text{Aout}_{intwall}$	Area of internal wall (out) [m²]	$\text{Aout}_{intwall} = h_R.(L_R + W_R).(0,5).4$	Wall Calculations
$\text{Ain}_{intwall}$	Area of internal wall (in) [m²]	$\text{Ain}_{intwall} = h_R.L_R.(Number_R - 4)$	Wall Calculations
$A_{intwall}$	Area of internal wall [m²]	$A_{intwall} = \text{Aout}_{intwall} + \text{Ain}_{intwall}$	Wall Calculations

IntWallMC	Maintenance costs of the internal wall per m^2	$\mathrm{IntWallMC} = \frac{IntWallIC}{10}$	2017 Ministry of Environment and Urbanization,
TotalIntWallIC	Total Investment Cost of Internal Wall [tl]	$\mathrm{TotalIntWallIC} = \mathrm{IntWallIC}.A_{intwall}$	2017 Ministry of Environment and Urbanization,
TotalIntWallMC	Total Maintenance Cost of Internal Wall [tl/year]	$\mathrm{TotalIntWallMC} = \mathrm{IntWallMC}.A_{intwall}$	2017 Ministry of Environment and Urbanization,
FLOOR			
Acronyms:	**Description:**	**Formula:**	**Source:**
$Uvalue_F$	heat transmission coefficient (U value) [W / m2. K.]	$\mathrm{Uvalue}_F = \frac{1}{R_i + R_1 + \cdots + R_e}$	BEP,Regulations, TS 825, TS EN ISO 13790, ISO 7345, ISO 7726, ISO 9869
$\mathrm{UAvalue}_F$	Floor UA value [W/K]	$\mathrm{UAvalue}_F = \mathrm{Uvalue}_F.A_R.\mathrm{R}F_F$	BEP,Regulations, TS 825, TS EN ISO 13370, TS EN ISO 13790, ISO 7345, ISO 7726, ISO 9869
FloorMC	Maintenance costs of the floor per m^2 [tl/m^2]	$\mathrm{FloorMC} = \frac{FloorIC}{10}$	2017 Ministry of Environment and Urbanization,
RoomFloorIC	Room Floor Investment Cost [tl]	$\mathrm{RoomFloorIC} = \mathrm{FloorIC}.A_R$	2017 Ministry of Environment and Urbanization,
RoomFloorMC	Room Floor Maintenance Cost [tl/year]	$\mathrm{FloorMC} = \mathrm{FloorMC}.A_R$	2017 Ministry of Environment and Urbanization
TotalFloorIC	Floor Investment Cost [tl]	$\mathrm{TotalFloorIC} = \mathrm{RoomFloorIC}.\mathrm{Number}_R$	Floor Calculations
TotalFloorMC	Floor Maintenance Cost [tl/year]	$\mathrm{TotalFloorMC} = \mathrm{RoomFloorMC}.\mathrm{Number}_R$	Floor Calculations
CEILING			
Acronyms:	**Description:**	**Formula:**	**Source:**
$Uvalue_C$	heat transmission coefficient (U value) [W / m2. K.]	$\mathrm{Uvalue}_C = \frac{1}{R_i + R_1 + \cdots + R_e}$	BEP Regulations, TS EN ISO 13790, TS 825, ISO 7345, ISO 7726, ISO 9869
	Ceiling of UA value [W/K]	$\mathrm{UAvalue}_C = \mathrm{Uvalue}_C.A_R.\mathrm{R}F_C$	BEP Regulations, TS EN ISO 13790, TS 825, ISO 7345, ISO 7726, ISO 9869

CeilingMC	Maintenance costs of the ceiling per m² [tl/m²]	$\text{CeilingMC} = \frac{\text{Ceiling}IC}{10}$	2017 Ministry of Environment and Urbanization,
RoomCeilingIC	Room Ceiling Investment Cost [tl]	$\text{RoomCeilingIC} = Ceiling\text{IC}.A_R$	2017 Ministry of Environment and Urbanization,
RoomCeilingMC	Room Ceiling Maintenance Cost [tl/year]	$\text{CeilingMC} = Ceiling\text{MC}.A_R$	2017 Ministry of Environment and Urbanization,
TotalCeilingIC	Ceiling Investment Cost [tl]	$\text{TotalCeilingIC} = \text{RoomCeilingIC}.\text{Number}_R$	2017 Ministry of Environment and Urbanization,
TotalCeilingMC	Ceiling Maintenance Cost [tl/year]	$\text{TotalCeilingMC} = \text{RoomCeilingMC}.\text{Number}_R$	2017 Ministry of Environment and Urbanization,
HEATING-COOLING			
Acronyms:	**Description:**	**Formula:**	**Source:**
$Q_{H,nd}$	Heating demand of the whole building [MJ]	$Q_{H,nd} = Q_{H,ht} - \eta_{H,gn}.Q_{H,gn}$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450, BS EN 12831-1, TS825, BS EN 15316-4-1, TS EN 14336,
$Q_{H,ht}$	The total heat transfer [MJ]	$Q_{H,ht} = Q_{tr} + Q_{ve}$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450, BS EN 12831-1, TS825, BS EN 15316-4-1, TS EN 14336,
Q_{tr}	The heat transfer by transmission for heating mode [MJ]	$Q_{tr} = [H_{tr}(\theta_{int,H,set} - \theta_e)]t$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450, BS EN 12831-1, TS825, BS EN 15316-4-1, TS EN 14336,
Q_{tr}	The heat transfer by transmission for cooling mode [MJ]	$Q_{tr} = [H_{tr}(\theta_e - \theta_{int,C,set})]t$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS 825, TS EN 15603
Q_{ve}	the heat transfer by ventilation for cooling mode [MJ]	$Q_{ve} = H_{tr}(\theta_e - \theta_{int,C,set})t$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS 825, TS EN 15603
Q_{ve}	the heat transfer by ventilation for heating mode [MJ]	$Q_{ve} = H_{tr}(\theta_{int,H,set} - \theta_e)\text{t}$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450, BS EN 12831-1, TS825, BS EN 15316-4-1, TS EN 14336,

$Q_{H,nd}$	Heating demand of the whole building in a specific month [MJ]	$Q_{H,nd} = \left[(H_{tr} + H_{ve})(\theta_{int,H,set} - \theta_{e}) - \eta_{H,gn}(\phi_{int} + \phi_{sol})\right]t$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450, BS EN 12831-1, TS825, BS EN 15316-4-1, TS EN 14336,
$Q_{H,nd}$	Cooling demand of the whole building in a specific month [MJ]	$Q_{C,nd} = [(\phi_{int} + \phi_{sol}) - \eta_{C,Is}\left[(H_{tr} + H_{ve})(\theta_{e} - \theta_{int,C,set})\right]t$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS 825, TS EN 15603
H_{tr}	heat transfer coefficient by transmission [W/K]	$H_{tr} = H_D + H_G + H_U + H_A$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450, BS EN 12831-1, TS825, BS EN 15316-4-1, TS EN 14336,
H_D	The direct transmission coefficient [W/K]	$H_D = \sum A_i\, U_i$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450, BS EN 12831-1, TS825, BS EN 15316-4-1, TS EN 14336,
H_X	The x transmission coefficient [W/K] ($H_X$represents H_G, H_U, H_A.)	$H_X = b_{tr}. \sum A_i\, U_i$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450, BS EN 12831-1, TS825, BS EN 15316-4-1, TS EN 14336,
H_{tr}	Transmission Heat Transfer Coefficient [W/K]	$H_{tr} = UAvalue_{W} + UAvalue_{extwall}$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450, BS EN 12831-1, TS825, BS EN 15316-4-1, TS EN 14336,
H_{ve}	The ventilation heat transfer coefficient [W/K]	$H_{ve} = \rho.c.q$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450, BS EN 12831-1, TS825, BS EN 15316-4-1, TS EN 14336,
q	the airflow rate (m^3/h)	$q = V_B.n_h$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450, BS EN 12831-1, TS825, BS EN 15316-4-1, TS EN 14336,
H_{ve}	Ventilation Heat Transfer Coefficient [W/K]	$H_{ve} = \rho.c.n_h.V_B$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450, BS EN 12831-1, TS825, BS EN 15316-4-1, TS EN 14336,
Q_{gn}	Total heat gains [MJ]	$Q_{gn} = Q_{int} + Q_{sol}$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450, BS EN 12831-1, TS825, BS EN 15316-4-1, TS EN 14336,

$Q_{C,\mathrm{nd}}$	The energy requirement for space cooling (MJ)	$Q_{C,\mathrm{nd}} = Q_{\mathrm{C,gn}} - \eta_{\mathrm{C,ls}} \cdot Q_{\mathrm{C,ht}}$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS 825, TS EN 15603
$Q_{C,nd}$	Cooling demand of the whole building in a specific month [kWh/year]	$Q_{C,nd} = \left[(H_{tr} + H_{ve})(\theta_{e} - \theta_{int,C,set}) - \eta_{C,gn}(\phi_{int} + \phi_{sol})\right]t$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS 825, TS EN 15603
$HeatingDemand$	Heating demand of the whole building in a year[kWh/year]	$HeatingDemand = \sum Q_{H,nd,months}$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450, BS EN 12831-1, TS825, BS EN 15316-4-1, TS EN 14336,
$CoolingDemand$	Cooling demand of the whole building in a year [kWh/year]	$CoolingDemand = \sum Q_{C,nd,months}$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS 825, TS EN 15603
$Cost_{cooling}$	Cost of Yearly Cooling [tl]	$Cost_{cooling} = CoolingDemand * price_{electricity}$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS 825, TS EN 15603 Energy Market Regulatory Authority www.enerjisa.com.tr
$TotalHeatingSystemIC$	Heating System Investment Cost [tl]	$TotalHeatingSystemIC = HeatingSystemFIC + HeatingSystemVIC$	Energy Market Regulatory Authority 2017 Ministry of Environment and Urbanization
$TotalHeatingSytemMC$	Heating System Maintenance Cost [tl/year]	$TotalHeatingSystemMC = \frac{TotalHeatingSystemIC}{10}$	2017 Ministry of Environment and Urbanization
$Qsystem$	Heating consumption [kWh/year]	$Qsystem = \frac{HeatingDemand}{\eta_{HS}}$	BEP Regulations, TS EN ISO 13790, TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450, BS EN 12831-1, TS825, BS EN 15316-4-1, TS EN 14336
$FuelCons$	Fuel consumption yearly [m3] [kg]	$FuelCons = \frac{Qsystem}{LHV}$	Ministry of Energy and Natural Resources, TS EN 15316-1,TS EN 15316-2,TS EN 15316-4-5, TS EN ISO 11855-4, TS EN 15450,TS EN 14336
$Cost_{FuelCons}$	Cost of the Fuel consumption yearly [tl]	$Cost_{FuelCons} = FuelCons.price_{fueltype}$	http://www.baskentdogalgaz.com.tr, http://www.tki.gov.tr
INTERNAL HEAT GAINING			
Acronyms:	**Description:**	**Formula:**	**Source:**
$\phi_{int,month}$	Internal heat gains monthly	$\phi_{int,month} = \phi_{int} \cdot A_B$	BEP Regulation, 2017 TS EN ISO 13790 TS 825

Q_{int}	the internal heat sources for the duration of the considered month [MJ]	$Q_{int} = \Phi_{int,mn} \cdot t$	BEP Regulation, 2017 TS EN ISO 13790 TS 825
ϕ_{int}	The internal heat gains [W]	$\Phi_{int} = \Phi_{int,sen,D} + \Phi_{int,sen,M} + \Phi_{int,App,lat} + \Phi_{int,Occ,lat} + \Phi_{int,W} + \Phi_{int,lg}$	BEP Regulation, 2017 TS EN ISO 13790 EN ISO 13791
$\phi_{int,sen}$	Sensible heat gains from occupants and living spaces[W]	$\Phi_{int,sen} = \Phi_{int,sen,M} + \Phi_{int,sen,D}$	BEP Regulation, 2017 TS EN ISO 13790 EN ISO 13791
$\phi_{int,sen,M}$	heated from the living room and kitchen [W]	$\Phi_{int,sen,M} = A_{f,M} \cdot \Phi_{int,sen,M,unit}$	BEP Regulation, 2017 TS EN ISO 13790 EN ISO 13791
$\phi_{int,sen,D}$	heated from the other spaces[W]	$\Phi_{int,sen,D} = A_{f,D} \cdot \Phi_{int,sen,D,unit}$	BEP Regulation, 2017 TS EN ISO 13790 EN ISO 13791
A_f	Total Floor area of the building [m2]	$A_f = A_{f,D} + A_{f,M}$	BEP Regulation, 2017 TS EN ISO 13790 EN ISO 13791
$\phi_{int,W}$	Heat gains from hot water use [W]	$\Phi_{int,W} = 25 + (15.N_P)$	BEP Regulation, 2017 TS EN ISO 13790 EN ISO 13791
$\phi_{int,App,lat}$	dissipated heat from appliances [W]	$\Phi_{int,App,lat} = \Phi_{int,App,lat,M} + \Phi_{int,App,lat,D}$	BEP Regulation, 2017 TS EN ISO 13790 EN ISO 13791
$\phi_{int,App,lat,M,nit}$	heated from the living room and kitchen appliances for m2 [W/m2]	$\Phi_{int,App,lat,M,unit} = \frac{\Phi_{int,App,sen,M,unit}}{0.77} - \Phi_{int,App,sen,M,unit}$	BEP Regulation, 2017 TS EN ISO 13790 TS EN ISO 13791
$\phi_{int,App,lat,D,unit}$	heated from the other spaces appliances for m2 [W/m2]	$\Phi_{int,App,lat,D,unit} = \frac{\Phi_{int,App,sen,D,unit}}{0.77} - \Phi_{int,App,sen,D,unit}$	BEP Regulation, 2017 TS EN ISO 13790 TS EN ISO 13791
$\phi_{int,App,lat,D}$	heated from the other spaces appliances [W]	$\phi_{int,App,lat,D} = A_{f,D} \cdot \phi_{int,App,sen,D,unit}$	BEP Regulation, 2017 TS EN ISO 13790 TS EN ISO 13791
$\phi_{int,App,lat,M}$	heated from the living room and kitchen appliances [W]	$\Phi_{int,App,lat,M} = A_{f,M} \cdot \Phi_{int,App,sen,M,unit}$	BEP Regulation, 2017 TS EN ISO 13790 TS EN ISO 13791

SOLAR HEAT GAINING

Acronyms:	**Description:**	**Formula:**	**Source:**
Q_{sol}	the solar heat source for the duration of the considered month [MJ]	$Q_{sol} = \phi_{sol,mn}.t$	TS EN ISO 13790, TS 825
ϕ_{sol}	the solar heat source [MJ]	$\phi_{sol} = \left(F_{sh,ob}.A_W.I_{sol}\right) - (F_r.\phi_r)$	TS EN ISO 13790, TS 825
ϕ_r	The extra heat flow due to thermal radiation to the sky (W)	$\phi_r = R_{se}.U_{op}.A_{op}.h_r.\Delta\theta_{er}$	TS EN ISO 13790, TS 825
A_{sol}	Solar Surfaces area (m2)	$A_{sol} = A_{sol,op} + A_{sol,gl}$	TS EN ISO 13790, TS 825
$A_{sol,op}$	Opaque surfaces (m2)	$A_{sol,op} = \alpha_{sol,em}.R_{se}.U_{op}.A_{op}$	TS EN ISO 13790, TS 825
$A_{sol,gl}$	Transparent surfaces (m2)	$A_{sol,gl} = F_{sh,gl}.gvalue.A_W.\left(1 - F_f\right)$	TS EN ISO 13790, TS 825
ϕ_{sol}	Total Solar irradiation per month [W/h]	$\phi_{sol} = S\phi_{sol} + N\phi_{sol} + W\phi_{sol} + E\phi_{sol}$	TS EN ISO 13790, TS 825
$S\phi_{sol}$	South Solar irradiation per month [W/h]	$\mathrm{S\phi_{sol} = gvalue.r_{i,ay}.A_{W,S}.I_{south}}$	TS EN ISO 13790, TS 825
$N\phi_{sol}$	North Solar irradiation per month [W/h]	$\mathrm{N}\phi_{sol} = \mathrm{gvalue}.r_{i,ay}.A_{W,N}.I_{north}$	TS EN ISO 13790, TS 825
$W\phi_{sol}$	West Solar irradiation per month [W/h]	$\mathrm{W}\phi_{sol} = \mathrm{gvalue}.r_{i,ay}.A_{W,W}.I_{west}$	TS EN ISO 13790, TS 825
$E\phi_{sol}$	East Solar irradiation per month [W/h]	$\mathrm{E}\phi_{sol} = \mathrm{gvalue}.r_{i,ay}.A_{W,E}.I_{east}$	TS EN ISO 13790, TS 825

UTILIZATION FACTOR

Acronyms:	**Description:**	**Formula:**	**Source:**
$\eta_{H,gn}$	Gain utilization factor for heating	$\eta_{H,gn} = 1 - e^{(-1/\gamma_H)}$	TS EN ISO 13790

$\eta_{H,gn}$	Gain utilization factor for heating if $\gamma_H > 0$ $\gamma_H \neq 1$	$\eta_{H,gn} = \frac{1-\gamma_H^{\alpha,H+1}}{1-\gamma_H^{\alpha,H+1}}$	TS EN ISO 13790
$\eta_{H,gn}$	Gain utilization factor for heating if $\gamma_H = 1$	$\eta_{H,gn} = \frac{\alpha_H}{\alpha_H + 1}$	TS EN ISO 13790
$\eta_{H,gn}$	Gain utilization factor for heating $\gamma_H <$ 0	$\eta_{H,gn} = \frac{1}{\gamma_H}$	TS EN ISO 13790
γ_H	Gain / loss ratio	$\gamma_H = \frac{Q_{H,gn}}{Q_{H,ht}}$	TS EN ISO 13790
γ_H	Gain / loss ratio	$\gamma_H = (\phi_{int} + \phi_{sol}) / (H_{tr} + H_{ve})(\theta_{\ int,H,set} - \theta_{\ e})$	TS EN ISO 13790
α_H	Numerical parameter in utilization factor	$\alpha_H = \alpha_{H,0} + \frac{\tau}{\tau_{H,0}}$	BEP Regulation TS EN ISO 13790
$\eta_{C,gn}$	Gain utilization factor for heating if $\gamma_C > 0$ $\gamma_C \neq 1$	$\eta_{C,gn} = \frac{1-\gamma_C^{-\alpha,C+1}}{1-\gamma_C^{\alpha,C+1}}$	BEP Regulation TS EN ISO 13790
$\eta_{C,gn}$	Gain utilization factor for heating if $\gamma_C = 1$	$\eta_{C,ls} = \frac{\alpha_C}{\alpha_C} + 1$	BEP Regulation TS EN ISO 13790
α_C	Numerical parameter in utilization factor	$\alpha_\mathrm{C} = \alpha_\mathrm{C,0} + \frac{\tau}{\tau_\mathrm{C,0}}$	BEP Regulation TS EN ISO 13790
τ	time constant	$\tau = \frac{\frac{c_m}{3600}}{H_{tr} + H_{ve}}$	BEP Regulation TS EN ISO 13790
HOT WATER			
Acronyms:	**Description:**	**Formula:**	**Source:**
$Q_{w,day}$	Daily Hot water energy consumption (mj)	$Q_{w,day} = \rho.c_w.V_{w,day}.(\theta_{w,del} - \theta_{w,0})$	BEP Regulation TS EN 15316-3 TS EN 15316-4-1
$Q_{w,month}$	Monthly Hot water energy consumption (kwh)	$Q_{w,month} = Q_{w,day}.30 * 0.278$	BEP Regulation TS EN 15316-3 TS EN 15316-4-1

$V_{w,day}$	the volume of hot water used for single-family houses and residences lt	$V_{w,day} = V_w . Number_{occupant}$	BEP Regulation TS EN 15316-3 TS EN 15316-4-1
$Q_{w,year}$	Hot water energy consumption in a year (kwh)	$Q_{w,year} = \sum Q_{w,month}$	BEP Regulation TSEN 15316-3 TSEN 15316-4-1
$CostQ_{hw}2$	Cost of Hot Water Energy Consumption Price in a year [TL] type 2	$CostQ_{hw}2 = Q_{w,year} . \frac{price_{naturelgas}}{LHV_{naturalgas}}$	TS EN 15316-3 http://www.baskentdogalgaz.com.tr, Ministry of Energy and Natural Resources
$CostQ_{hw}1$	Cost of Hot Water Energy Consumption Price in a year [TL] type 1	$CostQ_{hw}1 = Q_{w,year} . price_{electricity}$	TS EN 15316-3 Energy Market Regulatory Authority www.enerjisa.com.tr
V_{month}	Monthly Water Consumption [m3]	$V_{month} = \frac{Number_{occupant} . V_{dw} . 30}{1000}$	BEP Regulation General Directorate of Provincial Bank-TurkSTAT
V_{year}	Yearly Water Consumption [m3]	$V_{year} = V_{month} . 12$	BEP Regulation
$Cost_{DW}$	Cost of Yearly Water Consumption [tl]	$Cost_{DW} = V_{year} . price_{dailywater}$	BEP Regulation Ankara Water and Sewerage Administration (Aski)
$TotalHotWater\ SystemMC$	Total Hot Water System Maintenance Cost [tl/year]	$TotalHotWaterSystemMC = \frac{TotalHotWaterSystemIC}{10}$	2017 Ministry of Environment and Urbanization
$\sum HotWaterCost$	Building Hot Water Cost	$\sum HotWaterCost = CostQ_{hw} + Cost_{DW}$	BEP Regulation General Directorate of Provincial Bank Ankara Water and Sewerage Administration (Aski)

C. Constants

Acronyms:	Description:	Value:	Source:
totalLC	total life-cycle time	30	Scientific Articles
A_B	Area of the Building	75	TOKİ
h_R	Height of the Room	2,8	TOKİ
$Number_R$	Room Numbers	6	TOKİ
$ARatio_B$	Building Aspect Ratio	0,8	TOKİ
ϕ_{int}	Internal Heat Sources	10	BEP Regulation 2017, TS EN ISO 13790, TS 825
$\theta_{int,H,set}$	the internal set-point temperature for the heating mode	19	BEP Regulation, 2017, TS EN 15265, TS 825
$\theta_{\text{int,C,set}}$	the internal set-point temperature for the cooling mode	26	BEP Regulation, 2017, TS EN 15265, TS 825
$r_{i,ay\_}1$	ShadingFactor type 1	0.8	BEP Regulation, 2017, ISO 9050, TS 825
$r_{i,ay\_}2$	ShadingFactor type 2	0.6	BEP Regulation, 2017, ISO 9050, TS 825
$r_{i,ay\_}3$	ShadingFactor type 3	0.5	BEP Regulation, 2017, ISO 9050, TS 825
RegName	Name of Region	row	TS 825
gvalue_1	PVC frame single glazing unit	0.426	TS 2164, TS 825, ISO 10292, ISO 15099, ISO 12567-1
gvalue_2	PVC frame double glazing unit	0.375	TS 2164, TS 825, ISO 10292, ISO 15099, ISO 12567-1
gvalue_3	PVC frame double glazing unit (low-e)	0.364	TS 2164, TS 825, ISO 10292, ISO 15099, ISO 12567-1
gvalue_4	Timber Frame single glazing unit	0.426	TS 2164, TS 825, ISO 10292, ISO 15099, ISO 12567-1
gvalue_5	Timber Frame double glazing unit	0.375	TS 2164, TS 825, ISO 10292, ISO 15099, ISO 12567-1
gvalue_6	Timber Frame double glazing unit (low-e)	0.364	TS 2164, TS 825, ISO 10292, ISO 15099, ISO 12567-1
gvalue_7	Aluminium frame single glazing unit	0.488	TS 2164, TS 825, ISO 10292, ISO 15099, ISO 12567-1

gvalue_8	Aluminium frame double glazing unit	0.43	TS 2164, TS 825, ISO 10292, ISO 15099, ISO 12567-1
gvalue_9	Aluminium frame double glazing unit (low-e)	0.418	TS 2164, TS 825, ISO 10292, ISO 15099, ISO 12567-1
gvalue_10	Heat-retaining aluminum frame single glazing unit	0.488	TS 2164, TS 825, ISO 10292, ISO 15099, ISO 12567-1
gvalue_11	Heat-retaining aluminum frame double glazing unit	0.43	TS 2164, TS 825, ISO 10292, ISO 15099, ISO 12567-1
gvalue_12	Heat-retaining aluminum frame double glazing unit (low-e)	0.418	TS 2164, TS 825, ISO 10292, ISO 15099, ISO 12567-1
$Uvalue_{W_1}$	PVC frame single glazing unit	3.889	TS EN 673, ISO 10292, ISO 15099, BEP Regulation, ISO 10077-1, ISO 10077-2, ISO 12567-1
$Uvalue_{W_2}$	PVC frame double glazing unit	2.369	TS EN 673, ISO 10292, ISO 15099, BEP Regulation, ISO 10077-1, ISO 10077-2, ISO 12567-1
$Uvalue_{W_3}$	PVC frame double glazing unit (low-e)	1.844	TS EN 673, ISO 10292, ISO 15099, BEP Regulation, ISO 10077-1, ISO 10077-2, ISO 12567-1
$Uvalue_{W_4}$	Timber Frame single glazing unit	4.163	TS EN 673, ISO 10292, ISO 15099, BEP Regulation, ISO 10077-1, ISO 10077-2, ISO 12567-1
$Uvalue_{W_5}$	Timber Frame double glazing unit	2.643	TS EN 673, ISO 10292, ISO 15099, BEP Regulation, ISO 10077-1, ISO 10077-2, ISO 12567-1
$Uvalue_{W_6}$	Timber Frame double glazing unit (low-e)	2.118	TS EN 673, ISO 10292, ISO 15099, BEP Regulation, ISO 10077-1, ISO 10077-2, ISO 12567-1
$Uvalue_{W_7}$	Aluminium frame single glazing unit	7.886	TS EN 673, ISO 10292, ISO 15099, BEP Regulation, ISO 10077-1, ISO 10077-2, ISO 12567-1
$Uvalue_{W_8}$	Aluminium frame double glazing unit	6.146	TS EN 673, ISO 10292, ISO 15099, BEP Regulation, ISO 10077-1, ISO 10077-2, ISO 12567-1

$Uvalue_{W_9}$	Aluminium frame double glazing unit (low-e)	5.544	TS EN 673, ISO 10292, ISO 15099, BEP Regulation, ISO 10077-1, ISO 10077-2, ISO 12567-1
$Uvalue_{W_{10}}$	Heat-retaining aluminum frame single glazing unit	5.817	TS EN 673, ISO 10292, ISO 15099, BEP Regulation, ISO 10077-1, ISO 10077-2, ISO 12567-1
$Uvalue_{W_{11}}$	Heat-retaining aluminum frame double glazing unit	4.077	TS EN 673, ISO 10292, ISO 15099, BEP Regulation, ISO 10077-1, ISO 10077-2, ISO 12567-1
$Uvalue_{W_{12}}$	Heat-retaining aluminum frame double glazing unit (low-e)	3.474	TS EN 673, ISO 10292, ISO 15099, BEP Regulation, ISO 10077-1, ISO 10077-2, ISO 12567-1
Window_IC_1	Investment cost of Window Type 1	22.109	2017 Ministry of Environment and Urbanization, General Directorate of Rural Services
Window_IC_2	Investment cost of Window Type 2	43.509	2017 Ministry of Environment and Urbanization,
Window_IC_3	Investment cost of Window Type 3	55.509	2017 Ministry of Environment and Urbanization,
Window_IC_4	Investment cost of Window Type 4	94.842	2017 Ministry of Environment and Urbanization, General Directorate of Rural Services
Window_IC_5	Investment cost of Window Type 5	116.242	2017 Ministry of Environment and Urbanization,
Window_IC_6	Investment cost of Window Type 6	128.242	2017 Ministry of Environment and Urbanization,
Window_IC_7	Investment cost of Window Type 7	29.418	2017 Ministry of Environment and Urbanization, General Directorate of Rural Services
Window_IC_8	Investment cost of Window Type 8	50.818	2017 Ministry of Environment and Urbanization,

Window_IC_9	Investment cost of Window Type 9	62.818	2017 Ministry of Environment and Urbanization,
Window_IC_10	Investment cost of Window Type 10	30.152	2017 Ministry of Environment and Urbanization, General Directorate of Rural Services
Window_IC_11	Investment cost of Window Type 11	51.552	2017 Ministry of Environment and Urbanization,
Window_IC_12	Investment cost of Window Type 12	63.552	2017 Ministry of Environment and Urbanization,
$percentage_W$	Window area given as a percentage for width [%]	32.79	TOKİ
$percentage_L$	Window area given as a percentage for length [%]	16.4	TOKİ
R_{si}	Internal thermal resistance of external wall	0.13	TS 825, TS EN 13790
R_{se}	External thermal Resistance of external wall	0.04	TS 825, TS EN 13790
$R_{extplastering}$	External Plaster Resistance	0.021428571	ISO 6946, TS 825, TS EN 13790
$R_{intplastering}$	Internal Plaster Resistance	0.022988506	ISO 6946, TS 825, TS EN 13790
λ_{brick}	thermal conductivity coefficient of Brick Wall	0.45	ISO 6946, TS 825
λ_{AAC}	thermal conductivity coefficient of AAC	0.24	ISO 6946, TS 825
λ_{RC}	thermal conductivity coefficient of Reinforced concrete	2.5	ISO 6946, TS 825
λ_{EPS}	thermal conductivity coefficient of EPS	0.035	ISO 6946, TS 825
λ_{XPS}	thermal conductivity coefficient of XPS	0.031	ISO 6946, TS 825
λ_{RW}	thermal conductivity coefficient of RockWool	0.045	ISO 6946, TS 825
λ_{FG}	thermal conductivity coefficient of Fibreglass	0.050	ISO 6946, TS 825

$d_{brick8.5}$	Thickness of the brick in Wall type 1	0.085	TS 825, scientific articles
$d_{brick13.5}$	Thickness of the brick in Wall type 1	0.135	TS 825, scientific articles
$d_{brick20}$	Thickness of the brick in Wall type4	0.2	TS 825, scientific articles
d_{AAC}	Thickness of the AAC in Wall type2	0.15	TS 825, scientific articles
d_{RC}	Thickness of the RC in Wall type3	0.24	TS 825, scientific articles
$d_{ins}1$	Thickness of the insulation material	0.01	Scientific articles
$d_{ins}2$	Thickness of the insulation material	0.02	Scientific articles
$d_{ins}3$	Thickness of the insulation material	0.03	Scientific articles
$d_{ins}4$	Thickness of the insulation material	0.04	Scientific articles
$d_{ins}5$	Thickness of the insulation material	0.05	Scientific articles
$d_{ins}6$	Thickness of the insulation material	0.06	Scientific articles
$d_{ins}7$	Thickness of the insulation material	0.07	Scientific articles
$d_{ins}8$	Thickness of the insulation material	0.08	Scientific articles
$d_{ins}9$	Thickness of the insulation material	0.09	Scientific articles
$d_{ins}10$	Thickness of the insulation material	0.10	Scientific articles
$price_{ins}XPS$	price of XPS in 2017	220	2017 Ministry of Environment and Urbanization
$price_{ins}EPS$	price of EPS in 2017	138	2017 Ministry of Environment and Urbanization
$price_{ins}RW$	price of RockWool in 2017	283.3	2017 Ministry of Environment and Urbanization

$price_{ins}FG$	price of Fibreglass in 2017	284.3	2017 Ministry of Environment and Urbanization
$price_{extplastering}$	price of External Plaster of external wall in 2017	16.75	2017 Ministry of Environment and Urbanization
$price_{intplastering}$	price of Internal Plaster of external wall in 2017	19.31	2017 Ministry of Environment and Urbanization
$price_{brick8.5}$	price of Brick Wall (8,5) in 2017	29.16	2017 Ministry of Environment and Urbanization
$price_{brick13.5}$	price of Brick Wall (13,5) in 2017	32.86	2017 Ministry of Environment and Urbanization
$price_{brick20}$	price of Brick Wall (20) in 2017	30.23	2017 Ministry of Environment and Urbanization
$price_{AAC}$	price of AAC in 2017	47.51	2017 Ministry of Environment and Urbanization
$price_{RC}$	price of Reinforced concrete in 2017	24.00	2017 Ministry of Environment and Urbanization
$IntWallIC_1$	Investment costs of the internal wall per m² [tl/m²] type 1 (brick wall)	72.120	2017 Ministry of Environment and Urbanization
$IntWallIC_2$	Investment costs of the internal wall per m² [tl/m²] type 2 (AAC wall)	90.470	2017 Ministry of Environment and Urbanization
$IntWallIC_3$	Investment costs of the internal wall per m² [tl/m²] type 3 (RC wall)	66.960	2017 Ministry of Environment and Urbanization
$Uvalue_F1$	U value of the floor for Type 1 (basement)	0.72463323	TS 825, TS EN ISO 13370, TS EN ISO 13789, TS EN ISO 13790
$Uvalue_F2$	U value of the floor for Type 2 (intermediate level)	0	TS 825, TS EN ISO 13370, TS EN ISO 13789, TS EN ISO 13790
$Uvalue_F3$	U value of the floor for Type 3 (upper level)	0	TS 825, TS EN ISO 13370, TS EN ISO 13789, TS EN ISO 13790
RF_F	Reduction Factor For Floor	0.5	TS 825, TS EN ISO 13370
$FloorIC_1$	Investment costs of the floor per m² [tl/m²] for type 1	100.60	2017 Ministry of Environment and Urbanization

$FloorIC_2$	Investment costs of the floor per m² [tl/m²] for type 2	88.50	2017 Ministry of Environment and Urbanization
$FloorIC_3$	Investment costs of the floor per m² [tl/m²] for type 3	88.50	2017 Ministry of Environment and Urbanization
$Uvalue_C1$	U value of the ceiling for Type 1 (basement)	0	TS 825, TS EN ISO 13790, ISO 7345, ISO 7726, ISO 9869
$Uvalue_C2$	U value of the ceiling for Type 2 (intermediate level)	0	TS 825, TS EN ISO 13790, ISO 7345, ISO 7726, ISO 9869
$Uvalue_C3$	U value of the ceiling for Type 3 (upper level)	0.4390	TS 825, TS EN ISO 13790, ISO 7345, ISO 7726, ISO 9869
RF_C	Reduction Factor For Ceiling	0.8	TS 825, TS EN ISO 13790
$CeilingIC_1$	Investment costs of the ceiling per m² [tl/m²] for type 1	56.60	2017 Ministry of Environment and Urbanization
$CeilingIC_2$	Investment costs of the ceiling per m² [tl/m²] for type 2	56.60	2017 Ministry of Environment and Urbanization
$CeilingIC_3$	Investment costs of the ceiling per m² [tl/m²] for type 3	59.06	2017 Ministry of Environment and Urbanization
$\rho.c$	The heat capacity of air per volume	0.33	BEP Regulation, TS 825, TS EN 13790
n_h	the air change rate	0.8	BEP Regulation, TS 825, TS EN 13790
$t_{seconds}$	Time, 1-month time in seconds (86400 x 30)	2592000	BEP Regulation, TS 825, TS EN 13790
$\eta_{HS}1$	Efficiency of the heating system [%] Stand-alone Heating System, Natural Gas	85	TS EN 15265, TS EN 15316-1, TS EN 15316-2,TS EN 15316-4-5,TS EN ISO 13790,TS 2164,TS EN ISO 11855-4, TS EN 15451

$\eta_{HS}2$	Efficiency of the heating system [%] Central Heating System, Natural Gas	95	TS EN 15265, TS EN 15316-1, TS EN 15316-2, TS EN 15316-4-5,TS EN ISO 13790,TS 2164,TS EN ISO 11855-4, TS EN 15451
$\eta_{HS}3$	Efficiency of the heating system [%] Central Heating System, Fuel Oil	80	TS EN 15265, TS EN 15316-1, TS EN 15316-2,TS EN 15316-4-5,TS EN ISO 13790,TS 2164,TS EN ISO 11855-4, TS EN 15451
$\eta_{HS}4$	Efficiency of the heating system [%] Central Heating System, Coal	65	TS EN 15265, TS EN 15316-1,TS EN 15316-2,TS EN 15316-4-5,TS EN ISO 13790,TS 2164,TS EN ISO 11855-4, TS EN 15451
HeatingSystemFIC_1	Fixed investment costs for the heating system Type 1 [tl/m^2]	4294.22	Energy Market Regulatory Authority
HeatingSystemFIC_2	Fixed investment costs for the heating system Type 2 [tl/m^2]	4950.76	Energy Market Regulatory Authority
HeatingSystemFIC_3	Fixed investment costs for the heating system Type 3 [tl/m^2]	4115.23	Energy Market Regulatory Authority
HeatingSystemFIC_4	Fixed investment costs for the heating system Type 4 [tl/m^2]	3044.87	Energy Market Regulatory Authority
HeatingSystemVIC_1	Variable investment costs of the heating system Type 1 [tl/m^2]	1223	2017 Ministry of Environment and Urbanization
HeatingSystemVIC_2	Variable investment costs of the heating system Type 2 [tl/m^2]	1223	2017 Ministry of Environment and Urbanization
HeatingSystemVIC_3	Variable investment costs of the heating system Type 3 [tl/m^2]	1223	2017 Ministry of Environment and Urbanization
HeatingSystemVIC_4	Variable investment costs of the heating system Type 4 [tl/m^2]	304.49	2017 Ministry of Environment and Urbanization

LHV_1	Lower heating value of fuel type-Natural Gas [Kwh/m3]	9.588333315	Ministry of Energy and Natural Resources
LHV_2	Lower heating value of fuel type-Natural Gas [Kwh/m3]	9.588333315	Ministry of Energy and Natural Resources
LHV_3	Lower heating value of fuel type-Fuel Oil [Kwh/kg]	11.157333312	Ministry of Energy and Natural Resources
LHV_4	Lower heating value of fuel type-Coal [Kwh/kg]	5.73440443348	Ministry of Energy and Natural Resources
$price_{fueltype}1$	Fixed price for fuel type 1 [tl/year]	1.222	http://www.baskentdogalgaz.com.tr
$price_{fueltype}2$	Fixed price for fuel type 2 [tl/year]	1.222	http://www.baskentdogalgaz.com.tr
$price_{fueltype}3$	Fixed price for fuel type 3 [tl/year]	2.23	http://www.tppd.com.tr
$price_{fueltype}4$	Fixed price for fuel type 4 [tl/year]	0.96	http://www.tki.gov.tr
$\theta_{w,del}$	the average used water temperature (delivered)	60	BEP Regulation, TS EN 15316-3-1
$\theta_{w,0}$	the average monthly city water temperature	row	General Directorate of Meteorology
V_w	the volume of hot water used for single-family houses and residences lt	0.045	BEP Regulation
$\rho.c_w$	Specific heat capacity and water density	4.182	BEP Regulation
V_{dw}	Water consumption of the building per day per person [lt]	80	General Directorate of Provincial Bank
$Number_{occupant}$	Number of occupants using hot water	3	Turk STAT
$\phi_{int,Oc,sen,unit}$	Metabolic gains form occupants (sensible)[W/person]	75	BEP Regulation

$\phi_{int,Oc,lat,unit}$	Metabolic gains form occupants (lateral)[W/person]	55	BEP Regulation
$price_{electricity}$	Costs for one kWh of electricity consumption	0.2134	https://www.enerjisa.com.tr, Energy Market Regulatory Authority
$price_{naturelgas}$	Costs for one kWh of heat consumption.	1.22	http://www.baskentdogalgaz.com.tr
$price_{dailywater}$	Costs for m3 of water consumption.	6.02	Ankara Water and Sewerage Administration (Aski)
$LHV_{naturalgas}$	Lower heating value of natural gas	9.588333315	Ministry of Energy and Natural Resources
$HotWaterSystemIC1$	Investment costs for the hot water system [tl] for Type 1	521	2017 Ministry of Environment and Urbanization
$HotWaterSystemIC2$	Investment costs for the hot water system [tl] for Type 2	2150	2017 Ministry of Environment and Urbanization
$price_{Disposal}$	Disposal Cost Unit Price	33.05	2017 General Directorate of Highways

D. Delphi Research Questions and Answers

1. The LCC based model makes a significant difference when applied in the design phase.
    - Being (1) strongly disagree, (2) disagree; (3) neither agree nor disagree; (4) agree; and (5) strongly agree. For cases where there is disagreement, "suggestions" were asked for each question.

2. In the design stage, operational and maintenance costs of the building should be taken into consideration.
    - Being (1) strongly disagree, (2) disagree; (3) neither agree nor disagree; (4) agree; and (5) strongly agree. For cases where there is disagreement, "suggestions" were asked for each question.

3. It can be estimated the energy that the building will consume during its lifetime
    - Being (1) strongly disagree, (2) disagree; (3) neither agree nor disagree; (4) agree; and (5) strongly agree. For cases where there is disagreement, "suggestions" were asked for each dimension

4. There is a connection between the material used and the energy consumption of the building.
    - Being (1) strongly disagree, (2) disagree; (3) neither agree nor disagree; (4) agree; and (5) strongly agree. For cases where there is disagreement, "suggestions" were asked for each dimension

5. It is possible to create the most economically advantageous building combination in its lifecycle period.
    - Being (1) strongly disagree, (2) disagree; (3) neither agree nor disagree; (4) agree; and (5) strongly agree. For cases where there is disagreement, "suggestions" were asked for each dimension

6. In the early design phase, the high energy consumption of the building causes your design to change.
    - Being (1) strongly disagree, (2) disagree; (3) neither agree nor disagree; (4) agree; and (5) strongly agree. For cases where there is disagreement, "suggestions" were asked for each dimension

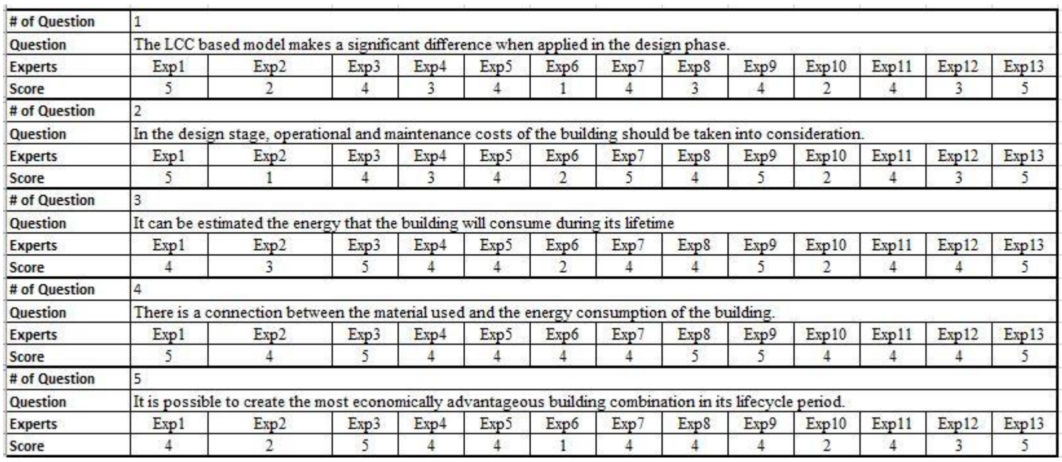
7. Using the LCC based model in the design phase will help to reduce the energy consumption of the building.
    - Being (1) strongly disagree, (2) disagree; (3) neither agree nor disagree; (4) agree; and (5) strongly agree. For cases where there is disagreement, "suggestions" were asked for each dimension

8. It is possible to reduce the total cost of the building by using an LCC based model.
    - Being (1) strongly disagree, (2) disagree; (3) neither agree nor disagree; (4) agree; and (5) strongly agree. For cases where there is disagreement, "suggestions" were asked for each dimension

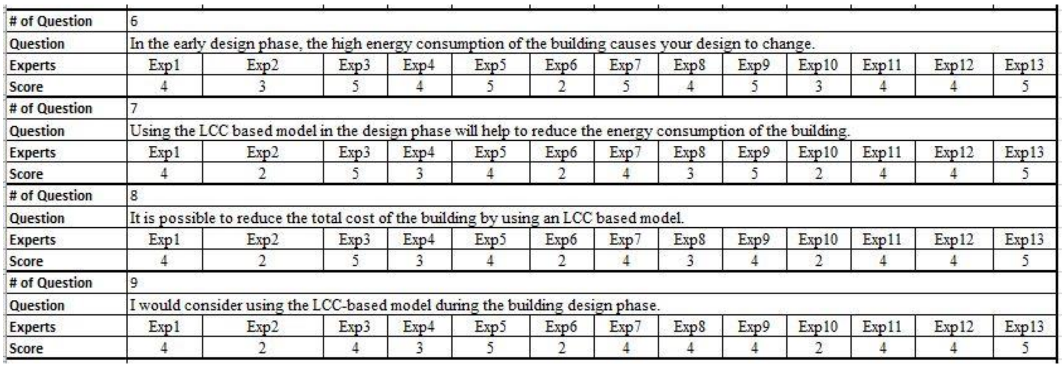
9. I would consider using the LCC-based model during the building design phase.
    - Being (1) strongly disagree, (2) disagree; (3) neither agree nor disagree; (4) agree; and (5) strongly agree. For cases where there is disagreement, "suggestions" were asked for each dimension

10. Identify the main factors responsible for estimated energy consumption for residential buildings.

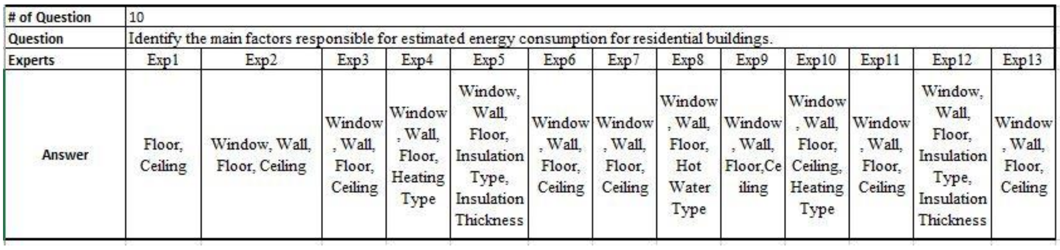
First Round Results



# of Question	1												
Question	The LCC based model makes a significant difference when applied in the design phase.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	5	2	4	3	4	1	4	3	4	2	4	3	5
# of Question	2												
Question	In the design stage, operational and maintenance costs of the building should be taken into consideration.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	5	1	4	3	4	2	5	4	5	2	4	3	5
# of Question	3												
Question	It can be estimated the energy that the building will consume during its lifetime												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	4	3	5	4	4	2	4	4	5	2	4	4	5
# of Question	4												
Question	There is a connection between the material used and the energy consumption of the building.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	5	4	5	4	4	4	4	5	5	4	4	4	5
# of Question	5												
Question	It is possible to create the most economically advantageous building combination in its lifecycle period.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	4	2	5	4	4	1	4	4	4	2	4	3	5

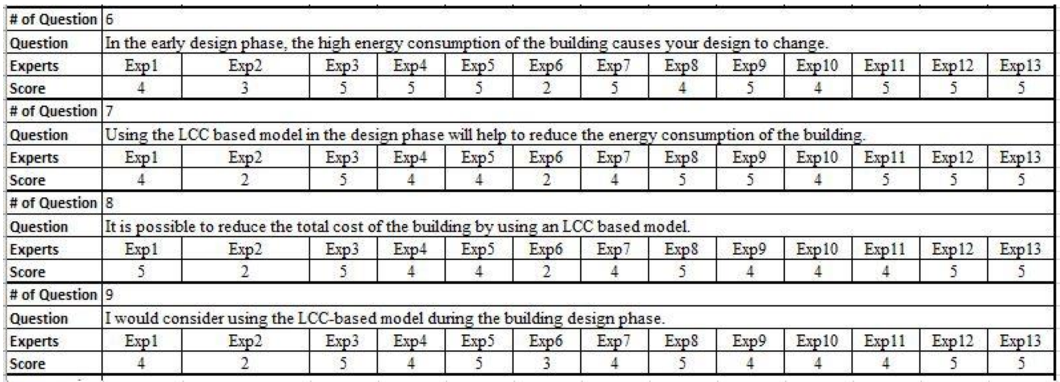


# of Question	6												
Question	In the early design phase, the high energy consumption of the building causes your design to change.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	4	3	5	4	5	2	5	4	5	3	4	4	5
# of Question	7												
Question	Using the LCC based model in the design phase will help to reduce the energy consumption of the building.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	4	2	5	3	4	2	4	3	5	2	4	4	5
# of Question	8												
Question	It is possible to reduce the total cost of the building by using an LCC based model.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	4	2	5	3	4	2	4	3	4	2	4	4	5
# of Question	9												
Question	I would consider using the LCC-based model during the building design phase.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	4	2	4	3	5	2	4	4	4	2	4	4	5

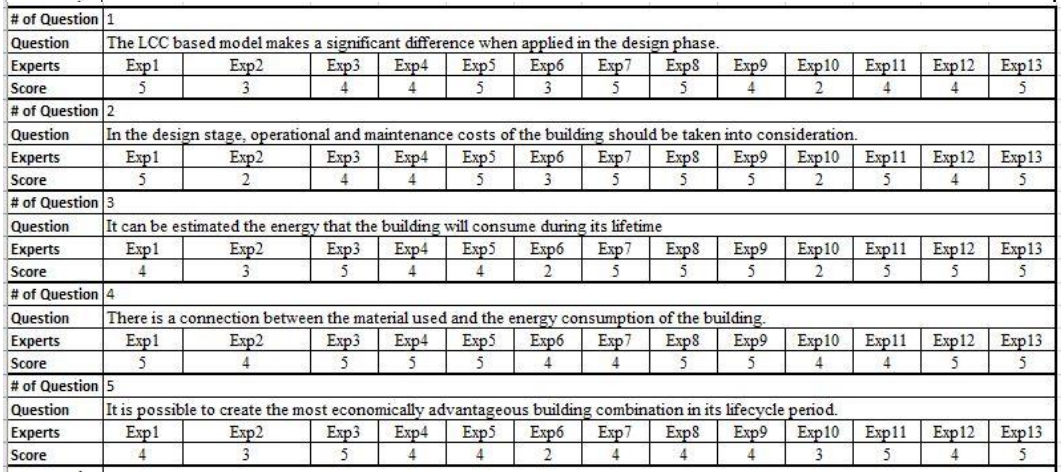


# of Question	10												
Question	Identify the main factors responsible for estimated energy consumption for residential buildings.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Answer	Floor, Ceiling	Window, Wall, Floor, Ceiling	Window, Wall, Floor, Ceiling	Window, Wall, Floor, Heating Type	Window, Wall, Floor, Insulation Type, Insulation Thickness	Window, Wall, Floor, Ceiling	Window, Wall, Floor, Ceiling	Window, Wall, Floor, Hot Water Type	Window, Wall, Floor,Ceiling	Window, Wall, Floor, Ceiling, Heating Type	Window, Wall, Floor, Ceiling	Window, Wall, Floor, Insulation Type, Insulation Thickness	Window, Wall, Floor, Ceiling

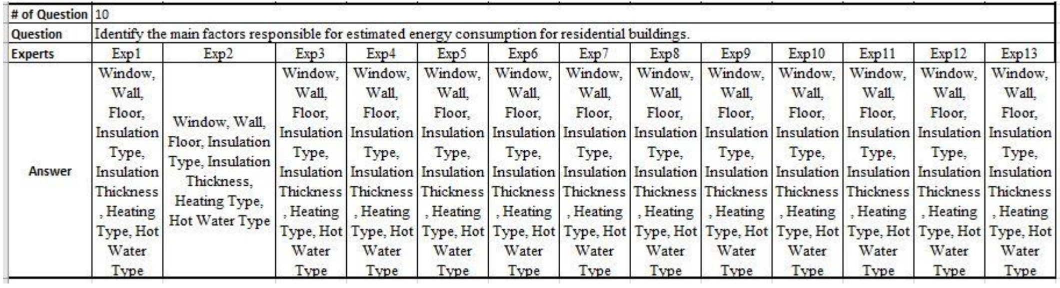
Second Round Results



# of Question	6												
Question	In the early design phase, the high energy consumption of the building causes your design to change.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	4	3	5	5	5	2	5	4	5	4	5	5	5
# of Question	7												
Question	Using the LCC based model in the design phase will help to reduce the energy consumption of the building.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	4	2	5	4	4	2	4	5	5	4	5	5	5
# of Question	8												
Question	It is possible to reduce the total cost of the building by using an LCC based model.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	5	2	5	4	4	2	4	5	4	4	4	5	5
# of Question	9												
Question	I would consider using the LCC-based model during the building design phase.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	4	2	5	4	5	3	4	5	4	4	4	5	5

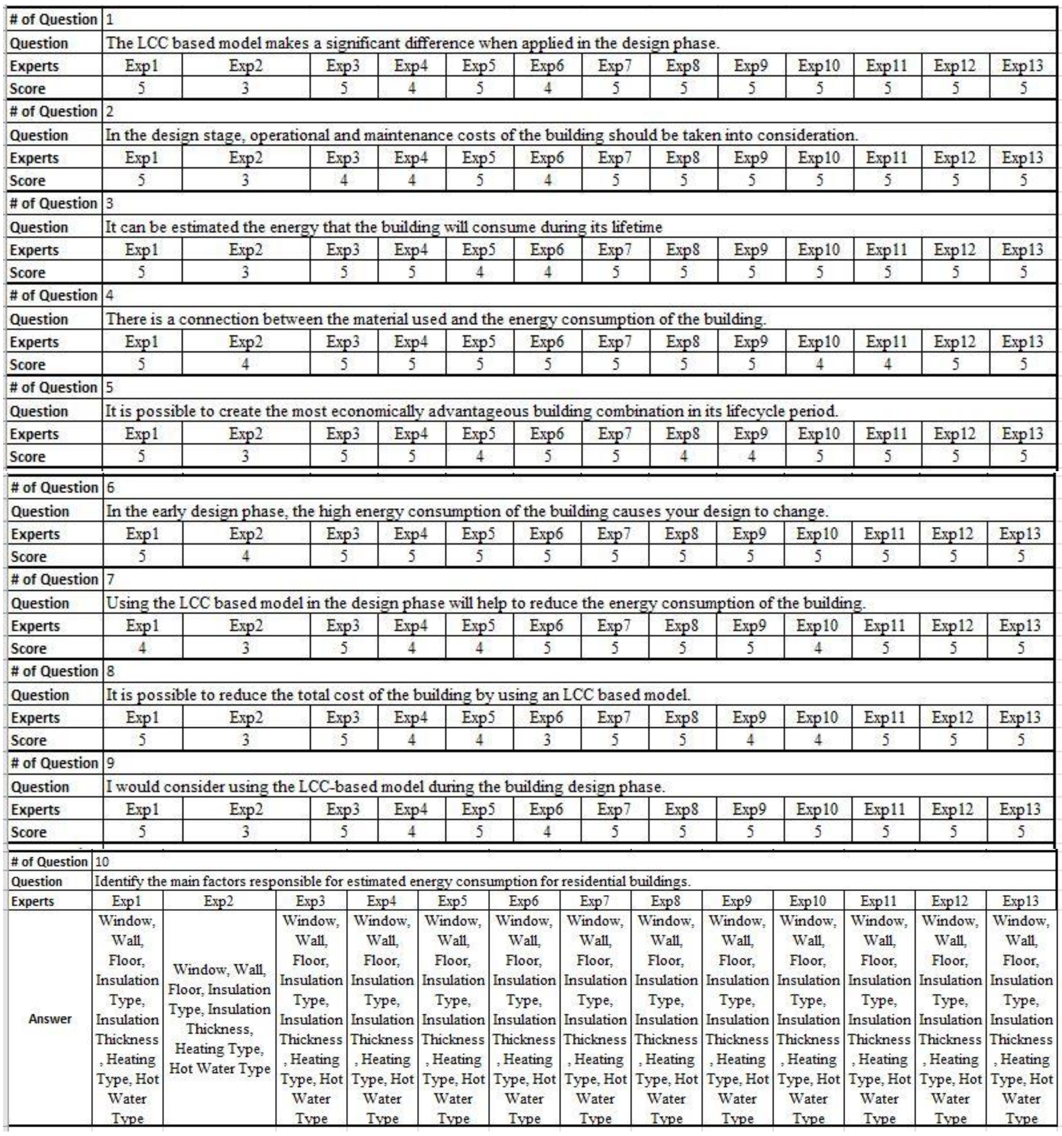


# of Question	1												
Question	The LCC based model makes a significant difference when applied in the design phase.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	5	3	4	4	5	3	5	5	4	2	4	4	5
# of Question	2												
Question	In the design stage, operational and maintenance costs of the building should be taken into consideration.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	5	2	4	4	5	3	5	5	5	2	5	4	5
# of Question	3												
Question	It can be estimated the energy that the building will consume during its lifetime												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	4	3	5	4	4	2	5	5	5	2	5	5	5
# of Question	4												
Question	There is a connection between the material used and the energy consumption of the building.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	5	4	5	5	5	4	4	5	5	4	4	5	5
# of Question	5												
Question	It is possible to create the most economically advantageous building combination in its lifecycle period.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	4	3	5	4	4	2	4	4	4	3	5	4	5



# of Question	10												
Question	Identify the main factors responsible for estimated energy consumption for residential buildings.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Answer	Window, Wall, Floor, Insulation Type, Insulation Thickness, Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness, Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness, Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness, Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness, Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness, Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness, Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness, Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness, Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness, Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness, Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness, Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness, Heating Type, Hot Water Type

Third Round Results



# of Question	1												
Question	The LCC based model makes a significant difference when applied in the design phase.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	5	3	5	4	5	4	5	5	5	5	5	5	5
# of Question	2												
Question	In the design stage, operational and maintenance costs of the building should be taken into consideration.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	5	3	4	4	5	4	5	5	5	5	5	5	5
# of Question	3												
Question	It can be estimated the energy that the building will consume during its lifetime												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	5	3	5	5	4	4	5	5	5	5	5	5	5
# of Question	4												
Question	There is a connection between the material used and the energy consumption of the building.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	5	4	5	5	5	5	5	5	5	4	4	5	5
# of Question	5												
Question	It is possible to create the most economically advantageous building combination in its lifecycle period.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	5	3	5	5	4	5	5	4	4	5	5	5	5
# of Question	6												
Question	In the early design phase, the high energy consumption of the building causes your design to change.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	5	4	5	5	5	5	5	5	5	5	5	5	5
# of Question	7												
Question	Using the LCC based model in the design phase will help to reduce the energy consumption of the building.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	4	3	5	4	4	5	5	5	5	4	5	5	5
# of Question	8												
Question	It is possible to reduce the total cost of the building by using an LCC based model.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	5	3	5	4	4	3	5	5	4	4	5	5	5
# of Question	9												
Question	I would consider using the LCC-based model during the building design phase.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Score	5	3	5	4	5	4	5	5	5	5	5	5	5
# of Question	10												
Question	Identify the main factors responsible for estimated energy consumption for residential buildings.												
Experts	Exp1	Exp2	Exp3	Exp4	Exp5	Exp6	Exp7	Exp8	Exp9	Exp10	Exp11	Exp12	Exp13
Answer	Window, Wall, Floor, Insulation Type, Insulation Thickness , Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness, Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness , Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness , Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness , Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness , Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness , Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness , Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness , Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness , Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness , Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness , Heating Type, Hot Water Type	Window, Wall, Floor, Insulation Type, Insulation Thickness , Heating Type, Hot Water Type

CURRICULUM VITAE

PERSONAL INFORMATION

Surname, Name: Emekci, Şeyda
Nationality: Turkish (TC)
Date and Place of Birth: 1 Ocak 1988, Kırıkkale

EDUCATION

Degree	Institution	Year of Graduation
Ph.D	METU Architecture	2018
MS	METU Architecture	2014
BS	METU Architecture	2011
High School	Science High School, Kırıkkale	2006

WORK EXPERIENCE

Year	Place	Enrollment
2017- Present	Yıldırım Beyazıt University	Research Assistant
2013-2017	Ministry of Forestry and Water Affairs	Expert
2011-2013	North Anatolian Development Agency	Expert

PUBLICATIONS

1. Emekci, S. & Kayasu, S. (2017). Urban form and sustainability: The case study of Gaziantep in Turkey (pp. 95–110). Presented at the SB-LAB 2017-International Conference on Advances on Sustainable Cities and Buildings Development.

2. Emekci, S. & Tanyer, A. M. (2016). New Perspective on More Sustainable and Affordable Housing for Lower Income Group in Turkey -Assessing Life Cycle Cost – (Vol. 1, pp. 555–564). Presented at the SUSTAINABLE HOUSING 2016- International Conference on Sustainable Housing Planning, Management and Sustainability, Green Lines Institute for Sustainable Development.

3. Yilmaz, S. (2014). An Assessment on the Link Between Sustainability and Urban Form: The Case Of Gaziantep. *Middle East Technical University, MSc Thesis*.