A COMPARATIVE LIFE CYCLE ASSESSMENT OF STRUCTURAL MATERIALS: A CASE STUDY ON TOKİ HOUSING

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ABSTRACT

A COMPARATIVE LIFE CYCLE ASSESSMENT OF STRUCTURAL MATERIALS: A CASE STUDY ON TOKİ HOUSING

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In Turkey, the Housing Development Administration of Turkey (TOKİ) has a significant proportion of housing stock and prepares typical housing projects. Reinforced concrete shear wall system (also named as tunnel form system) is preferred in these projects. This reinforced concrete system may have structural advantages but may also have more CO2 emissions. Therefore, the potentials of a steel system in terms of sustainability are investigated in this study. TOKİ buildings are classified according to their typology. Then, a representative typology is selected and modeled as 5-, 10-, and 14-story buildings with reinforced concrete shear-wall and steel braced-frame systems. Structural models are designed and analyzed by the ProtaStructure program for both high and low seismicity levels. A Life Cycle Assessment (LCA) program, OneClickLCA, is used to evaluate the impacts of alternative models on nature according to ecological parameters. Comparing 5-, 10-, and 14-story models with alternative materials shows that steel models have lower negative impacts than reinforced concrete models except for the formation of summer smog and total energy need. On the other hand, the minimum-maximum boundary analysis of 5-story models indicates that the steel model with minimum recycled content is the most harmful model to nature. The results of 5- and 14-story steel models in low seismic regions demonstrate that the harmful effects of steel get lower (steel is more advantageous for the environment) with increasing building height. Consequently, this study shows the potentials of steel compared to reinforced concrete so that a more sustainable approach can be preferred starting from TOKİ projects.

Keywords: TOKİ Housing, Structural System, Reinforced Concrete Tunnel Form, Steel Braced Frame, Life Cycle Assessment

ÖZ

TAŞIYICI SİSTEM MALZEMELERİNİN KARŞILAŞTIRMALI YAŞAM DÖNGÜSÜ ANALİZİ: TOKİ KONUTU ÖRNEĞİ

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Toplu Konut İdaresi (TOKİ), Türkiye'deki konut stoku üretiminde önemli bir paya sahiptir. TOKİ konutlarında tipik projeler uygulanmakta olup bu projelerde betonarme perde duvar sistemi (tünel kalıp sistemi) tercih edilmektedir. Bu sistem yapısal avantajlara sahip olmakla birlikte daha fazla CO2 salınımlarına da neden olabilmektedir. Bu nedenle, bu çalışmada çelik bir sistemin sürdürülebilirlik açısından potansiyeli araştırılmıştır. TOKİ binaları tipolojilerine göre sınıflandırılmış, temsili bir tipoloji seçilerek 5, 10 ve 14 katlı betonarme perde duvar sistemli ve çelik çapraz çerçeve sistemli binalar modellenmiştir. Yapısal modeller ProtaStructure programında hazırlanmış; hem yüksek hem de düşük tehlike seviyelerine göre modelleme ve analizleri yapılmıştır. Alternatif modellerin doğa üzerindeki etkilerini ekolojik parametrelere göre değerlendirmek için bir Yaşam Döngüsü Değerlendirmesi (LCA) programı olan OneClickLCA kullanılmıştır. 5, 10 ve 14 katlı modellerin karşılaştırılması, çelik modellerin yaz sisi oluşumu ve toplam enerji ihtiyacı dışında, betonarme modellere göre daha az olumsuz etkiye sahip olduğunu göstermektedir. 5 katlı modellerin minimum-maksimum sınır analizi, minimum geri dönüştürülmüş içeriğe sahip olan çelik modelin doğaya en zararlı model olduğunu ortaya çıkarmaktadır. Düşük riskli deprem bölgelerinde analiz edilmiş, 5 ve 14 katlı çelik modellerin sonuçları, bina yüksekliği arttıkça çeliğin zararlı etkilerinin azaldığını (çeliğin çevre için daha avantajlı olduğunu) göstermektedir. Sonuç olarak, bu çalışmada, TOKİ projelerinden başlayarak daha sürdürülebilir bir yaklaşımın tercih edilebilmesi için çeliğin potansiyelleri betonarme ile karşılaştırılarak analiz edilmektedir.

Anahtar Kelimeler: TOKİ Konutları, Taşıyıcı Sistem, Betonarme Tünel Kalıp, Çelik Çaprazlı Çerçeve, Yaşam Döngüsü Değerlendirmesi

To my family, Ege-Birsen-Feyzi Dener and my husband, Umut Uysal,
Also to Grandfather and Grandmother,

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ABBREVIATIONS

AP : Acidification Potential

BF : Basement Floor

BKS : The Usage Class of Building (Bina Kullanım Sınıfı)

BYS : The Classes of Building Height (Bina Yükseklik Sınıfı)

CF : Carbon Footprint

CO_2 : Carbon Dioxide

DD-2 : Earthquake Ground Motion Level of 10% (repetition period 475 years) over 50 Years

DTS : The Classes of Earthquake Design (Deprem Tasarım Sınıfı)

EP : Eutrophication Potential

F2 Scheme : Floor plan with 1 core and 2 apartments

F4 Scheme : Floor plan with 1 core and 4 apartments

F6 Scheme : Floor plan with 1 core and 6 apartments

FOLA : Formation of Ozone of Lower Atmosphere

GFA : Gross Floor Area

GHG : Greenhouse Gas

GIFA : Gross Internal Floor Area

GWP : Global Warming Potential

HEB : Section of Structural Steel (I-Beam)

ISO 14040 : International Standard (Environmental Management-Life Cycle Assessment-Principles and Framework)

LCA : Life-Cycle Assessment

LCE : Life Cycle Explorer

LCI : Life Cycle Inventory

LCIA : Life Cycle Impact Assessment

NA : Not Applicable

ODP : Ozone Depletion Potential

PGA : Peak Ground Acceleration

RC10 : 10-Story Reinforced Concrete Model

RC14 : 14-Story Reinforced Concrete Model

RC5 : 5-Story Reinforced Concrete Model

RC5-max : Maximum Case of 5-Story Reinforced Concrete Model

RC5-min : Minimum Case of 5-Story Reinforced Concrete Model

RC5-typ : Typical Case of 5-Story Reinforced Concrete Model

SS10 : 10-Story Steel Model

SS14 : 14-Story Steel Model

SS14-high : 14-Story Steel Model in High Seismicity

SS14-low : 14-Story Steel Model in Low Seismicity

SS5 : 5-Story Steel Model

SS5-high : 5-Story Steel Model in High Seismicity

SS5-low : 5-Story Steel Model in Low Seismicity

SS5-max : Maximum Case of 5-Story Steel Model

SS5-min : Minimum Case of 5-Story Steel Model

SS5-typ : Typical Case of 5-Story Steel Model

TEAM : Tool for Environmental Analysis

TEC 2018 : Turkish Earthquake Code/Turkish Seismic Design Code for Buildings

TOKİ : Housing Development Administration of Turkey

TOTAL UPE : Total Use of Primary Energy

TS498 : Design Loads for Buildings

TS500 : Requirements for Design and Construction of Reinforced Concrete Structures

TSE : Turkish Standard

TSSC : Design, Calculation and Construction Principles of Steel Structures

TUBO : Section of Structural Steel (Hollow Steel Section)

TÜİK : Turkish Statistical Institute

TURKSTAT : Turkish Statistical Institute

ZC : Soil Type (very tight layers of sand, gravel, and hard clay, or weathered, very cracked weak rocks)

LIST OF SYMBOLS

SYMBOLS

A13 : Type of Load-Bearing System (buildings that all of the earthquake effects are faced by reinforced concrete shear walls which have high ductility level)

A1-A3 : Life Cycle Stage of Construction Materials

A4 : Life Cycle Stage of Transportation to Site

C13 : Type of Load-Bearing System (buildings that all of the earthquake effects are faced by central braced steel frames which have high ductility level)

C1-C4 : Life Cycle Stage of End-of-Life Phase

D : Overstrength Factor

f_c : Characteristic Compressive Strength of Concrete

f_y : Yield Strength of STEEL

G : Dead Loads

H^+ : Hydrogen Ion

H_N : Total Building Height

M_{a1}, M_{a2} : Overturning Moments of Floors

M_{p1}, M_{p2} : Overturning Resisting Moments of floors

N : Nitrogen

P : Phosphorus

Q : Live Loads

R : Response Modification Coefficient

S1 : Map Spectral Acceleration Coefficient for the 1.0 Second Period

S_{DS} : Short Period Design Spectral Acceleration Coefficient

Ss : Short Period Map Spectral Acceleration Coefficient

W : Seismic Weight of Floors

CHAPTER 1

INTRODUCTION

This chapter begins with the motivation for the research topic. After that, the research problem is explained. Then, the aim and objectives of the study are defined. The chapter is ended with the part of disposition.

1.1 Motivation

Sustainability is one of the important issues that architects take into consideration nowadays. Environment-friendly projects have become very popular because of the reason that construction is a sector that affects the environment directly. Especially residential buildings are among the priority areas in terms of sustainability because of their high CO_2 emissions and energy-saving potentials (Dino & Meral Akgül, 2019).

With the growth of the cities in Turkey because of the increased human population, the need for dwelling units occurs for people. Therefore; the construction sector grows fast to fulfill this need. This situation can be understood easily with the number of dwelling units in Turkey. If the recent ten years are examined, it is clear to see that the dwelling unit number is increasing from past to present according to the data of TURKSTAT (TÜİK-Turkish Statistical Institute). In 2009, nearly 500,000 dwelling units took occupancy permits while this number approaches 900,000 in 2018 (Figure 1.1). However, this fast increase affects the nature of the cities negatively and the environmental properties of produced dwelling units become more essential. In Turkey, dwelling units are produced by the public and private sectors. There is a public institution constructing buildings, which is TOKİ (Housing Development Administration of Turkey). According to TOKİ, it produces solutions to the problems about housing and urbanization, it targets an adequate number of qualified housing in a healthy urban environment of the country (2021). Today, TOKİ aims to meet 5-10% of the housing need in Turkey. The main target of TOKİ for the 2019-2023 period is to put 250,000 houses to tender (TOKİ, 2021).

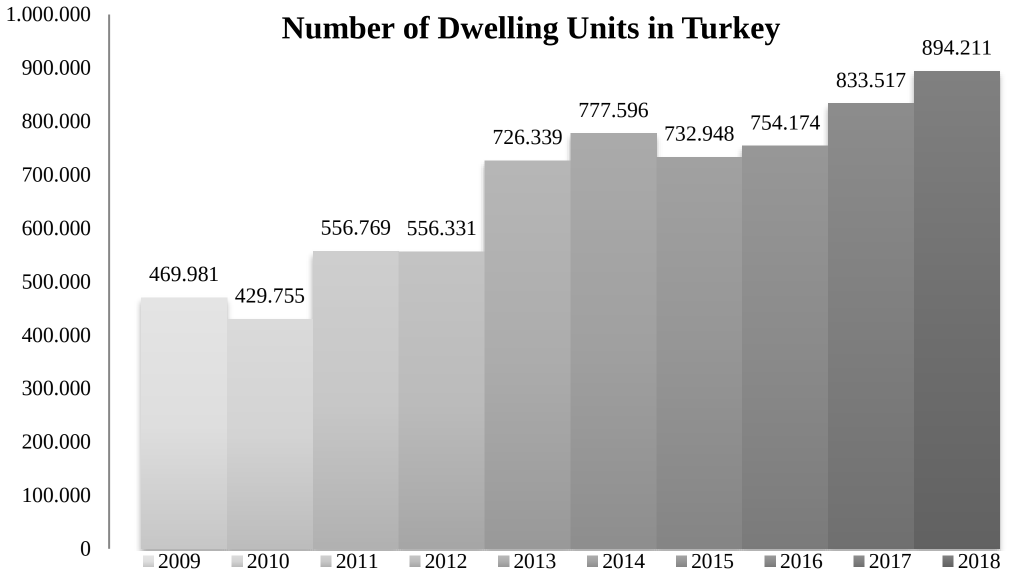


Figure 1.1. Number of Dwelling Units Taking Occupancy Permit from 2009 to 2018 (TURKSTAT-Turkish Statistical Institute, 2020)

To understand the target of TOKİ, the values of the past four years (2015-2018) are analyzed. According to the data of TURKSTAT, the total number of dwellings is 3,214,850 between 2015-2018 (Figure 1.2). The total number is used to compare the target of TOKİ. In Figure 1.3, the main target of TOKİ for the years between 2019 and 2023 is compared with 10% of TURKSTAT's total data belonging to the period from 2015 to 2018 which is calculated in Figure 1.2. So, the target of TOKİ (250,000 Houses) is very close to 7-8% of the total number of dwelling units. As a result, it can be said that TOKİ's target corresponds to 5% to 10% of the total dwelling unit number.

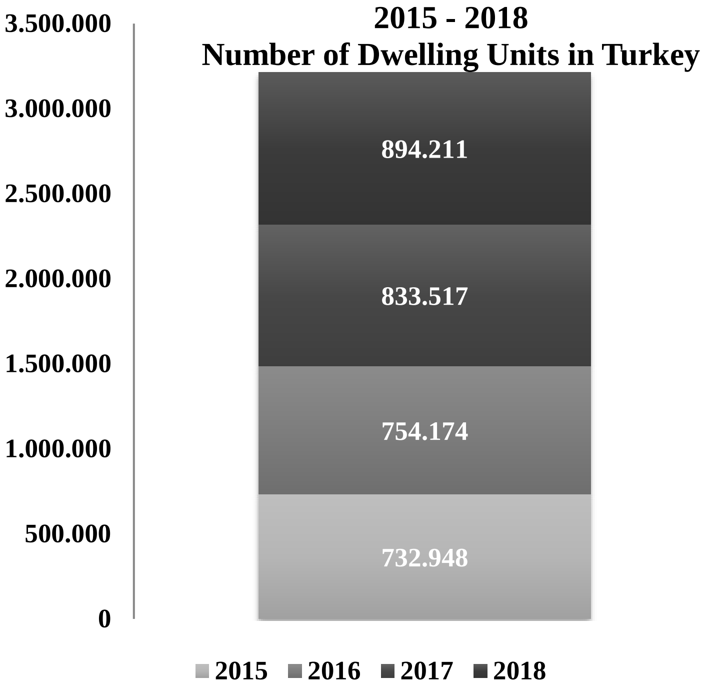


Figure 1.2. Focused Past 4 Years

(TURKSTAT-Turkish Statistical Institute, 2020)

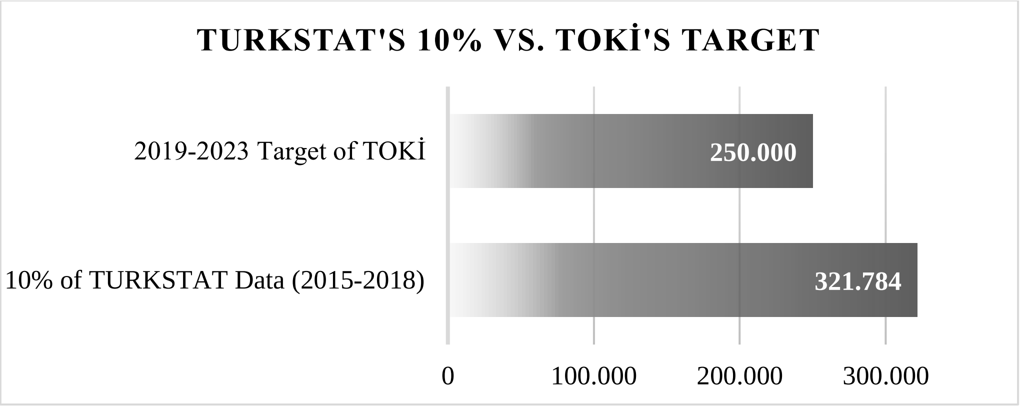


Figure 1.3. Evaluation of TOKİ’s Target

Between 2002 and 2016, the dwelling unit number which is produced by TOKİ is 583,515 and this is 9.2% of the total number (Figure 1.4) which takes occupancy permits between those years (TOKİ, 2016). Figure 1.5 shows that 85.20% of TOKİ houses are produced as "social type housing" for low and middle-income people (TOKİ, 2017). On the other hand, 15% of TOKİ houses are built for high-income people that is defined with the part of "other" in the figure. So, TOKİ produces dwelling units for not only low-income groups but also high-income groups. TOKİ declares that the production of 847,954 dwelling units has been achieved since 2003 (TOKİ, 2019).

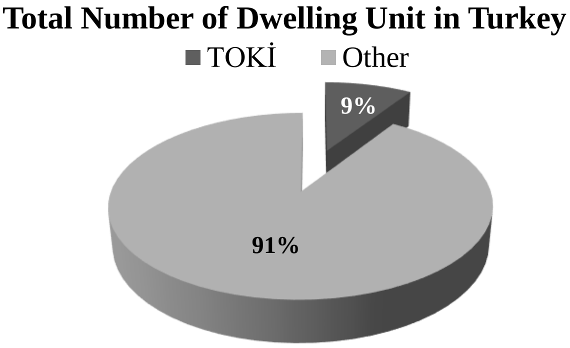


Figure 1.4. Percentage of TOKİ

(TOKİ, 2016)

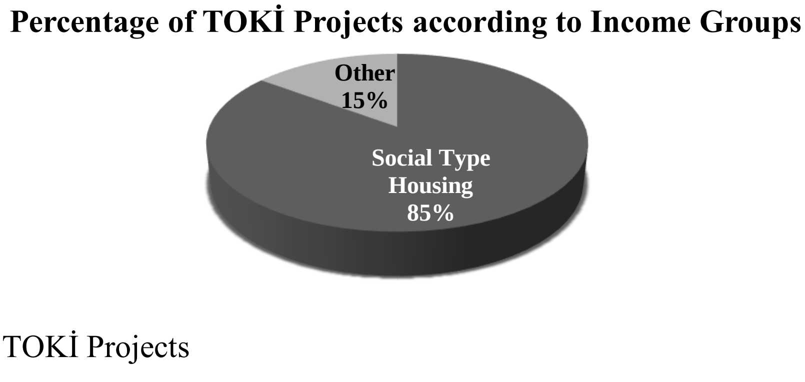


Figure 1.5. TOKİ Projects

(TOKİ, 2017)

In brief, housing units that are produced by TOKİ have a considerable amount in this sector for Turkey. Within this context, examining the sustainability of TOKİ houses is a very critical issue for the future of the environment and nature considering TOKİ's percentage in the entire sector.

1.2 Research Problem

From past to present, the construction sector prefers concrete to produce buildings generally, in Turkey. According to data of TURKSTAT about the number of buildings in terms of structural systems, concrete has been the most prevalent structural material which is used to form structural systems in both 2010 and 2019 years (Figure 1.6). The reason can be related to the fact that the contractors in Turkey are familiar with applying concrete in building construction. Moreover, concrete is seen as an economic material by contractors. The construction sector founds steel as an expensive material. TOKİ, also, considers the economic aspect of the projects. Since it is a public institution, the economy of these projects is taken into consideration. About TOKİ housing, two different studies are investigated. Parlak (2015) declares that the tunnel formwork method is preferred by the administration and Sezer (2009) says that TOKİ's construction technique is the reinforced concrete tunnel formwork system. So, TOKİ uses reinforced concrete as the structural material of the housing projects, and the tunnel formwork system is preferred for the construction of housing units. This structural system is preferred by TOKİ due to the fact that it is time and cost-efficient as is stated in the study of Parlak (2015). According to Sezer (2009), the tunnel formwork system has many advantages but also disadvantages. This system is economic, speedy and it decreases the usage of wooden formwork. Moreover, one whole floor can be built in one day with this system. However, reinforced concrete may not be a sustainable material compared to steel, wood, and stone according to Sezer (2009).

In another study (López et al., 2016), researchers declare that concrete produces a greater environmental impact because concrete includes cement and cement has large CO_2 emissions. Further, they add that the model with the lowest cement amount has the lowest carbon footprint. According to the report of the Turkish Ready Mixed Concrete Association (2021), the main inputs of concrete production are cement, aggregate, water, chemical additives, and in some cases mineral additives. Among these inputs, cement is the component that causes the most emissions. Almost 90% of the embedded carbon in concrete comes from cement. Clinker is the main component of cement and almost one-to-one CO_2 emissions occur in the production of this material. For the aggregate, the emissions arise from the removal and breaking of the material from the quarry (Turkish Ready Mixed Concrete Association, 2021). In brief, this choice of reinforced concrete as the structural material may have some negative effects on nature. It can be more harmful to the environment than other materials such as wood or steel.

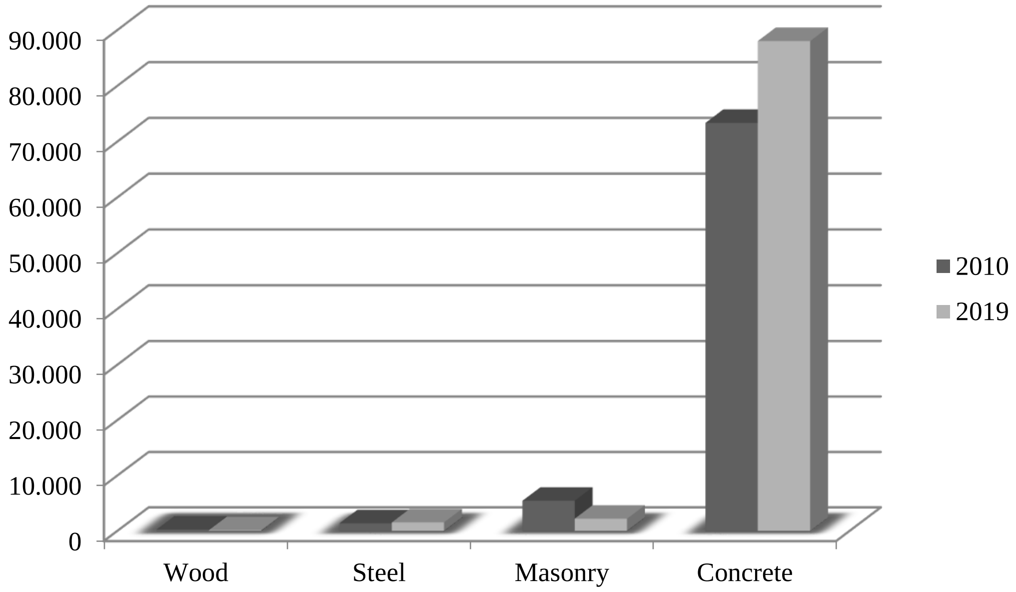


Figure 1.6. Dwelling Unit Number of Turkey according to Structural Systems

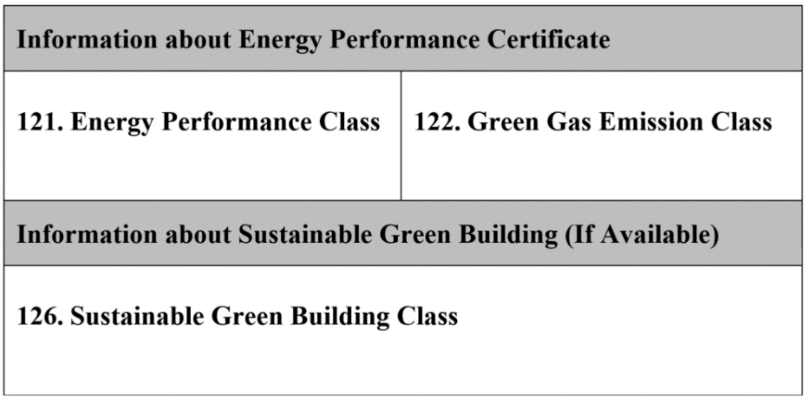
(TURKSTAT-Turkish Statistical Institute, 2010-2019)

Further, TOKİ housing projects are applied as typical projects. It means that the same rights and wrongs are practiced many times. If there is an issue in these typical projects, the same issues occur again and again or if they have negative impacts on nature, damage to the earth increases project by project.

Accordingly, another material, steel, is studied in this thesis rather than reinforced concrete as the structural material for a TOKİ project. The potentials of steel are examined in terms of sustainability by comparing the models according to the results of environmental parameters.

1.3 Aim and Objectives

Today, Turkey has two new parts in the occupancy permit document about sustainability. In Figure 1.7, there is a section that shows Energy Performance Class -Section 121 and Green Gas Emission Class-Section 122. The other section shows Sustainable Green Building Class-Section 126 (TSE-Turkish Standard, 2016). So, it is evidence that sustainability has started to be essential for Turkey.



Information about Energy Performance Certificate	
121. Energy Performance Class	**122. Green Gas Emission Class**
Information about Sustainable Green Building (If Available)	
126. Sustainable Green Building Class	

Figure 1.7. Sustainability Sections in Occupancy Permit Document of Turkey

(TSE-Turkish Standard, 2016)

This thesis investigates the potentials of steel material, as a second option instead of reinforced concrete, in order to use it for the structural systems of TOKİ housing projects in terms of sustainability. To study sustainability, the full span of building life is considered and Life Cycle Assessment (LCA) is used for the examination. TOKİ’s buildings are created with reinforced concrete and steel structural elements to compare the environmental properties of the models. In this thesis, it is tried to find an answer what is the potential of another structural material for the models.

The aim of this thesis is to compare the sustainability of reinforced concrete and steel material for the structural systems of TOKİ houses based on the Life Cycle Assessment (LCA) results.

There are three objectives in this thesis. The first one is to analyze the effect of building height on sustainability results. Therefore, three different heights are applied to the models. The second objective is to find the influence of the recyclability of materials. In this thesis, the recyclability percentage of the materials is studied to see all options for a specific material. The third objective of the thesis is to show the change of the models according to the seismic regions. Models are evaluated in high and low seismicity.

Sezer (2009) expresses that TOKİ, as the pioneer Turkish housing builder, may have a very significant role in a sustainable environment, a great potential to apply and promote a sustainable approach to all housing projects of Turkey because this governmental institution controls the decision-making mechanism. If TOKİ has the sustainability paradigm, this may be a model for the projects in the whole country.

In short, this thesis shows that TOKİ, as a public institution, may have a chance to make its projects more sustainable by changing the material of the structural systems in its typical projects. It may be possible to obtain an overall ecological development from a dwelling unit by demonstrating the potentials of another alternative.

1.4 Disposition

The thesis has five main chapters which start with Introduction and end with Conclusion. The topic of the thesis is given by explaining the motivation of research in the Introduction Chapter. It expresses the problem statement and the aim of the thesis that is clarified with the help of the general objectives of the research.

Chapter 2 finds out works about sustainability, methods to examine sustainability, structural systems, and typologies of TOKİ. In this chapter, the place of this thesis in the literature is explained by studying other works about the relation between structural systems and sustainability. At this part, the absence of a study in Turkey which deals with the sustainability potential of another material as a structural element is explored.

Chapter 3 defines the scope and method of the research. The scope is determined as a project of TOKİ. The focus of the thesis is the structural systems' materials of these houses in order to compare their effects to the ecology via LCA method which implies the life of a building from beginning to the end. In this part, sample models are produced in a structural analysis program which is ProtaStructure. Then, the properties of created models are transferred to LCA program which is OneClickLCA. In this program, life cycle analyses are run out.

Chapter 4 is the part that the results and the discussion part are given. Firstly, ProtaStructure's results are shown. After that, the outcomes of models that are reached from OneClickLCA are demonstrated with graphs to understand the differences between models. Then, the minimum-maximum boundary analysis is clarified. At the end of the results part, the analysis of steel models under low seismic effects is explained. The discussion part involves the explanation of the results and referencing the literature.

The last chapter, Conclusion; summarizes the results of the study, makes the assessment of the research and reveals the importance of this thesis for literature. Then, the limitations of the study are explained. Finally, the suggestions are given for the next studies in the department of recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

In this literature review chapter, first of all, sustainable housing design is defined. Building material options are given to explore their potentials to be sustainable and the preference of different structural systems are explained, which are used in the world since the selection of structural systems and structural material affects the sustainability of a project. Secondly, the methodology is studied to examine sustainability. Common methods are found for the analysis of a project's environmental impacts. LCA and Carbon Footprint Calculation are presented as analysis methods. In this part, also, some programs are determined for environmental analysis. Evaluation of the project's environmental impact is analyzed by explaining the outputs of LCA. In the third part of this chapter, examples from existing studies that compare structural systems are given to learn the comparison way in the literature. Moreover, the seismic effects for models are explained for Turkey in this part because they are very critical for structural models. Then, the programs for structural analyses are stated that are found in the literature. TOKİ houses are investigated in terms of common typologies according to their massive properties, heights, and plan configurations in the fourth part. The projects are classified according to the plan scheme to select a sample project. Finally, the inferences which are drawn from literature are explained.

2.1 Sustainable Designs for Housing

Sustainability is defined as the continuation of stable ecosystems without deterioration of natural balance which is formed by self-controlled and self-repaired ecological systems (Yüceer, 2015).

According to Sev (2009), sustainable architecture is all activities that are conducted for producing buildings that prefer renewable energy by considering present with the future; that is sensitive to the environment; that use energy, water, material, and land efficiently; also that protect human health and comfort. In other words, it is the art of meeting the human need for space without damaging the presence and the future of natural systems (Sev, 2009).

Today, it is a well-known fact that construction activities consume a huge amount of natural raw sources (Zabalza Bribián et al., 2011). As it is shown in Table 2.1 when the amount of energy consumption at different sectors is analyzed in Turkey until 2008 the industrial sector consumes more energy than the housing sector. In 2008, the housing sector passed the industrial sector in the amount of energy consumption due to the increased population. Even if total energy consumption decreased because of the global economic crisis in 2008 and 2009, the housing sector consumes more energy than the industrial sector after 2007 (Çevresel Etki Değerlendirmesi İzin ve Denetim Genel Müdürlüğü, 2011).

Table 2.1 Energy Consumption according to years in Turkey

	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
Total	*78.331*	*83.826*	*87.818*	*91.074*	*99.641*	*107.627*	*106.241*	*106.138*
Housing	18.463	19.634	20.952	22.923	23.677	24.623	**28.323**	**29.466**
Industry	24.782	27.777	28.789	28.084	30.966	32.466	**26.906**	**25.966**
Transportation	11.405	12.395	13.775	13.849	14.994	17.284	15.996	15.916
Agriculture	3.030	3.086	3.314	3.359	3.610	3.945	5.174	5.073
Non-Energy	1.806	2.098	2.174	3.296	4.163	4.430	3.244	4.153
Cycle Sector	18.845	18.836	18.814	19.564	22.201	24.879	26.779	25.565

(Çevresel Etki Değerlendirmesi İzin ve Denetim Genel Müdürlüğü, 2011)

At this point, the decisions of the housing sector are very important since the impacts of these decisions are very dominant among the other sectors like transportation, agriculture, non-energy, and cycle sectors. From the beginning of the design, the selection of building material or structural system has a great influence on the projects in terms of sustainability. For example, wrong material selection may cause interior pollution which damages people's health and decreases productivity who spend 70% of their time in closed spaces (Sev, 2009).

2.1.1 Building Material Selection

During building construction, a variety of natural or manufactured materials is used. They have substantial energy associated with obtaining, processing, transferring, using, and disposing of them as they are shown in Figure 2.1 (Bougdah & Sharpless, 2010).

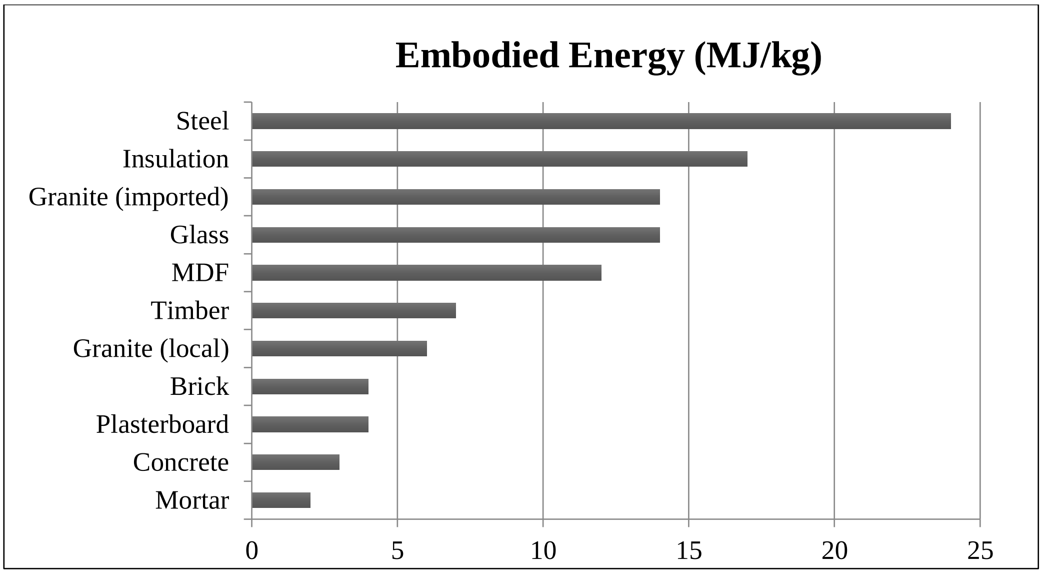


Figure 2.1. Embodied Energy of Building Materials

(Bougdah & Sharpless, 2010)

According to the graph, steel has the highest embodied energy per unit mass while mortar has the lowest value. Concrete is placed just from mortar and its embodied energy is quite low when compared to steel. However, the important thing is the total amount of material used for a project at this point.

In this thesis, material selection is discussed for the structure of buildings. Therefore; the selection of the structural system that is preferred in Turkey is investigated. Table 2.2 shows that reinforced concrete frame has become the most used system between 2002 and 2015 in Turkey. According to TURKSTAT data, all structural systems which are made up of concrete are shown as the reinforced concrete frame but still, this means concrete is generally selected for building construction. On the other hand, steel frame has preferred rarely especially in residential buildings (Ay et al., 2016). Actually, in order to decrease the negative environmental impacts of buildings, lightweight structures can be preferred rather than massive ones (Hegger et al., 2010). Concrete buildings may be heavier than steel buildings and this situation may increase the embodied energy inside concrete buildings which affects the sustainability of a building. In short, concrete has widespread usage but in terms of embodied energy or some other sustainability measures, structural steel can be more advantageous than reinforced concrete.

Table 2.2 The Percentage of Buildings with Respect to Building Use and Structural System

2002-2015	**Masonry**	**Steel Frame**	**Wood Frame**	**Reinforced Concrete Frame**	**Composite**	**Prefabricated**	**Total**
Residential	5.001	0.196	0.196	78.726	0.551	0.551	*84.988*
Non-residential	0.530	0.977	0.058	12.004	0.389	0.389	*15.012*

(Ay et al., 2016)

2.1.2 Structural System Selection

Even if the construction sector in Turkey generally uses concrete, there are other structural materials that are used in the world. In addition to this, different structural systems are applied for buildings with alternative materials. Rigid frame systems, flat plate or flat slab systems, core systems, shear wall systems, and shear walled frame systems can be used as structural systems for buildings (Günel & Ilgın, 2010). For example, reinforced concrete moment-resisting frame structure and reinforced concrete frame-wall structure are studied for concrete material when steel moment-resisting frame structure and steel braced-frame structure are analyzed for steel material in the Turkish Earthquake Code Examples Workbook (Yakut et al., 2018). Moussavi Nadoushani and Akbarnezhad (2015) used a moment-resisting frame, braced frame, and a combination of these systems on a sample square plan for comparison of structural systems in terms of the life cycle carbon footprint. In this study, 15 different alternative structural systems are compared by considering the life cycle carbon in the stage of structural design. The outcome shows that there are significant differences in the life cycle carbon of a building designed with different structural systems with different materials. This situation highlights the importance of considering the life cycle carbon footprint in the design of structures. So, it is very critical to decide not only the structural system of a building but also the structural material in terms of environmental impact.

2.2 Methods to Examine Sustainability

Sustainability is an extensive concept. Ahmad, Thaheem, Anwarb, and Dinc (2016) summarize three dimensions of sustainability in one table Figure 2.2 presents the environmental, economic, and social dimensions of sustainability as well as corresponding indicators and parameters.

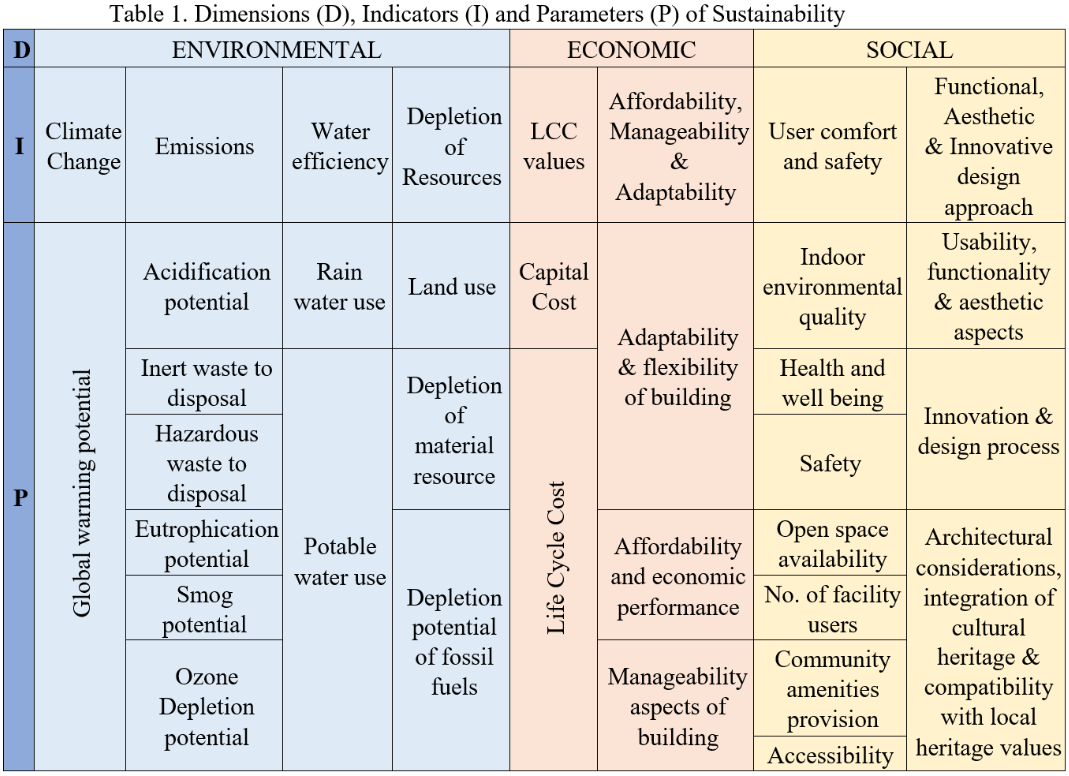


Table 1. Dimensions (D), Indicators (I) and Parameters (P) of Sustainability

D	ENVIRONMENTAL				ECONOMIC		SOCIAL	
I	Climate Change	Emissions	Water efficiency	Depletion of Resources	LCC values	Affordability, Manageability & Adaptability	User comfort and safety	Functional, Aesthetic & Innovative design approach
P	Global warming potential	Acidification potential	Rain water use	Land use	Capital Cost	Adaptability & flexibility of building	Indoor environmental quality	Usability, functionality & aesthetic aspects
		Inert waste to disposal	Potable water use	Depletion of material resource	Life Cycle Cost		Health and well being	Innovation & design process
		Hazardous waste to disposal					Safety	
		Eutrophication potential		Depletion potential of fossil fuels		Affordability and economic performance	Open space availability	Architectural considerations, integration of cultural heritage & compatibility with local heritage values
		Smog potential					No. of facility users	
		Ozone Depletion potential				Manageability aspects of building	Community amenities provision	
							Accessibility	

Figure 2.2. Sustainable Design Principles

(Ahmad et al., 2016)

For sustainable development, all dimensions should be considered for projects. Sezer (2009) studies housing projects in Turkey and states that applying sustainable design principles to these projects will provide firstly, environmental benefits like protecting nature, secondly, social benefits such as increasing the quality of the housing blocks with the occupants' life and thirdly, economic benefits in the short and long term. In order to analyze the sustainability of TOKİ houses, three different projects are selected by Sezer (2009). After determining the defective parts in these projects, many proposals are given to increase the sustainability level of TOKİ projects (Sezer, 2009).

In this thesis, the focus is environmental sustainability. Therefore, economic and social sustainability is not the scope of the thesis. To evaluate environmental parameters, steps of building construction are investigated. The system boundary is demonstrated in Figure 2.3 and it expresses the steps of "Building Life Cycle" from the beginning to the end. Each step of the traditional building life cycle has an impact on the environment (Mithraratne et al., 2007).

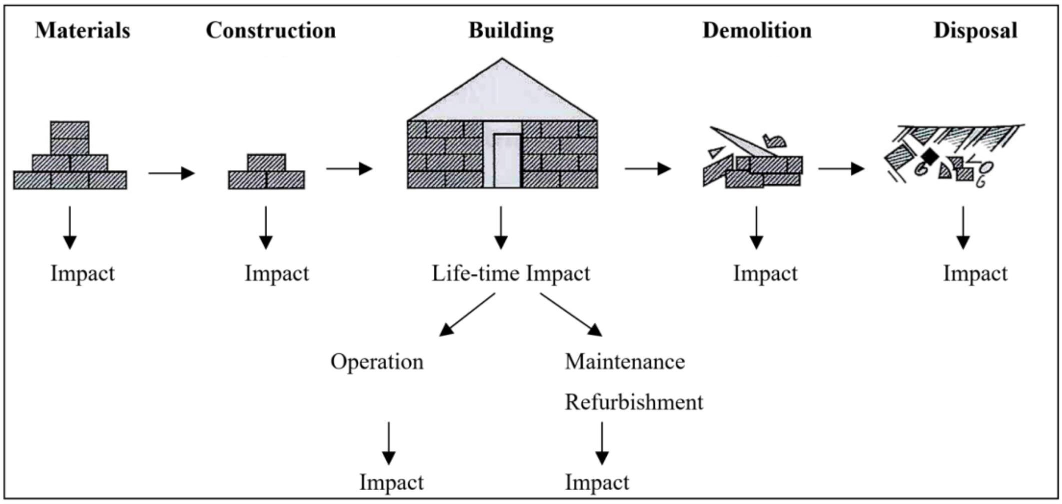


Figure 2.3. Sample System Boundary for a Building Life Cycle

(Mithraratne et al., 2007)

The life cycle of sustainable buildings has some other steps differently from the traditional building life cycle like recycling, reuse, or renovation. Figure 2.4 shows the sustainable building life cycle in a clear way (Sev, 2009).

In brief, "life cycle thinking is the most comprehensive way to evaluate buildings and products" according to Henderson (2012) since it shows the full life span of a building which includes:

- Extraction of materials
- Assembly or manufacture of materials

- Packaging and transportation of materials to the site
- Installation of materials on the site
- Operation of building and use of materials
- Maintenance of materials
- Repair or replacement of materials
- End of life

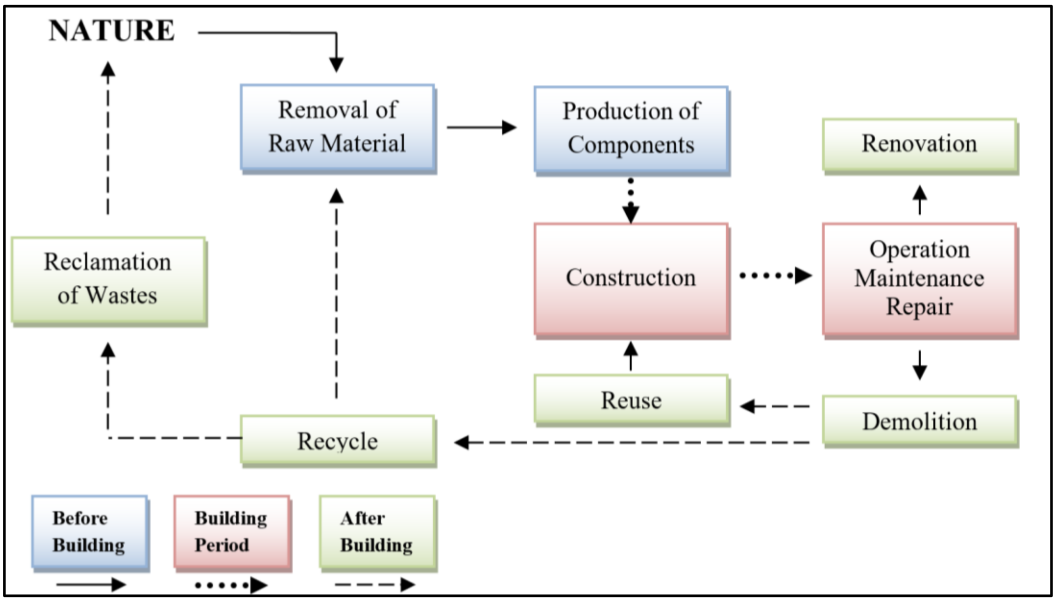


Figure 2.4. Model for Life Cycle of Sustainable Buildings

(Sev, 2009)

2.2.1 Analyses Types

As an analysis method, LCA is used to calculate the environmental impact of a building by considering the full span of building life.

According to ISO 14040:2006, LCA consists of four main steps which are clarified in Figure 2.5 (Singh et al., 2011). The goal and scope definition step includes the purpose of the study. At the inventory analysis step, the Life Cycle Inventory (LCI) is defined as the environmental inputs and outputs related to a project or a product for the entire life cycle. Inventory analysis detects the inputs of water, energy, raw materials, and the releases to air, land, water.

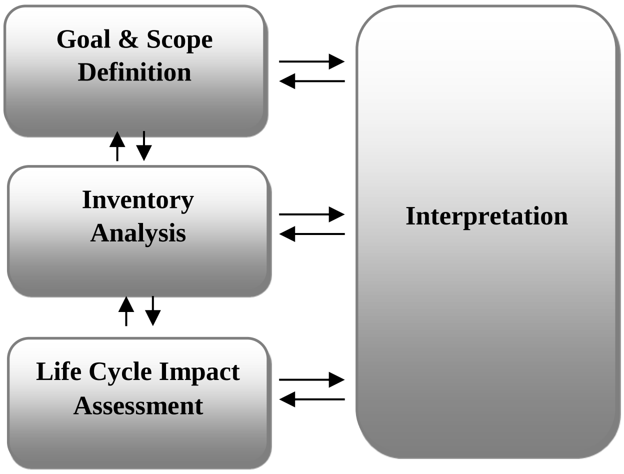


Figure 2.5. Steps of Life Cycle Assessment

(Singh et al., 2011)

Life Cycle Impact Assessment (LCIA) deals with this inventory in terms of environmental impacts as identified in the LCI step. The last step, the interpretation, gathers the environmental effects in accordance with the purpose of the study (Sinha et al., 2013).

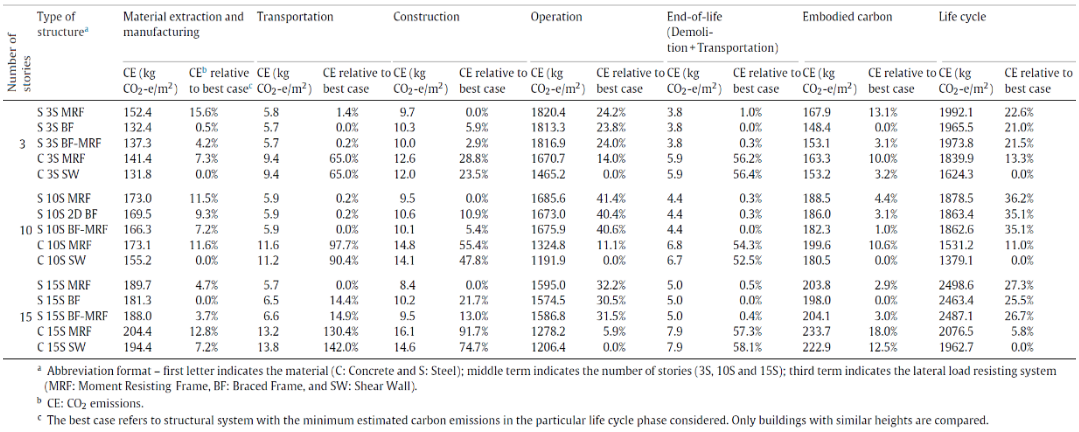
In the literature, there is a study (Passer et al., 2007) that compares three office building models with load bearings systems made of reinforced concrete, steel, and timber. The LCI and LCIA are both conducted in this study.

LCA can be performed at various stages. For example, if it is calculated as “cradle to gate or site” analysis, it refers to LCA from the raw material stage to the point it is transferred to the field. “Cradle to grave” analysis involves LCA of all stages, starting from raw material procurement to end of life (Sinha et al., 2013).

LCA comprises Carbon Footprint (CF) values of all life cycle steps. Indeed, CF calculation of one step from all life cycles may be another way to find the environmental impacts of buildings rather than carrying out a whole analysis. CF shows greenhouse gas (GHG) emissions that cause global warming and measures the emission which heats the world in carbon dioxide (CO_2) equivalents per unit of time (Alhorr et al., 2014).

CF is still the primary environmental indicator, for concrete according to Nielsen (2008). However, the selection of the best structural system to reduce negative environmental impacts should be based on the calculation of the life cycle carbon footprint rather than CF of individual life cycle phases for Moussavi Nadoushani and Akbarnezhad (2015). They prepare a comprehensive work that is summarized in Table 2.3 via showing the CF emission of each phase separately with Total Life Cycle CF emission at the end.

Table 2.3 The Results of Each Life Cycle Phase in the Total Life Cycle Carbon Emission



Number of stories	Type of structure[a]	Material extraction and manufacturing		Transportation		Construction		Operation		End-of-life (Demolition + Transportation)		Embodied carbon		Life cycle	
		CE (kg CO_2-e/m^2)	CE[b] relative to best case[c]	CE (kg CO_2-e/m^2)	CE relative to best case	CE (kg CO_2-e/m^2)	CE relative to best case	CE (kg CO_2-e/m^2)	CE relative to best case	CE (kg CO_2-e/m^2)	CE relative to best case	CE (kg CO_2-e/m^2)	CE relative to best case	CE (kg CO_2-e/m^2)	CE relative to best case
3	S 3S MRF	152.4	15.6%	5.8	1.4%	9.7	0.0%	1820.4	24.2%	3.8	1.0%	167.9	13.1%	1992.1	22.6%
	S 3S BF	132.4	0.5%	5.7	0.0%	10.3	5.9%	1813.3	23.8%	3.8	0.0%	148.4	0.0%	1965.5	21.0%
	S 3S BF-MRF	137.3	4.2%	5.7	0.2%	10.0	2.9%	1816.9	24.0%	3.8	0.3%	153.1	3.1%	1973.8	21.5%
	C 3S MRF	141.4	7.3%	9.4	65.0%	12.6	28.8%	1670.7	14.0%	5.9	56.2%	163.3	10.0%	1839.9	13.3%
	C 3S SW	131.8	0.0%	9.4	65.0%	12.0	23.5%	1465.2	0.0%	5.9	56.4%	153.2	3.2%	1624.3	0.0%
10	S 10S MRF	173.0	11.5%	5.9	0.2%	9.5	0.0%	1685.6	41.4%	4.4	0.3%	188.5	4.4%	1878.5	36.2%
	S 10S 2D BF	169.5	9.3%	5.9	0.2%	10.6	10.9%	1673.0	40.4%	4.4	0.3%	186.0	3.1%	1863.4	35.1%
	S 10S BF-MRF	166.3	7.2%	5.9	0.0%	10.1	5.4%	1675.9	40.6%	4.4	0.0%	182.3	1.0%	1862.6	35.1%
	C 10S MRF	173.1	11.6%	11.6	97.7%	14.8	55.4%	1324.8	11.1%	6.8	54.3%	199.6	10.6%	1531.2	11.0%
	C 10S SW	155.2	0.0%	11.2	90.4%	14.1	47.8%	1191.9	0.0%	6.7	52.5%	180.5	0.0%	1379.1	0.0%
15	S 15S MRF	189.7	4.7%	5.7	0.0%	8.4	0.0%	1595.0	32.2%	5.0	0.5%	203.8	2.9%	2498.6	27.3%
	S 15S BF	181.3	0.0%	6.5	14.4%	10.2	21.7%	1574.5	30.5%	5.0	0.0%	198.0	0.0%	2463.4	25.5%
	S 15S BF-MRF	188.0	3.7%	6.6	14.9%	9.5	13.0%	1586.8	31.5%	5.0	0.4%	204.1	3.0%	2487.1	26.7%
	C 15S MRF	204.4	12.8%	13.2	130.4%	16.1	91.7%	1278.2	5.9%	7.9	57.3%	233.7	18.0%	2076.5	5.8%
	C 15S SW	194.4	7.2%	13.8	142.0%	14.6	74.7%	1206.4	0.0%	7.9	58.1%	222.9	12.5%	1962.7	0.0%

[a] Abbreviation format – first letter indicates the material (C: Concrete and S: Steel); middle term indicates the number of stories (3S, 10S and 15S); third term indicates the lateral load resisting system (MRF: Moment Resisting Frame, BF: Braced Frame, and SW: Shear Wall).

[b] CE: CO_2 emissions.

[c] The best case refers to structural system with the minimum estimated carbon emissions in the particular life cycle phase considered. Only buildings with similar heights are compared.

(Moussavi Nadoushani & Akbarnezhad, 2015)

By performing an LCA, other types of results can be obtained, which show not only CF but also different impact categories. For example, the results of primary energy demand, acidification, eutrophication, global warming, ozone depletion, and smog formation potentials are examined in a study (López et al., 2016) by giving the mass of three different models (Table 2.4).

Table 2.4 The Categories of Results

Structural System	Mass	Acidification Potential	Eutrophication Potential	Global Warming Potential	Ozone Depletion Potential	Smog Formation Potential	Primary Energy Demand
	kg	kg SO_2-eq	kg N-eq	kg CO_2-eq	CFC-11 eq	O_3-eq	MJ
Model 1	755.5	0.79	0.04	208.53	1.40E-06	11.00	2,064.49
Model 2	591.8	0.57	0.03	167.74	1.02E-06	7.98	1,911.88
Model 3	726.3	0.84	0.04	203.21	1.84E-06	11.54	1,765.42

(López et al., 2016)

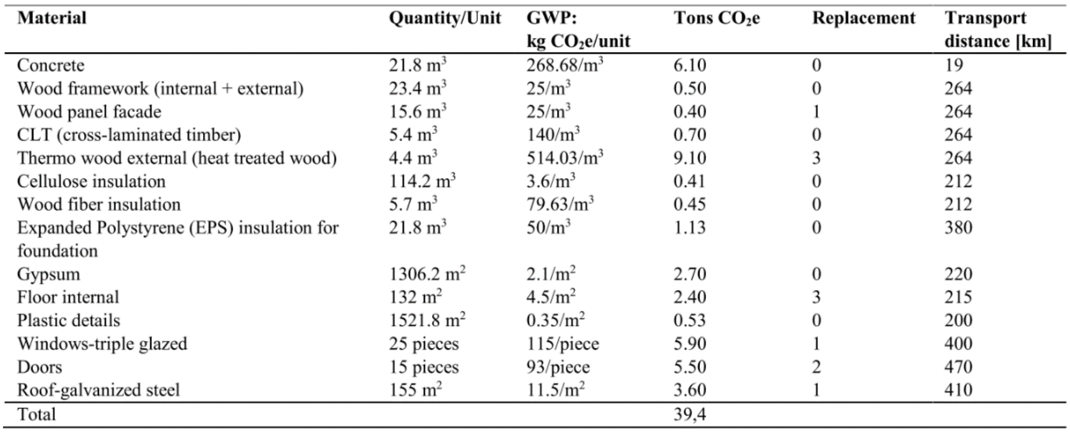
Another study (Ong et al., 2017) analyzes four models for a housing unit and LCA is used for the evaluation. The study investigates the results of human toxicity, ocean acidification, global warming potential, abiotic material depletion, and energy use.

In another study (Buckley et al., n.d.), the environmental impact of a cast-in-place concrete system is compared with a structural steel system for a learning center in Canada. The first three stages of the building life cycle are considered which are the extraction of resources, processing, and installation by including the transportation within and between stages. The results are evaluated in terms of weighted resource use, global warming potential, air toxicity index, water toxicity index, solid waste emission, and embodied energy inputs.

A case study (Petrovic et al., 2019) of a single-family house in Sweden analyzes the environmental impacts of building materials. GWP results of main construction materials are given with replacement and transport distance (Table 2.5). However, researchers state that other environmental impact indicators are also important for the evaluation of the models by conducting LCA such as the potentials of global warming, acidification, eutrophication, ozone depletion, and formation of ozone of lower atmosphere.

In the study of Trusty and Meil (2009), LCA results of three alternative models of a single-family home including wood, steel, and concrete designs are given according to the embodied energy, global warming potential, air toxicity, water toxicity, weighted resource use, and solid wastes (Table 2.6).

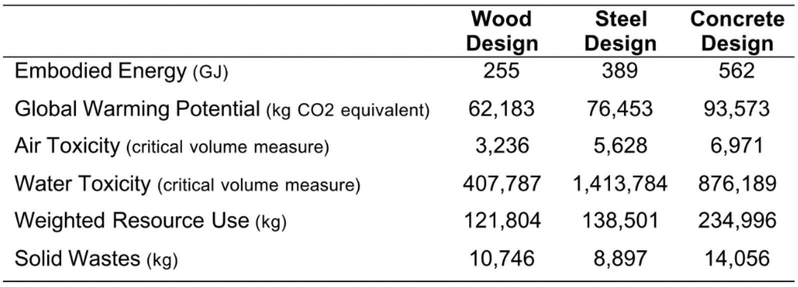
Table 2.5 GWP Results of Each Material



Material	**Quantity/Unit**	**GWP: kg CO_2e/unit**	**Tons CO_2e**	**Replacement**	**Transport distance [km]**
Concrete	21.8 m^3	268.68/m^3	6.10	0	19
Wood framework (internal + external)	23.4 m^3	25/m^3	0.50	0	264
Wood panel facade	15.6 m^3	25/m^3	0.40	1	264
CLT (cross-laminated timber)	5.4 m^3	140/m^3	0.70	0	264
Thermo wood external (heat treated wood)	4.4 m^3	514.03/m^3	9.10	3	264
Cellulose insulation	114.2 m^3	3.6/m^3	0.41	0	212
Wood fiber insulation	5.7 m^3	79.63/m^3	0.45	0	212
Expanded Polystyrene (EPS) insulation for foundation	21.8 m^3	50/m^3	1.13	0	380
Gypsum	1306.2 m^2	2.1/m^2	2.70	0	220
Floor internal	132 m^2	4.5/m^2	2.40	3	215
Plastic details	1521.8 m^2	0.35/m^2	0.53	0	200
Windows-triple glazed	25 pieces	115/piece	5.90	1	400
Doors	15 pieces	93/piece	5.50	2	470
Roof-galvanized steel	155 m^2	11.5/m^2	3.60	1	410
Total			39,4		

(Petrovic et al., 2019)

Table 2.6 LCA Results of Three Models

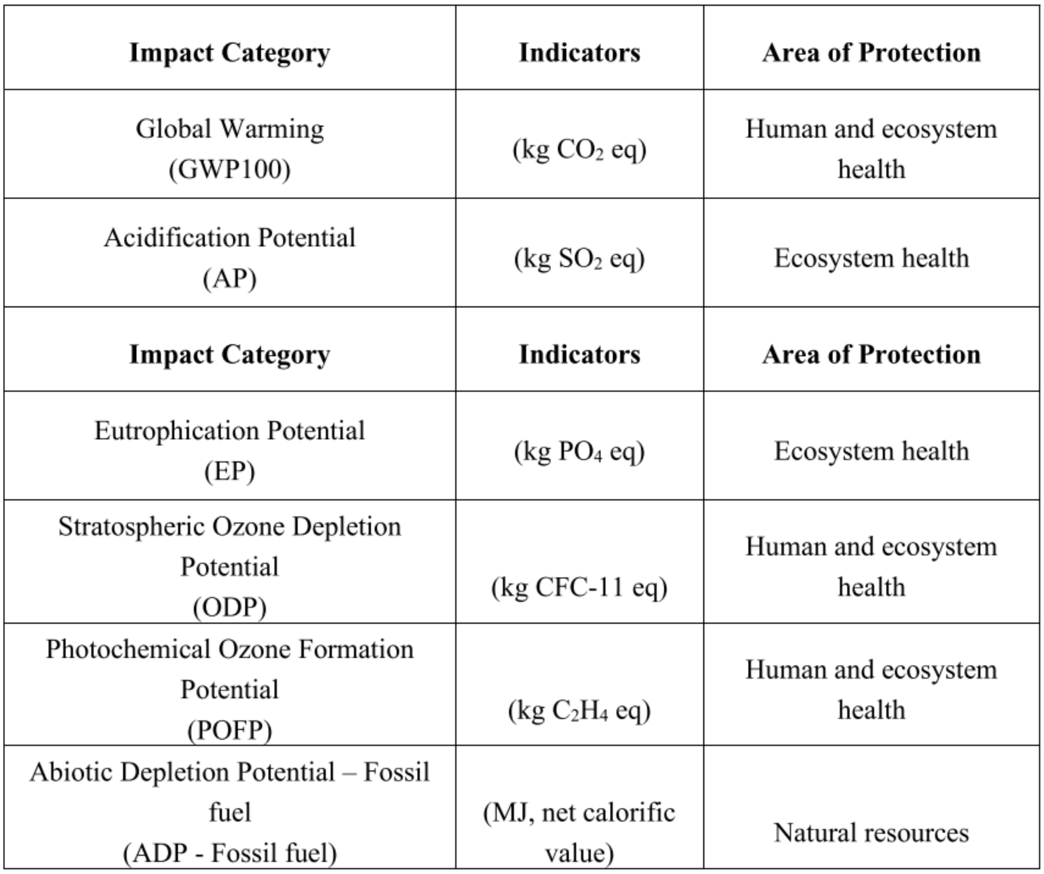


	Wood Design	**Steel Design**	**Concrete Design**
Embodied Energy (GJ)	255	389	562
Global Warming Potential (kg CO2 equivalent)	62,183	76,453	93,573
Air Toxicity (critical volume measure)	3,236	5,628	6,971
Water Toxicity (critical volume measure)	407,787	1,413,784	876,189
Weighted Resource Use (kg)	121,804	138,501	234,996
Solid Wastes (kg)	10,746	8,897	14,056

(Trusty & Meil, 2009)

In the thesis of Aygenç (2019), the LCA of a headquarter building is studied with two different LCA programs. The impact categories used to compare the results are given in Table 2.7.

Table 2.7 Impact Categories



Impact Category	**Indicators**	**Area of Protection**
Global Warming (GWP100)	(kg CO_2 eq)	Human and ecosystem health
Acidification Potential (AP)	(kg SO_2 eq)	Ecosystem health
Impact Category	**Indicators**	**Area of Protection**
Eutrophication Potential (EP)	(kg PO_4 eq)	Ecosystem health
Stratospheric Ozone Depletion Potential (ODP)	(kg CFC-11 eq)	Human and ecosystem health
Photochemical Ozone Formation Potential (POFP)	(kg C_2H_4 eq)	Human and ecosystem health
Abiotic Depletion Potential – Fossil fuel (ADP - Fossil fuel)	(MJ, net calorific value)	Natural resources

(Aygenç, 2019)

In another thesis (Torkan Fazlı, 2013), four different building envelopes are studied according to conventional construction techniques in Turkey in terms of environmental impacts. The results are compared according to six impact categories which are global-warming-potential, fossil fuels consumption, freshwater consumption, ozone layer depletion, and acidification.

2.2.2 Programs for Analyses

LCA is performed by using some computer programs which define these four steps automatically according to the given data. Singh, Berghorn, Joshi, and Syal (2011) express common tools for LCA as GaBi, SimaPro, Tool for Environmental Analysis (TEAM), The Athena EcoCalculator, Envest 2, Life Cycle Explorer (LCE), LISA, and ECO-BAT in their study. For example, SimaPro7.2 is used by Biswas (2014) to calculate the greenhouse gas emissions of the Engineering Pavilion at Curtin University Western Australia. Moreover, LCA of an example building modeled by three different structural systems which are light wood frame, light gauge steel frame, and 3D Panels is conducted using Athena in the thesis of Naji in 2012. In another research, Athena is used for modeling and comparing the environmental impact of a cast-in-place concrete system with a structural steel system for the Queen's University Integrated Learning Centre in Kingston, Canada and also the researchers say that “Athena does not include the impact of disposal at the end of the building service life which may affect the results from life cycle analyses.” (Buckley et al., n.d.). So, some of these programs may not consider the total life cycle of a building.

Generally, these programs use a similar database for LCA but today one of the important things has become the integration of computer programs with other software. Therefore, some tools like Tally have started to be used for LCA, which is a plug-in for Revit that enables to work within BIM environment and it uses GaBi 6 database representing the United States in the year 2013 (López et al., 2016).

There are other programs that have a direct connection or plugin for BIM models like Tally, called OneClickLCA. The study, that compares Tally with OneClickLCA, expresses that Tally works directly in Revit, while OneClickLCA analyzes in the cloud (Mora et al., 2019). Actually, OneClickLCA is an online LCA application with the words of Nilsen and Bohne (2019). In another study, the researchers indicate that it is possible to choose and change the materials of buildings and simulate how to decrease carbon emissions within OneClickLCA (Petrovic et al., 2019). Also, another research emphasizes that, as a product of the Bionova Ltd Organization, OneClickLCA is compliant with the EN 15978 standard and its database uses European Product Declaration (EPD), environmental statements in accordance with ISO 14044 and EN 15804 standards. The environmental profile of each product is externally defined, validated, detailed and standardized in EPD. It includes clear information about the environmental effects of the product throughout its lifetime (Lis et al., 2019).

2.2.3 Evaluation in terms of Environmental Impacts

In order to determine the environmental impacts of a produced model, the life span of a building is defined, firstly. Life span is selected 50 years in the studies of Moussavi Nadoushani & Akbarnezhad (2015) and López & Villareal & Cabrera & Moreno (2016). On the one hand, the life period is given as 60 years by Bull & Gupta & Mumovic & Kimpian (2014) and Schwartz & Raslan & Mumovic (2016).

After specifying the life span, LCA programs are run out to obtain the results according to particular values. The outputs of LCA are a range of environmental impacts but these impacts are often converted to CO_2e to evaluate the building's Global Warming Potential (GWP) (Schwartz et al., 2016). In fact, Carbon Footprint (CF) is the main index for buildings' environmental impact that is measured in kilograms of equivalent CO_2 (kg CO_2-eq) and it is obtained from GWP (López et al., 2016).

According to Turkey Statistical Institute (2011), “The GWP represents how much a given mass of a chemical contributes to global warming over a given period compared to the same mass of carbon dioxide. Carbon dioxide's GWP is defined as 1.0. Greenhouse”. So, LCA programs use GWP, as the main indicator of building environmental impacts but other results are examined also in some programs. For example, ATHENA shows a comprehensive value set of embodied energy, resource use, global warming, air and water toxicity, solid waste emissions (Buckley et al., n.d.). OneClickLCA gives the results of six different categories which are global warming, acidification, eutrophication, ozone depletion potential, formation of ozone of lower atmosphere, and total use of primary energy ex. raw materials.

2.3 Examination of Structural Systems

This part explains the ways of the structural system comparison and then seismic effects are emphasized since it is very critical for a structural model. Also, programs for structural analyses are analyzed to explore the proper program for this study.

2.3.1 Comparison of Structural Systems

When creating structural systems, some parameters are important like the lateral load resisting, shear capacity of columns, seismic forces, design loads, or dead loads. Moreover, the building material is important because the yield strength of steel (f_y) and the characteristic compressive strength of concrete (f_c) affect the structural system design. Also, the regulations are very determinant while designing the structural system.

In the literature, two ways are observed to design the structural systems for comparison. The first way is creating a sample plan and section, then applying all material types and systems to that sample project. The second is using an existing project with its plans and sections by applying different materials or other systems to this existing project.

The study of Moussavi Nadoushani and Akbarnezhad (2015) uses the first way and they create a sample plan. In their study, fifteen types of structural systems are compared by using this sample plan. Three different heights and the same square plan are defined for all systems. Moment resisting frames, braced frames, and a combination of two systems are created with steel material (Figure 2.6).

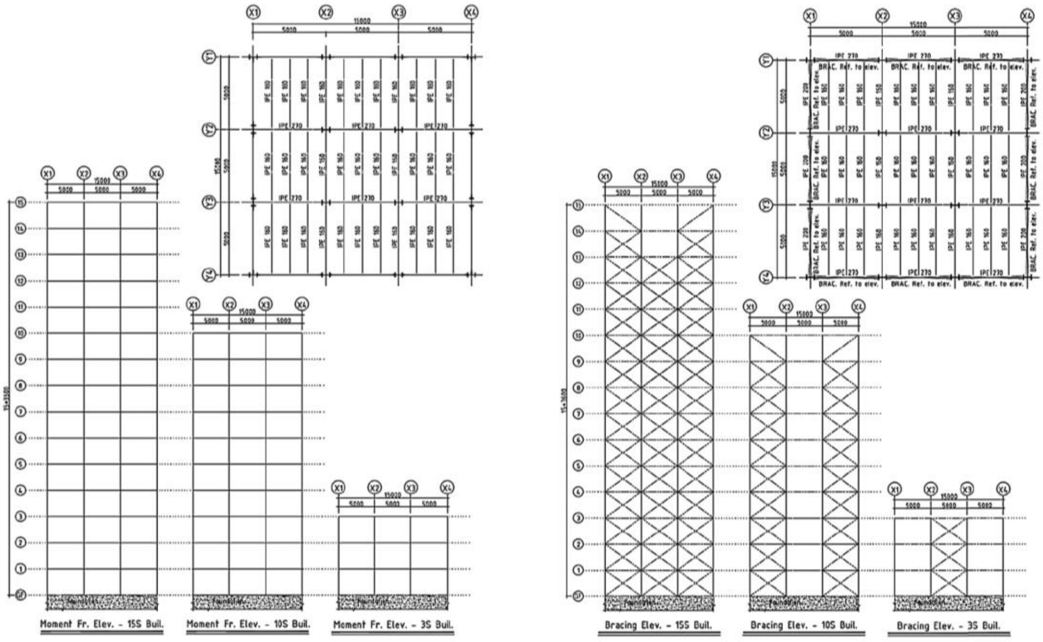


Figure 2.6. Steel Moment Resisting Frame (Left) and Braced Frame (Right) Structure Models

(Moussavi Nadoushani & Akbarnezhad, 2015)

For reinforced concrete structures, moment resisting frames, shear wall system, and a dual system (moment resisting frame-wall systems) are modeled by Moussavi Nadoushani & Akbarnezhad (2015) (Figure 2.7).

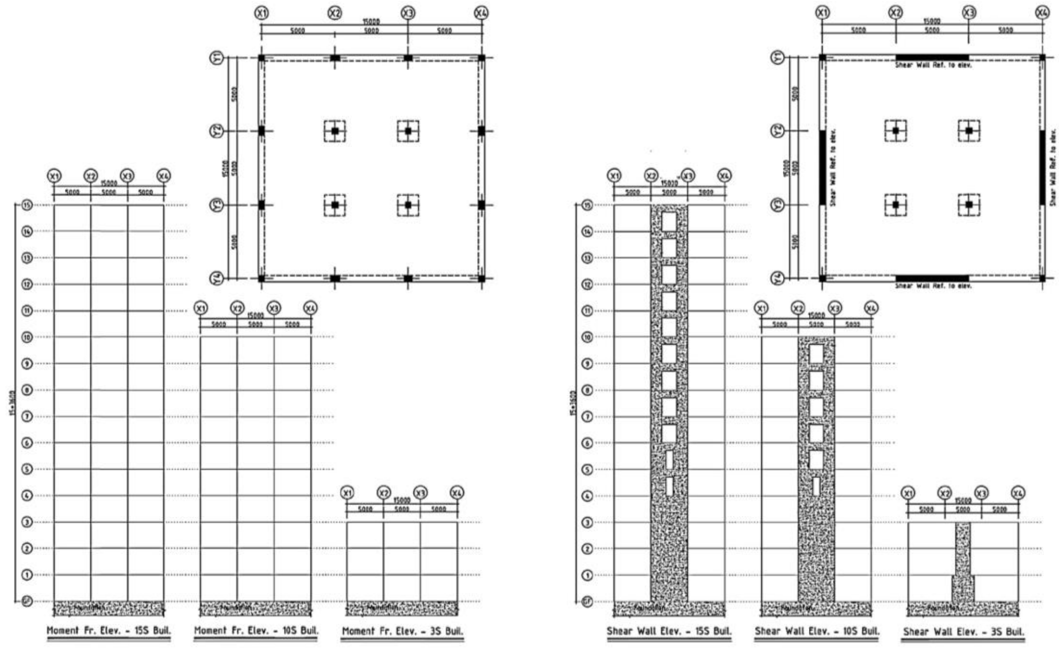


Figure 2.7. Concrete Moment Resisting Frame (Left) and Shear Wall (Right) Structure Models

(Moussavi Nadoushani & Akbarnezhad, 2015)

López, Villareal, Cabrera, and Moreno prefer the second way for comparison (using an existing project with its plans). Researchers select a building that has 6 floors and 4 dwellings per floor. The architectural and structural plans of the selected building are obtained directly from the construction company, as a BIM model that is created with the industrialized system in Autodesk Revit. The BIM model of the structural masonry system is generated from the industrialized system model by changing the properties of walls. This system can be thought of as an unconfined masonry system. For the confined masonry model, the columns are located according to the axes of the original design. The foundation is modified for footings with tie beams. A new structural design is formed with columns and beams. Figure 2.8 shows these three systems which are the industrialized system, structural masonry system, and confined masonry system (López et al., 2016).

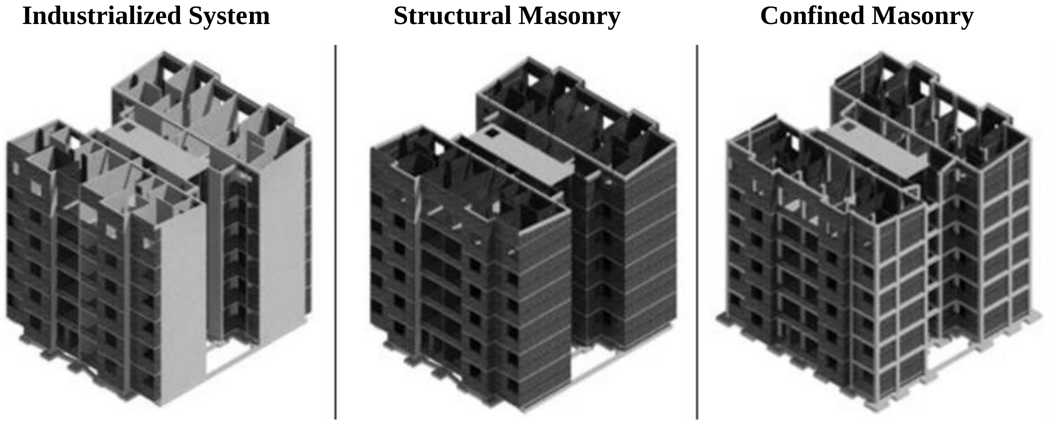


Figure 2.8. BIM Models Created in Revit for Each Structural System

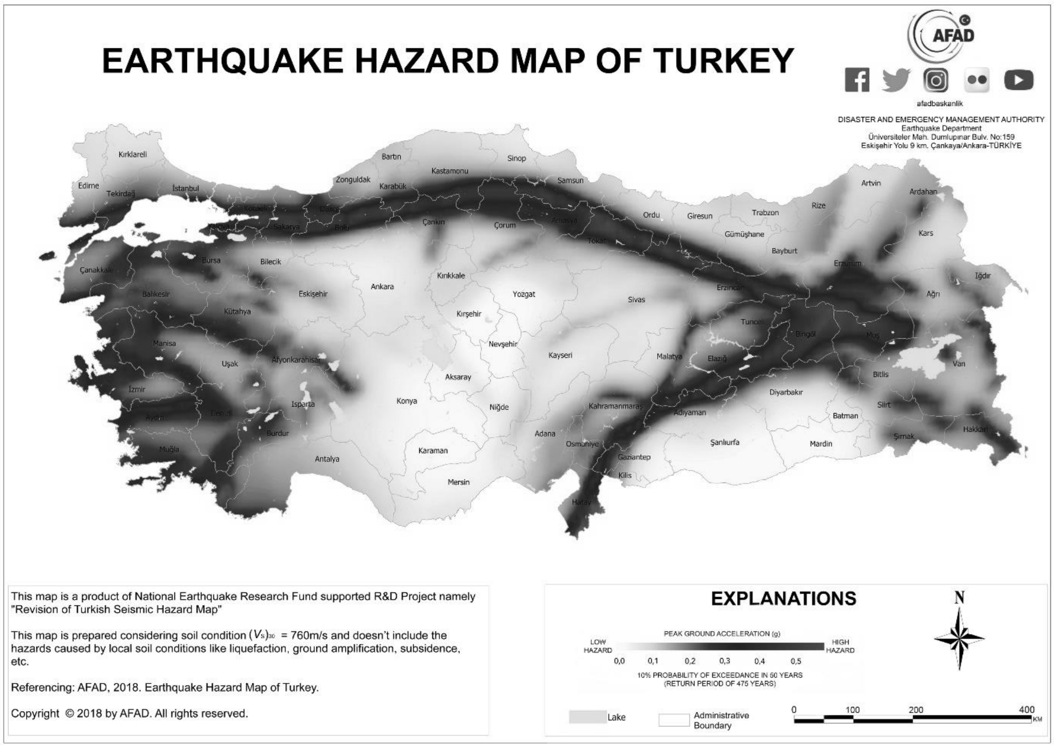
(López et al., 2016)

2.3.2 Seismic Effects for Models

Another subject for structural systems is the seismic effects in a specific region and Turkey is a country whose location is very critical in terms of fault lines. Therefore; the earthquake is very important as one of the parameters for structural analyses.

In 2018, the Turkish Earthquake Code (TEC 2018) is updated and Turkey Earthquake Hazard Map is changed with this new regulation (Figure 2.9). The earthquake intensity value changes according to the coordinates in this new map.

One of the most critical locations in Turkey is İstanbul and the peak ground acceleration (PGA) for rock exceeds 0.40g in some locations in this city. For the design of the structures, seismicity is very determinant.



This map is a product of National Earthquake Research Fund supported R&D Project namely "Revision of Turkish Seismic Hazard Map"

This map is prepared considering soil condition $(V_S)_{30} = 760$m/s and doesn't include the hazards caused by local soil conditions like liquefaction, ground amplification, subsidence, etc.

Referencing: AFAD, 2018. Earthquake Hazard Map of Turkey.

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Figure 2.9. Turkey Earthquake Hazard Map

(AFAD, 2018)

2.3.3 Programs for Structural Analyses

Moussavi Nadoushani and Akbarnezhad (2015) use ETABS for their study that compares fifteen alternative steel and concrete structural systems. They are modeled three-, ten-, and fifteen-story buildings with different structural systems which include moment-resisting frames, braced frames, shear wall systems, and dual systems. Naji (2012), also, preferred ETABS to investigate the structural behavior of three possible systems in the thesis. Because of a similar reason for using Tally, Lopez, Villareal, and Moreno (2016) chose to implement BIM tools like Robot for structural analysis, together with ETABS. BIM model is exported to Robot for verifying the requirements and, also, the structure is created in ETABS to compare the results with Robot.

As an alternative to ETABS, Prota Structure, which is developed by a Turkish company called Prota Engineering, is used in some studies in the literature (e.g., Mikinga, 2019 and Korkmaz, 2020). According to Mkinga (2019), Prota Structure is a powerful application that helps engineers in modeling, analyzing, and designing steel and concrete buildings quickly and accurately. In Mkinga (2019), ArchiCAD is used for the phase of architectural design. Then, Prota Structure is preferred for the structural analysis of a single-family detached house that is composed of reinforced concrete members. After structural analysis, the researcher emphasizes "Prota Structure and Autodesk Revit use mainly custom links called bi-directional links to enhance project coordination and workflow."; which means that the model prepared in Prota Structure can be exported to Revit considerably easily. Also, Korkmaz (2020) makes an analysis by using Prota Structure in order to compare the resulting data of a sample educational building that has one basement floor and six floors, in terms of TDY 2007 and TEC, 2018. So, it means that Prota Structure includes required regulations of Turkey which are TDY 2007 and TEC, 2018.

2.4 Typologies of TOKİ Housing

2.4.1 Definition According to Mass and Height

TOKİ (2017) states that "The historical course of the traditional city implementations of Turkey shows that architectural structuring is shaped within a horizontal design approach. Horizontal implementations which occasionally reflect block of houses discipline demonstrate a "humane" approach to the relationship of space ad height. Based on that architectural approach, TOKİ takes low-rise housing construction as a basis in its new housing productions; and realizes exemplary housing projects in the fields.". TOKİ's horizontal architecture approach can be explained by the linear block definition in the architecture (TOKİ, 2017).

TOKİ has 3 general types as it is shown in Figure 2.10. A Block is used to create linear low-rise buildings whose floor number is up to four. B Block can reach up to nine floors when C Block can rise to fourteen floors. Generally, B and C Blocks represent the point block according to the document of Konu Tipleri Anahtar Planı (n.d.).

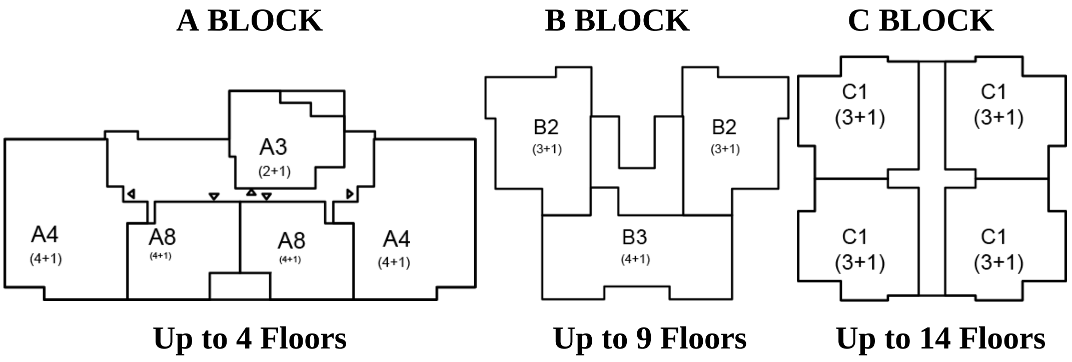


Figure 2.10. Housing Types Key Plans

(*Konu Tipleri Anahtar Planı*, n.d.)

2.4.2 Definition According to Plan Configuration

According to the floor plans of TOKİ projects available on the corporate websites, TOKİ produces housing units starting from one room and one living room called as 1+1 flat to five rooms and one living room 5+1 flat.

For example, one of the projects of TOKİ that is applied in Kayabaşı Region in İstanbul has a detailed document that shows floor plans of housing blocks (TOKİ Kayabaşı Yerleşimi 879-1 ve 876-3 Ada Toplu Konut Projesi, n.d.).

To illustrate the different flat types and various floor plans of TOKİ projects, some examples are given that are belong to the Kayabaşı Region project of TOKİ. A Block has both 2+1 and 3+1 apartments (Figure 2.11). B1 Block has 1+1 apartments (Figure 2.12) and 2+1 apartments (Figure 2.13); B2 Block has 3+1 apartments (Figure 2.14); and B3 Block has 4+1 apartments (Figure 2.15). C Block has both 2+1 and 3+1 apartments (Figure 2.16) and 4+1 apartments (Figure 2.17).

Figure 2.11. A Block Floor Plan 2+1 (2 Units) and 3+1 (2 Units) Apartments

(*TOKİ Kayabaşı Yerleşimi 879-1 ve 876-3 Ada Toplu Konut Projesi*, n.d.)

Figure 2.12. B1 Block Floor Plan 1+1 Apartments

(*TOKİ Kayabaşı Yerleşimi 879-1 ve 876-3 Ada Toplu Konut Projesi*, n.d.)

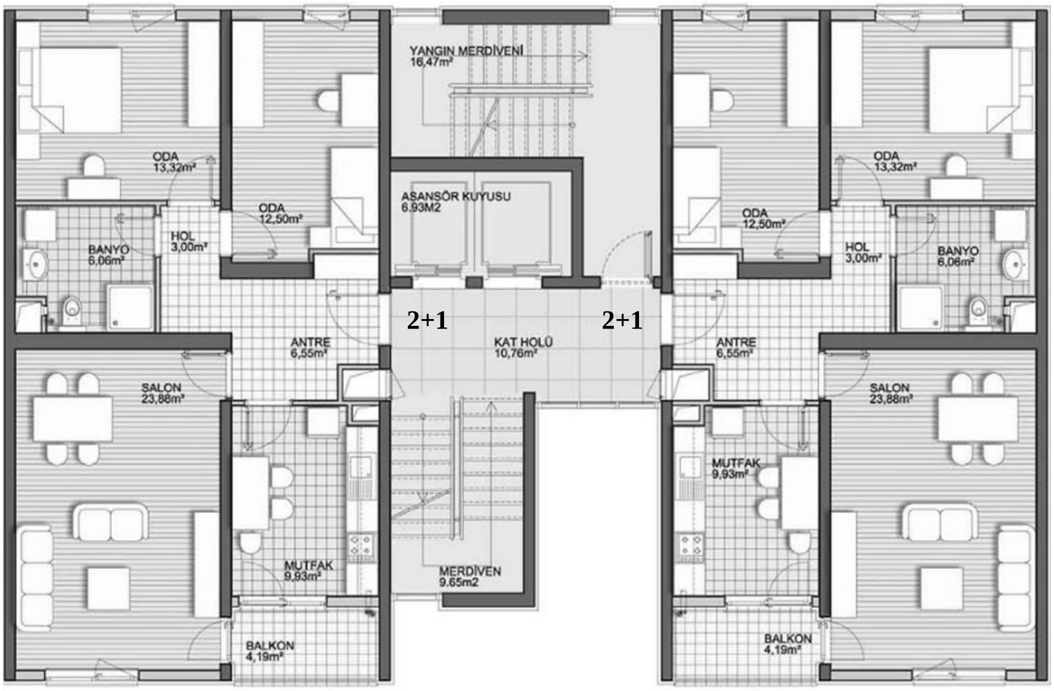


Figure 2.13. B1 Block Floor Plan 2+1 Apartments

(*TOKİ Kayabaşı Yerleşimi 879-1 ve 876-3 Ada Toplu Konut Projesi*, n.d.)

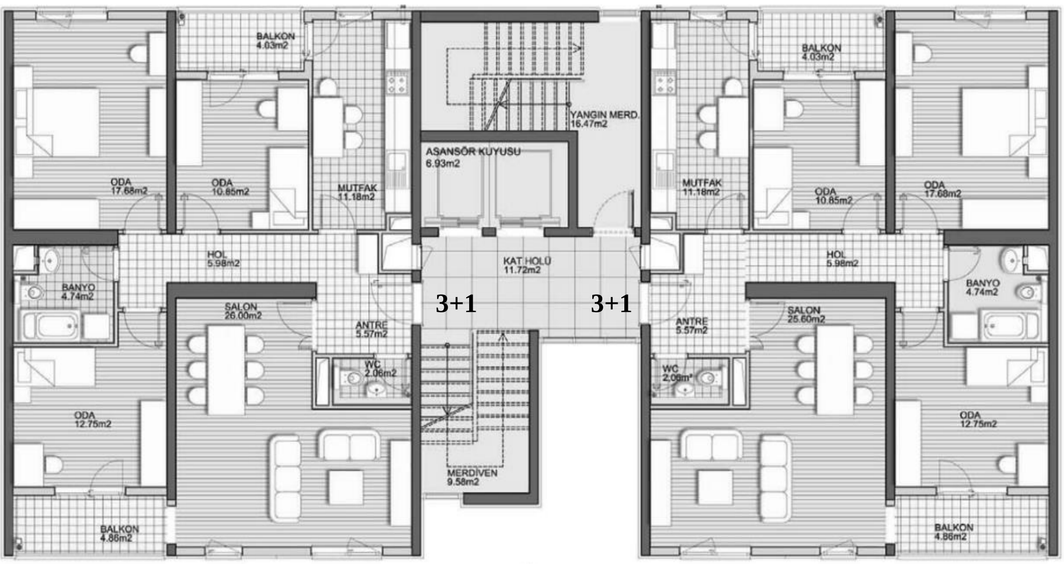


Figure 2.14. B2 Block Floor Plan 3+1 Apartments

(*TOKİ Kayabaşı Yerleşimi 879-1 ve 876-3 Ada Toplu Konut Projesi*, n.d.)

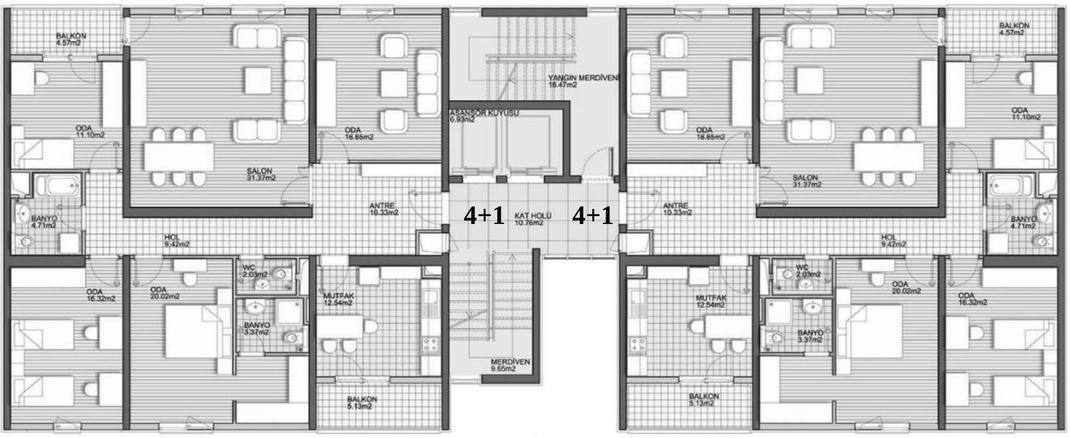


Figure 2.15. B3 Block Floor Plan 4+1 Apartments

(*TOKİ Kayabaşı Yerleşimi 879-1 ve 876-3 Ada Toplu Konut Projesi*, n.d.)

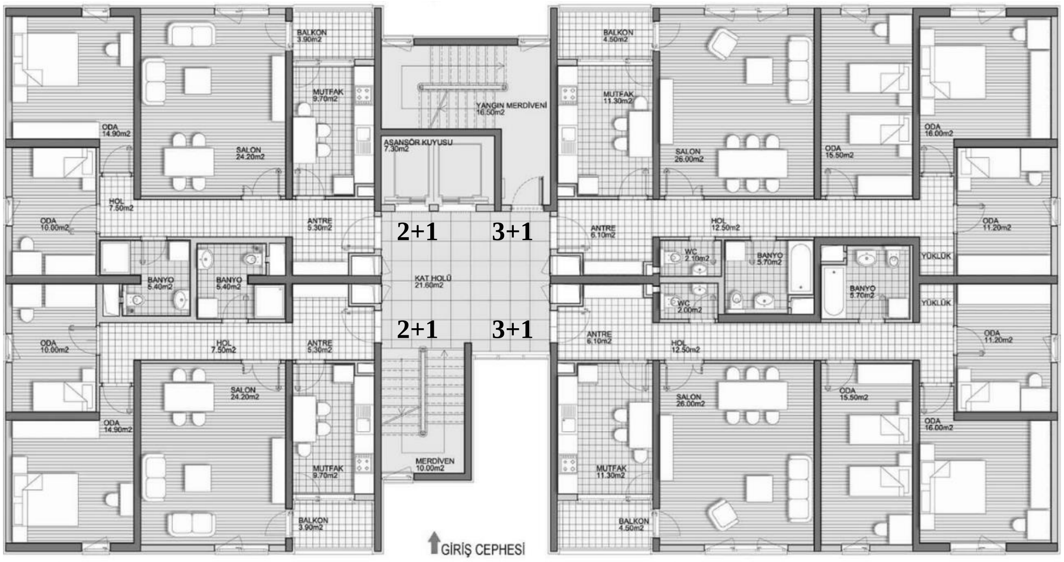


Figure 2.16. C Block Floor Plan 2+1 and 3+1 Apartments

(*TOKİ Kayabaşı Yerleşimi 879-1 ve 876-3 Ada Toplu Konut Projesi*, n.d.)

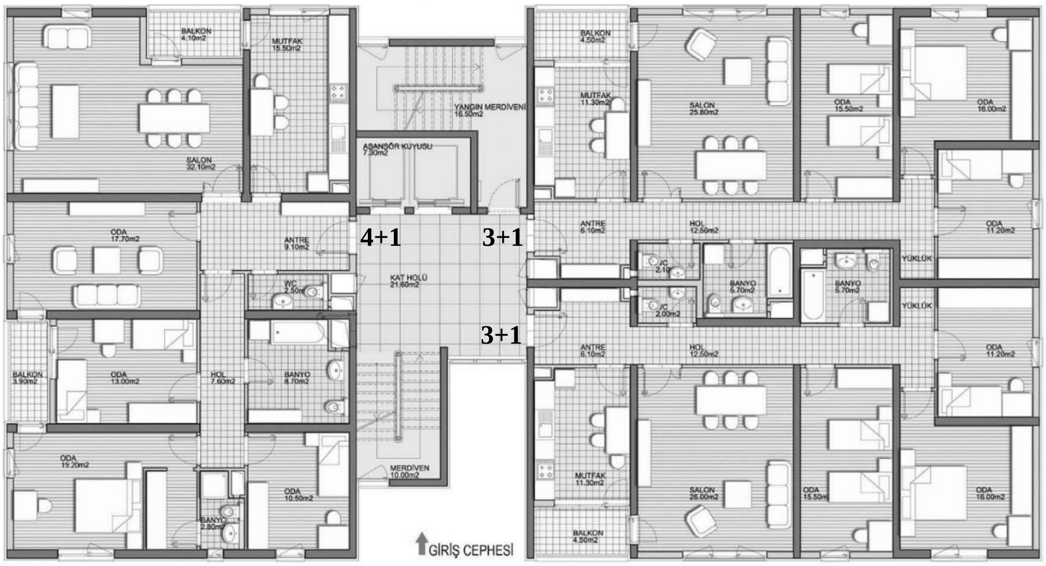


Figure 2.17. C Block Floor Plan 3+1 and 4+1 Apartments

(*TOKİ Kayabaşı Yerleşimi 879-1 ve 876-3 Ada Toplu Konut Projesi*, n.d.)

Except this project, different projects of TOKİ are analyzed with their floor plans, site plans and number of floors. Among these, three projects are from Ankara (*Ankara Gölbaşı İncek 2. Etap 1585 Konut Tic. Mer. 3 Büfe*, n.d.), (*Ankara Sincan Saraycık Mah. Kentsel Dönüşüm Projesi 3. Bölge 2. Etap 502 Konut*, n.d.), (*Ankara Yukarı Yurtçu K. Turkuaz 1. Bölge 1152 Konut Tic. Mer*, n.d.). One project is from Gaziantep (*Gaziantep Şehitkamil Kuzeyşehir Projesi 3. Etap 694 Adet Konut*, n.d.), one project is from Denizli (*Denizli Acıpayam Oğuz Mahallesi 440 Adet Konut ve 2 Adet Ticaret Merkezi İşi*, n.d.), one project is from Elazığ (*Elazığ İli Cumhuriyet Mahallesi Kentsel Dönüşüm Projesi 277 Adet Konut*, n.d.).

All plans have similarities but also specific differences. For example, there are TOKİ buildings that comprise only one type of dwelling unit (only 2+1 or 3+1 or 4+1 or 5+1 flats) on a floor. On the other hand, some TOKİ blocks can have different types of dwelling units (2+1 flats and 3+1 flats) on the same floor. Since these properties change from one project to another, an architectural method is preferred in order to categorize them.

It is clear that all housing blocks have a central core and they mostly have either 2 or 4 apartments on a floor. Alternatively, there are 6 apartments on a floor in some projects. So, TOKİ projects which are available at TOKİ's corporate website are divided into 3 groups, which are summarized in Figure 2.18.

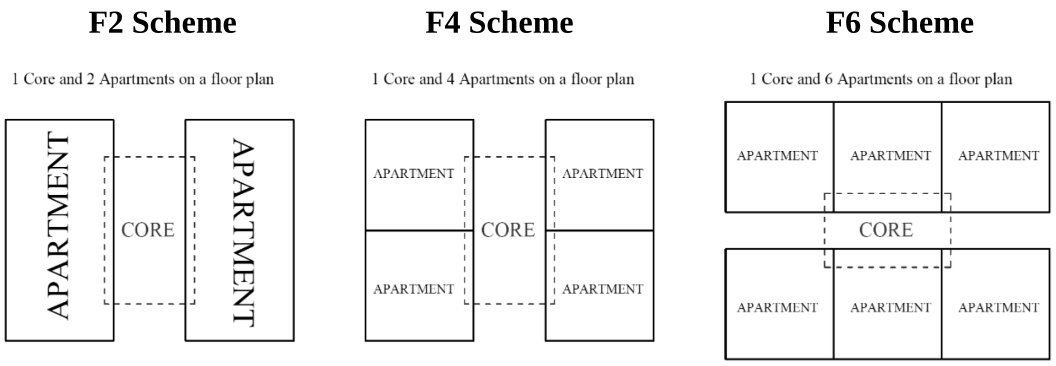


Figure 2.18. Number of Apartments on Floor Plan at TOKİ Blocks

F2 Scheme represents the floor plan that has 1 core and 2 apartments on a floor. One of the examples is given in Figure 2.19.

Figure 2.20 shows a plan of the projects that have F4 Scheme which means the floor plan has 1 core and 4 apartments.

A representative floor plan of F6 Scheme is given in Figure 2.21. In this scheme, 1 core and 6 apartments are located on a floor.

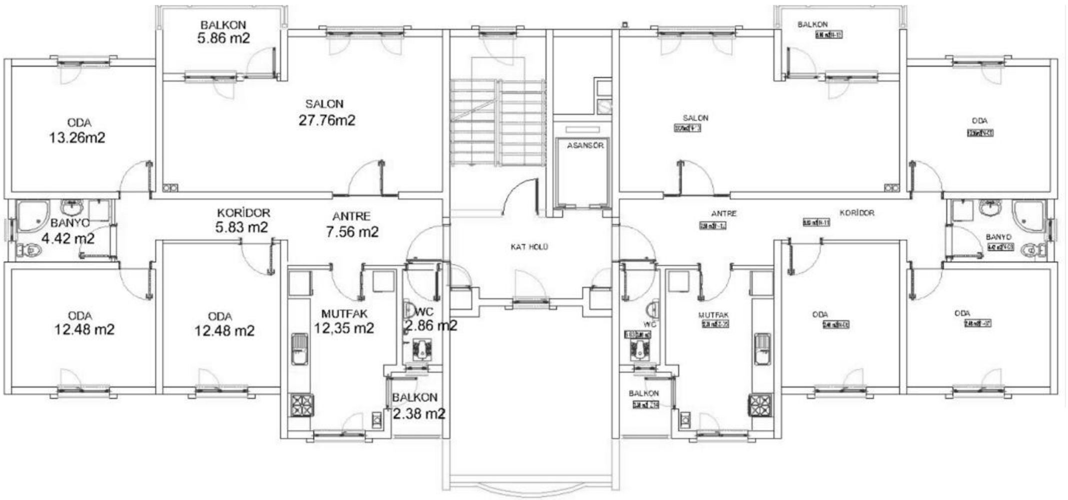


Figure 2.19. F2 Scheme

(*Ankara Yukarı Yurtçu K. Turkuaz 1. Bölge 1152 Konut Tic. Mer*, n.d.)

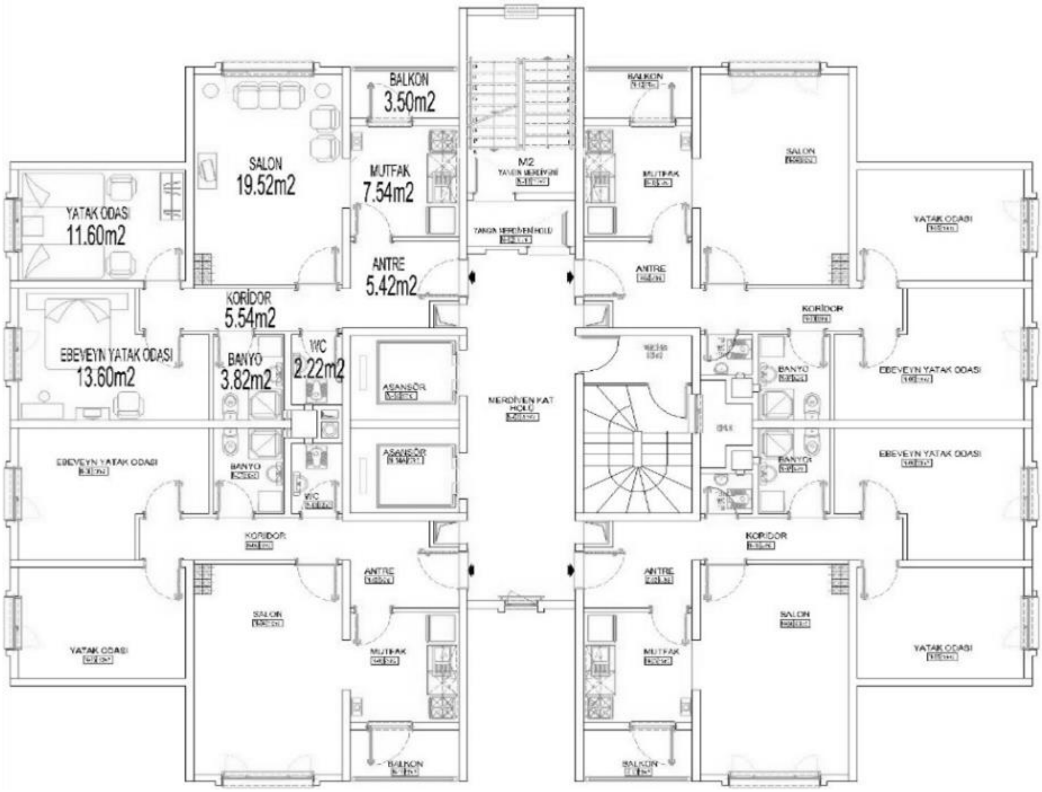


Figure 2.20. F4 Scheme

(*Ankara Yukarı Yurtçu K. Turkuaz 1. Bölge 1152 Konut Tic. Mer*, n.d.)

Figure 2.21. F6 Scheme

(*Ankara Sincan Saraycık Mah. Kentsel Dönüşüm Projesi 3. Bölge 2. Etap 502 Konut*, n.d.)

To classify these schemes, floor numbers observed in TOKİ projects are classified according to the 3 schemes in Table 2.8. The numbers of the basement floors (as 3BF, 2BF, BF) are also given in the table.

Table 2.8 Number of Floors according to Plan Schemes

	TOKİ Projects		
HEIGHT	**F2 Scheme**	**F4 Scheme**	**F6 Scheme**
Floor Numbers	3BF-2BF-BF-2-3-4-5-8-14	3BF-2BF-BF-5-6-7-8-9-10-11-12-13-14-25	3BF-2BF-BF-5-6-7-8-9

F2 Scheme floor plan is observed with 2,3,4 or 5 floors in projects whereas some projects have 8 floors and some others have 14 floors (Figure 2.22).

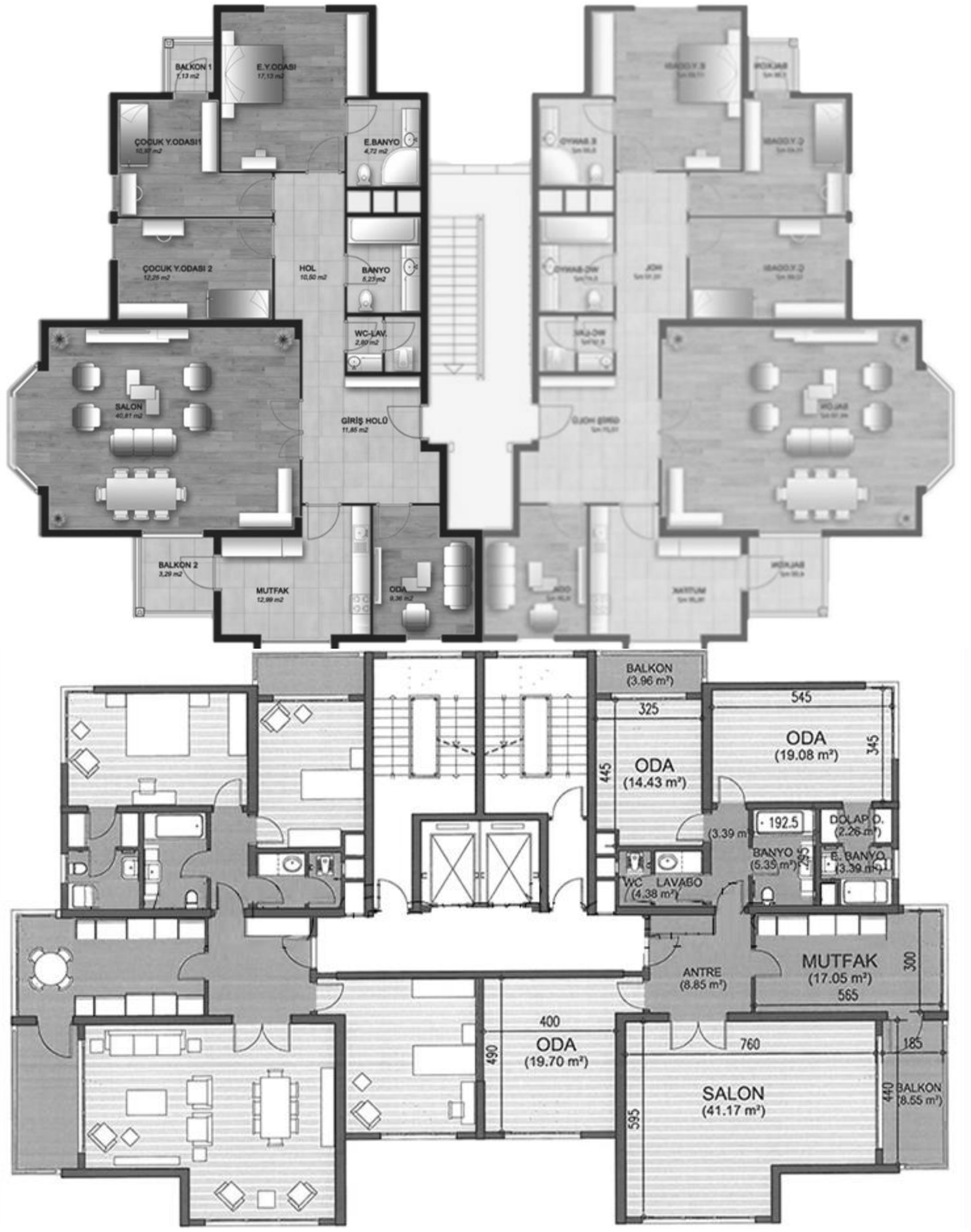


Figure 2.22. F2 Scheme with 5 floors (above) and 14 floors (below)

Above (*Kuzey Ankara Kent Girişi 1.Bölge 474 Adet Konut*, n.d.)

Below (*Ankara Gölbaşı İncek 2. Etap 1585 Konut Tic. Mer. 3 Büfe*, n.d.)

F4 Scheme floor plan is seen in the buildings whose floor number ranges from 5 to 14 in examined projects of TOKİ. An example of 25 floors also exists with F4 Scheme (Figure 2.23).

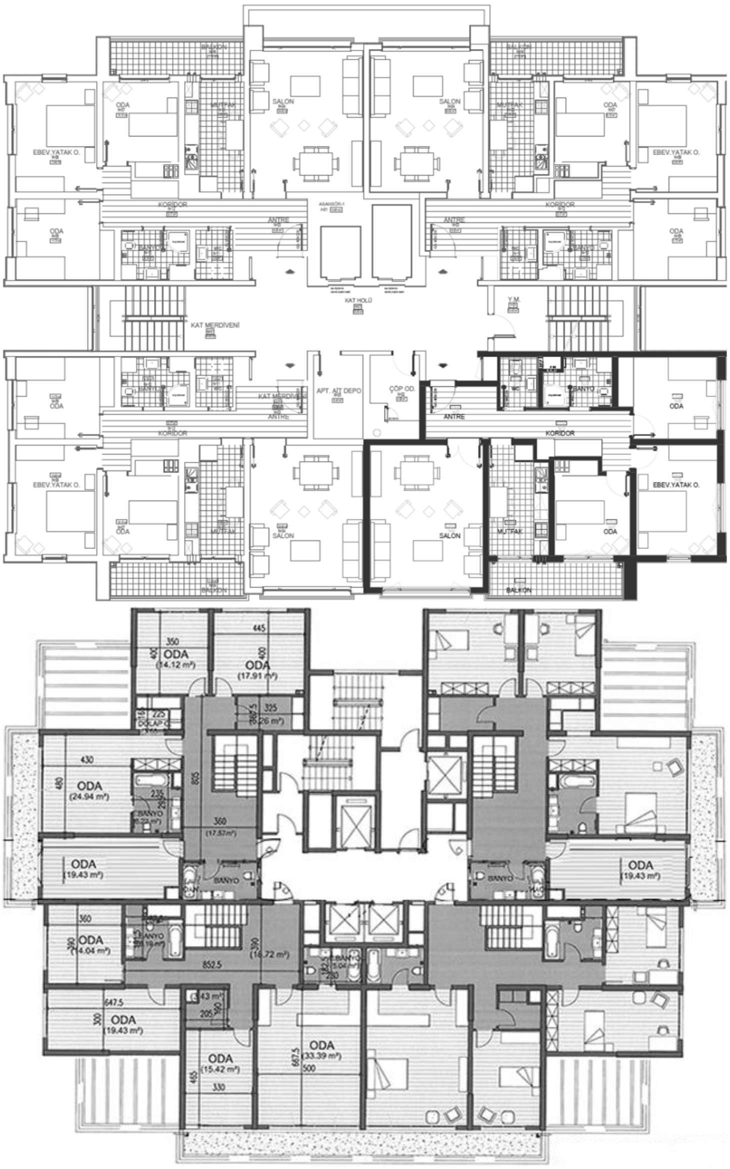


Figure 2.23. F4 Scheme with 6-7-8 floors (above) and 25 floors (below)

Above (*Ankara Sincan Saraycık Mah. Kentsel Dönüşüm Projesi 3. Bölge 2. Etap 502 Konut*, n.d.)

Below (*Ankara Gölbaşı İncek 2. Etap 1585 Konut Tic. Mer. 3 Büfe*, n.d.)

F6 Scheme is a relatively rare floor plan in TOKİ projects and it is observed in the buildings having 5,6,7,8 or 9 floors (Figure 2.24).

Figure 2.24. F6 Scheme with 5-6-7-8 floors (above) and 8-9 floors (below)

Above (*Ankara Sincan Saraycık Mah. Kentsel Dönüşüm Projesi 3. Bölge 2. Etap 502 Konut*, n.d.)

Below (*Kuzey Ankara Kent Girişi 5. Bölge 809 Adet Konut*, n.d.)

To analyze the floor numbers of TOKİ projects, TEC 2018 is studied in terms of building heights. TEC divides the building heights into eight categories for the designs under the influence of earthquakes. The classes of building height (BYS as given in TEC 2018) are shown in Table 2.9. The classes of earthquake design (DTS as given in TEC 2018) is expressed with the numbers of "1, 1a, 2, 2a, 3, 3a, 4, 4a".

Table 2.9 The Ranges of Building Height Defined by The Classes of Building Height and The Classes of Earthquake Design

The Class of Building Height (BYS)	The Ranges of Building Height Defined According to The Classes of Earthquake Design		
	The Classes of Earthquake Design (DTS) = 1, 1a, 2, 2a	DTS = 3, 3a	DTS = 4, 4a
BYS = 1	H > 70m	H > 91m	H > 105m
BYS = 2	56m < H ≤ 70m	70m< H ≤ 91m	91m < H ≤ 105m
BYS = 3	42m < H ≤ 56m	56m < H ≤ 70m	56m < H ≤ 91m
BYS = 4	28m < H ≤ 42m	42m < H ≤ 56m	
BYS = 5	17.5m < H ≤ 28m	28m < H ≤ 42m	
BYS = 6	10.5m < H ≤ 17.5m	17.5m < H ≤ 28m	
BYS = 7	7m < H ≤ 10.5m	10.5m < H ≤ 17.5m	
BYS = 8	H ≤7m	H ≤ 10.5m	

(H: Height, m: meter)

In order to find the BYS range of TOKİ projects, the building height is calculated for each scheme by assuming the floor height as 3 meters. In the literature, there are studies floor height is taken as 3m for the analyses. To illustrate, the story height of 3m is assumed for general practice in the study of Bekir Özer Ay and Erberik (2008). The study of Mkinga (2019) is conducted by ProtaStructure and the height of the walls on each floor is defined as 3000 mm.

For the first category (DTS= 1, 1a, 2, 2a) of Table 2.9, the building heights are shown according to the BYS ranges in Table 2.10. F2 scheme has different BYS ranges; it includes 4, 5, 6, 7, and 8. F4 scheme has 1, 4, 5, and 6 whereas F6 scheme has only 5 and 6. In short, F2 scheme is selected since it has a wide spectrum changing from 4 to 8.

Table 2.10 BYS of TOKİ Projects

	BYS Ranges of TOKİ Projects											
F2 Scheme	**Number of Floors**	2	3	4	5	9	14					
	Building Height (m)	6	9	12	15	27	42					
	BYS	**8**	**7**	**6**	**6**	**5**	**4**					
F4 Scheme	**Number of Floors**	5	6	7	8	9	10	11	12	13	14	25
	Building Height (m)	15	18	21	24	27	30	33	36	39	42	75
	BYS	**6**	**5**	**5**	**5**	**5**	**4**	**4**	**4**	**4**	**4**	**1**
F6 Scheme	**Number of Floors**	5	6	7	8	9						
	Building Height (m)	15	18	21	24	27						
	BYS	**6**	**5**	**5**	**5**	**5**						

(m: meter)

To define the floor number of the models in this thesis, the level of rising is studied in the literature. As is explained in the study of Ay, Azak, and Erberik (2016); different cut-off values are used in the literature to classify low-rise, mid-rise, high-rise, and tall buildings. Therefore; 5, 10, 14-story are selected to define the limits between, the low-rise and mid-rise buildings, the mid-rise and high-rise buildings, the high-rise and tall buildings, respectively. In the examined projects of TOKİ, they have basement floors, generally. So, 5, 10, 14-story models are created with a basement in this thesis.

2.5 Inferences Drawn from Literature Review

Sustainability has started to take its place inside the architecture in a very fast way. Many researchers deal with this issue for residential units, also. As being one of the important components of sustainability, material selection has become a major subject. Building materials have different impacts on nature in terms of environmental parameters. As a part of material selection, the materials of structural systems have been analyzed as reinforced concrete or structural steel by researchers. Residential units have been modeled with different structural systems for comparison. Therefore; sustainability and structural systems are searched in the literature. Also, TOKİ housing is examined to understand the typology of this type of housing.

Examination of sustainability is studied according to analysis types. LCA is one of the most common methods in the literature. This method considers the full span of building life. Specific impact categories show LCA results and there are some programs to run LCA like GaBi, ATHENA, Tally, or OneClickLCA. According to the program, LCA results are obtained in certain types of impact categories.

The comparison method of structural systems, also, is investigated. There are two approaches to compare the structures. One of these is using a sample plan and the other one is selecting a real building to create the structural systems. Seismic effects and regulations are critical for structural design. In the literature, some programs are observed to create structural systems like ETABS, Robot, and ProtaStructure.

TOKİ housing is analyzed according to its mass and height. Moreover, the plan configuration of TOKİ housing is studied. In this way, TOKİ projects are categorized into three schemes.

In the literature, there are some studies about TOKİ housing. According to Şener and Torus (2016), TOKİ frequently uses the tunnel formwork system since this system is a prefabricated and economical system that can be produced fast. Sezer (2009) says that the tunnel formwork system can be evaluated as sustainable for both environment and economy but evaluating the construction technique does not make building structure sustainable. Reinforced concrete is not sustainable compared to other materials like steel, wood, and stone, in terms of embodied energy (Sezer, 2009). TOKİ housing is studied in terms of some sustainable parameters like site selection, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality by Sezer (2009). However, the LCA or sustainability at TOKİ housing is not investigated by the researchers in terms of structural material selection.

At this point, one of the most important facts about TOKİ housing is that these houses are produced by the reinforced concrete tunnel formwork system since the institution wants to build fast and resist the seismic forces without considering the environmental impacts of this construction method, structural material, and corresponding structural system. The reinforced concrete tunnel formwork system may have negative impacts on nature. Producing buildings with this method may damage the ecology.

To sum up, there is a gap in the literature about the examination of the structural material at TOKİ housing in terms of environmental parameters. Therefore, this thesis investigates the potentials and the limitations of steel, compared to reinforced concrete, for being used in TOKİ's projects as the structural material.

CHAPTER 3

MATERIAL AND METHOD

This part includes the material and the method of the thesis. In the material part, one sample of the floor plans at TOKİ projects is shown. This sample floor plan represents a specific typology. Also, the programs for analyses are clarified in the material part. The method part of this chapter expresses the process of the research. It shows the steps of analyses in two sections. The former starts with creating the sample floor plan of a real project by using AutoCAD. The latter is related to the quantity survey of the models and the LCA of the models. So, the method part ends with LCA that is conducted by OneClickLCA.

3.1 Material of Research

The main material of this thesis is an existing TOKİ building. As it is explained in the part of "Typologies of TOKİ Housing" in the second chapter; one of the three groups, F2 Scheme, is selected to create a sample floor plan from a real project. Kayabaşı Project of TOKİ in İstanbul has detailed floor plans and B1 floor plan is selected as an example of F2 Scheme (Figure 3.1). The floor plan of B Block is drawn in AutoCAD. According to the existing plan configuration, the structural axes are tried to be defined. Considering the block plan, a basic model is created with structural elements in ProtaStructure. This program includes the latest codes and regulations (e.g., TEC, 2018; TS500, 2000; TSSC, 2016; TS498, 1997) regarding the structural design of buildings in Turkey. The axes of the existing floor plan are simplified in ProtaStructure. In this way, the walls of the model are arranged on new axes so that the model meets the requirements of the regulation. After that, the data of models are taken from ProtaStructure to OneClickLCA. Then, LCA is performed on the webpage of OneClickLCA according to the quantity survey of Prota models.

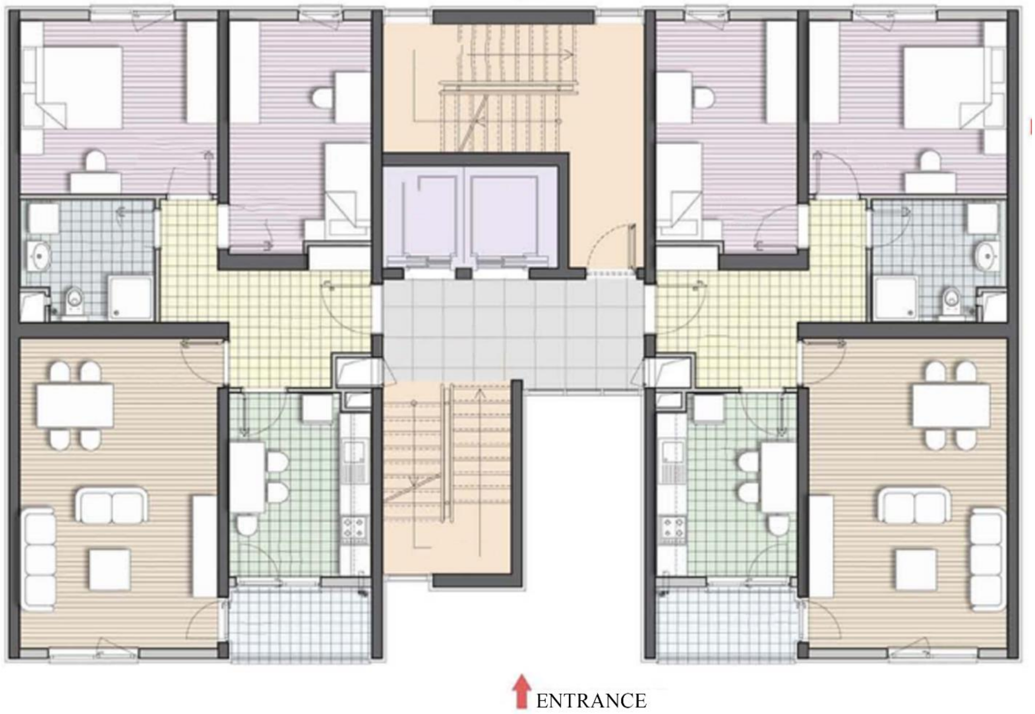


Figure 3.1. B1 Block Floor Plan

(*TOKİ Kayabaşı Yerleşimi 879-1 ve 876-3 Ada Toplu Konut Projesi*, n.d.)

The quantity survey of reinforced concrete models is taken from ProtaStructure (Figure 3.2). For steel models, one of the subprograms of ProtaStructure, ProtaSteel is used to gain the quantity survey of steel elements (Figure 3.3). To sum up, the floor plan of an existing TOKİ Building is one of the materials of this thesis. As programs; AutoCAD, ProtaStructure, ProtaSteel, and OneClickLCA are used in this thesis.

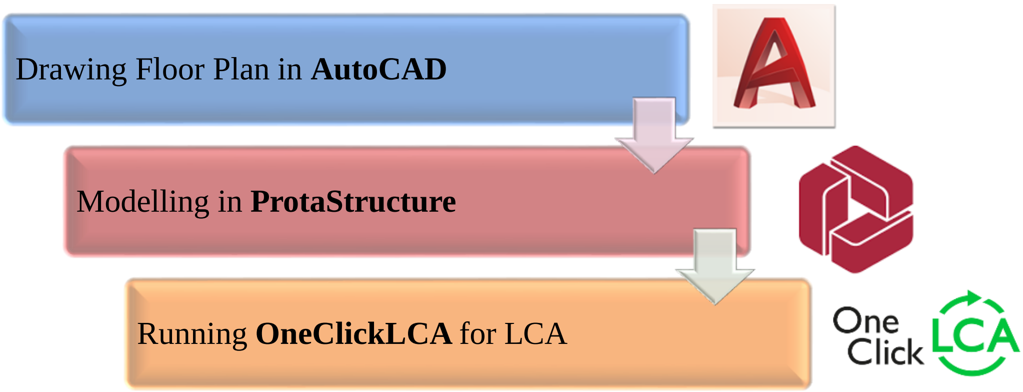


Figure 3.2. Process of Research for Reinforced Concrete Models

(*AutoCAD*, n.d.), (*ProtaStructure*, n.d.), (*OneClickLCA*, n.d.)

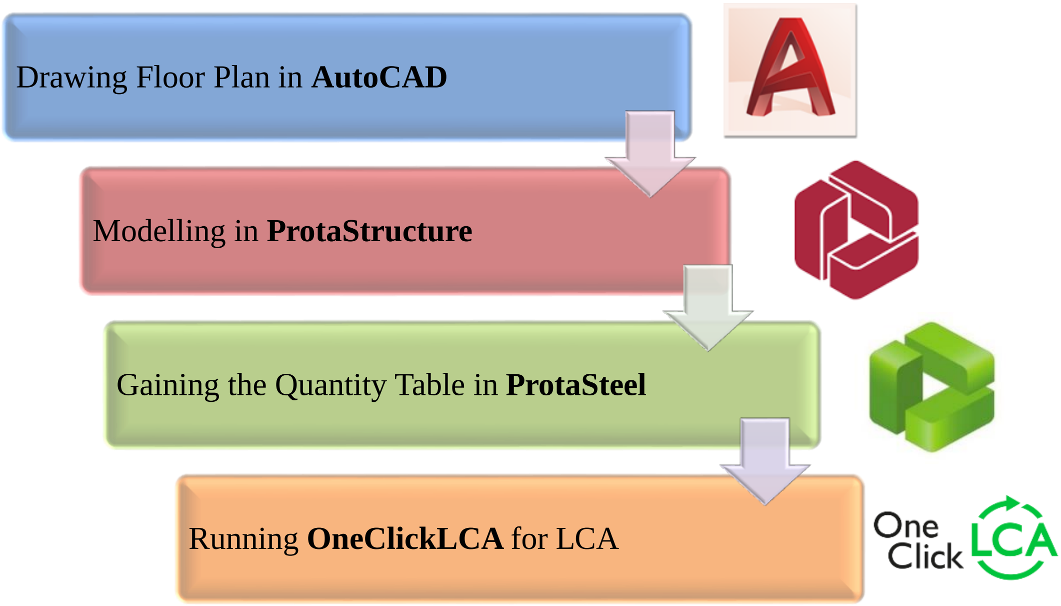


Figure 3.3. Process of Research for Steel Models

(*AutoCAD*, n.d.), (*ProtaStructure*, n.d.), (*OneClickLCA*, n.d.)

3.2 Analyses of Models

The analyses of this thesis can be explained in two parts. The first part starts with Autocad process and continues with structural analysis at ProtaStructure. The second part is related to LCA; therefore, it includes gaining the quantity survey of the models.

3.2.1 Structural Modelling

First of all, B Block is drawn in AutoCAD. The axes of this plan are defined according to structural elements. And then, all axes are measured (Figure 3.4).

After that, the axes of the floor plan are simplified as it is shown in Figure 3.5 in order to create structural axes in ProtaStructure. Shear walls are used as the structural member which represents the reinforced concrete shear wall system of TOKİ.

The wall thickness is 20cm regarding the minimum wall thickness allowed by the current standard and codes. Slab thickness is defined as 14cm for all levels. Stair cores and elevator shafts are modeled without slabs to reflect reality (Figure 3.6). After forming one floor of the model, 5 floors are created by reproducing from the first floor. The story height is defined as 3m and one basement floor is added to the model as described in the literature.

In the end, the first model is created as it has 1 basement and 5 floors. This model represents a reinforced concrete low-rise building whose height is 15m (Model RC5). 3D view of RC5 model is shown in Figure 3.7.

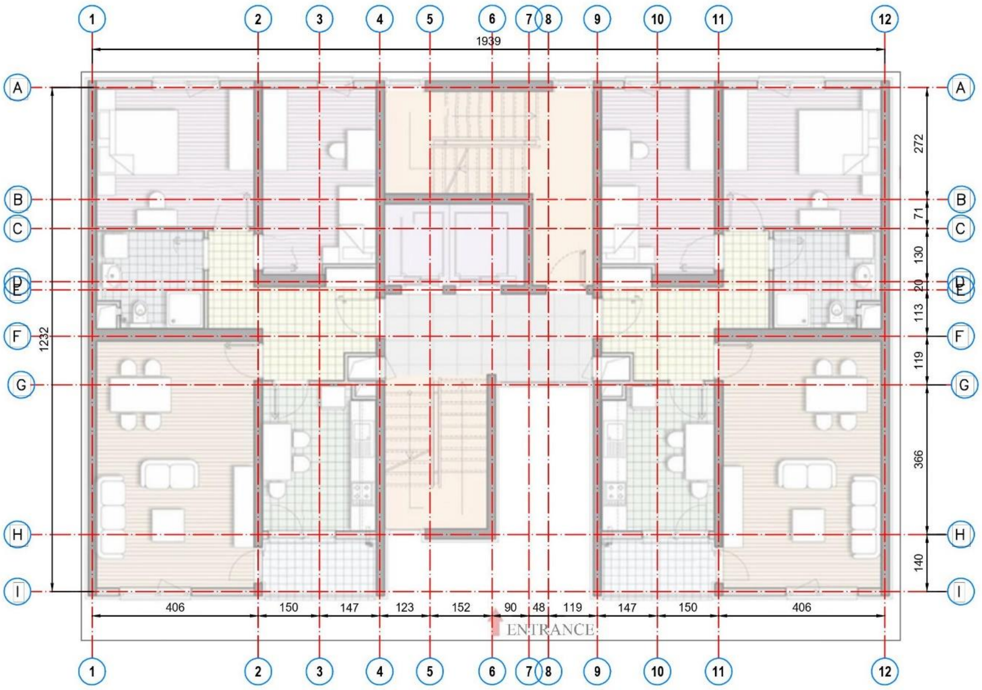


Figure 3.4. Floor Plan of B Block in AutoCAD

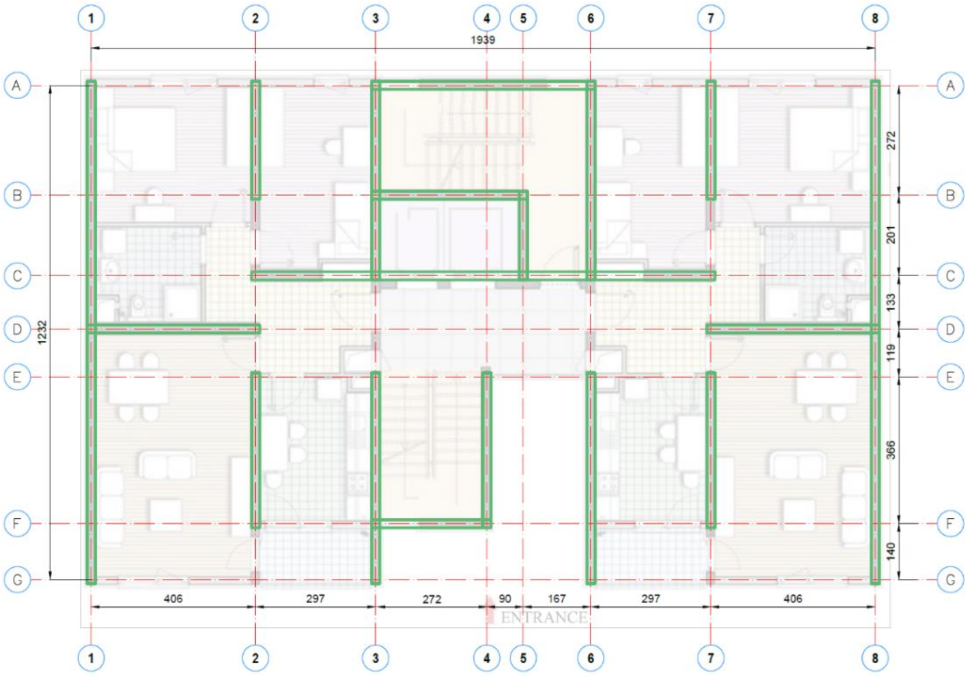


Figure 3.5. Simplified Floor Plan of B Block

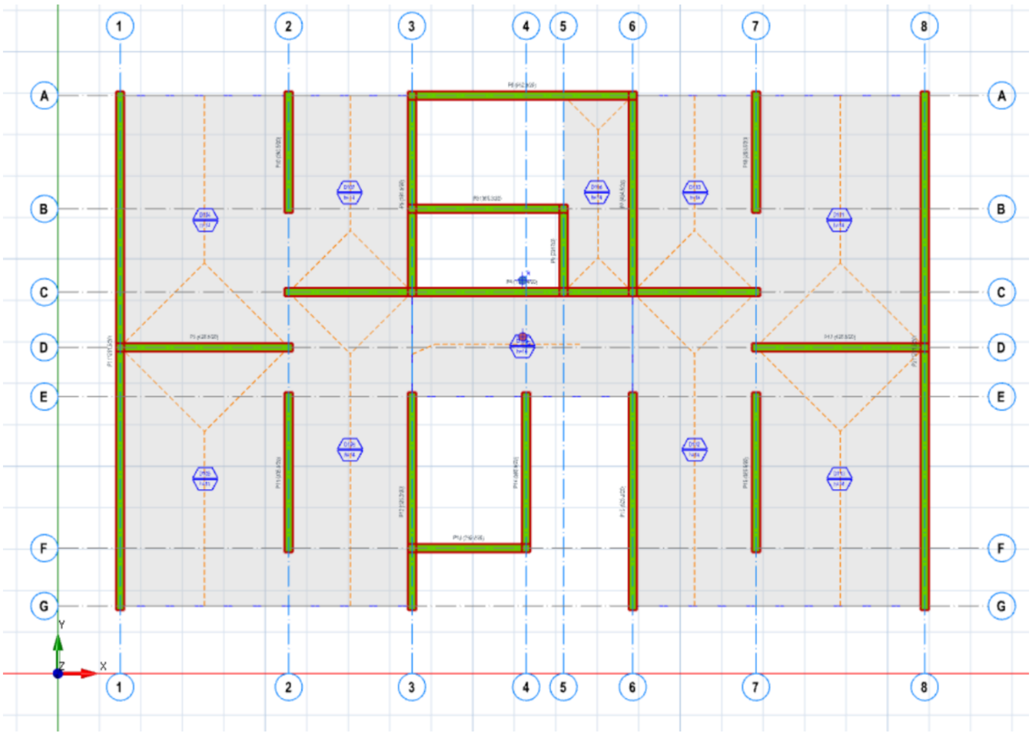


Figure 3.6. Floor Plan of Reinforced Concrete Model in ProtaStructure

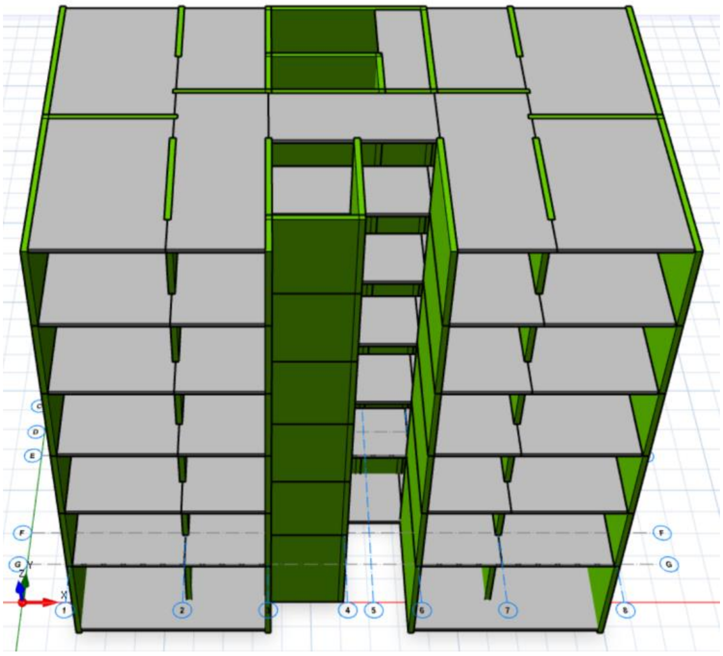


Figure 3.7. RC5 Model (Reinforced Concrete Model - 5 Floors with 1 Basement)

When RC5 model is completed in ProtaStructure, the model is checked to find the design violations if any exist. Then, the parameters of the model are determined for structural analysis. In Table 3.1, the parameters of the project are explained in terms of the regulations used for the structural analysis by ProtaStructure. The latest version of the Turkish regulations is selected to reflect the recent design practice as close as possible in this thesis.

Table 3.1 The Selected Regulations in ProtaStructure

Reinforced Concrete Design	Requirements for Design and Construction of Reinforced Concrete Structures (2000) - **TS500-2000**
Structural Steel Design	Design, Calculation and Construction Principles of Steel Structures (YDKT) - **TSSC, 2016 (LRFD)**
Design of Loads	Design Loads for Buildings - **TS498**
Earthquake Resistant Design	Turkish Seismic Design Code for Buildings: Specification for Structures to be Built in Disaster Areas. Ministry of Public Works and Settlement, Ankara. - **TEC, 2018**

Before running the analysis, values about earthquake parameters are adjusted according to the new earthquake regulation of Turkey. The values of some parameters are arranged automatically by ProtaStructure according to building height or selected location or selected usage class of building. Some others are selected by users such as soil type, project location, usage class of building, ductility level, type of load-bearing system for the direction 1 and 2. The values about the parameters of the earthquake are explained below:

- Type of soil = ZC (Very tight layers of sand, gravel, and hard clay, or weathered, very cracked weak rocks)
- The location of the project = 41.01112218°, 28.95439629° (Fatih, İstanbul, Turkey)
- The peak ground acceleration (PGA) ≅ 0.40g

- The spectral acceleration and ground effect factors for DD-2 (Earthquake ground motion level of 10% (repetition period 475 years) over 50 years)
  $S_s = 0.959$ (S_s: Short period map spectral acceleration coefficient)
- The spectral acceleration and ground effect factors for DD-2 (Earthquake ground motion level of 10% (repetition period 475 years) over 50 years)
  $S_1 = 0.266$ (S_1: Map spectral acceleration coefficient for the 1.0 second period)
- The usage class of building (BKS) = 3 (The other buildings like houses, offices, hotels, building type industry structures, etc.)
- The class of earthquake design (quantity) = 1 ($0.75 \leq S_{DS}$ and BKS=3)
  (S_{DS}: Short period design spectral acceleration coefficient)
- The class of building height (BYS) = 6 (DTS = 1 and $10.5\text{m} < H_N \leq 17.5\text{m}$)
  (H_N: Total building height)
- The level of ductility = High
- The type of load-bearing system for the direction 1 (x-direction) = A13
  (A13: The buildings that all of the earthquake effects are faced by reinforced concrete shear walls which have high ductility level.)
- The type of load-bearing system for the direction 2 (y-direction) = A13
- The response modification coefficient (R) = 6
- The overstrength factor (D) = 2.5
- The connections of infill wall = Flexible Jointless Attached
  (No infill wall is used in the models.)
- The aim of building usage = Residential
- The number of modes for analysis = 12

Material information is determined as C30 for all reinforced concrete elements including shear walls, floors, and foundation. The class of reinforcement steel is selected as S420. The combination of loadings is arranged automatically by ProtaStructure when 14cm thick slabs are defined with 0.350t self-weight, 0.237t superdead load (weight of floor covering and plastering), and 0.200t live load. There is no wind load for the model. For the shear walls, a finite element shell model is used. The rigid diaphragm is formed on all floors and they are included in the model for the structural calculation. In the end, the analysis is run. If any mistakes or any failure occurs, ProtaStructure warns in the Post-Analysis Control Report. In this way, the code compatible reinforced concrete model is obtained.

After creating a successful reinforced concrete model, a 5-story steel model is formed from the same simplified floor plan of the B block. The same axes are used in ProtaStructure (Figure 3.8).

The slabs of steel structure are modeled as 8cm thick reinforced concrete carried by primary and secondary steel beams. HEB200 section is used for steel columns, whereas HEB100 section is used both for main (primary) and secondary beams, TUBO100x100x5.4 section is used for braces. The optimum design is aimed (minimum sections are selected) for the model as possible.

After forming one floor of the steel model, 5 floors are reproduced from the first floor. And then, 1 basement is added to the model like the reinforced concrete model. In the end, the second model is created. It has 1 basement and 5 floors by representing a low-rise building that is composed of structural steel elements. The height of this model is 15m from the top of the basement to the roof like the reinforced concrete model (Model SS5). 3D view of SS5 model is shown in Figure 3.9.

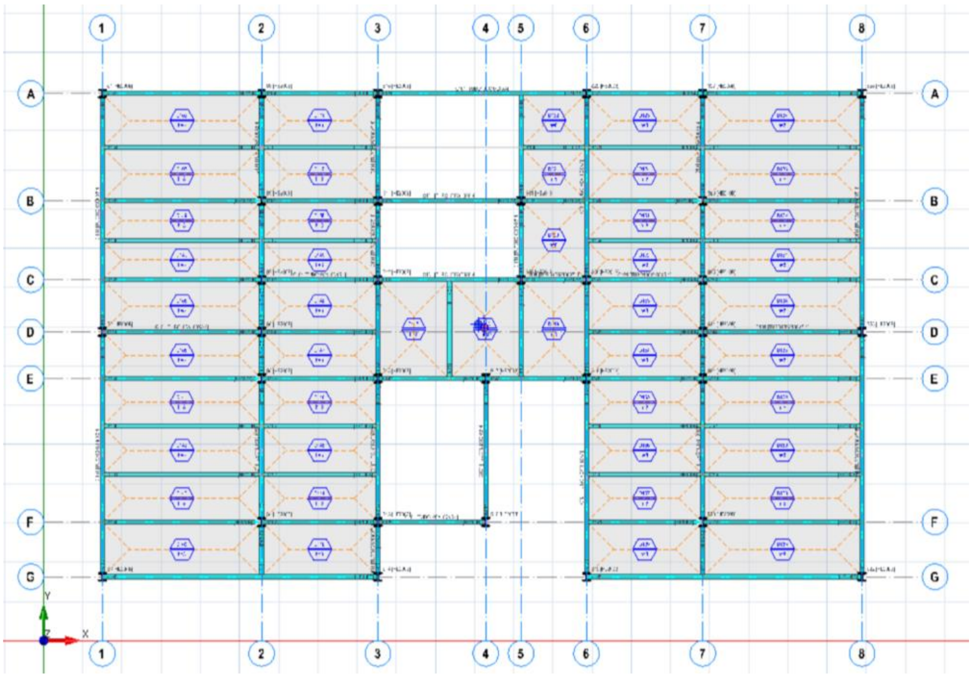


Figure 3.8. Floor Plan of Steel Model in ProtaStructure

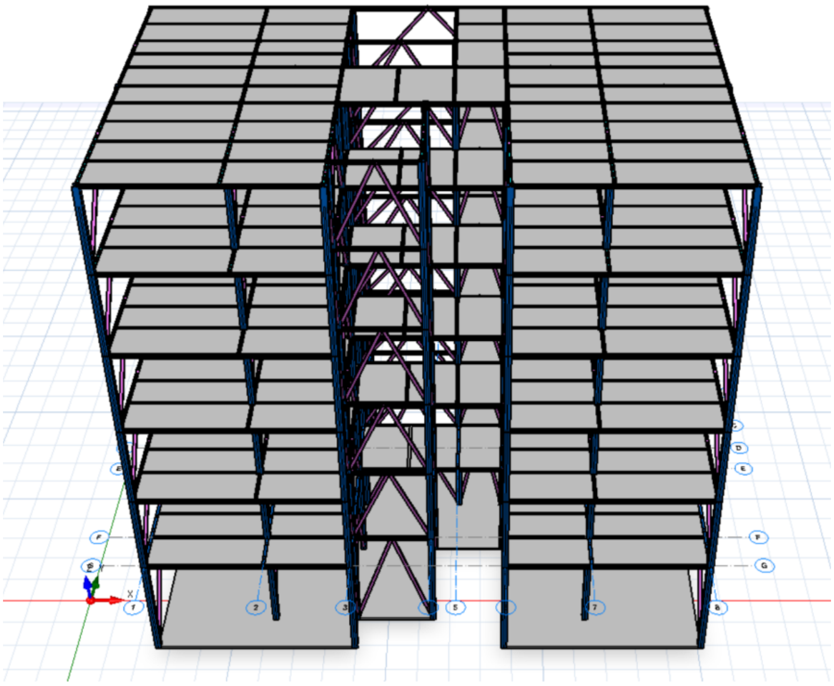


Figure 3.9. SS5 Model (Steel Model - 5 Floors with 1 Basement)

When SS5 model is completed, the model is checked like the reinforced concrete model before determining the parameters for structural analysis. The same regulations in Table 3.1 are valid for the steel model.

Values about the earthquake parameters are adjusted to be similar in the reinforced concrete model but some parameters are arranged automatically by ProtaStructure. Different values of the parameters are explained below:

- The type of load-bearing system for the direction 1 (x-direction) = C13
  (C13: The buildings that all of the earthquake effects are faced by central braced steel frames which have high ductility level.)
- The type of load-bearing system for the direction 2 (y-direction) = C13
- The response modification coefficient (R) = 5
- The overstrength factor (D) = 2

Material information is determined as C30 for reinforced concrete floors and S420 for reinforcement steel. Structural steel is defined as S275. In a similar way, load combination is arranged automatically by ProtaStructure for steel models when 8cm thick slabs are defined with 0.200t self-weight, 0.237t superdead load, and 0.200t live load. Wind load is not applied for the steel model since there is no wind load for the reinforced concrete model. Other parameters are kept as similar as the reinforced concrete model. In short; 2 models are formed as 5-story buildings that represent low-rise buildings. One model has reinforced concrete walls and slabs. The other one has steel structural elements and reinforced concrete slabs. So, the low-rise building type of TOKİ housing block is ready for comparison in terms of sustainability.

At this point, mid-rise and high-rise building samples are started to be modeled with 10 floors for the mid-rise sample and 14 floors for the high-rise sample. For the reinforced concrete mid-rise building sample, RC5 model is used as a base model. The 5-story model is raised to a 10-story building by adding 5 floors to RC5. In this way, the model has 1 basement and 10 floors whose height is 30m. It represents the reinforced concrete mid-rise building (Model RC10). For structural analysis in ProtaStructure, the same regulations and same parameters are applied to RC10.

The hypothetical location of the building, usage class of building, soil type, ductility level, type of load-bearing system for the direction 1 and 2 are similar with RC5 model. The only different value is the class of building height, 'BYS' value since it is defined automatically by ProtaStructure according to the height. In RC10 model, BYS is equal to 4 because DTS is 1 and H_N (Total Building Height) is between 28m and 42m. In short, different parameters are summarized below:

- The class of building height (BYS) = 4 (DTS = 1 and $28m < H_N \leq 42m$) (H_N: Total Building Height)
- The type of load-bearing system for the direction 1 (x-direction) = A13 (A13: The buildings that all of the earthquake effects are faced by reinforced concrete shear walls which have high ductility level.)
- The type of load-bearing system for the direction 2 (y-direction) = A13
- The response modification coefficient (R) = 6
- The overstrength factor (D) = 2.5
- The class of reinforced concrete = C30
- The class of reinforcement steel = S420
- The load combination is arranged automatically for reinforced concrete buildings by ProtaStructure.
- Self-weight = 0.350t, Superdead load = 0.237t, Live load = 0.200t
- There is no wind load.
- The finite element shell model is used.
- The rigid diaphragm is formed on all floors.

In the end, the analysis is run. Since RC10 is created from RC5, it has 20cm wall thickness and 14cm slab thickness like RC5. However, ProtaStructure warns about the thickness of shear walls at RC10 model that is placed along direction 1. It means the shear walls of the x-direction do not have enough thickness for 30m height. To succeed in structural analysis, shear walls of direction 1 are increased. RC10 become a successful model with 25cm thickness for the shear walls along the x-direction and 20cm thickness for the shear walls along the y-direction (Figure 3.10). RC10 represents the mid-rise buildings of TOKİ housing that consists of reinforced concrete (Figure 3.11).

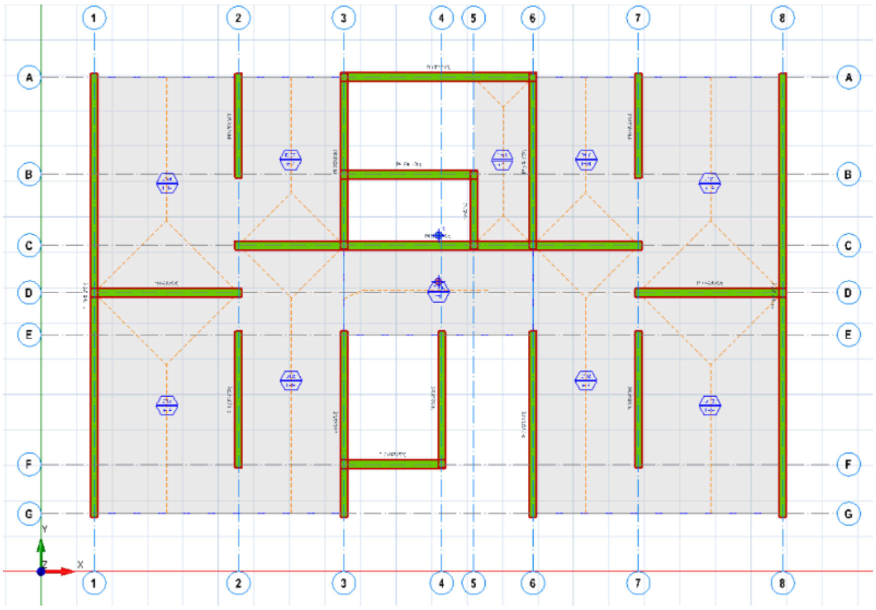


Figure 3.10. Floor Plan of RC10 Model in ProtaStructure

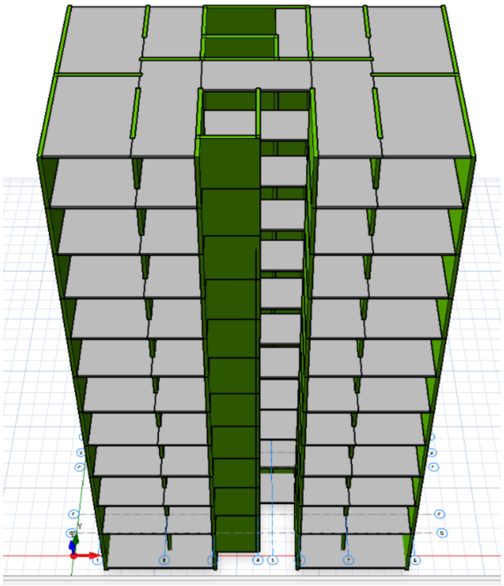


Figure 3.11. RC10 Model (Reinforced Concrete Model - 10 Floors with 1 Basement)

In order to create the steel model that has 10 floors like RC10, SS5 model is used as a base. It is raised to a 10-story building by adding 5 floors to SS5. Now, the steel version of RC10 model is formed that has 1 basement and 10 floors. Its height is 30m and it consists of structural steel elements (Model SS10). Same regulations with SS5 are applied for structural analysis in ProtaStructure. Similarly; the location of the model, the usage class of building, soil type, project location, usage class of building, ductility level, type of load-bearing system for the direction 1 and 2 are similar with SS5 model. Other parameters are below:

- The class of building height (BYS) = 4 (DTS = 1 and $28m < H_N \leq 42m$)
  (H_N: Total Building Height)
- The type of load-bearing system for the direction 1 (x-direction) = C13
  (C13: The buildings that all of the earthquake effects are faced by central braced steel frames which have high ductility level.)
- The type of load-bearing system for the direction 2 (y-direction) = C13
- The response modification coefficient (R) = 5
- The overstrength factor (D) = 2
- The class of reinforced concrete = C30
- The class of reinforcement steel = S420
- The class of structural steel elements like columns, beams, and braces = S275
- The load combination is arranged automatically for steel buildings by ProtaStructure.
- Self-weight = 0.200t, Superdead load = 0.237t, Live load = 0.200t
- There is no wind load.
- The finite element shell model is used.
- The rigid diaphragm is formed on all floors.

When the analysis is run, ProtaStructure reports that the sections of steel elements that are used in SS5 are not enough for SS10 model. Therefore, the sections are increased to gain a successful model (Figure 3.12). For the successful SS10 model, HEB300 columns are used on the basement floor. HEB 200 columns are used between the 1st and 10th floors. HEB100 beams are used for all floors. On the basement floor, TUBO100x100x7.1 braces are used. Between the 1st and 10th floors, TUBO100x100x5.4 braces are used. In the end, SS10 is a sample model of the steel mid-rise buildings of TOKİ housing (Figure 3.13).

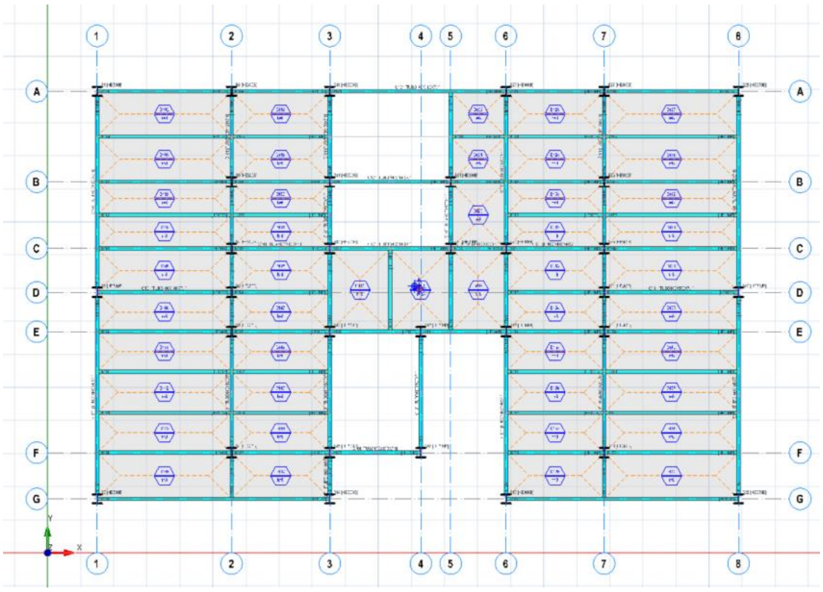


Figure 3.12. Floor Plan of SS10 Model in ProtaStructure

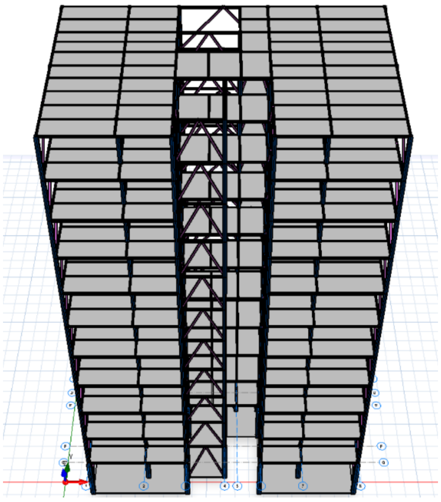
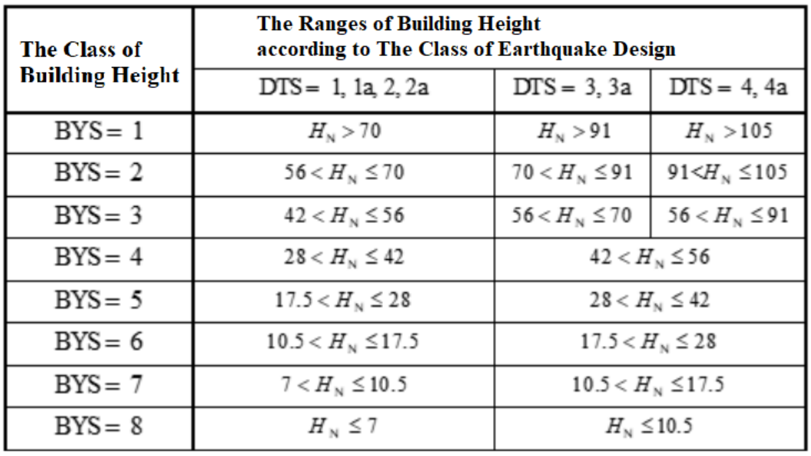


Figure 3.13. SS10 Model (Steel Model - 10 Floors with 1 Basement)

When producing a high-rise building for reinforced concrete and steel models, parameters in regulations are considered because the ranges of building height change at 42m building height, and it affects the value of BYS. When the total building height is higher than 42m which means that the model has more than 14 floors, the BYS value becomes 3 as is seen in Table 3.2. This situation influences the steel high-rise model because the type of load-bearing system at SS5 and SS10 models is determined as ‘C13’ which means the buildings that all of the earthquake effects are faced by central braced steel frames which have high ductility levels. This explanation is valid for all steel models of this thesis. Since the value of DTS is equal to 1 in the models, C13 is applicable when BYS is equal and higher than 4. Therefore; the floor number of high-rise samples is arranged as a 14-story building so that all steel models have the same type of load-bearing system which is C13.

Table 3.2 The Ranges of Building Height according to The Class of Earthquake Design



The Class of Building Height	**The Ranges of Building Height according to The Class of Earthquake Design**		
	DTS = 1, 1a, 2, 2a	DTS = 3, 3a	DTS = 4, 4a
BYS = 1	$H_N > 70$	$H_N > 91$	$H_N > 105$
BYS = 2	$56 < H_N \leq 70$	$70 < H_N \leq 91$	$91 < H_N \leq 105$
BYS = 3	$42 < H_N \leq 56$	$56 < H_N \leq 70$	$56 < H_N \leq 91$
BYS = 4	$28 < H_N \leq 42$	$42 < H_N \leq 56$	
BYS = 5	$17.5 < H_N \leq 28$	$28 < H_N \leq 42$	
BYS = 6	$10.5 < H_N \leq 17.5$	$17.5 < H_N \leq 28$	
BYS = 7	$7 < H_N \leq 10.5$	$10.5 < H_N \leq 17.5$	
BYS = 8	$H_N \leq 7$	$H_N \leq 10.5$	

(BYS: The Class of Building Height, DTS: The Class of Earthquake Design, H_N: Building Height)

In short, the high-rise sample is modeled with 14 floors for both reinforced concrete and steel models. For the high-rise reinforced concrete model, RC10 is used as a base, again. By adding 4 floors to RC10, the 10-story model is raised to a 14-story building. So, the model has 1 basement and 14 floors and the model height becomes 42m which symbolizes the high-rise reinforced concrete building (Model RC14). Similarly, structural analysis is conducted with the same regulations and same parameters of RC10 in ProtaStructure. Since RC14 is created from RC10, it has 25cm thickness for the shear walls of the x-direction and 20cm thickness for the shear walls of the y-direction with 14cm slab thickness. When ProtaStructure runs the analysis, the Post-Analysis Control Report says that the shear walls of the x-direction are not enough. For this reason, shear walls of the x-direction are increased and RC14 becomes successful with 35 cm thick shear walls at the x-direction and 20cm thick shear walls at the y-direction (Figure 3.14). Thus, the reinforced concrete high-rise building sample of TOKİ housing becomes RC14 (Figure 3.15).

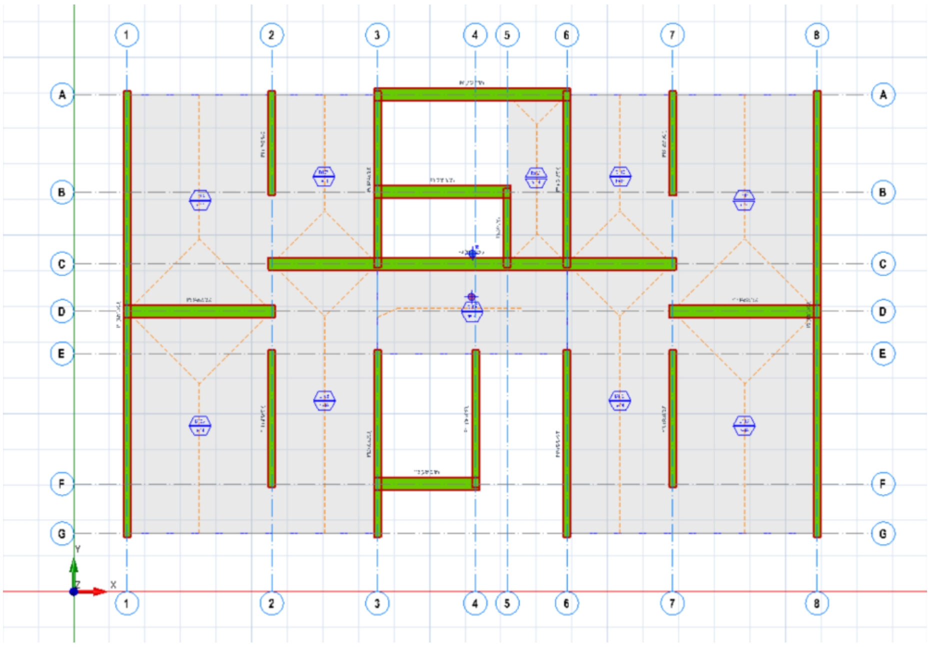


Figure 3.14. Floor Plan of RC14 Model in ProtaStructure

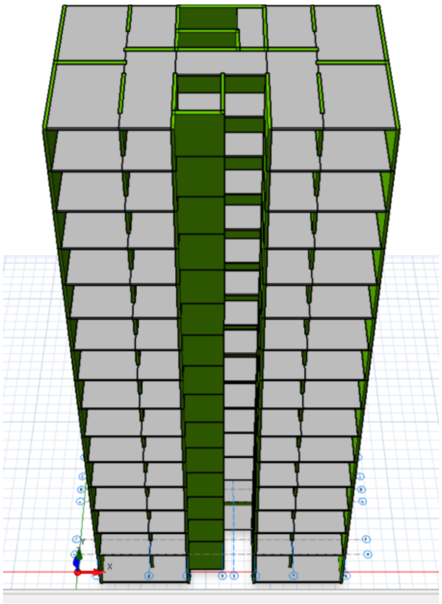


Figure 3.15. RC14 Model (Reinforced Concrete Model – 14 Floors with 1 Basement)

A high-rise steel model is generated from SS10 model by adding 4 floors. A 14-story steel model is formed with 1 basement and 14 floors, which is 42m in height (Model SS14). There are no different parameters or regulations from SS10 for structural analysis. When ProtaStructure runs the analysis, the sections are not enough again since SS14 owns the same steel elements as SS10. Due to this reason, the sections of steel elements are increased in order to get a successful model (Figure 3.16). The sections of elements for the SS14 model become HEB300 columns between the basement floor and 2nd floor, HEB200 columns between 3rd and 14th floors, HEB120 beams for all floor levels, TUBO100x100x7.1 braces at the basement floor, TUBO100x100x5.4 braces between the 1st and 14th floors. So, SS14 represents the steel high-rise buildings of TOKİ housing (Figure 3.17).

To sum up, 6 successful models are produced in ProtaStructure according to 3 different types of height. Reinforced concrete models have the shear wall system. Steel models have a concentrically v-braced frame system. 3 reinforced concrete models are expressed with the sections of walls and slabs in Table 3.3. The steel sections and slabs of 3 steel models are remarked in Table 3.4.

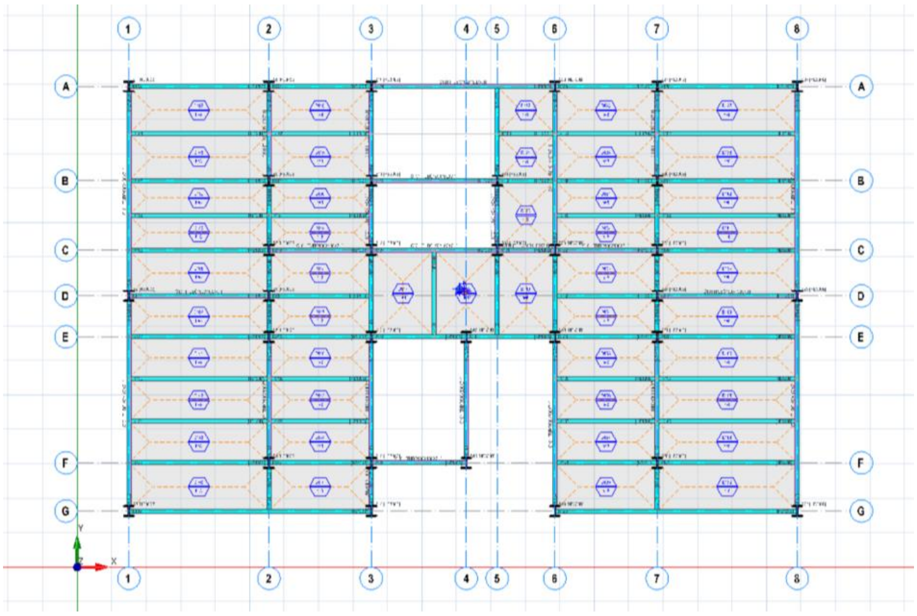


Figure 3.16. Floor Plan of SS14 Model in ProtaStructure

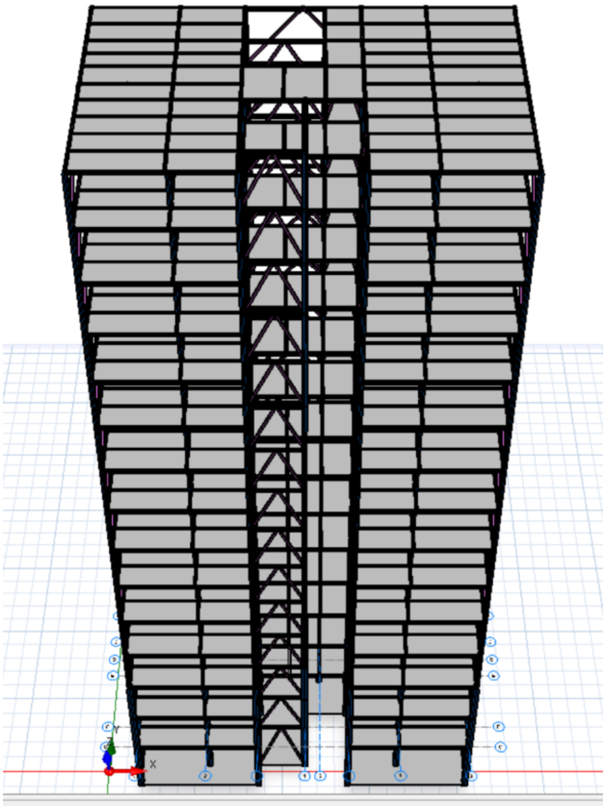


Figure 3.17. SS14 Model (Steel Model – 14 Floors with 1 Basement)

Table 3.3 Sections of Reinforced Concrete Models

(h:height)	**Slabs**	**Shear Walls along X-direction**	**Shear Walls along Y- direction**
RC5 **h=15m**	14cm Reinforced Concrete	20cm Reinforced Concrete	20cm Reinforced Concrete
RC10 **h=30m**	14cm Reinforced Concrete	25cm Reinforced Concrete	20cm Reinforced Concrete
RC14 **h=42m**	14cm Reinforced Concrete	35cm Reinforced Concrete	20cm Reinforced Concrete

Table 3.4 Sections of Steel Models

(h:height)	**Slabs**	**Columns**	**Beams**	**Braces**
SS5 **h=15m**	8cm Reinforced Concrete	HEB200 (for all floors)	HEB100	TUBO100x100x5.4
SS10 **h=30m**	8cm Reinforced Concrete	HEB300 (at the basement floor) HEB200 (between 1st and 10th floors)	HEB100	TUBO100x100x7.1 (at the basement floor) TUBO100x100x5.4 (between 1st and 10th floors)
SS14 **h=42m**	8cm Reinforced Concrete	HEB300 (between basement floor and 2nd floor) HEB200 (between 3rd and 14th floors)	HEB120	TUBO100x100x7.1 (at the basement floor) TUBO100x100x5.4 (between 1st and 14th floors)

3.2.2 Life Cycle Assessment

After creating 6 successful models in ProtaStructure, quantity surveys of these models are obtained. The volume or the weight of the elements is put into OneClickLCA so that it can compare the models in terms of sustainability. ProtaStructure gives the volume of concrete directly in the quantity table of reinforced concrete models. The volume of concrete used for members of RC5, RC10, and RC14 models is shown in Table 3.5. For the steel models, the concrete volume in reinforced concrete slabs is taken from ProtaStructure using the quantity table of concrete. After that, ProtaSteel is used to get the weight of the structural steel elements (Figure3.18).

Table 3.5 Quantity Table of Materials in Reinforced Concrete Models

	Slabs (Concrete Volume) (m^3)	**Shear Walls (Concrete Volume) (m^3)**	**TOTAL (Concrete Volume) (m^3)**
RC5	185	372	557
RC10	312	719	1,031
RC14	410	1,121	1,531

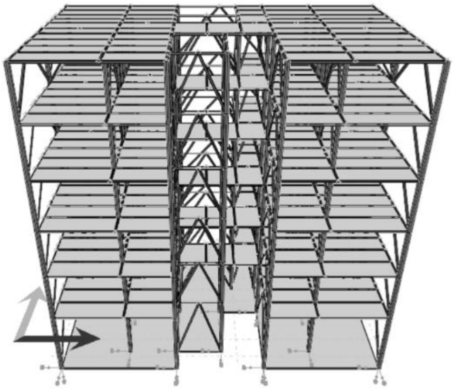


Figure 3.18. View from ProtaSteel

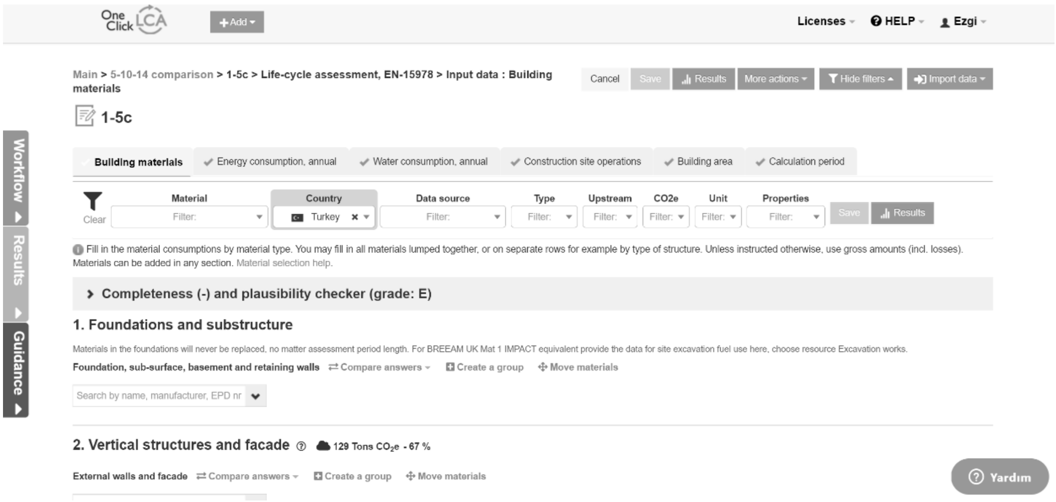
In ProtaSteel, the material list of the raw profile shows a report which includes the properties of steel elements like name, length, surface area, and also, the total weight of all elements at the end of the report. Table 3.6 shows the volume of concrete used in slabs and the weight of steel used in columns, beams, and braces of steel models.

Table 3.6 Quantity Table of Materials in Steel Models

	Slabs (Concrete Volume m^3)	**Columns, Beams, and Braces (Steel Weight t)**
SS5	102	88
SS10	171	167
SS14	223	260

After determining the volumes and the weights of the materials, all these values are put into OneClickLCA. OneClickLCA is a website that the users can upload proper data to conduct LCA. OneClickLCA contains the material information according to different countries and it includes Turkey. Therefore; the data about the models can be selected from Turkey as shown in Figure 3.19. In other words, OneClickLCA includes local generic data for the materials.

There is a tab of “Data Input” on the website of OneClickLCA. In order to conduct LCA, 6 different segments are filled with data under this tab. These segments are listed in Table 3.7.



Main > 5-10-14 comparison > 1-5c > Life-cycle assessment, EN-15978 > Input data : Building materials

1-5c

Fill in the material consumptions by material type. You may fill in all materials lumped together, or on separate rows for example by type of structure. Unless instructed otherwise, use gross amounts (incl. losses). Materials can be added in any section. Material selection help.

Completeness (-) and plausibility checker (grade: E)

1. Foundations and substructure

Materials in the foundations will never be replaced, no matter assessment period length. For BREEAM UK Mat 1 IMPACT equivalent provide the data for site excavation fuel use here, choose resource Excavation works.

Foundation, sub-surface, basement and retaining walls

2. Vertical structures and facade 129 Tons CO_2e - 67 %

External walls and facade

Figure 3.19. Interface of OneClickLCA

Table 3.7 Segments of Data Input

Building Materials
Energy Consumption (annual)
Water Consumption (annual)
Construction Site Operations
Building Area
Calculation Period

In this thesis, 3 segments are not included in the study, which are energy consumption (annual), water consumption (annual), and construction site operations. In this thesis, the structural materials are compared. The data about the annual consumption of energy and water is not added to the study. Also, the data about the site operations of the construction is not within the scope of this study.

The segment of Building Materials is filled with the quantity value of the models. This segment includes 6 categories:

1. Foundations and substructure
2. Vertical structures and facade
3. Horizontal structures: beams, floors, and roofs
4. Other structures and materials
5. External areas and site elements
6. Building technology

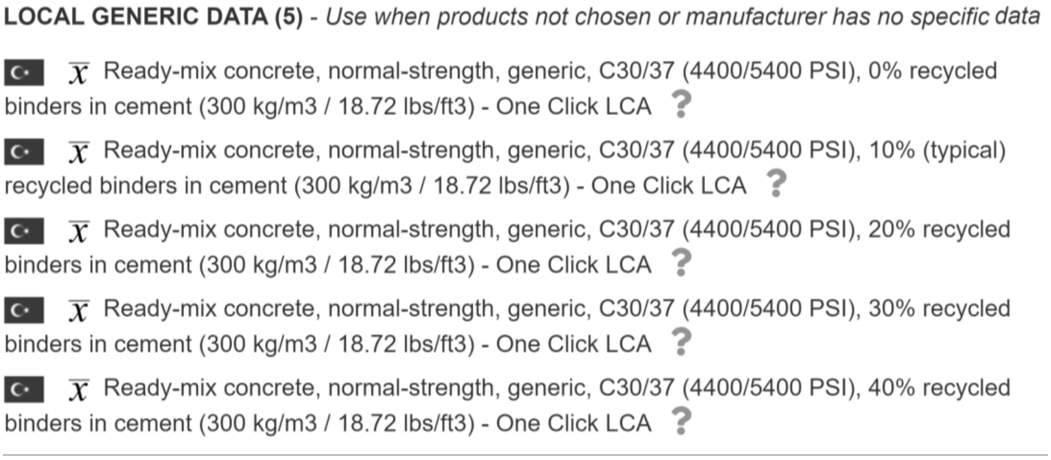
The second and third categories (vertical structures and façade; horizontal structures: beams, floors, and roofs) are used in this thesis because the data belong to other types of materials is not included in the models.

There is a comprehensive library in the material selection at this Building Materials segment. Since the class of the reinforced concrete models is defined as C30 in ProtaStructure, the material of reinforced concrete is selected from the choices of C30 in OneClickLCA.

There are 5 types of ready-mix, normal-strength, generic, C30/37 (4400/5400 PSI) concrete. They are categorized according to the properties of the binders in the cement. Figure 3.20 demonstrates these five types of ready-mix C30/37 concrete.

The recycle ratio of the binders ranges from 0% to 40%. Moreover, one of these types is determined as ‘typical’ by OneClickLCA. This is ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 PSI), 10% (typical) recycled binders in cement (300 kg/m^3 / 18.72 lbs/ft^3).

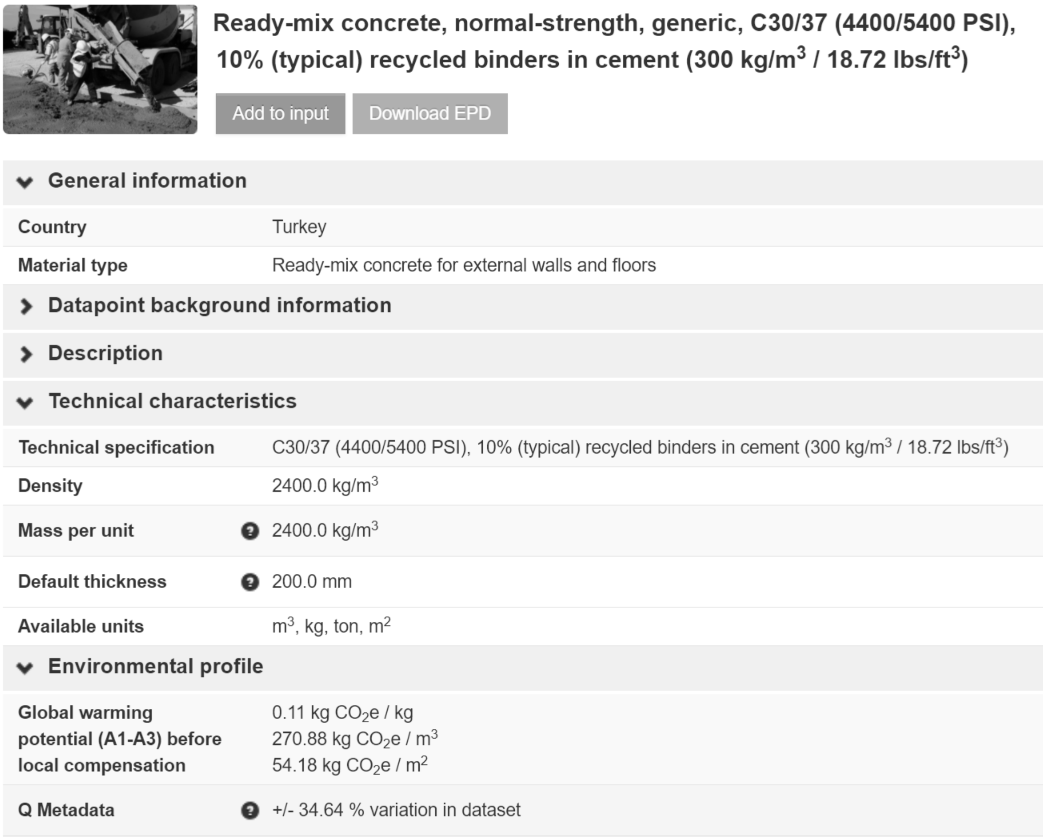
For each type of material, OneClickLCA provides basic data which includes general information, datapoint background information, description, technical characteristics, and environmental profile as shown in Figure 3.21.



LOCAL GENERIC DATA (5) - *Use when products not chosen or manufacturer has no specific data*

- $\bar{x}$ Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 PSI), 0% recycled binders in cement (300 kg/m3 / 18.72 lbs/ft3) - One Click LCA ?
- $\bar{x}$ Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 PSI), 10% (typical) recycled binders in cement (300 kg/m3 / 18.72 lbs/ft3) - One Click LCA ?
- $\bar{x}$ Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 PSI), 20% recycled binders in cement (300 kg/m3 / 18.72 lbs/ft3) - One Click LCA ?
- $\bar{x}$ Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 PSI), 30% recycled binders in cement (300 kg/m3 / 18.72 lbs/ft3) - One Click LCA ?
- $\bar{x}$ Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 PSI), 40% recycled binders in cement (300 kg/m3 / 18.72 lbs/ft3) - One Click LCA ?

Figure 3.20. Types of C30 Concrete in OneClickLCA



Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 PSI), 10% (typical) recycled binders in cement (300 kg/m^3 / 18.72 lbs/ft^3)

General information

Country	Turkey
Material type	Ready-mix concrete for external walls and floors

Datapoint background information

Description

Technical characteristics

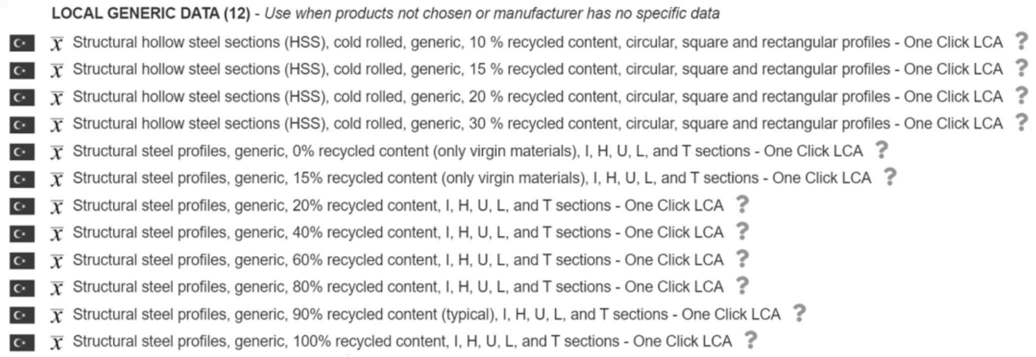
Technical specification	C30/37 (4400/5400 PSI), 10% (typical) recycled binders in cement (300 kg/m^3 / 18.72 lbs/ft^3)
Density	2400.0 kg/m^3
Mass per unit	2400.0 kg/m^3
Default thickness	200.0 mm
Available units	m^3, kg, ton, m^2

Environmental profile

Global warming potential (A1-A3) before local compensation	0.11 kg CO_2e / kg 270.88 kg CO_2e / m^3 54.18 kg CO_2e / m^2
Q Metadata	+/- 34.64 % variation in dataset

Figure 3.21. Properties of C30 Concrete (10% recycled binders in cement) at OneClickLCA

For steel models, structural steel elements are searched in OneClickLCA because HEB and TUBO sections are used in ProtaStructure. Figure 3.22 indicates the structural hollow steel sections and steel profiles within the library of OneClickLCA for Turkey.



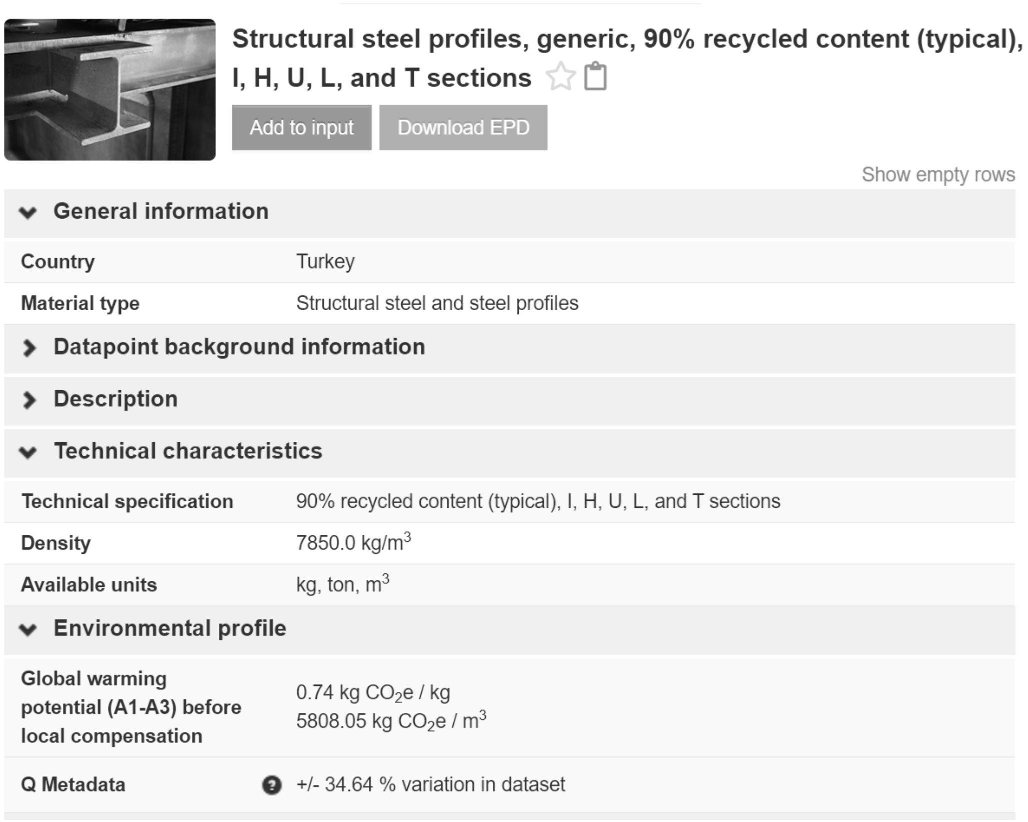
LOCAL GENERIC DATA (12) - *Use when products not chosen or manufacturer has no specific data*

Structural hollow steel sections (HSS), cold rolled, generic, 10 % recycled content, circular, square and rectangular profiles - One Click LCA ?
Structural hollow steel sections (HSS), cold rolled, generic, 15 % recycled content, circular, square and rectangular profiles - One Click LCA ?
Structural hollow steel sections (HSS), cold rolled, generic, 20 % recycled content, circular, square and rectangular profiles - One Click LCA ?
Structural hollow steel sections (HSS), cold rolled, generic, 30 % recycled content, circular, square and rectangular profiles - One Click LCA ?
Structural steel profiles, generic, 0% recycled content (only virgin materials), I, H, U, L, and T sections - One Click LCA ?
Structural steel profiles, generic, 15% recycled content (only virgin materials), I, H, U, L, and T sections - One Click LCA ?
Structural steel profiles, generic, 20% recycled content, I, H, U, L, and T sections - One Click LCA ?
Structural steel profiles, generic, 40% recycled content, I, H, U, L, and T sections - One Click LCA ?
Structural steel profiles, generic, 60% recycled content, I, H, U, L, and T sections - One Click LCA ?
Structural steel profiles, generic, 80% recycled content, I, H, U, L, and T sections - One Click LCA ?
Structural steel profiles, generic, 90% recycled content (typical), I, H, U, L, and T sections - One Click LCA ?
Structural steel profiles, generic, 100% recycled content, I, H, U, L, and T sections - One Click LCA ?

Figure 3.22. Types of Structural Steel Profiles in OneClickLCA

Compared to the concrete, the structural steel profiles have more extensive choices in terms of the recycled content. The ratio ranges from 0% to 100%. Similar to concrete, one of them is identified as ‘typical’ by OneClickLCA. This is shown in OneClickLCA as “structural steel profiles, generic, 90% recycled content (typical), I, H, U, L, and T sections”. OneClickLCA provides basic information also for steel materials (Figure 3.23).

According to the basic information that is provided by OneClickLCA, the quantity table of the models can be examined in a detailed manner. OneClickLCA says that the density of C30 is 2,400kg/m^3. It means that the quantity survey of reinforced concrete models (Table 3.5) can be revised from ‘m^3’ to ‘kg’ or ‘t’ value. In this calculation, the reinforcement weight is not considered, only concrete volume (m^3) is converted to the concrete weight (t). The weights of steel models in the quantity table (Table 3.6) are shown with "t" value. In this way, the weights of the models can be compared.



Structural steel profiles, generic, 90% recycled content (typical), I, H, U, L, and T sections

General information

Country	Turkey
Material type	Structural steel and steel profiles

Datapoint background information

Description

Technical characteristics

Technical specification	90% recycled content (typical), I, H, U, L, and T sections
Density	7850.0 kg/m^3
Available units	kg, ton, m^3

Environmental profile

Global warming potential (A1-A3) before local compensation	0.74 kg CO_2e / kg 5808.05 kg CO_2e / m^3
Q Metadata	+/- 34.64 % variation in dataset

Figure 3.23. Properties of Structural Steel Profiles I, H, U, L, and T sections (90% recycled content) at OneClickLCA

When all quantity tables are arranged according to ‘t’ value, Figure 3.24 demonstrates the situation according to reinforced concrete shear walls and slabs for reinforced concrete models. Figure 3.25 shows the circumstance according to steel columns, beams, braces, and reinforced concrete slabs for steel models.

Figure 3.26 shows the percentages of the elements in total. Shear wall percentage of RC5 is %67 of the total model when slab percentage is %33 of all. At RC10, slab percentage decreases to %30 of total weight and shear wall percentage becomes %70 of all models. The slab percentage of RC14 falls to %27 while the shear wall percentage increases to %73. In short, the weight percentage of shear walls rises with the increase of the floor number in reinforced concrete models.

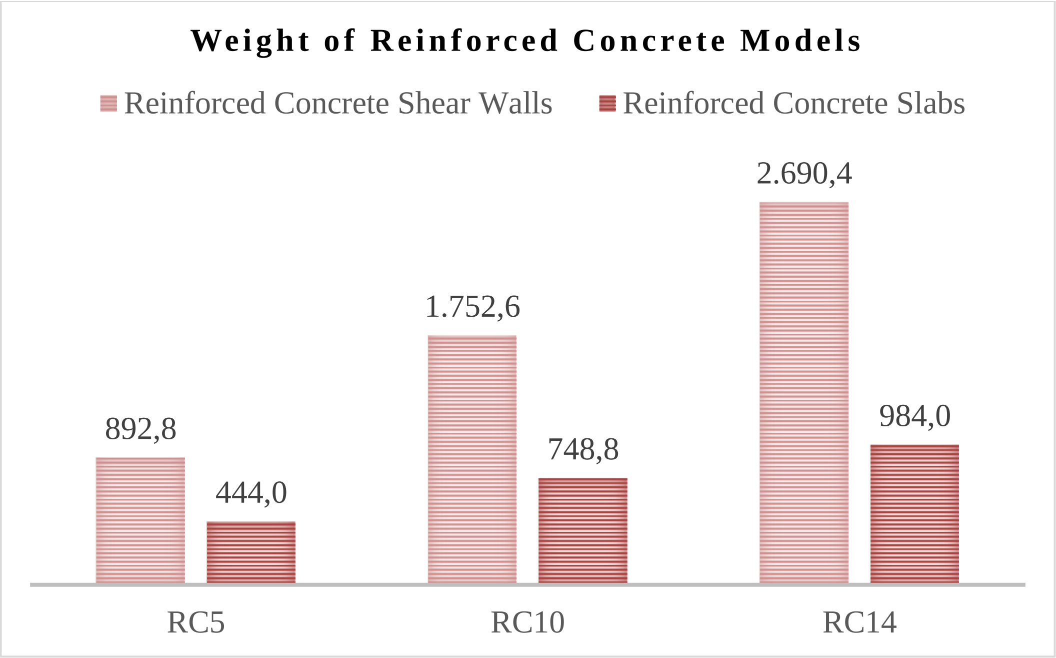


Figure 3.24. The Quantity Survey of Reinforced Concrete Models (t)

*The weight (t) is calculated from the volume (m^3) of reinforced concrete ($2.4t/m^3$).

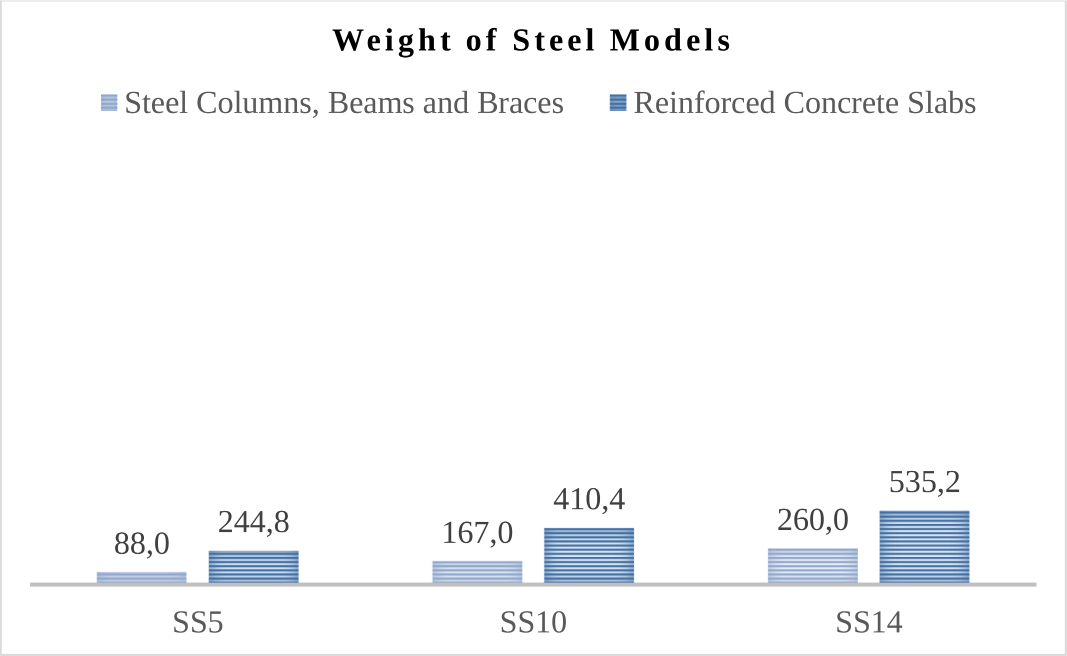


Figure 3.25. The Quantity Survey of Steel Models (t)

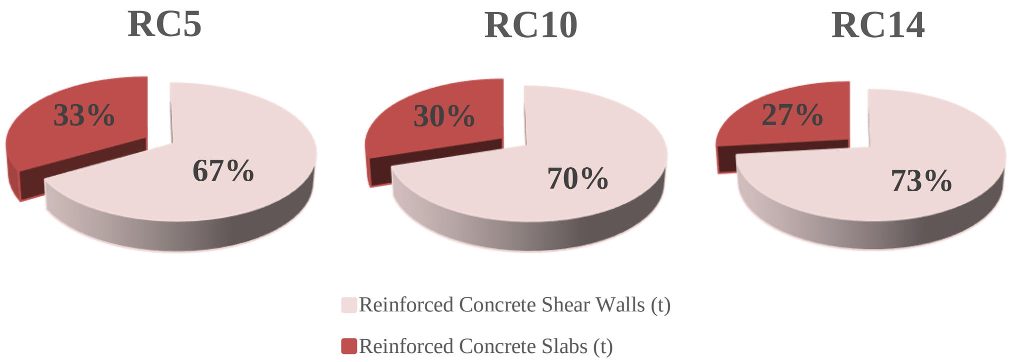


Figure 3.26. Weight Percentage of Elements in Reinforced Concrete Models

For steel models, Figure 3.27 summarizes the weight percentage of elements. As different from reinforced concrete models, the slab weight percentage of steel models is much higher than the percentage of steel elements.

At SS5, the percentage of concrete slabs is %74 while the total weight of steel models is %26 of the model. Concrete slab percentage of SS10 decreases to %71 and steel elements' percentage increases to %29. For SS14, the percentage of steel models becomes %33 and concrete slabs' percentage falls to %67 of total weight. In a word, the weight percentage of steel elements rises with the increase of the floor number in steel models.

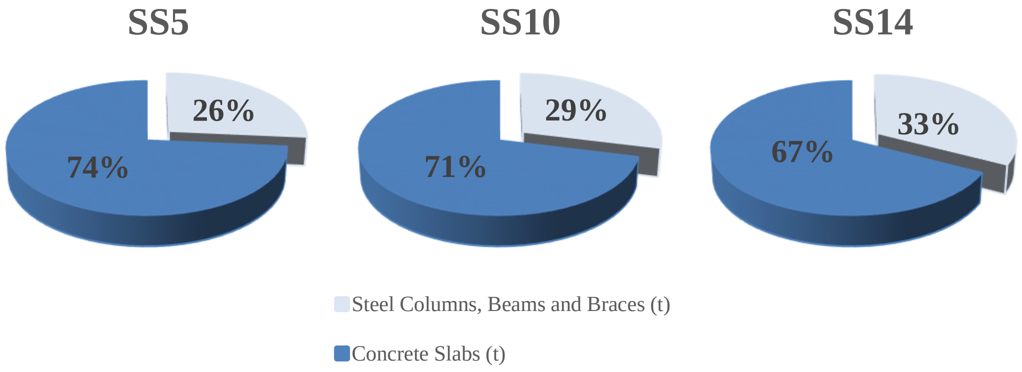


Figure 3.27. Weight Percentage of Elements in Steel Models

In OneClickLCA, the other segment is ‘Building Area’ that is filled with the data for LCA. This segment needs the value of Gross Internal Floor Area (GIFA). OneClickLCA gives a table to calculate the GIFA, correctly (*Building Area*, n.d.). Table 3.8 shows in a simple way, the boundaries of the calculation are given. “YES” means that it should be taken into the count and “NO” means that it should not be included in the count. In this way, the value of floor area is calculated as the boundary is shown in Figure 3.28.

Table 3.8 The Counting Method of Floor Area

(NA = Not Applicable)	GFA (Gross Floor Area)	**GIFA (Gross Internal Floor Area, IPMS/RICS)**	GIFA (Gross Internal Floor Area, ASHRAE)
Country	Worldwide	**Worldwide**	US/Canada
Internal Walls	YES	**YES**	YES
External walls	YES	**NO**	NO
Internal Floors	YES	**YES**	YES
Basement	YES	**YES**	YES
Attic	NO	**NO**	NO
Stairs	NO	**YES**	YES
Use Area	NA	**NA**	NA
Technical Area	NA	**NA**	NA
Traffic Area	NA	**NA**	NA
Parking Area	NO	**YES**	NO
Gross Volume	NA	**NA**	NA

(*Building Area*, n.d.)

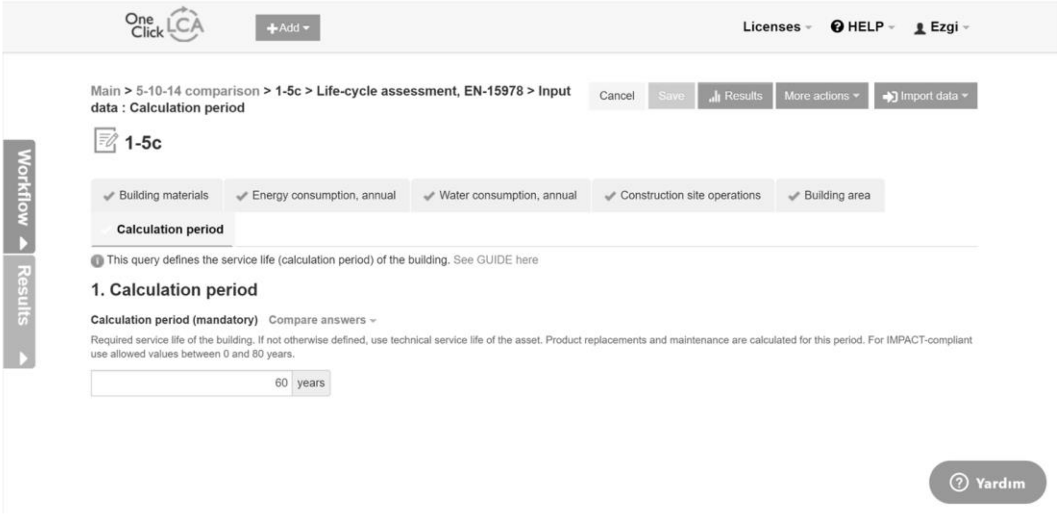
Figure 3.28. The Gross Internal Floor Area of B Block

The GIFA value of the models is given in Table 3.9, by counting according to the floor number of the models. According to the table below, these GIFA values are put in OneClickLCA.

Table 3.9 GIFA of The Models

	5-STORY MODELS	**10-STORY MODELS**	**14-STORY MODELS**
	Total Floor Number with the Basement		
	6	11	15
Area of a Floor (m^2)	**GIFA of the Models (m^2)**		
214	1,284	2,354	3,210

‘Calculation Period’ is the last segment that is filled with the data in OneClickLCA (Figure 3.29). This value is tried to be defined according to the literature review. In the literature review, the life span of a building is defined as 50 or 60 years. Hence, the calculation period is limited to “60 years” of life span in this thesis.



Main > 5-10-14 comparison > 1-5c > Life-cycle assessment, EN-15978 > Input data : Calculation period

1-5c

This query defines the service life (calculation period) of the building. See GUIDE here

1. Calculation period

Calculation period (mandatory)

Required service life of the building. If not otherwise defined, use technical service life of the asset. Product replacements and maintenance are calculated for this period. For IMPACT-compliant use allowed values between 0 and 80 years.

60 years

Figure 3.29. The Calculation Period

When the data input is finished, OneClickLCA gives the results by saving the data. Also, OneClickLCA provides a sample report for the projects, which explains LCA, the scope of the analysis, the impact categories, the method for showing the results of LCA (Bionova, 2018). The scope of the life cycle analysis and the boundaries of the system (all stages taken into the consideration by OneClickLCA) are explained in a detailed manner, in this report. Life cycle stages are shown in Table 3.10.

The first one, the product stage, has 3 phases. The second stage, the construction process stage, owns 2 phases. The use stage contains 7 phases. The end-of-life stage has 4 phases. The last stage is explained as benefits and loads beyond the system boundary. This stage has 3 phases including reuse, recovery, and recycling.

Table 3.10 The Life Cycle Stages and Analysis Scope

PRODUCT STAGE	Raw material supply	A1
	Transport	A2
	Manufacturing	A3
CONSTRUCTION PROCESS STAGE	Transport to the building site	A4
	Installation into building	A5
USE STAGE	Use/application	B1
	Maintenance	B2
	Repair	B3
	Replacement	B4
	Refurbishment	B5
	Operational energy use	B6
	Operational water use	B7
END-OF-LIFE STAGE	Deconstruction/demolition	C1
	Transport	C2
	Waste processing	C3
	Disposal	C4
BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARY	Reuse	D
	Recovery	D
	Recycling	D

(Bionova, 2018)

Raw material supply (A1) includes the emissions when the materials are taken from nature and transported to industry. Loss of raw material and energy are also taken into account.

Transport (A2) involves exhaust emissions because of the transport of the materials from producers to the factory of the manufacturer and it contains the effects of fuels.

Manufacturing (A3) which means the production effects, covers the production of the materials and the fuels used by devices. Also, it comprises the treatment of the waste generated during the production processes in the manufacturer's production facilities until the waste is exhausted.

Transport to the building site (A4) includes the negative effects of the spent fuel and also exhaust emissions due to the transportation of building materials from the factory to the construction site.

Installation into the building (A5) contains the exhaust emissions caused by the energy use during the field operations, environmental impacts of fuel, energy, and water production processes, and additionally, processing waste to the end.

In the use stage, the part starting with the use/application (B1) and ending with the refurbishment (B5) is named maintenance and material replacement. The environmental impacts of this part involve the negative effects resulting from replacing building materials after they reach the end of their service life. The emissions comprise the effects from the supply of raw material, the transportation, the production of the changed material, and also the process of waste until the end-of-waste state.

Operational energy use (B6) covers the impacts of the exhaust emissions caused by energy production of buildings, also the process of fuel production, and the energy generated externally. Moreover, the losses of energy transmission are taken into consideration.

Operational water use (B7) contains the negative effects of freshwater production and the treatment of wastewater.

The end-of-life stage starts with deconstruction/demolition (C1) and ends with disposal (C4). This part is named deconstruction, also. The deconstruction stage covers the environmental effects of the recycling process of building waste (C3) until the end of waste or the pre-process and landfill effects of non-recyclable (C4) waste depending on material type. Additively, this stage covers the emissions from waste energy recovery.

The stage of benefits and loads beyond the system boundary (D) is named as external impacts/end-of-life benefits, also. This stage involves the emission benefits from the recycling of recyclable building waste. The benefits of re-used or recycled materials contain the positive effects of the replacement of virgin materials with recycled materials. The benefits of recyclable materials for energy contain the positive effects for changing other energy flows depending on the average effects of energy production.

Table 3.11 shows the scope of analysis in this thesis. The stage of the product (A1-A2-A3), transport to the building site (A4), end-of-life stage (C1-C2-C3-C4), and the benefits, the loads beyond the system boundary (D) are calculated by OneClickLCA for this thesis.

The use stage is not considered since the structural materials are compared in the scope of this research. Energy consumption (annual), water consumption (annual), and construction site operations represent the use stage, thus they are not filled with data. Proper data is entered in the segments of building materials, building area, and calculation period.

According to the life cycle stages and the scope of the analysis, OneClickLCA gives results in 6 categories of impacts. Table 3.12 shows the categories and their units. These categories of impacts are also, explained in the sample report of OneClickLCA.

Table 3.11 The Analysis Scope of This Thesis

PRODUCT STAGE	Raw material supply	A1
	Transport	A2
	Manufacturing	A3
CONSTRUCTION PROCESS STAGE	Transport to the building site	A4
END-OF-LIFE STAGE	Deconstruction/demolition	C1
	Transport	C2
	Waste processing	C3
	Disposal	C4
BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARY	Reuse	D
	Recovery	D
	Recycling	D

Table 3.12 The Categories of Impacts

IMPACT CATEGORY	UNIT
Global warming potential (greenhouse gases)	$kgCO_2eq$
Acidification potential	$kgSO_2eq$
Eutrophication potential	$kgPO_4$-eq
Ozone depletion potential	kgCFC11eq
Formation of ozone of lower atmosphere	kgC_2H_4eq
Primary energy	MJ

Global warming potential, also known as greenhouse gases, describes the changes in surface temperatures due to the high greenhouse gas concentration in the atmosphere. It is often called “carbon footprint”, either. The burning of fossil fuels causes high greenhouse gas emissions. ISO 14040-14044, another standard of LCA, explains global warming potential as a measure of greenhouse gas emissions. It leads to an increase in the absorption of radiation emitted by the earth. This may have adverse effects on ecosystem health, human health, and material welfare (International Organization for Standardization, 2006). Furthermore; the emissions of greenhouse gas are related to two other impact categories that are acidification and smog.

Acidification potential is the acidifying impact of hazardous substances in nature. Substances like carbon dioxide dissolve easily in water and enhance acidity. The acidification potential is a measure of capacity to increase the concentration of hydrogen ion (H^+) in the water, which decreases the pH value of the water. Its influences are fish mortality, forest decline, and the deterioration of building materials (International Organization for Standardization, 2006). The emissions of sulfuric acid (H_2SO_4) and sulfur dioxide (SO_2) cause acidification (Süratam, 2020). Combustion of both is an air-polluting process and leads to acid rain. The acidification potential of pollutants can be measured by their capacity to form H+ ions. The acidification potential is defined as the number of H+ ions produced per kg relative to SO_2 (Irbaş & Dadaşer Çelik, 2021).

Eutrophication potential is the impact of adding minerals to nature like water or soil that causes the domination of one species in nature. This situation endangers the other species and it results in the death of the populations. In detail, eutrophication potential covers the potential effects at high levels of macronutrients. The most important ones are nitrogen (N) and phosphorus (P). Nutrient enrichment causes a shift in species and biomass production in ecosystems. This brings about low oxygen levels, due to the additional consumption of oxygen in biomass decomposition (International Organization for Standardization, 2006).

Ozone depletion potential describes the effect of hazardous substances in the atmosphere to degrade the ozone layer. The ozone layer absorbs and prevents harmful solar UV lights from reaching Earth's surface. In other words, it is a measure of air emissions contributing to the depletion of the stratospheric ozone layer. This causes higher levels of UVB ultraviolet rays that reach the earth's surface with harmful impacts on humans and plants (International Organization for Standardization, 2006). Degradation of the ozone layer is mainly due to the group of fluorochlorohydrocarbons (CFCs), which are part of greenhouse gases. Therefore; the emissions of this environmental impact category are reported as CFC11 equivalents (Süratam, 2020).

The formation of ozone of lower atmosphere is also named smog formation potential (International Organization for Standardization, 2006). It describes the impact of particles in the atmosphere to generate photochemical smog, known as summer smog. It is related to ground-level ozone. Prolonged exposure to ozone may cause some problems in human health like bronchitis, asthma, permanent lung damage, etc. The primary sources of ozone precursors are motor vehicles, electric power utilities, and industrial facilities. Ozone acts as a protector in the ozone layer (in the higher atmosphere). However, if it forms in the troposphere (in the lower atmosphere), it is a harmful substance. Since ethene (C_2H_4) is the reference substance for ozone formation in the lower atmosphere, C_2H_4 is the indicator of this potential (Süratam, 2020).

Primary energy is used as a measure of the total energy extracted from the earth. That is the energy demand from non-renewable resources like petroleum, natural gas, etc., and the energy demand from renewable resources like hydropower, wind energy, solar, etc. (International Organization for Standardization, 2006).

In brief, OneClickLCA gives the results through 6 impact categories based on the life cycle stages and the data that is filled.

To sum up, the method of this thesis is summarized in Figure 3.30 to illustrate the process of analysis. It starts with using the floor plan of the existing project and continuing with creating models in ProtaStructure by using reinforced concrete and structural steel. After obtaining the volume and the weight of the materials, LCA is conducted in OneClickLCA.

OneClickLCA gives the results of LCA and these results are evaluated according to the impact categories and the life cycle stages in this thesis. In Figure 3.31, this evaluation is demonstrated. Also, the life cycle stages which are included and excluded in this thesis are given.

In this thesis, three analyses are studied. The first analysis is related to the building height whereas the second analysis examines the effect of material recyclability and the last analysis investigates the seismicity for steel models (Figure 3.32).

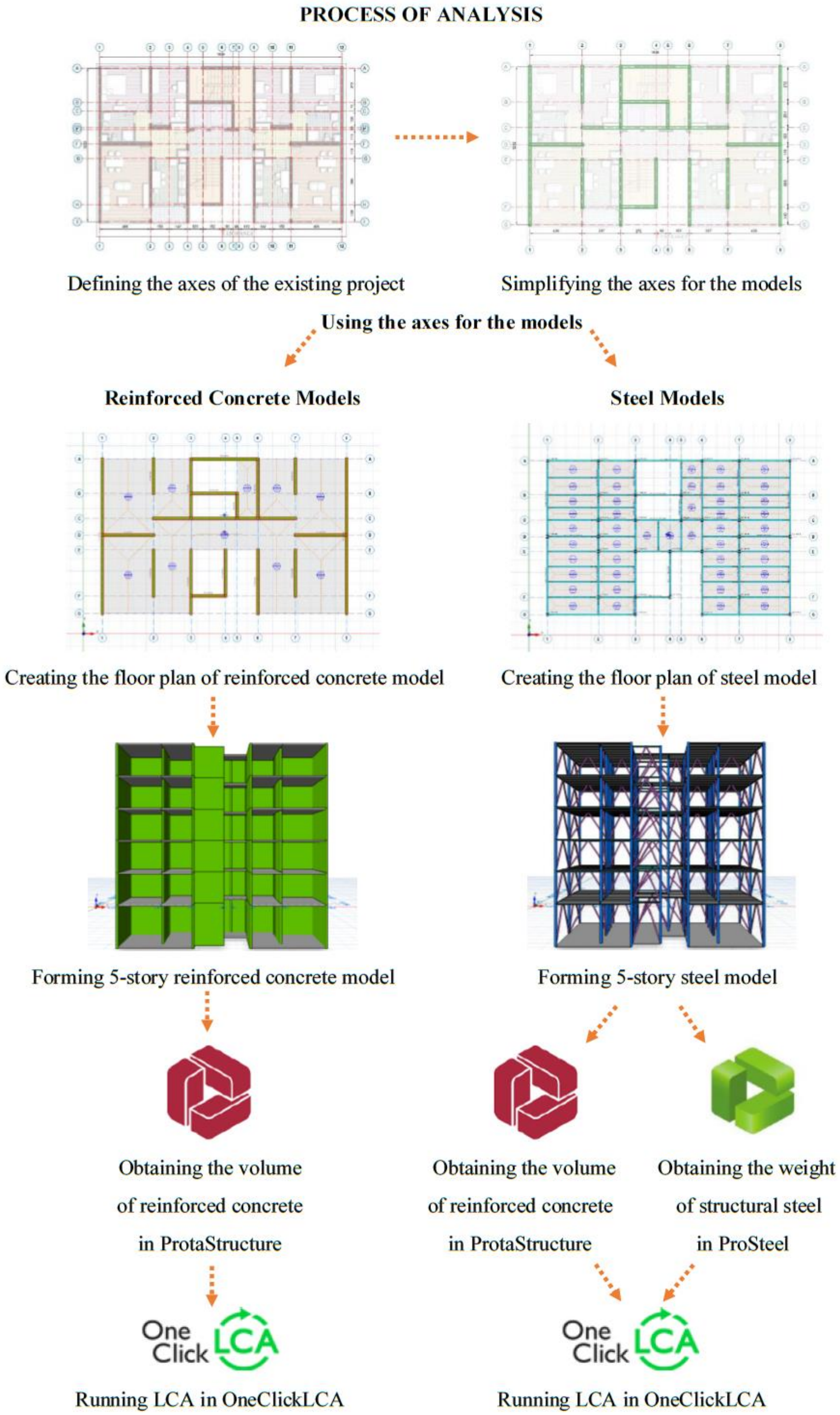


Figure 3.30. The Process of Analysis

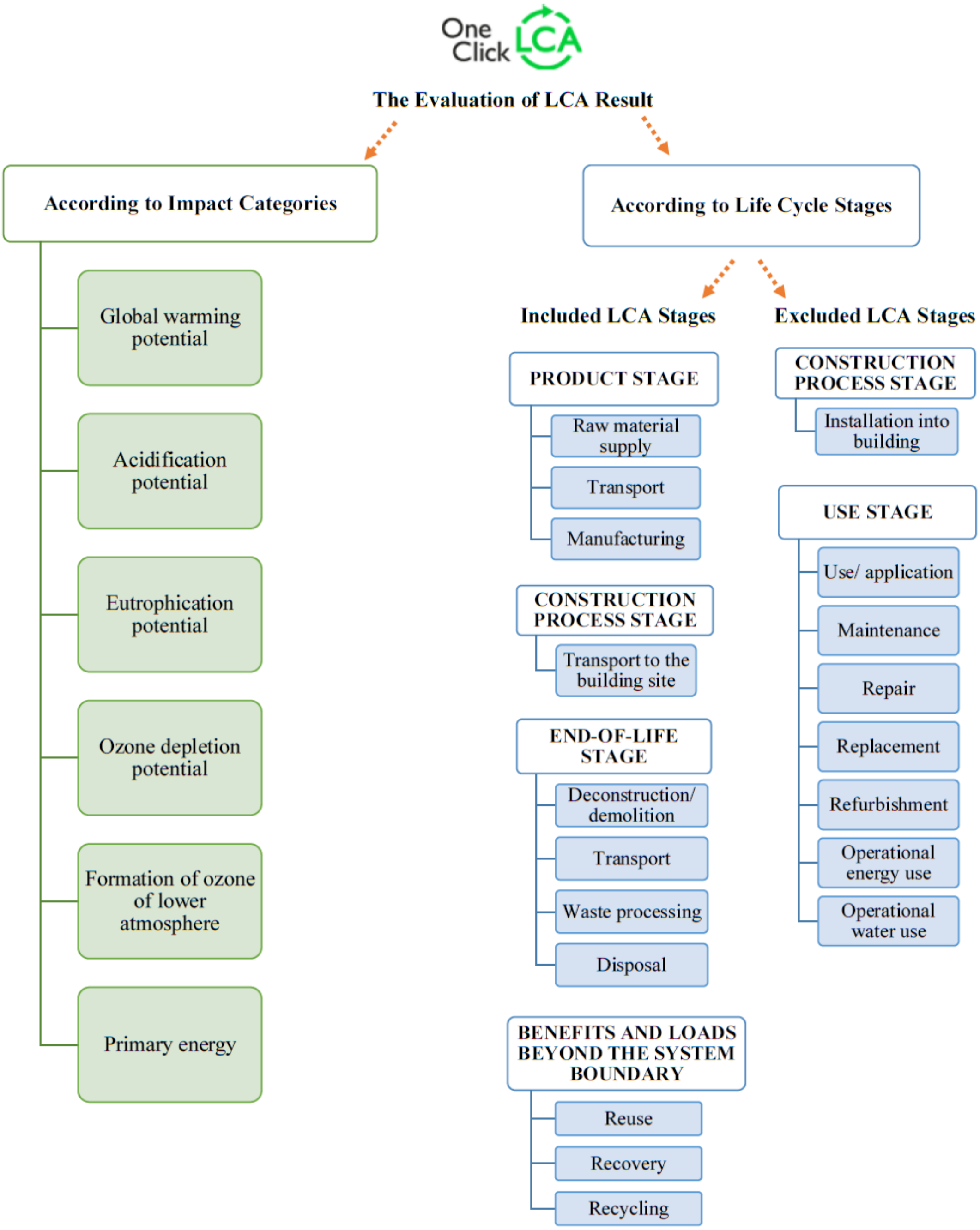


Figure 3.31. The Evaluation of LCA Result

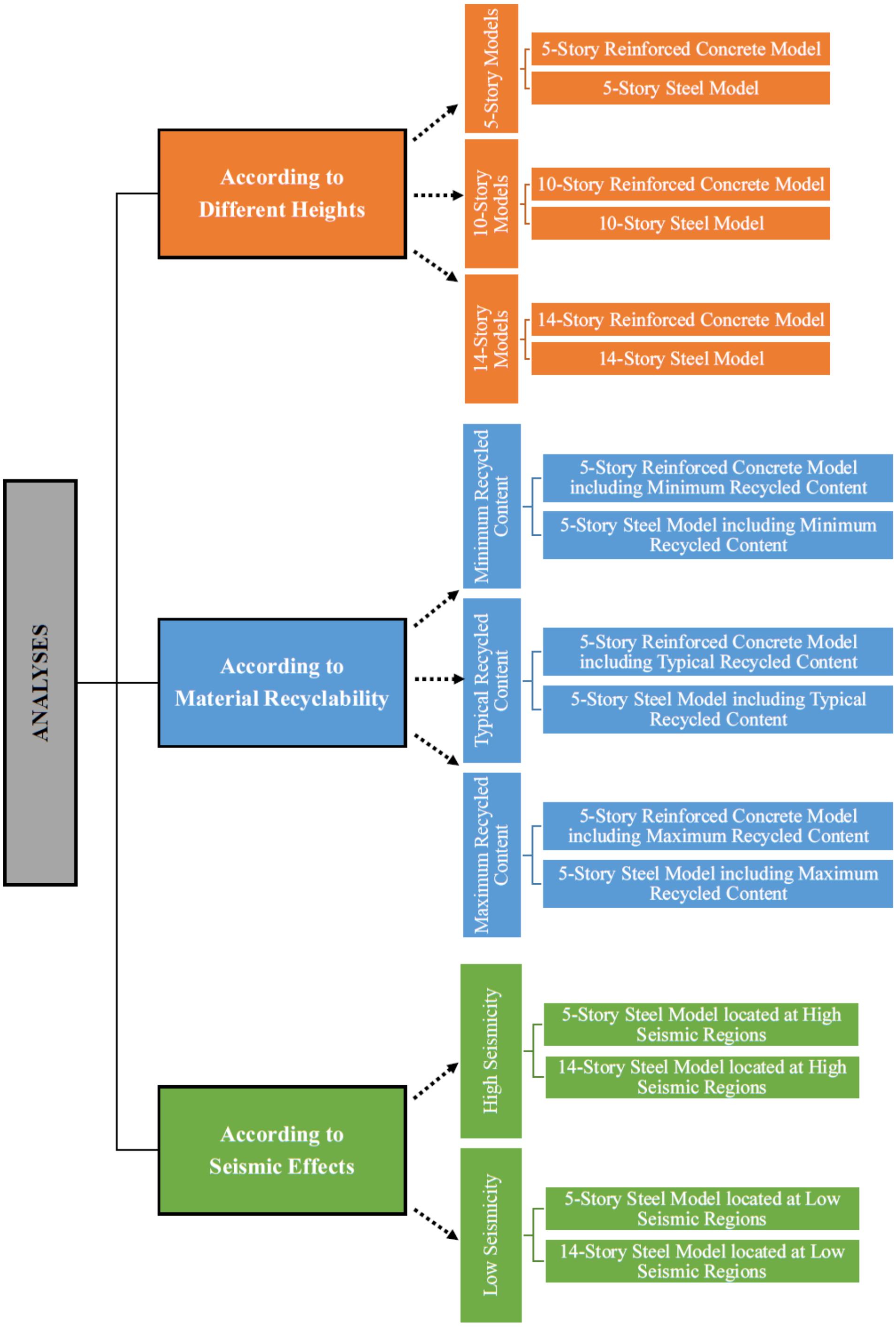


Figure 3.32. The Analysis Types

CHAPTER 4

ANALYSES AND RESULTS

This part involves the results of the analysis and it continues with the discussion part. In the results part, there are four sections including the result of structural analyses, the results of life cycle assessment studies, the comparison of the results belonging to typical-minimum-maximum sustainable models, the case of low seismicity for low-rise and high-rise steel models. The discussion part contains the clarification of the results and the comparison of this thesis with previous studies.

4.1 Results of Research

4.1.1 Results of ProtaStructure's Analyses

In this section, the structural analysis results of successful models are given and compared by categorizing models according to their heights.

Firstly, to fairly represent the building height between low-rise and mid-rise buildings, 5-story models are designed in ProtaStructure. RC5 (5-story reinforced concrete model) and SS5 (5-story steel model) are shown in Figure 4.1.

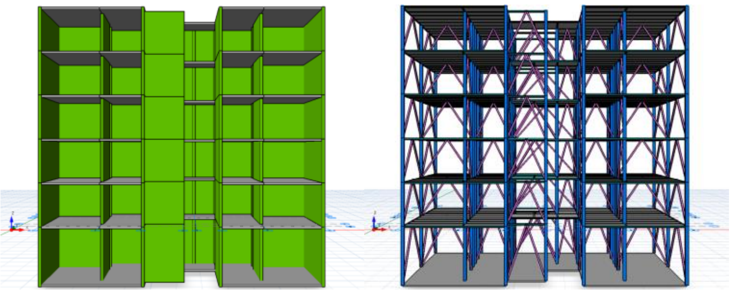


Figure 4.1. 5-Story Reinforced Concrete Model (left) and 5-Story Steel Model (right)

Table 4.1 shows the vibration period and mass participation ratio of RC5. The vibration period of the model along the X-direction is close to 0.24 seconds while The vibration period of the model along the Y-direction is nearly 0.19 seconds.

Table 4.1 The Vibration Period and Mass Participation Ratio of RC5

	X Direction			Y Direction		
	Natural Vibration Period (sec.)	**Mode Number**	**Mass Participation Ratio**	**Natural Vibration Period (sec.)**	**Mode Number**	**Mass Participation Ratio**
All Model	0.237211	1	71.12	0.191765	2	72.02

Table 4.2 shows the vibration period and mass participation ratio of SS5. Nearly 0.48 seconds is the vibration period of the model along the X-direction and approximately 0.35 seconds is the vibration period of the model along the Y-direction.

Table 4.2 The Vibration Period and Mass Participation Ratio of SS5

	X Direction			Y Direction		
	Natural Vibration Period (sec.)	**Mode Number**	**Mass Participation Ratio**	**Natural Vibration Period (sec.)**	**Mode Number**	**Mass Participation Ratio**
All Model	0.485514	1	84.29	0.346896	2	84.05

In the structural analysis, 12 modes are taken into account and the mass participation ratio value is automatically controlled by ProtaStructure to satisfy the requirements of TEC 2018. Periods of RC5 are about half of SS5 at both X and Y directions since it is made up of reinforced concrete and has a lot of shear walls for both two directions. 6 modes of the five-story reinforced concrete model and five-story steel model are compared in Table 4.3. Since the steel model has higher periods, the design spectrum (TEC, 2018) yields lower acceleration values for the steel model compared to the reinforced concrete model.

Table 4.3 Periods of Five-Story Models

Periods (6 Modes)	**RC5**	**SS5**
Mode 1	0.237	0.486
Mode 2	0.192	0.347
Mode 3	0.156	0.322
Mode 4	0.062	0.166
Mode 5	0.047	0.118
Mode 6	0.042	0.110

The report shows the mass of the models below the title of Floor Mass, Floor Weights, and Diaphragm Definitions. Table 4.4 shows the total seismic weight of the models for RC5 and SS5. The total seismic floor weight of RC5 is more than 2.5 times the total floor weight of SS5 as is understood from the table.

Table 4.4 Total Seismic Weight of Floors Belonging to RC5 and SS5

	G(t)	**Q(t)**	**W(t)**
Total of RC5	1,536.86	233.54	**1,606.92**
Total of SS5	568.58	233.54	**638.64**

(G, Q: Dead and Live Loads - W: Seismic Weight of Floors) (W = G + nQ) (n=0.3)

Thereafter, the report explains the earthquake loads with the fundamental periods of the floors. It is gathered in Table 4.5 for RC5 and SS5. For X-direction, the earthquake load of RC5 is nearly equal to 4.5 times SS5’s earthquake load. For Y-direction, RC5’s earthquake load is approximately 3.5 times SS5’s earthquake load.

Table 4.5 Earthquake Loads with Periods for RC5 and SS5

	Earthquake Loads of RC5		**Earthquake Loads of SS5**	
Floors	**Fx (t)**	**Fy (t)**	**Fx (t)**	**Fy (t)**
5	141.708	156.366	31.306	43.680
4	101.503	112.002	22.424	31.287
3	76.127	84.001	16.818	23.465
2	50.751	56.001	11.212	15.643
1	25.376	28.000	5.606	7.822
Total	**395.465**	**436.370**	**87.367**	**121.897**
Basement Floor	82.202	82.202	33.348	33.348
	X Direction	**Y Direction**	**X Direction**	**Y Direction**
Periods (second)	0.237	0.192	0.486	0.347
Spectral Acceleration	0.295	0.326	0.165	0.230

In the title of Earthquake Overturning Control of Building, ProtaStructure calculates the modal overturning moment of the floors. Total overturning resisting moment of floors is divided into the total overturning moment of floors and this value should be higher than or equal to 2 according to the regulation.

As it is seen in Table 4.6, the modal overturning control of direction 1 (X) is proper with 3.68 whereas it is slightly higher than 2.00 for direction 2 (Y) in the RC5 model.

Table 4.7 shows the control of the modal overturning moment that belongs to SS5. For direction 1, the value of moment division is higher than 5.24 while it is higher than 2.32 for direction 2.

In Table 4.6 and Table 4.7, M_{a1} and M_{a2} represent the overturning moments of floors while M_{p1} and M_{p2} show the overturning resisting moments of floors.

Table 4.6 Overturning Control of RC5

	Direction 1 (X)		**Direction 2 (Y)**	
	M_{a1} (t.m)	**M_{p1} (t.m)**	**M_{a2} (t.m)**	**M_{p2} (t.m)**
Total of Floors	**3,527.55**	**12,973.45**	**3,892.42**	**7,795.30**
Overturning Control	**M_{p1} / M_{a1} = 12,973.45 / 3,527.55 = 3.6777 ≥ 2.0 √**		**M_{p2} / M_{a2} = 7,795.30 / 3,892.42 = 2.0027 ≥ 2.0 √**	

Table 4.7 Overturning Control of SS5

	Direction 1 (X)		**Direction 2 (Y)**	
	M_{a1} (t.m)	**M_{p1} (t.m)**	**M_{a2} (t.m)**	**M_{p2} (t.m)**
Total of Floors	**974.14**	**5,109.23**	**1,359.15**	**3,163.72**
Overturning Control	**M_{p1} / M_{a1} = 5,109.23 / 974.14 = 5.2449 ≥ 2.0 √**		**M_{p2} / M_{a2} = 3,163.72 / 1,359.15 = 2.3277 ≥ 2.0 √**	

Secondly, to present the building height between mid-rise and high-rise buildings, 10-story models are formed in ProtaStructure. RC10 (10-story reinforced concrete model) and SS10 (10-story steel model) are shown in Figure 4.2.

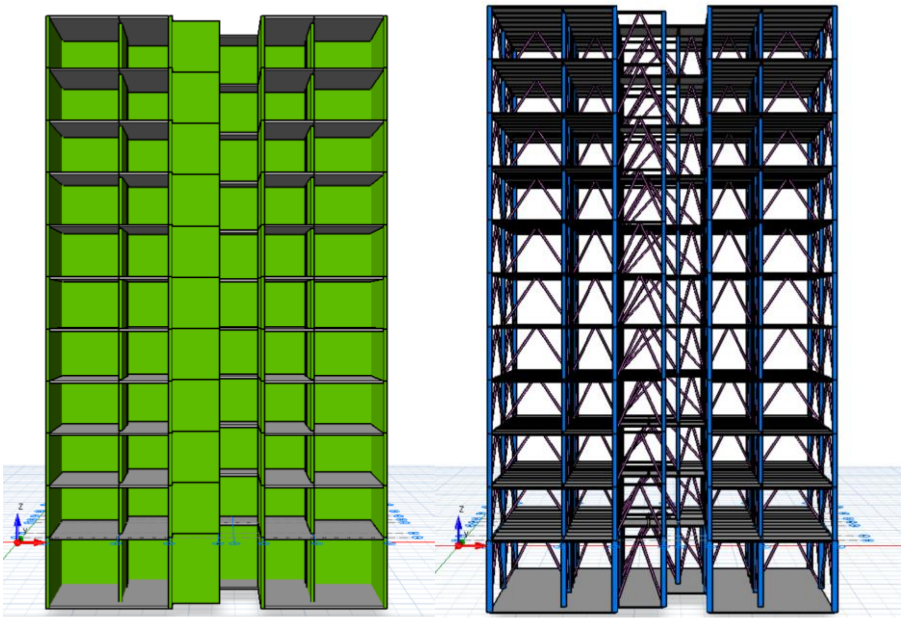


Figure 4.2. 10-Story Reinforced Concrete Model (left) and 10-Story Steel Model (right)

Table 4.8 shows the vibration period and mass participation ratio for RC10. The period of X-direction at the model is close to 0.56 seconds while the period of Y-direction at the model is nearly 0.53 seconds. The values of SS10 are shown in Table 4.9 about the vibration period and mass participation ratio. In the model, 0.90 seconds is the period of X-direction and 0.71 seconds is the period of Y-direction.

Table 4.8 The Vibration Period and Mass Participation Ratio of RC10

	X Direction			**Y Direction**		
	Natural Vibration Period (sec.)	**Mode Number**	**Mass Participation Ratio**	**Natural Vibration Period (sec.)**	**Mode Number**	**Mass Participation Ratio**
All Model	0.558948	1	66.87	0.530209	2	66.83

Table 4.9 The Vibration Period and Mass Participation Ratio of SS10

	X Direction			Y Direction		
	Natural Vibration Period (sec.)	**Mode Number**	**Mass Participation Ratio**	**Natural Vibration Period (sec.)**	**Mode Number**	**Mass Participation Ratio**
All Model	0.906446	1	73.64	0.710229	2	72.10

Periods of SS10 are higher than periods of RC10 at both X and Y directions. For X-direction, SS10's period is nearly 1.6 times RC10's period but for Y-direction, it is nearly 1.3 times RC10's period. The periods of the ten-story reinforced concrete model and ten-story steel model are compared in Table 4.10.

Table 4.10 Periods of Ten-Story Models

Periods (6 Modes)	**RC10**	**SS10**
Mode 1	0.559	0.906
Mode 2	0.530	0.710
Mode 3	0.368	0.625
Mode 4	0.132	0.294
Mode 5	0.110	0.216
Mode 6	0.092	0.200

Table 4.11 shows the total seismic floor weight for the 10-story models. The total seismic floor weight of RC10 is approximately 3 times SS10's total floor weight. The earthquake loads of RC10 and SS10 are gathered in Table 4.12. For X-direction, the earthquake load of RC10 is more than 3.5 times SS10's earthquake load. For Y-direction, RC10's earthquake load is nearly equal to 3 times SS10's earthquake load.

Table 4.11 Total Seismic Weight of Floors Belonging to RC10 and SS10

	G(t)	Q(t)	W(t)
Total of RC10	2,947.164	428.152	**3,075.610**
Total of SS10	1,048.335	428.152	**1,176.781**

(G, Q: Dead and Live Loads - W: Seismic Weight of Floors) (W = G + nQ) (n=0.3)

Table 4.12 Earthquake Loads with Periods for RC10 and SS10

	Earthquake Loads of RC10		**Earthquake Loads of SS10**	
Floors	**Fx (t)**	**Fy (t)**	**Fx (t)**	**Fy (t)**
10	81.229	85.409	22.784	29.057
9	50.559	53.161	14.181	18.086
8	44.942	47.254	12.606	16.076
7	39.324	41.347	11.030	14.067
6	33.706	35.441	9.454	12.057
5	28.088	29.534	7.879	10.048
4	22.471	23.627	6.303	8.038
3	16.853	17.720	4.727	6.029
2	11.235	11.814	3.151	4.019
1	5.618	5.907	1.576	2.010
Total	**334.025**	**351.213**	**93.691**	**119.486**
Basement Floor	85.818	85.818	35.847	35.847
	X Direction	**Y Direction**	**X Direction**	**Y Direction**
Periods (second)	0.559	0.530	0.906	0.710
Spectral Acceleration	0.119	0.126	0.088	0.113

Earthquake Overturning Control of Building for RC10 is demonstrated in Table 4.13. The division of total overturning resisting moment of floors to the total overturning moment of floors is checked according to the regulation by ProtaStructure. In the RC10 model, the modal overturning control of direction 1 is valid with 3.74 when it is proper with the value of 2.12 for direction 2.

Table 4.14 shows the control of the modal overturning moment for SS10. For direction 1, the value of moment division is very close to 5.00 when it is 2.44 for direction 2. They are proper according to the regulation since both of them are higher than 2.0.

In Table 4.13 and Table 4.14, M_{a1} and M_{a2} represent the overturning moments of floors while M_{p1} and M_{p2} show the overturning resisting moments of floors.

Table 4.13 Overturning Control of RC10

	Direction 1 (X)		**Direction 2 (Y)**	
	M_{a1} (t.m)	**M_{p1} (t.m)**	**M_{a2} (t.m)**	**M_{p2} (t.m)**
Total of Floors	**7,240.00**	**27,108.14**	**7,612.54**	**16,131.92**
Overturning Control	**M_{p1} / M_{a1} = 27,108.14 / 7,240.00 = 3.7442 $\geq$ 2.0 √**		**M_{p2} / M_{a2} = 16,131.92 / 7,612.54 = 2.1191 $\geq$ 2.0 √**	

Table 4.14 Overturning Control of SS10

	Direction 1 (X)		**Direction 2 (Y)**	
Floors	**M_{a1} (t.m)**	**M_{p1} (t.m)**	**M_{a2} (t.m)**	**M_{p2} (t.m)**
Total	**2,030.75**	**10,218.46**	**2,589.87**	**6,327.45**
Overturning Control	**M_{p1} / M_{a1} = 10,218.46 / 2,030.75 = 5.0319 $\geq$ 2.0 √**		**M_{p2} / M_{a2} = 6,327.45 / 2,589.87 = 2.4432 $\geq$ 2.0 √**	

Thirdly, to present the building height between high-rise and tall buildings, 14-story models are created in ProtaStructure. Figure 4.3 shows RC14 (14-story reinforced concrete model) and SS14 (14-story steel model).

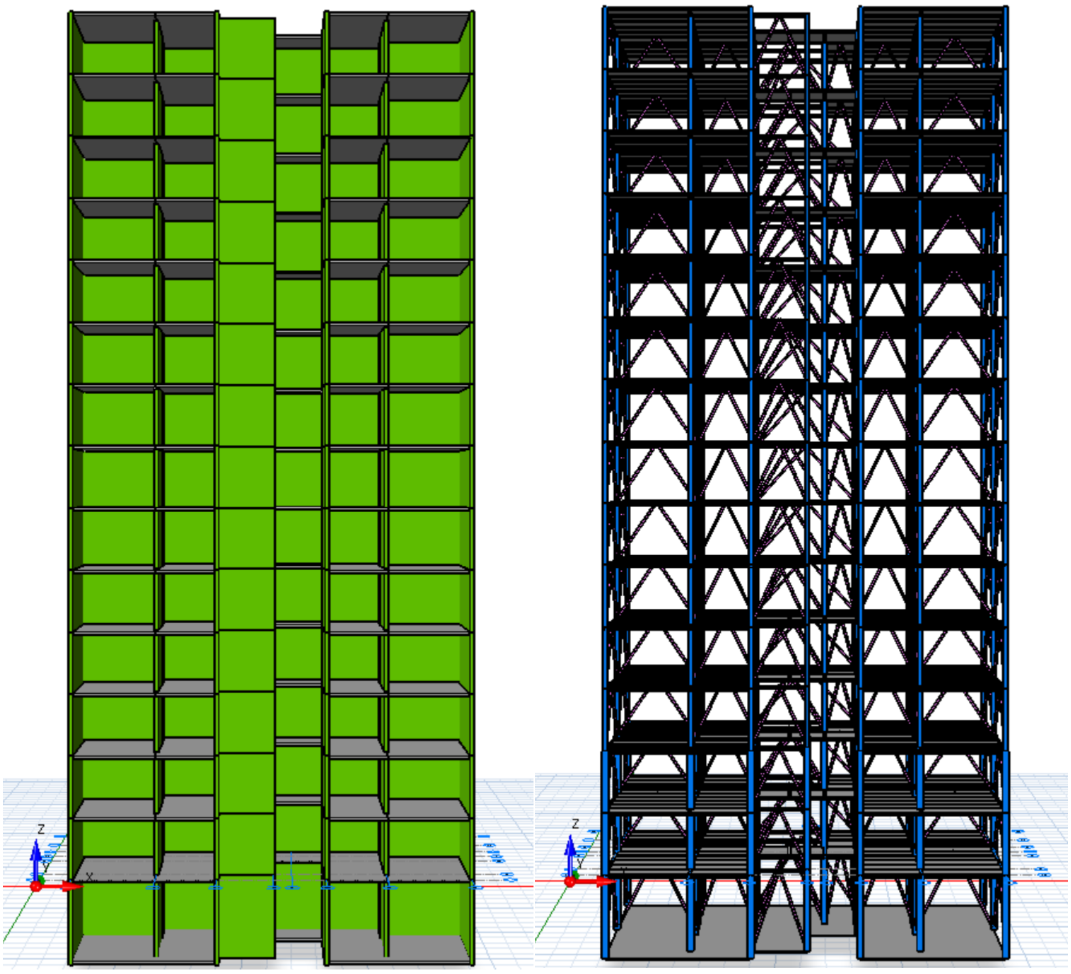


Figure 4.3. 14-Story Reinforced Concrete Model (left) and 14-Story Steel Model (right)

Table 4.15 shows the values of RC14 about the vibration period and mass participation ratio. The period of X-direction is very close to 0.86 seconds at the model and the period is nearly 0.91 seconds for Y-direction at the model.

Table 4.15 The Vibration Period and Mass Participation Ratio of RC14

	X Direction			**Y Direction**		
	Natural Vibration Period (sec.)	**Mode Number**	**Mass Participation Ratio**	**Natural Vibration Period (sec.)**	**Mode Number**	**Mass Participation Ratio**
All Model	0.857751	2	65.85	0.914711	1	65.38

Table 4.16 shows the values of SS14 about the vibration period and mass participation ratio. The period of X-direction at the model is nearly 1.27 seconds and almost 1.06 seconds is the period of Y-direction.

Table 4.16 The Vibration Period and Mass Participation Ratio of SS14

	X Direction			**Y Direction**		
	Natural Vibration Period (sec.)	**Mode Number**	**Mass Participation Ratio**	**Natural Vibration Period (sec.)**	**Mode Number**	**Mass Participation Ratio**
All Model	1.266771	1	70.01	1.058524	2	68.90

If periods of RC14 and SS14 are examined, it is seen that SS14 exceeds 1.0 seconds at both two directions when RC14 still has lower periods than 1.0 seconds at two directions. The periods of the fourteen-story reinforced concrete model and fourteen-story steel model are compared in Table 4.17.

Table 4.17 Periods of Fourteen-Story Models

Periods (6 Modes)	**RC14**	**SS14**
Mode 1	0.915	1.267
Mode 2	0.858	1.059
Mode 3	0.554	0.906
Mode 4	0.196	0.408
Mode 5	0.181	0.312
Mode 6	0.142	0.284

Table 4.18 shows the values of the total seismic weight for 14-story models. RC14's total floor weight is closely 3 times SS14's total floor weight.

Table 4.18 Total Seismic Weight of Floors Belonging to RC14 and SS14

	G(t)	**Q(t)**	**W(t)**
Total of RC14	4,372.536	583.844	**4,547.689**
Total of SS14	1,447.392	583.844	**1,622.545**

(G, Q: Dead and Live Loads - W: Seismic Weight of Floors) (W = G + nQ) (n=0.3)

Table 4.19 is prepared to gather the earthquake loads of RC14 and SS14. As similar to RC10 and SS10, the earthquake load of RC14 is very close to 3.5 times SS14's earthquake load for X-direction. For Y-direction, RC14's earthquake load is more than 2.5 times SS14's earthquake load.

Table 4.19 Earthquake Loads with Periods for RC14 and SS14

	Earthquake Loads of RC14		**Earthquake Loads of SS14**	
Floors	**Fx (t)**	**Fy (t)**	**Fx (t)**	**Fy (t)**
14	74.237	69.445	21.270	25.514
13	36.670	34.303	10.514	12.612
12	33.849	31.664	9.706	11.642
11	31.028	29.025	8.897	10.672
10	28.207	26.387	8.088	9.702
9	25.387	23.748	7.279	8.732
8	22.566	21.109	6.470	7.762
7	19.745	18.471	5.662	6.791
6	16.924	15.832	4.853	5.821
5	14.104	13.193	4.044	4.851
4	11.283	10.555	3.235	3.881
3	8.462	7.916	2.426	2.911
2	5.641	5.277	1.698	2.037
1	2.821	2.639	0.849	1.018
Total	**330.925**	**309.564**	**94.991**	**113.946**
Basement Floor	93.055	93.055	36.079	36.079
	X Direction	**Y Direction**	**X Direction**	**Y Direction**
Periods (second)	0.858	0.915	1.267	1.059
Spectral Acceleration	0.078	0.073	0.063	0.076

For RC14, Earthquake Overturning Controls of Building is demonstrated in Table 4.20. The modal overturning control of direction 1 is 4.09 and it is 2.56 for direction 2, in the RC14 model.

For SS14, Table 4.21 shows the control of the modal overturning moment. For direction 1, the moment division is very close to 5.00 when it is very close to 2.50 for direction 2. Since both of these divisions are higher than 2.0, they are valid for the regulation.

In Table 4.20 and Table 4.21, M_{a1} and M_{a2} represent the overturning moments of floors while M_{p1} and M_{p2} show the overturning resisting moments of floors.

Table 4.20 Overturning Control of RC14

	Direction 1 (X)		**Direction 2 (Y)**	
	M_{a1} (t.m)	**M_{p1} (t.m)**	**M_{a2} (t.m)**	**M_{p2} (t.m)**
Total of Floors	**10,048.53**	**41,077.57**	**9,399.90**	**24,101.22**
Overturning Control	**M_{p1} / M_{a1} = 41,077.57 / 10,048.53 = 4.0879 $\geq$ 2.0** √		**M_{p2} / M_{a2} = 24,101.22 / 9,399.90 = 2.564 $\geq$ 2.0** √	

Table 4.21 Overturning Control of SS14

	Direction 1 (X)		**Direction 2 (Y)**	
	M_{a1} (t.m)	**M_{p1} (t.m)**	**M_{a2} (t.m)**	**M_{p2} (t.m)**
Total of Floors	**2,881.15**	**14,511.55**	**3,456.07**	**8,980.72**
Overturning Control	**M_{p1} / M_{a1} = 14,511.55 / 2,881.15 = 5.0367 $\geq$ 2.0** √		**M_{p2} / M_{a2} = 8,980.72 / 3,456.07 = 2.5985 $\geq$ 2.0** √	

When the results and properties of the six models are examined, it is seen that the periods are increasing with the floor number, firstly. Figure 4.4 summarizes this increase in the X and Y direction. The periods of the reinforced concrete models start with 0.192 seconds at RC5 and rise to 0.915 seconds at RC14. However, steel models have much higher periods than reinforced concrete models. Steel models begin with

0.347 at SS5 and reach 1.267 at SS14. As a result, the value of the design spectral acceleration of the reinforced concrete models is higher than that of the steel models because the periods reinforced concrete models are lower than the steel models. This situation increases the loads affecting the reinforced concrete models since the seismic force is proportional to the mass and the acceleration.

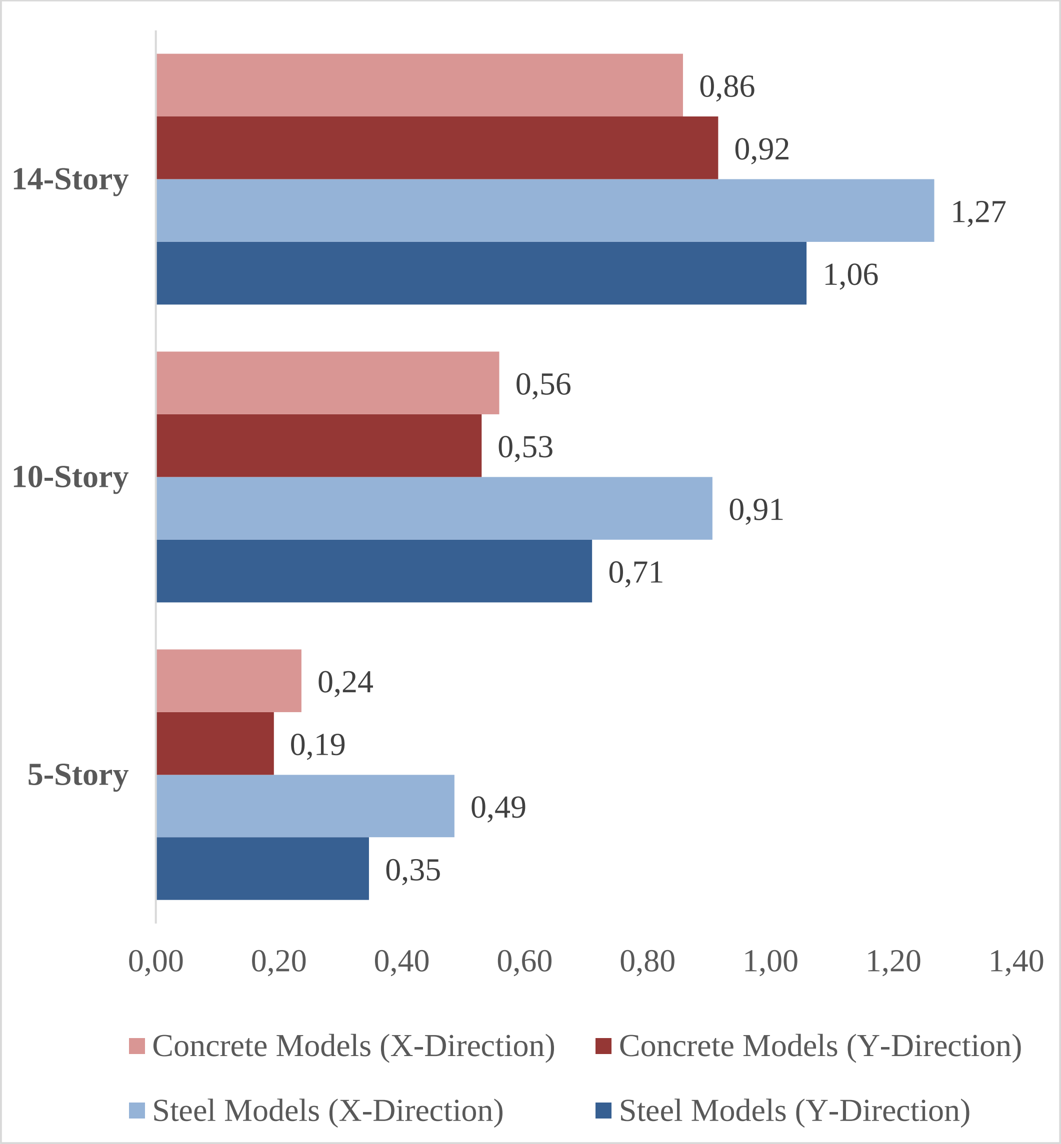


Figure 4.4. Fundamental Periods in Both Principle Directions

Figure 4.5 shows the summary of the total seismic weight that belongs to six models. The seismic weight of the models is calculated from dead and live loads. Same live loads are applied to the models. According to the table, the values of reinforced concrete models are higher than the values of steel models. This is a result of the fact that dead loads of steel are lower than the reinforced concrete models. Moreover, if the total floor weight of a reinforced concrete model is divided into the steel model's total floor weight, it is easily seen that the ratio between reinforced concrete and steel models is increasing with the increase of floor number. From 10-story models to 14-story ones, there is a more dramatic rise than the increase ratio from 5-story models to 10-story ones (Figure 4.6). So, it means that the total seismic floor weight of reinforced concrete models increases sharply with the rise of floor number while the total seismic floor weight of steel models goes up slightly with floor number.

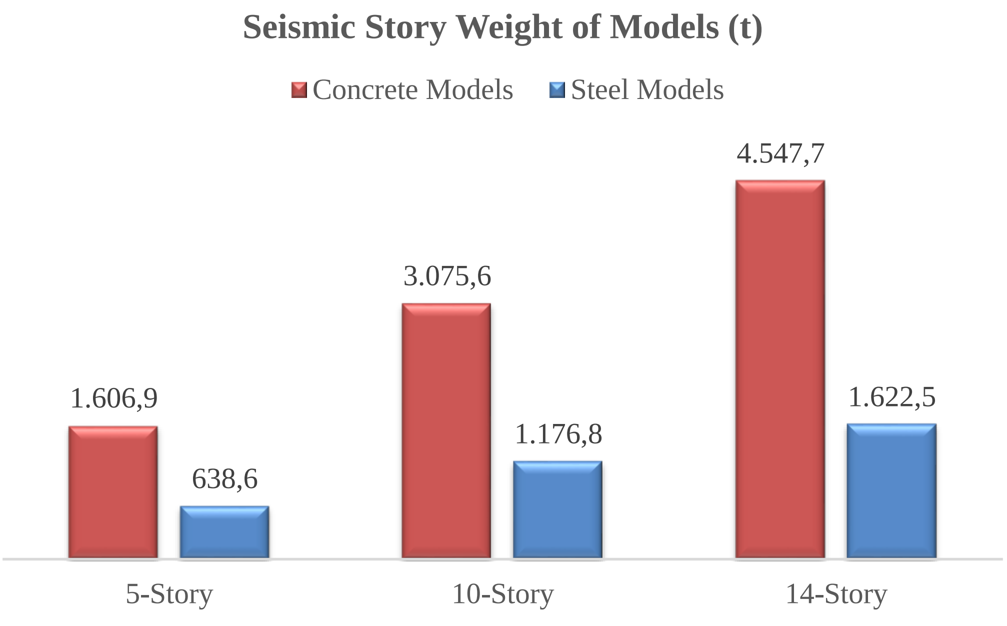


Figure 4.5. Total Seismic Weight of Models

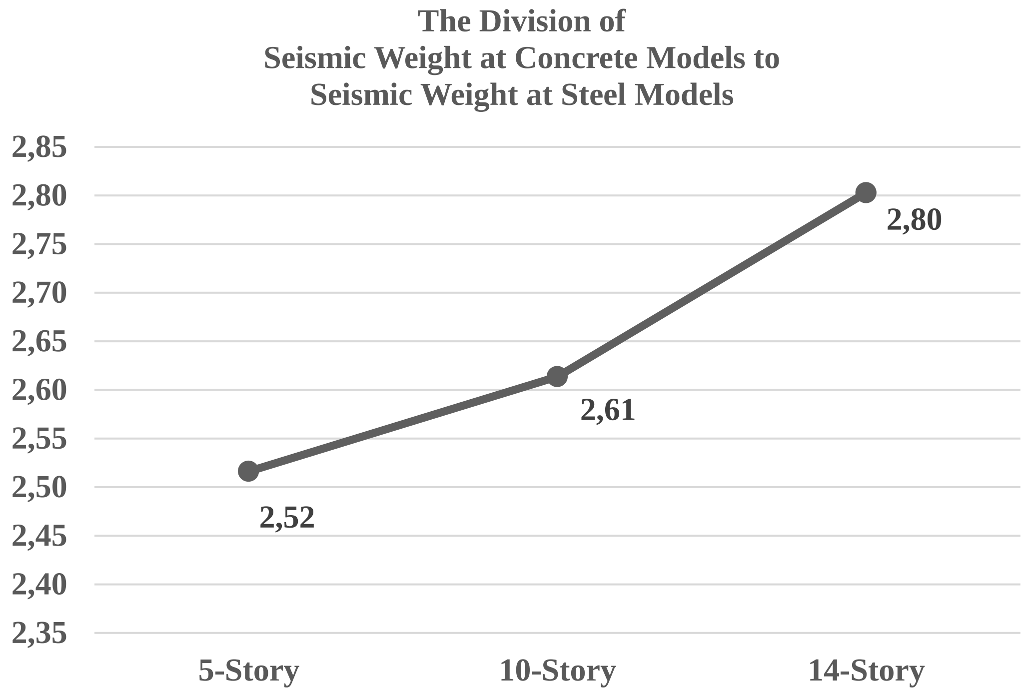


Figure 4.6. The Floor Weight Ratio between Reinforced Concrete and Steel Models

When earthquake loads of models are compared, steel models are affected by lower values of earthquake loads differently from reinforced concrete models (Figure 4.7). If the load of a reinforced concrete model is divided to the load of the steel model for each X and Y direction, a ratio is gained. For X-direction, the earthquake load of the reinforced concrete model is almost 3.5 times of the steel model as the minimum ratio. As the maximum ratio for X-direction, the reinforced concrete model is nearly 4.5 times of the steel model. For Y-direction, the earthquake load of the reinforced concrete model is about 3 times of the steel model and it exceeds 3.5 times of the steel model at the 5-story sample (Figure 4.8).

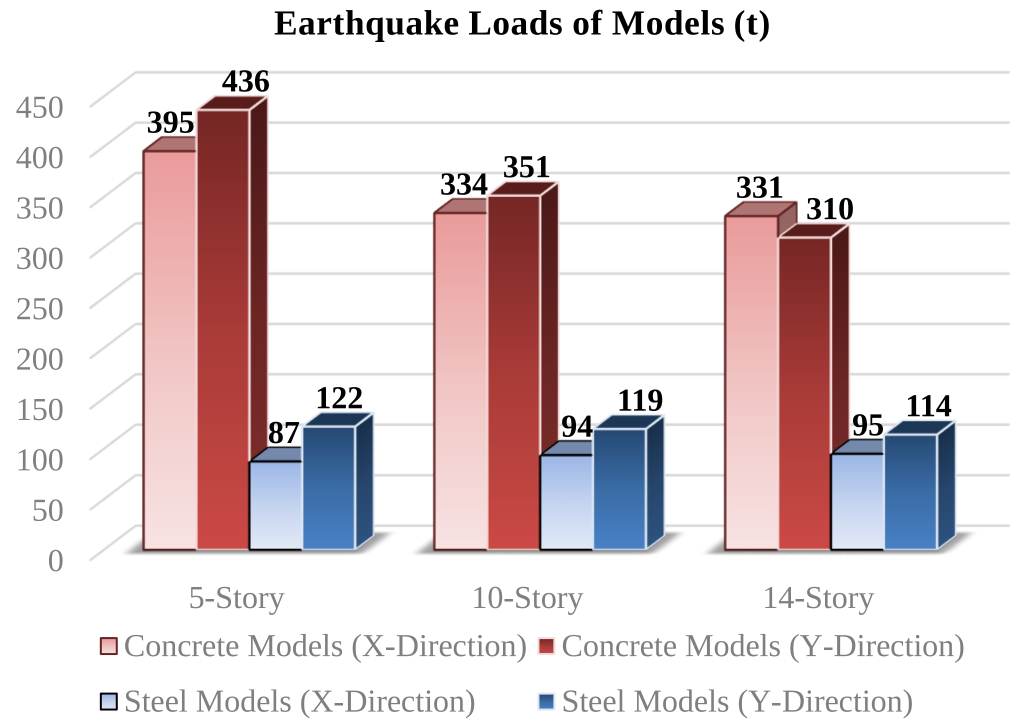


Figure 4.7. Earthquake Loads of Models according to X and Y Direction

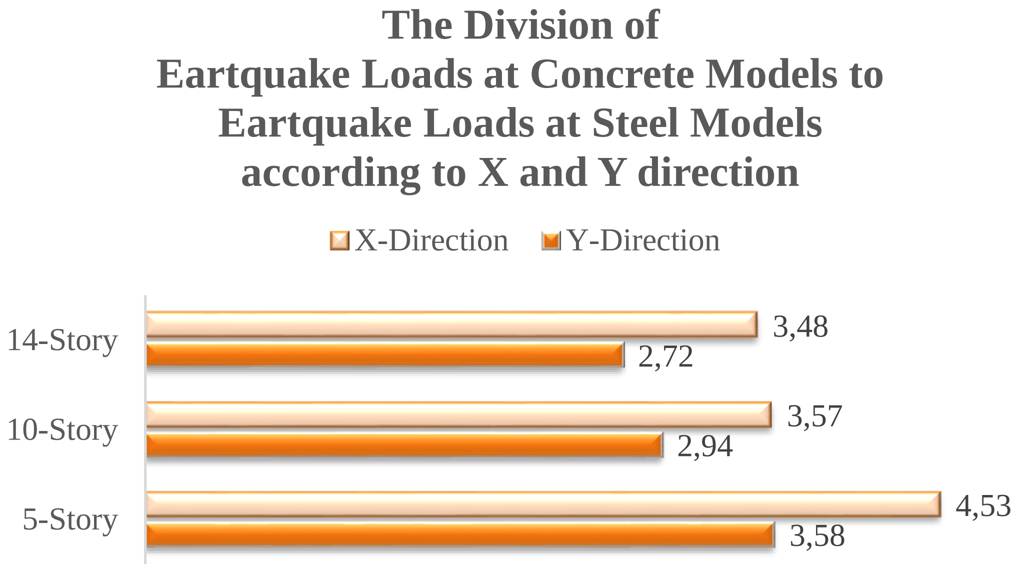


Figure 4.8. Earthquake Loads Ratio between Reinforced Concrete and Steel Models

In short, the structural analysis conducted in ProtaStructure reveals that steel models have much higher periods than reinforced concrete models in three different heights. However, total seismic floor weight increases in reinforced concrete models with a rising ratio. Also, earthquake loads of reinforced concrete models are always much more than steel models in both two directions.

4.1.2 Results of OneClickLCA Studies

This section explains the LCA results of reinforced concrete and steel models taken from OneClickLCA. When proper data is uploaded to OneClickLCA as is explained in Chapter 3, the program gives a result page on the website for each model. Moreover, OneClickLCA presents a material library. The materials have a different ratio of recyclability in this library and there is a typical option for each material. The results of the models that are analyzed with the typical option of the selections are studied in this section (Table 4.22).

Table 4.22 Selection of Material in OneClickLCA

	Slabs	**Walls**
Reinforced Concrete Models (RC5, RC10, RC14)	**Ready-mix reinforced concrete**, normal-strength, generic, **C30/37 (4400/5400 PSI), 10% (typical) recycled binders in cement** (300 kg/m^3 / 18.72 lbs/ft^3)	**Ready-mix reinforced concrete**, normal-strength, generic, **C30/37 (4400/5400 PSI), 10% (typical) recycled binders in cement** (300 kg/m^3 / 18.72 lbs/ft^3)
	Slabs	**Steel Columns, Beams and Braces**
Steel Models (SS5, SS10, SS14)	**Ready-mix reinforced concrete**, normal-strength, generic, **C30/37 (4400/5400 PSI), 10% (typical) recycled binders in cement** (300 kg/m^3 / 18.72 lbs/ft^3)	**Structural steel profiles,** generic, **90% recycled content (typical),** I, H, U, L, and T sections

The recyclability of reinforced concrete materials is expressed with the percentage of “recycled binders in cement”. For the production of concrete, Portland cement is generally used and the production requires a lot of energy. Indeed, each kg of Portland clinker releases approximately 1 kg of CO_2 into the atmosphere (Nielsen, 2008). Therefore; alternative binders to Portland cement are used to decrease the emission value of the concrete. The expression of “recycled binders in cement” represents these alternative binders.

The recyclability of steel materials is given with the description of “recycled content”. Steel is preferred because of its recyclability and recycled content (Sinha et al., 2013). If only raw materials are used during the production of structural steel profiles, this means that this steel includes 0% recycled content and 100% raw sources. Accordingly, the expression of “90% recycled content” defines that this type of structural steel includes 10% raw materials.

OneClickLCA gives a detailed result table for each model. This table shows the values of LCA parameters which are global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), formation of ozone of lower atmosphere (FOLA), total use of primary energy (TOTAL UPE). These values are demonstrated in this table according to the life cycle stages which are construction materials, transportation to site, construction/installation process, maintenance and material replacement, energy use, water use, deconstruction, external impacts. Also, the table shows the values of these parameters according to the unit floor area via dividing the result by the total gross internal floor area. The construction phase, usage stage, maintenance, and material replacement of the models are not in the scope of this thesis. This is because appropriate data is needed for these stages. Therefore; the results of four parameters including construction/installation process, maintenance and material replacement, energy use, and water use have the value of zero “0”.

The results of the 5-story reinforced concrete (RC5) and steel (SS5) models are given in Table 4.23 and Table 4.24, respectively. The results of the 10-story models are shown in Table 4.25 for the reinforced concrete model (RC10) and Table 4.26 for the steel model (SS10). For the 14-story models, Table 4.27 gives the results of the reinforced concrete model (RC14) and Table 4.28 for the steel model (SS14). The stages having the value of zero “0” for the result are not shown in these tables.

Table 4.23 LCA Results of RC5

	Result category	**GWP**	**AP**	**EP**	**ODP**	**FOLA**	**TOTAL UPE**
		kg CO_2e	**kg SO_2e**	**kg PO_4e**	**kg CFC11e**	**kg Ethenee**	**MJ**
A1-A3	Construction materials	168,540.86	399.19	53.08	0.00440	17.11	862,249.23
A4	Transportation to site	10,427.04	15.24	3.11	0.00180	1.56	158,811.84
C1-C4	Deconstruction	14,825.4	47.79	11.49	0.00280	1.33	363,134.87
D	External impacts (not included in totals)	-32,764.63	-68.22	-23.56	-0.00082	-3.98	-167,974.85
	Total	**193,793.3**	**462.21**	**67.68**	**0.00900**	**20**	**1,384,195.94**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	150,93	0,36	0,05	6.943E-6	0,02	1,078.03

Table 4.24 LCA Results of SS5

	Result category	**GWP**	**AP**	**EP**	**ODP**	**FOLA**	**TOTAL UPE**
		kg CO_2e	**kg SO_2e**	**kg PO_4e**	**kg CFC11e**	**kg Ethenee**	**MJ**
A1-A3	Construction materials	99,148.84	333.3	49.18	0.00620	32.93	1,315,181.29
A4	Transportation to site	3,156.25	8.53	1.82	0.00057	0.36	64,572.86
C1-C4	Deconstruction	3,396.88	11.46	2.67	0.00064	0.34	85,887.71
D	External impacts (not included in totals)	-19,015.19	-68.67	-23.09	-0.00081	-10.45	-174,705.33
	Total	**105,701.97**	**353.29**	**53.67**	**0.00741**	**33.62**	**1,465,641.86**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	82.32	0.28	0.04	5.785E-6	0.03	1,141.47

Table 4.25 LCA Results of RC10

	Result category	GWP	AP	EP	ODP	FOLA	TOTAL UPE
		kg CO_2e	**kg SO_2e**	**kg PO_4e**	**kg CFC11e**	**kg Ethenee**	**MJ**
A1-A3	Construction materials	311,967.02	738.89	98.25	0.0081	31.67	1,596,012.48
A4	Transportation to site	19,300.32	28.21	5.76	0.0033	2.9	293,958.72
C1-C4	Deconstruction	27,441.62	88.45	21.26	0.0051	2.47	672,158.08
D	External impacts (not included in totals)	-60,646.93	-126.28	-43.62	-0.0015	-7.37	-310,919.34
	Total	**358,708.96**	**855.55**	**125.27**	**0.0165**	**37.03**	**2,562,129.28**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	152.38	0.36	0.05	7.01E-6	0.02	1,088.42

Table 4.26 LCA Results of SS10

	Result category	GWP	AP	EP	ODP	FOLA	TOTAL UPE
		kg CO_2e	**kg SO_2e**	**kg PO_4e**	**kg CFC11e**	**kg Ethenee**	**MJ**
A1-A3	Construction materials	181,328.62	616.34	91.18	0.0120	61.79	2,460,919.33
A4	Transportation to site	5,567.22	15.58	3.33	0.0010	0.61	116,107.03
C1-C4	Deconstruction	5,845.67	19.81	4.6	0.0011	0.58	148,278.17
D	External impacts (not included in totals)	-34,758.1	-127.55	-42.86	-0.0015	-19.68	-324,737.16
	Total	**192,741.51**	**651.73**	**99.11**	**0.0141**	**62.99**	**2,725,304.53**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	150.11	0.51	0.08	5.835E-6	0.05	2,122.51

Table 4.27 LCA Results of RC14

	Result category	GWP	AP	EP	ODP	FOLA	TOTAL UPE
		kg CO_2e	kg SO_2e	kg PO_4e	kg CFC11e	kg Ethenee	MJ
A1-A3	Construction materials	463,260.43	1,097.22	145.9	0.0120	47.03	2,370,024.36
A4	Transportation to site	28,660.32	41.89	8.55	0.0048	4.3	436,518.72
C1-C4	Deconstruction	40,749.88	131.35	31.57	0.0076	3.66	998,131.93
D	External impacts (not included in totals)	-90,058.63	-187.52	-64.77	-0.0022	-10.95	-461,704.67
	Total	**532,670.63**	**1,270.46**	**186.03**	**0.0244**	**54.99**	**3,804,675.01**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	165.94	0.4	0.06	7.634E-6	0.02	1,185.26

Table 4.28 LCA Results of SS14

	Result category	GWP	AP	EP	ODP	FOLA	TOTAL UPE
		kg CO_2e	kg SO_2e	kg PO_4e	kg CFC11e	kg Ethenee	MJ
A1-A3	Construction materials	269,227.94	928.59	137.84	0.0180	94.87	3,764,454.14
A4	Transportation to site	7,858.31	23.07	4.94	0.0014	0.83	168,440.4
C1-C4	Deconstruction	7,950.48	27.14	6.26	0.0015	0.8	202,670.14
D	External impacts (not included in totals)	-51,571.62	-193.28	-64.9	-0.0023	-30.32	-492,542.65
	Total	**285,036.73**	**978.8**	**149.04**	**0.0206**	**96.51**	**4,135,564.69**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	221.99	0.76	0.12	6.446E-6	0.08	3,220.84

These LCA results of each parameter (GWP, AP, EP, ODP, FOLA, and TOTAL UPE) are compared for 5, 10, 14-story reinforced concrete and steel models in Figure 4.9, 4.10, 4.11, 4.12, 4.13, and 4.14, respectively. The red color is used for reinforced concrete models while steel models are shown with the blue color. The x-axis of figures demonstrates the results and the y-axis gives the number of floors.

One of the most important parameters about LCA is global warming potential, called greenhouse gasses. When the greenhouse gasses in the atmosphere increases, the atmospheric layers near the earth are heated up which results in climate change. When GWP values of six models are compared, reinforced concrete models have higher values than steel models for all types of building height (Figure 4.9). The reason may be the cement inside the reinforced concrete models because cement production is associated with large energy consumption and high CO_2 emissions (Turkish Ready Mixed Concrete Association, 2021). This means reinforced concrete models cause climate change or global warming more than steel models. When the number of floors increases, reinforced concrete models give higher results than steel models. The difference between the results of the reinforced concrete and steel models increases strongly with the rising of the building.

The second parameter is acidification potential. When acidifying substances react with water and fall as “acid rain”, this causes the decomposition of root systems and leaching of nutrients from plants. Figure 4.10 shows the AP results of the models. Reinforced concrete models have higher values than steel models as it happens in global warming potential. So, reinforced concrete models lead to acid rain more than steel models at all building heights.

Figure 4.11 shows the EP results of the models. If this potential is high, excessive food supply occurs and it causes unwanted plant growth in fragile ecosystems like algae growth which results in fish death. The results express that the steel models have lower effects on eutrophication than reinforced concrete models.

Another parameter about LCA is ozone depletion potential which expresses the depletion of the stratospheric ozone layer protecting flora and fauna against harmful UVA and UVB radiation from the sun. OneClickLCA shows the ODP values at models and these values are given with very small numbers by OneClickLCA (Figure 4.12). According to the results, reinforced concrete models have higher potential than steel models in terms of causing the depletion of the ozone layer. The effect of the increase in floor number on AP, EP, and ODP results is similar for reinforced concrete and steel models. As the building rises, the difference between the results of the reinforced concrete and steel models increases slightly.

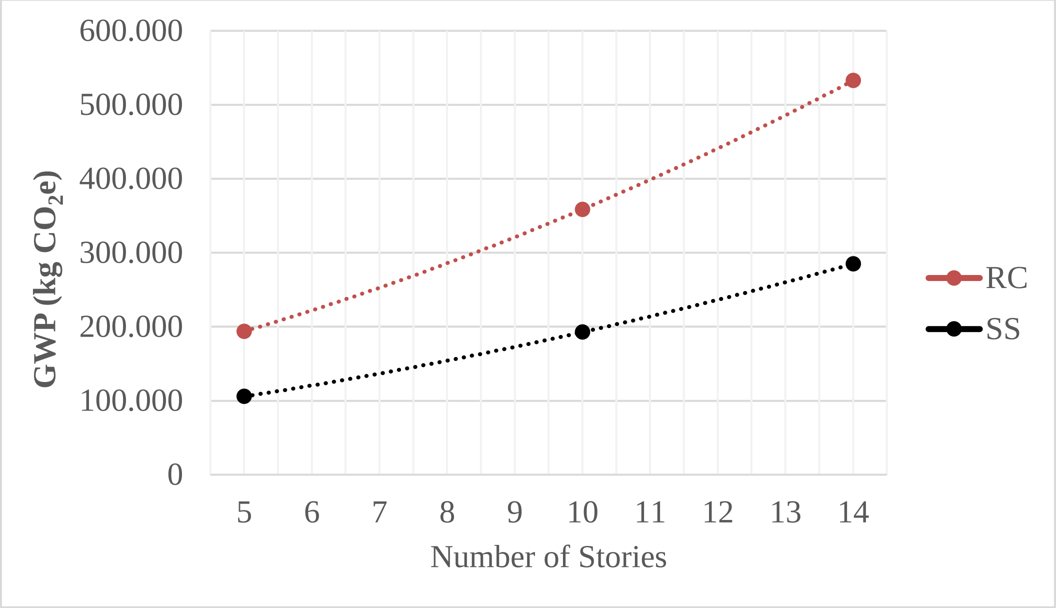


Figure 4.9. The Results of Global Warming Potential

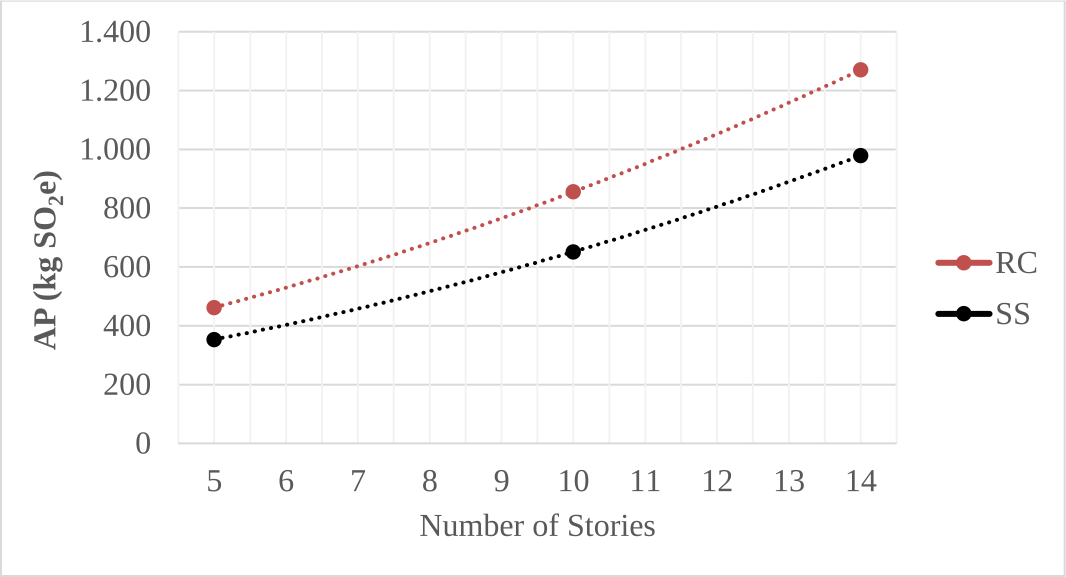


Figure 4.10. The Results of Acidification Potential

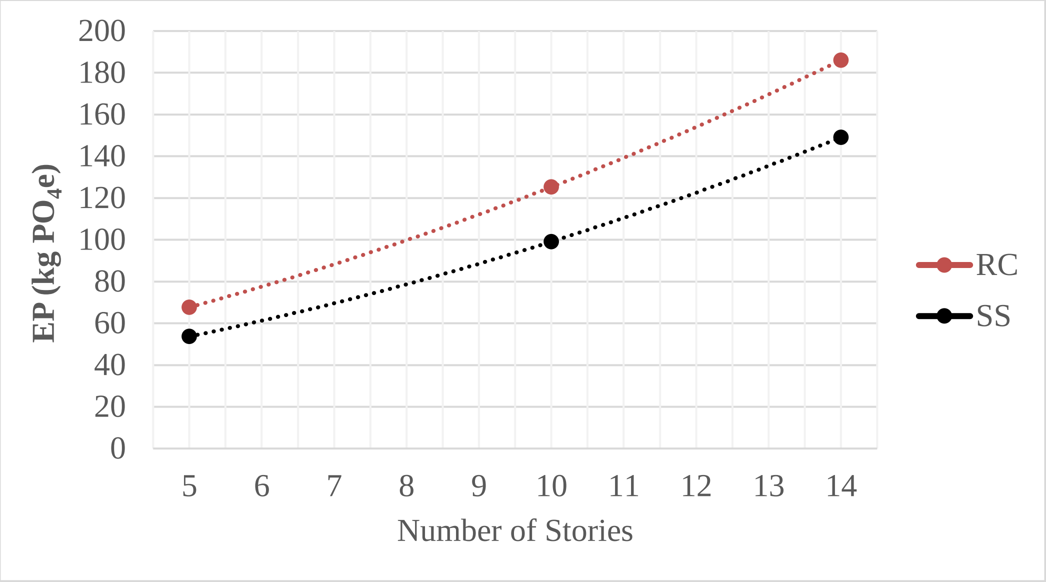


Figure 4.11. The Results of Eutrophication Potential

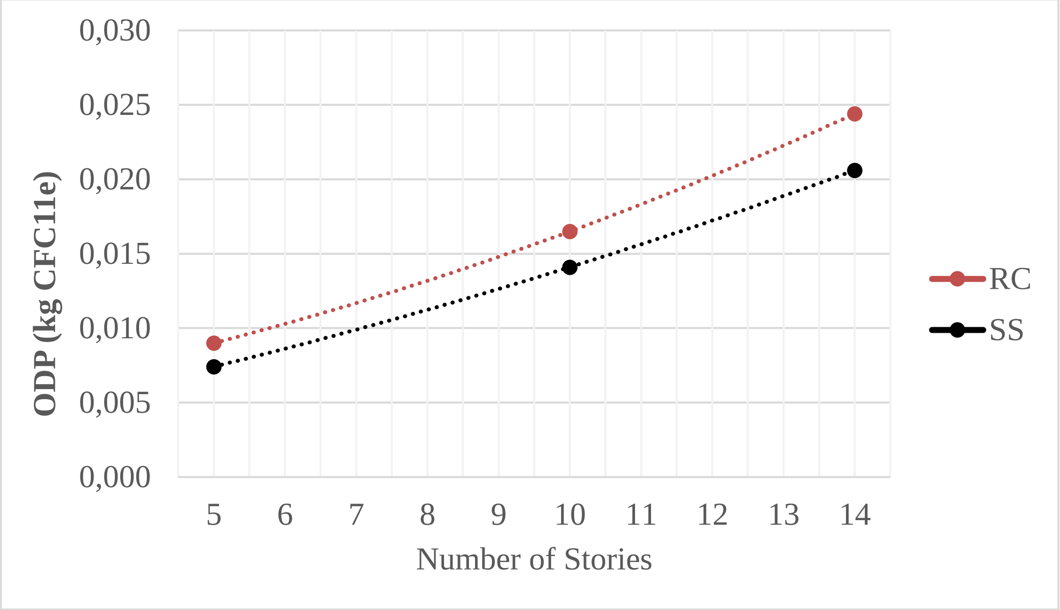


Figure 4.12. The Results of Ozone Depletion Potential

Figure 4.13 compares the FOLA results. This parameter promotes the connection with UV radiation to ozone formation in the lower atmosphere. This is called summer smog harming the respiratory system of people. According to the results, steel models have a higher potential to cause summer smog, and also this danger increases when building height rises. The difference between the results of the reinforced concrete and steel models rises considerably with the increase of the floor number.

The last parameter is the total use of primary energy. This is the sum of non-renewable primary energy use excluding non-renewable primary energy sources used as raw materials and renewable primary energy use excluding renewable primary energy sources used as raw materials. For the models with the same number of stories, the steel models consume more energy than the reinforced concrete models. This is an expected result because steel has the highest embodied energy per unit mass as is explained in Chapter 2. Furthermore, the results of both models rise similarly with the increase in the number of floors. However, the results are higher at steel models for all heights than reinforced concrete models (Figure 4.14).

Figure 4.15 summarizes all results of the models for all parameters. The higher result in a parameter between models is arranged as %100 and the other results are arranged in proportion to 100. In this way, the model that has the highest value is seen easily in the graph.

To sum up the results; three parameters of LCA, GWP, AP, and EP show that reinforced concrete models have higher negative impacts on the environment since these models cause global warming, acid rain, and fragile ecosystems. In terms of ozone depletion, the results of all models have very small values but it is easy to say that reinforced concrete models damage more than steel models. Another parameter of LCA, smog formation occurs more at steel models than reinforced concrete models. Finally, when the total energy use of models is compared, steel models need more energy from the materials of the earth.

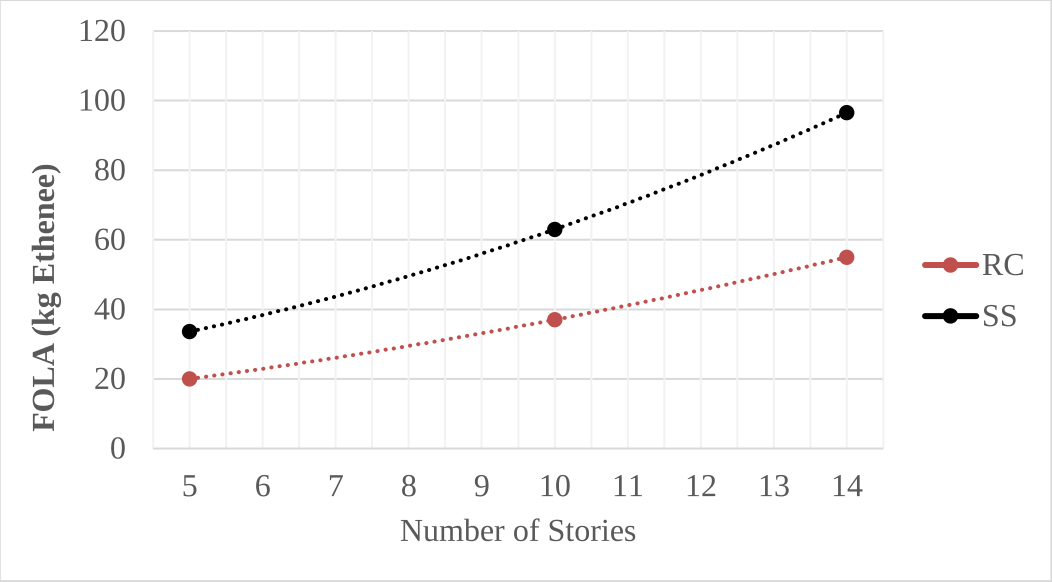


Figure 4.13. The Results of Formation of Ozone of Lower Atmosphere

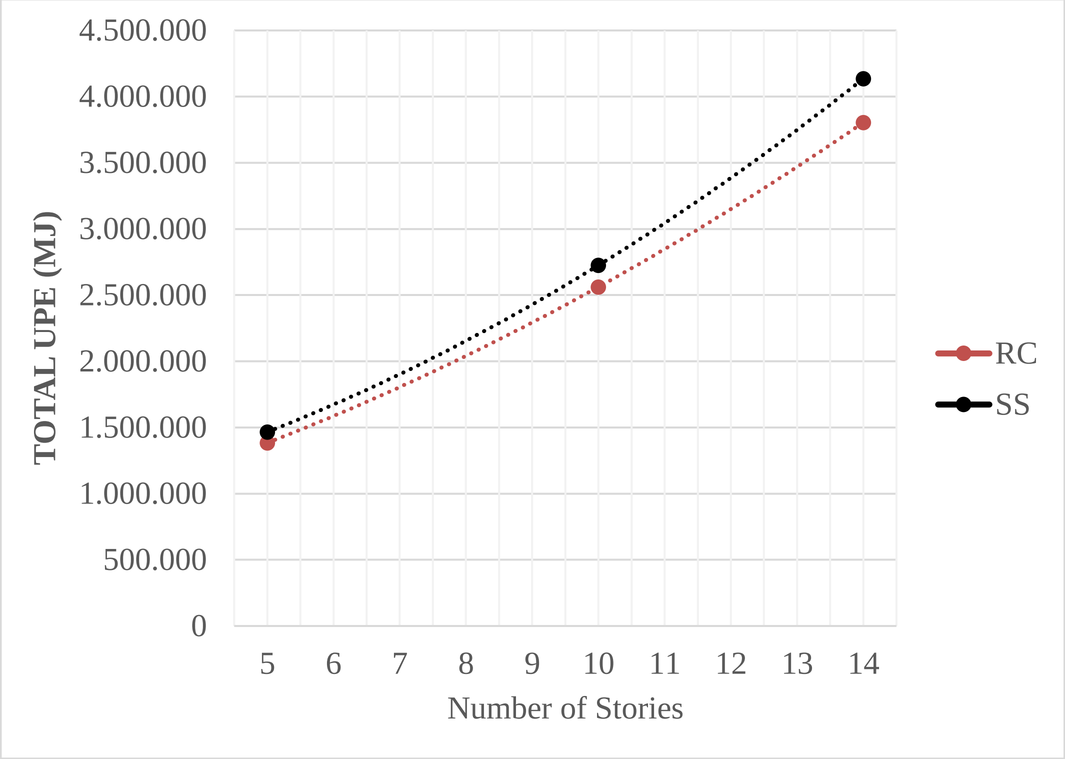


Figure 4.14. The Results of Total Use of Primary Energy

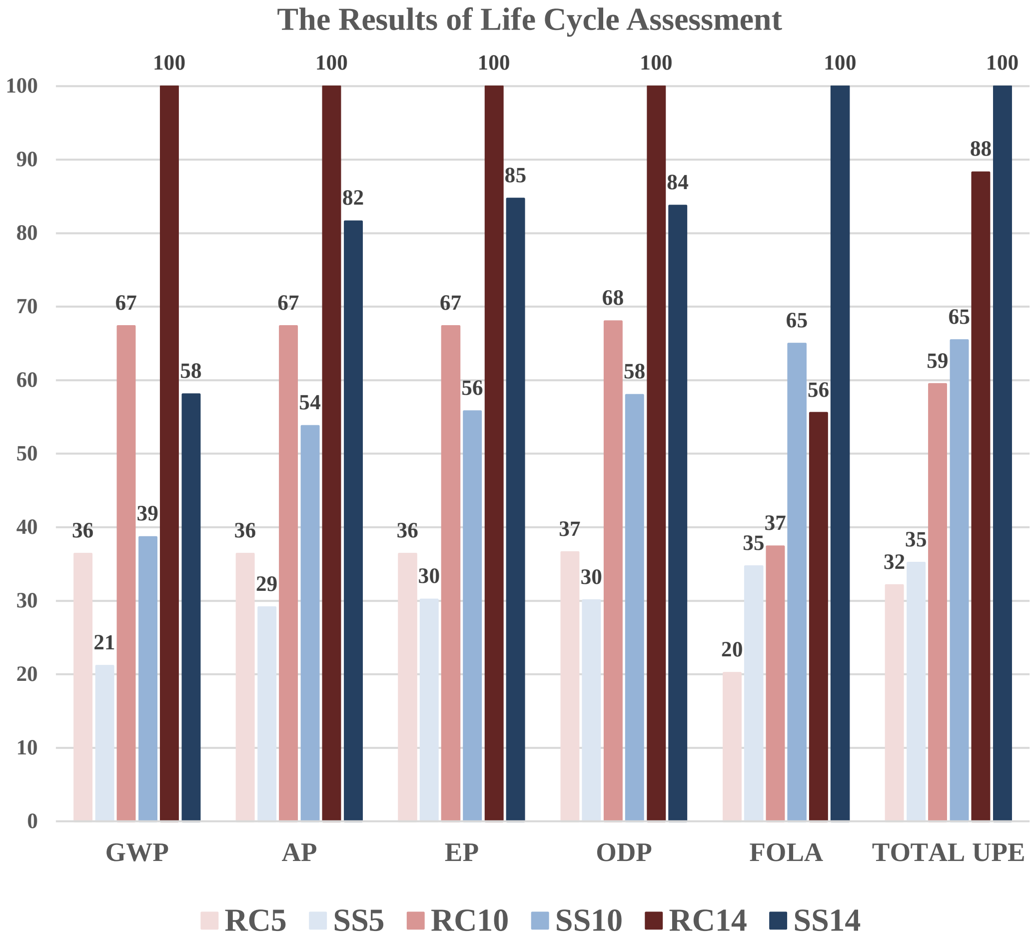


Figure 4.15. The Results of Life Cycle Assessment for All Impact Categories

Until this part, the total results of the parameters about LCA are shown for each model. When the results of each model are analyzed, OneClickLCA gives the values according to the stages of the life cycle for each parameter. A1-A3 is the value of the construction materials when A4 represents the value of the transportation to the site. C1-C4 means the value of the end-of-life phase. The percentages of each phase are calculated according to the data in Table 4.23 for the 5-story reinforced concrete model and in Table 4.24 for the 5-story steel model. In these tables, the results of each impact category are given according to the life cycle stages (A1-A3, A4, and C1-C4).

Figure 4.16 shows GWP, AP, EP results of RC5 and SS5 according to the life cycle phases. According to the three impact categories (GWP, AP, EP), the A1-A3 stage has the highest ratio both for reinforced concrete and steel models.

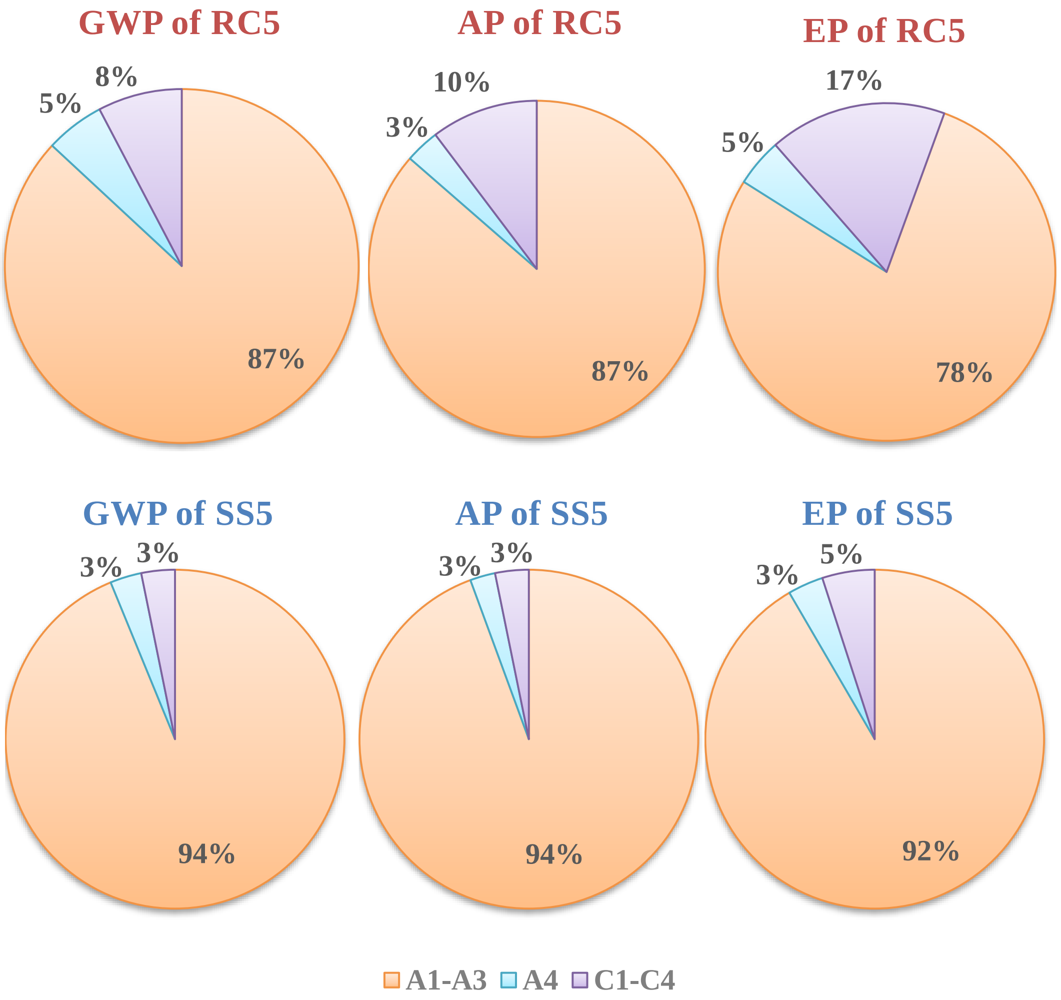


Figure 4.16. GWP, AP, EP Results of RC5 and SS5 according to Life Cycle Stages

ODP, FOLA, and TOTAL UPE results of RC5 and SS5 according to the life cycle phases are shown in Figure 4.17. Even if the A1-A3 stage has higher ratios like GWP, AP, EP results; the percentage decreases for reinforced concrete models. The percentage of C1-C4 rises for ODP and TOTAL UPE results of RC5.

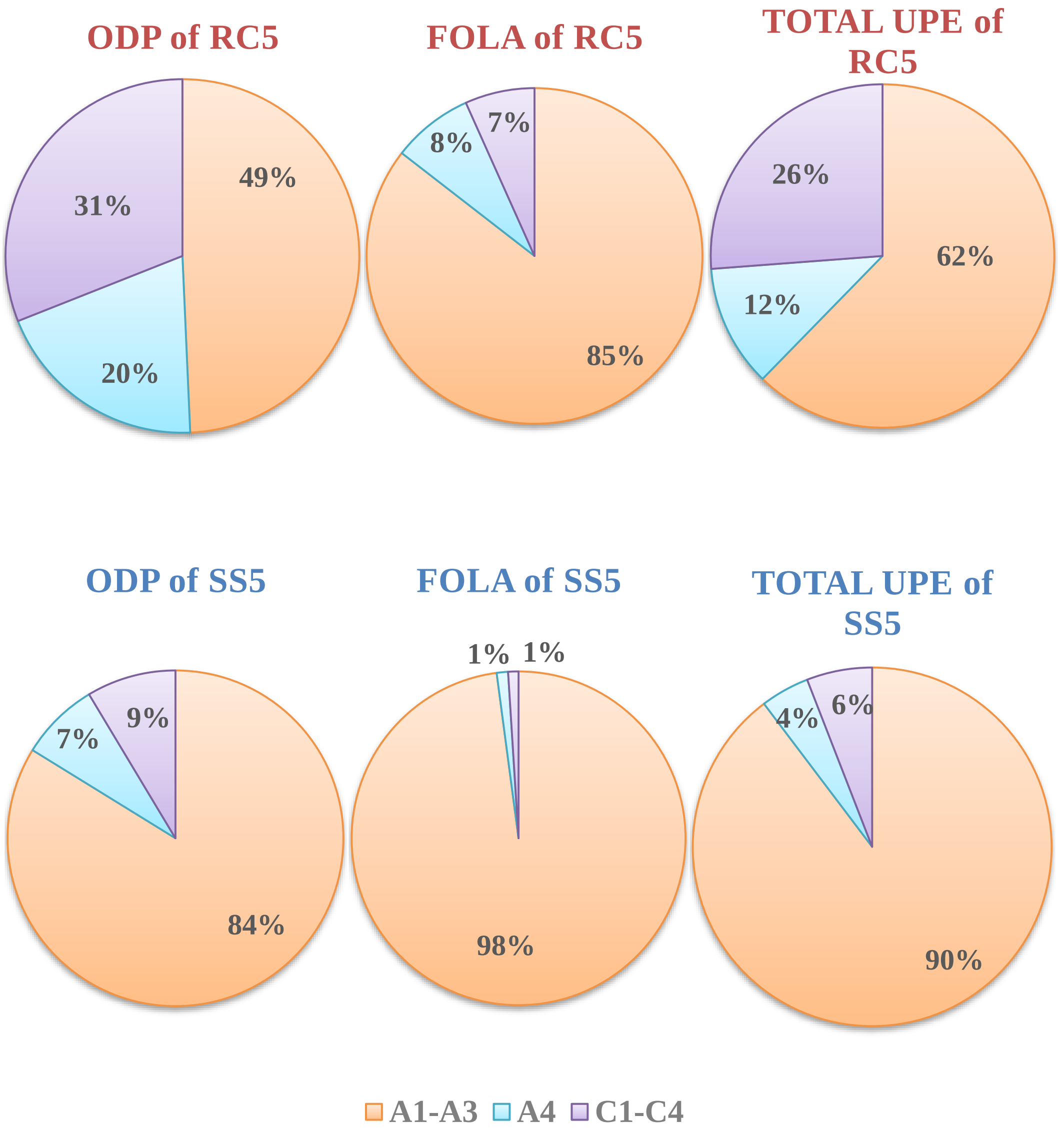


Figure 4.17. ODP, FOLA, TOTAL UPE Results of RC5 and SS5 according to Life Cycle Stages

If all results of the reinforced concrete model are examined according to the stages of the life cycle, it is easily seen that has the highest percentage belongs to A1-A3. A4 has the lowest percentage except for FOLA in all parameters. The most different ratio is observed in ODP. These percentages are very close to the values of other reinforced concrete models which are RC10 and RC14. It means that the percentages of life cycle stages do not depend on the number of floors.

When all results of the steel model according to the stages of the life cycle are studied, the graphs say that A1-A3 is very dominant. It means that the most effective stage is the construction material for steel models like reinforced concrete ones. For steel models, A4 has always the minimum percentage of all; so, transportation is the less effective stage. Like reinforced concrete models, the percentages of 5-story steel models are very similar to the values of 10-story and 14-story models. In short, the percentage of the stages changes slightly when the building height increases or decreases.

4.1.3 Minimum-Maximum Boundary Analysis

In this section, 5-story reinforced concrete and steel models are analyzed with the minimum and the maximum recycled material selection. Then, LCA results are compared with the typical case's results in order to understand the effects of the recycling property of the selected material on the LCA results.

Selected materials for models are shown in Table 4.29. %0 recycled ingredient is selected for the minimum case for reinforced concrete (RC5-min) and steel models (SS5-min). For reinforced concrete material, the typical option is given as "10% (typical) recycled binders in cement". "RC5-typ" means the 5-story reinforced concrete model that is composed of 10% (typical) recycled binders in cement. The typical option of steel material is "90% recycled content (typical)" and "SS5-typ" is the 5-story steel model. This model has reinforced concrete slabs containing 10% (typical) recycled binders in cement and structural steel profiles containing 90% recycled content (typical). The maximum recycled option is "40% recycled binders in cement" for reinforced concrete. "RC5-max" represents the 5-story reinforced concrete model having 40% recycled binders in cement as the maximum selection. The maximum recycled option for steel is "100% recycled content". "SS5-max" has reinforced concrete slabs containing 40% recycled binders in cement and structural steel profiles containing 100% recycled content.

Table 4.29 "Minimum-Typical-Maximum" Recycled Material Selection

	Slabs	**Walls**
Reinforced Concrete Model RC5-min	Ready-mix reinforced concrete, normal-strength, generic, C30/37 (4400/5400 PSI), **0% recycled binders in cement** (300 kg/m^3 / 18.72 lbs/ft^3)	Ready-mix reinforced concrete, normal-strength, generic, C30/37 (4400/5400 PSI), **0% recycled binders in cement** (300 kg/m^3 / 18.72 lbs/ft^3)
Reinforced Concrete Model RC5-typ	Ready-mix reinforced concrete, normal-strength, generic, C30/37 (4400/5400 PSI), **10% (typical) recycled binders in cement** (300 kg/m^3 / 18.72 lbs/ft^3)	Ready-mix reinforced concrete, normal-strength, generic, C30/37 (4400/5400 PSI), **10% (typical) recycled binders in cement** (300 kg/m^3 / 18.72 lbs/ft^3)
Reinforced Concrete Model RC5-max	Ready-mix reinforced concrete, normal-strength, generic, C30/37 (4400/5400 PSI), **40% recycled binders in cement** (300 kg/m^3 / 18.72 lbs/ft^3)	Ready-mix reinforced concrete, normal-strength, generic, C30/37 (4400/5400 PSI), **40% recycled binders in cement** (300 kg/m^3 / 18.72 lbs/ft^3)
	Slabs	**Steel Columns, Beams and Braces**
Steel Model SS5-min	Ready-mix reinforced concrete, normal-strength, generic, C30/37 (4400/5400 PSI), **0% recycled binders in cement** (300 kg/m^3 / 18.72 lbs/ft^3)	Structural steel profiles, generic, **0% recycled content (only virgin materials)** I, H, U, L, and T sections
Steel Model SS5-typ	Ready-mix reinforced concrete, normal-strength, generic, C30/37 (4400/5400 PSI), **10% (typical) recycled binders in cement** (300 kg/m^3 / 18.72 lbs/ft^3)	Structural steel profiles, generic, **90% recycled content (typical),** I, H, U, L, and T sections
Steel Model SS5-max	Ready-mix reinforced concrete, normal-strength, generic, C30/37 (4400/5400 PSI), **40% recycled binders in cement** (300 kg/m^3 / 18.72 lbs/ft^3)	Structural steel profiles, generic, **100% recycled content,** I, H, U, L, and T sections

Minimum case LCA results of 5-story models are shown in Table 4.30 for RC5-min and Table 4.31 for SS5-min.

Table 4.30 LCA Results of RC5-min

	Result category	**GWP**	**AP**	**EP**	**ODP**	**FOLA**	**TOTAL UPE**
		kg CO$_2$e	**kg SO$_2$e**	**kg PO$_4$e**	**kg CFC11e**	**kg Ethenee**	**MJ**
A1-A3	Construction materials	181,547.55	424.46	56.66	0.00470	18.06	922,385.03
A4	Transportation to site	10,427.04	15.24	3.11	0.00180	1.56	158,811.84
C1-C4	Deconstruction	14,825.4	47.79	11.49	0.00280	1.33	363,134.87
D	External impacts (not included in totals)	-33,179.38	-69.09	-23.86	-0.00083	-4.03	-170,101.12
	Total	**206,799.98**	**487.49**	**71.26**	**0.00930**	**20.95**	**1,444,331.74**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	161.06	0.38	0.06	7.19E-6	0.02	1,124.87

Table 4.31 LCA Results of SS5-min

	Result category	**GWP**	**AP**	**EP**	**ODP**	**FOLA**	**TOTAL UPE**
		kg CO$_2$e	**kg SO$_2$e**	**kg PO$_4$e**	**kg CFC11e**	**kg Ethenee**	**MJ**
A1-A3	Construction materials	318,972.33	1,234.45	211.52	0.01800	170.14	4,569,250.21
A4	Transportation to site	3,156.25	8.53	1.82	0.00057	0.36	64,572.86
C1-C4	Deconstruction	3,396.88	11.46	2.67	0.00064	0.34	85,887.71
D	External impacts (not included in totals)	-136,227.94	-574.4	-192.12	-0.00670	-97.98	-1,470,600.78
	Total	**325,525.46**	**1,254.45**	**216.01**	**0.01921**	**170.83**	**4,719,710.77**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	253.52	0.98	0.17	1.5E-5	0.13	3,675.79

The results of typical models are demonstrated in Table 4.32 for RC5-typ and in Table 4.33 for SS5-typ.

Table 4.32 LCA Results of RC5-typ

	Result category	**GWP**	**AP**	**EP**	**ODP**	**FOLA**	**TOTAL UPE**
		kg CO$_2$e	**kg SO$_2$e**	**kg PO$_4$e**	**kg CFC11e**	**kg Ethenee**	**MJ**
A1-A3	Construction materials	168,540.86	399.19	53.08	0.00440	17.11	862,249.23
A4	Transportation to site	10,427.04	15.24	3.11	0.00180	1.56	158,811.84
C1-C4	Deconstruction	14,825.4	47.79	11.49	0.00280	1.33	363,134.87
D	External impacts (not included in totals)	-327,64.63	-68.22	-23.56	-0.00082	-3.98	-167,974.85
	Total	**193,793.3**	**462.21**	**67.68**	**0.00900**	**20**	**1,384,195.94**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	150,93	0,36	0,05	6.943E-6	0,02	1,078,03

Table 4.33 LCA Results of SS5-typ

	Result category	**GWP**	**AP**	**EP**	**ODP**	**FOLA**	**TOTAL UPE**
		kg CO$_2$e	**kg SO$_2$e**	**kg PO$_4$e**	**kg CFC11e**	**kg Ethenee**	**MJ**
A1-A3	Construction materials	99,148.84	333.3	49.18	0.00620	32.93	1,315,181.29
A4	Transportation to site	3,156.25	8.53	1.82	0.00057	0.36	64,572.86
C1-C4	Deconstruction	3,396.88	11.46	2.67	0.00064	0.34	85,887.71
D	External impacts (not included in totals)	-19,015.19	-68.67	-23.09	-0.00081	-10.45	-174,705.33
	Total	**105,701.97**	**353.29**	**53.67**	**0.00741**	**33.62**	**1,465,641.86**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	82.32	0.28	0.04	5.785E-6	0.03	1,141.47

The values of the maximum case are given in Table 4.34 for RC5-max and in Table 4.35 for SS5-max.

Table 4.34 LCA Results of RC5-max

	Result category	**GWP**	**AP**	**EP**	**ODP**	**FOLA**	**TOTAL UPE**
		kg CO_2e	**kg SO_2e**	**kg PO_4e**	**kg CFC11e**	**kg Ethenee**	**MJ**
A1-A3	Construction materials	129,520.81	323.35	42.34	0.00340	14.26	681,841.83
A4	Transportation to site	10,427.04	15.24	3.11	0.00180	1.56	158,811.84
C1-C4	Deconstruction	14,825.4	47.79	11.49	0.00280	1.33	363,134.87
D	External impacts (not included in totals)	-31,520.41	-65.63	-22.67	-0.00079	-3.83	-161,596.06
	Total	**154,773.24**	**386.37**	**56.94**	**0.00800**	**17.16**	**1,203,788.54**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	120.54	0.3	0.04	6.201E-6	0.01	937.53

Table 4.35 LCA Results of SS5-max

	Result category	**GWP**	**AP**	**EP**	**ODP**	**FOLA**	**TOTAL UPE**
		kg CO_2e	**kg SO_2e**	**kg PO_4e**	**kg CFC11e**	**kg Ethenee**	**MJ**
A1-A3	Construction materials	85,995.53	280.64	36.62	0.00650	23.38	1,277,146.58
A4	Transportation to site	3,156.25	8.53	1.82	0.00057	0.36	64,572.86
C1-C4	Deconstruction	3,396.88	11.46	2.67	0.00064	0.34	85,887.71
D	External impacts (not included in totals)	147,347.86	648.86	216.73	0.00760	113.7	1,663,879.9
	Total	**92,548.66**	**300.64**	**41.11**	**0.00771**	**24.07**	**1,427,607.15**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	72.08	0.23	0.03	6.019E-6	0.02	1,111.84

As similar to the previous study comparing LCA results of 5-10-14 story reinforced concrete and steel models, construction/installation process, maintenance and material replacement, energy use, and water use have the value of zero “0”. Therefore, they are not shown in tables.

LCA results of each parameter (GWP, AP, EP, ODP, FOLA, and TOTAL UPE) are compared for minimum-typical-maximum reinforced concrete and steel models in Figure 4.18, 4.19, 4.20, 4.21, 4.22, and 4.23, respectively. Reinforced concrete models are shown with the red color and the blue color is used for steel models. The x-axis gives minimum-typical-maximum selection while the y-axis shows the results.

The results of GWP are shown in Figure 4.18 while AP’s results are shown in Figure 4.19. The graphs say that reinforced concrete models have higher values than steel models at both of the parameters except the minimum cases of reinforced concrete and steel models.

Typical and maximum cases of reinforced concrete models lead to release greenhouse gasses more than typical and maximum cases of steel models. Also, steel models except for the minimum case cause acid rain less than reinforced concrete models even if they consist of typical recyclable contents. The steel model including minimum recycled content has the highest values in both GWP and EP.

Figure 4.20 explains the comparison of EP results. The graph of EP says that when the reinforced concrete model has the maximum recyclable cement, the value is very close to the typical steel model. However, the value of EP at the maximum case of the steel model is very low regarding other models. So, SS5-max has the lowest potential in terms of unwanted plant growth but the EP result of SS5-min is much higher than other models.

The results of ODP are demonstrated in Figure 4.21. For ozone depletion potential, reinforced concrete models have higher values than steel models except for the minimum cases of reinforced concrete and steel models. The minimum case of the steel model has the highest value in terms of ozone depletion.

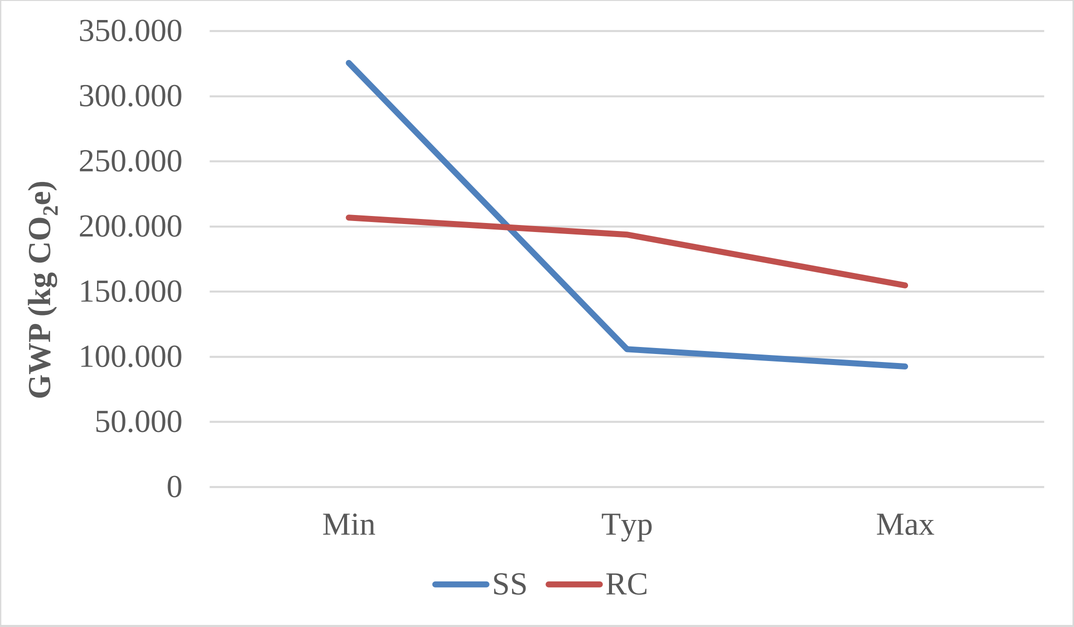


Figure 4.18. The Global Warming Potential Results of The Minimum-Maximum Boundary Analysis

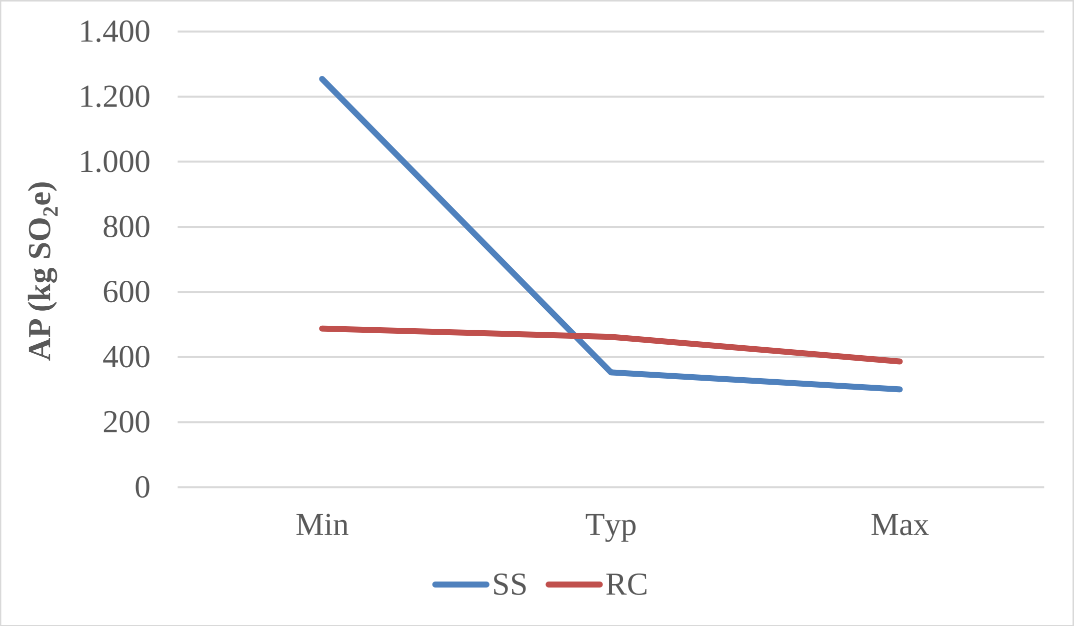


Figure 4.19. The Acidification Potential Results of The Minimum-Maximum Boundary

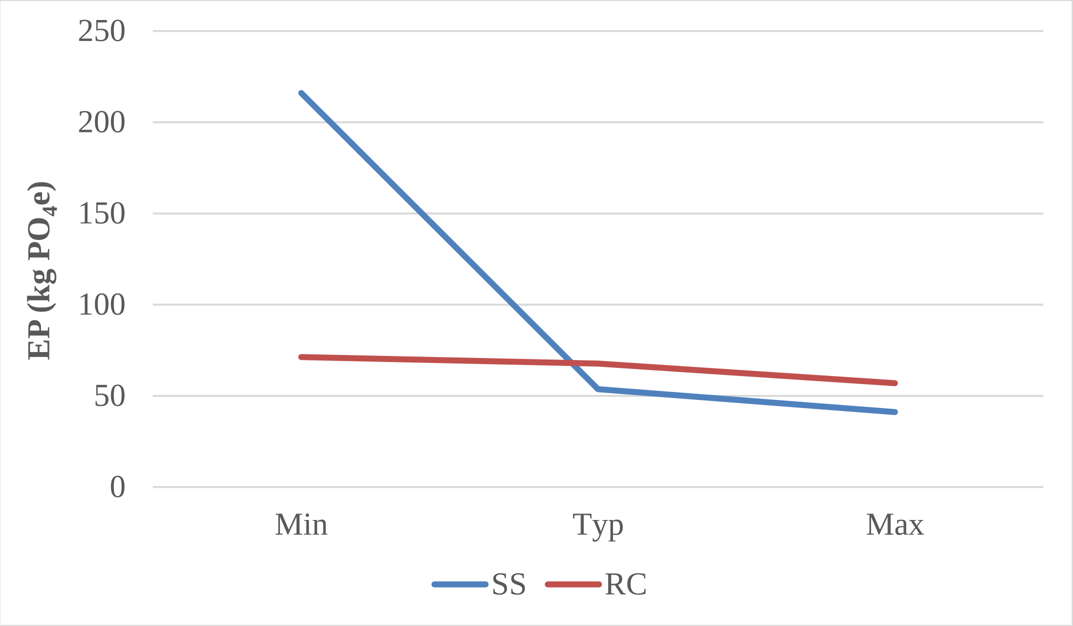


Figure 4.20. The Eutrophication Potential Results of The Minimum-Maximum Boundary Analysis

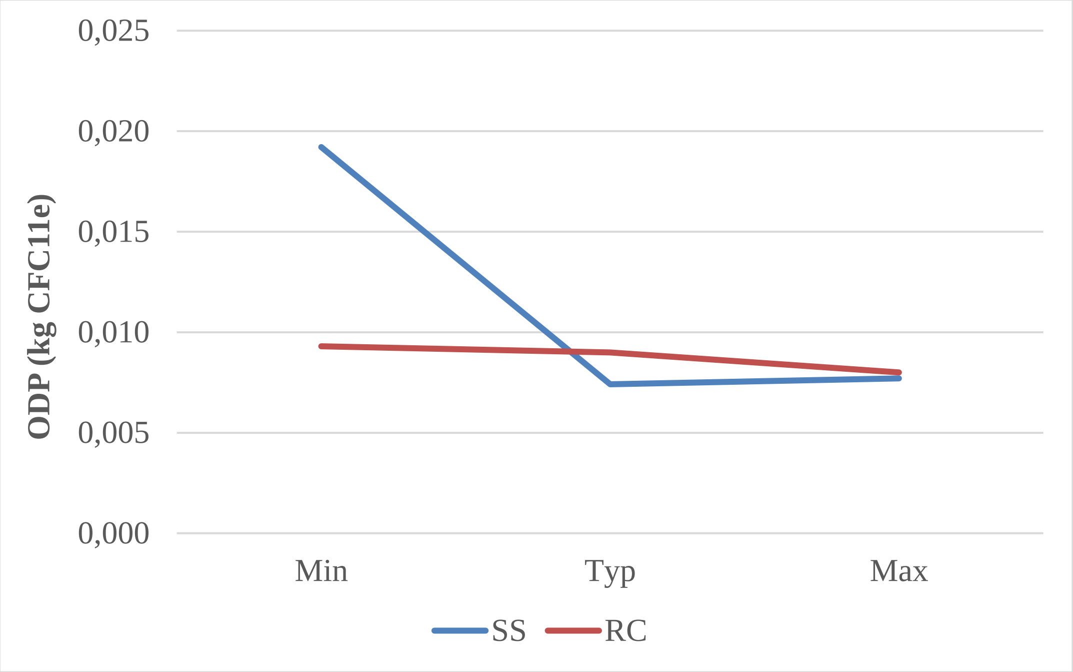


Figure 4.21. The Ozone Depletion Potential Results of The Minimum-Maximum Boundary Analysis

In Figure 4.22, there are the results of FOLA. In terms of summer smog formation, steel models have much higher values than reinforced concrete ones even if they have maximum recyclable materials inside. All cases of steel models lead to more ozone formation in the lower atmosphere than reinforced concrete models.

The values of TOTAL UPE are illustrated in Figure 4.23. In terms of energy use from the raw resources of the earth, steel models need more energy than reinforced concrete models. Maximum recyclable content does not decrease the value of steel models enough and the maximum case of the reinforced concrete model has the lowest value in terms of total energy use.

GWP, AP, EP, and OPD show that steel models which include typical content in terms of recyclability have a less negative impact on the environment than reinforced concrete models including maximum recyclable content. For FOLA, steel models in all cases cause more formation of summer smog at the lower atmosphere than reinforced concrete models. Finally, the values of TOTAL UPE say that steel models use more energy from the earth than reinforced concrete models even if steel models have the most recyclable ingredients.

In all graphs, SS5-min has the highest value and this means that the steel model including minimum recycled content is the most harmful model to nature. Since OneClickLCA shows that steel material has a larger library in terms of recyclability starting from %0 and ending with %100, the difference between the minimum and maximum case of steel models is much higher than reinforced concrete models. The library of reinforced concrete starts with %0 recycled cement and ends with %40 recycled cement. Therefore; the change in results between the minimum and maximum case of reinforced concrete models is much less than the change of steel samples.

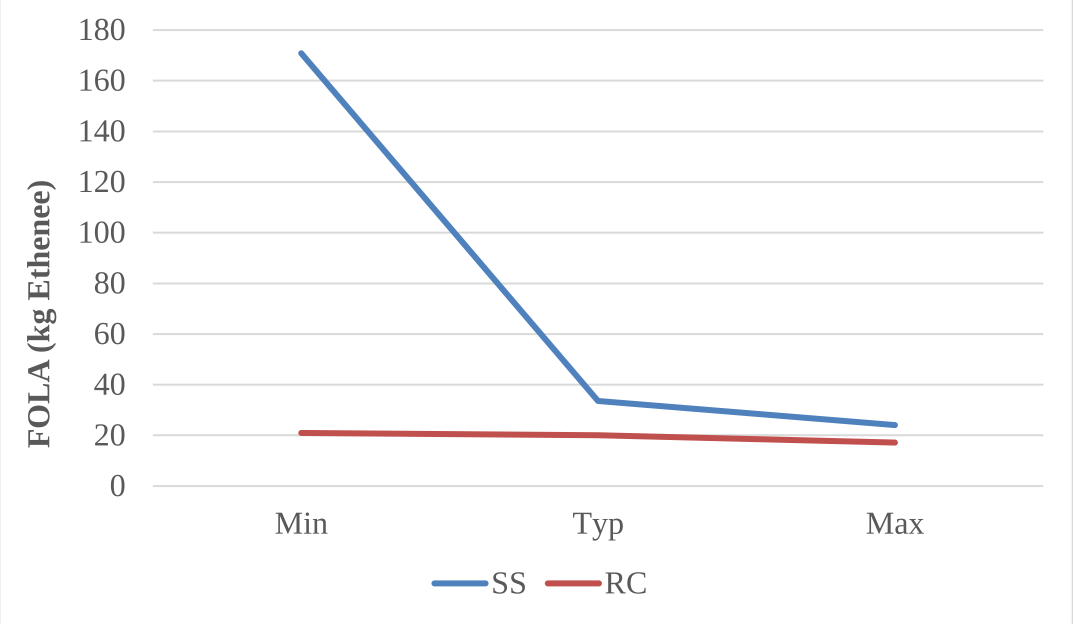


Figure 4.22. The Formation of Ozone of Lower Atmosphere Results of The Minimum-Maximum Boundary Analysis

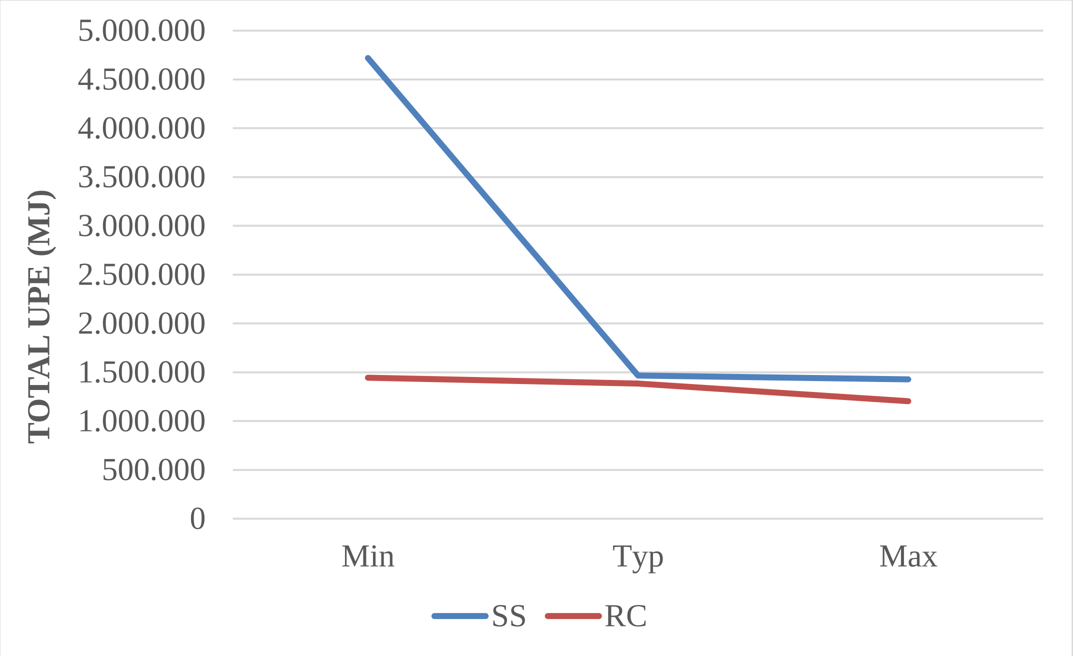


Figure 4.23. The Total Use of Primary Energy Results of The Minimum-Maximum Boundary Analysis

In order to see the boundary of the results, the results of minimum-maximum and typical cases are gathered in Figure 4.24 for reinforced concrete models and in Figure 4.25 for steel models by arranging the highest value as %100 and proportioning the other results to 100 for each category.

For reinforced concrete models, the results change slightly from the minimum case to the typical one and then the maximum case. The difference between the minimum case of the steel model and the typical case of the steel model is easily seen. In steel models, the change occurs dramatically from minimum case to typical case but a very small change happens from typical one to maximum case.

According to the American Institute of Steel Construction (2020), “steel is the most recycled material in the world and structural steel includes 93% recycled content”. In short, the steel commonly used in the world is very close to the maximum case. However, if steel that includes the least recycled content is preferred, it can become one of the most harmful materials for the environment.

This section shows the comparison of minimum, typical and maximum cases to see the boundary of the results. In the end, it is understood that the selection between reinforced concrete and steel is very important in terms of the effect on nature. Also, one of the important things is the recyclability of a material. By changing the content of material even if it is reinforced concrete or steel, the impacts to the environment of a building can be increased or decreased easily.

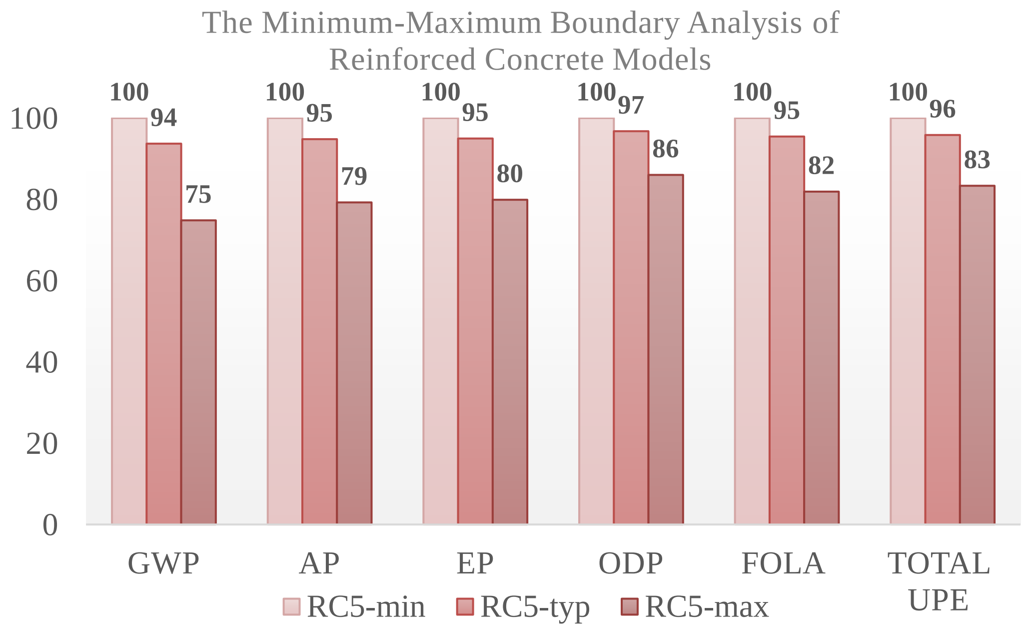


Figure 4.24. The Minimum-Maximum Boundary Analysis of Reinforced Concrete Models for All Impact Categories

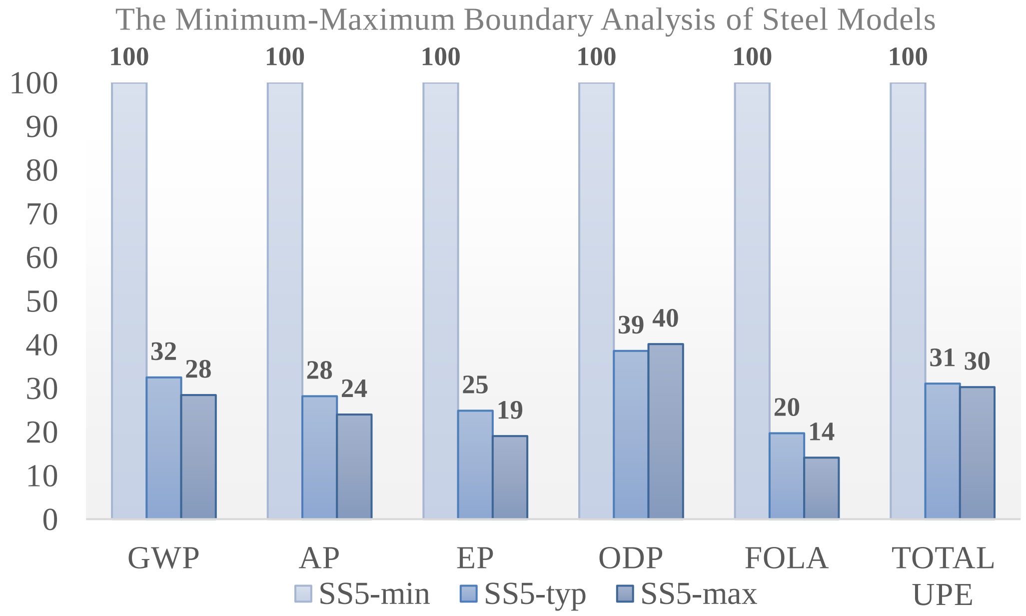


Figure 4.25. The Minimum-Maximum Boundary Analysis of Steel Models for All Impact Categories

4.1.4 Analysis for Low Seismicity

In this section, 5-story and 14-story steel models are designed for a location with a peak ground acceleration value of 0.10g according to the recent Turkish Seismic Hazard Map. These models are compared with the structures which are designed according to the code based design spectrum for an arbitrary region where the peak ground acceleration is 0.40g according to the recent Turkish Seismic Hazard Map.

In ProtaStructure, the location of the project is defined as 38.72487854°, 34.01831528° (Aksaray, Turkey). At this location, the peak ground acceleration (PGA) is 0.10g. Other parameters of ProtaStructure are the same as the models that are explained in Chapter 3.

Models are formed with the steel elements which have the smallest sections. The floor section of the models is the same, 8cm reinforced concrete slab. Firstly, a 5-story steel model is analyzed for 0.10g to achieve a successful model in terms of regulation. For the 5-story model, the analysis showed that the model owning HEB160 steel columns, HEB100 steel beams, and TUBO100x100x5.4 steel braces become successful (SS5-low).

After that, the 14-story steel model is analyzed in ProtaStructure. In this sample, the successful model has sections that consist of HEB220 steel columns (at the basement floor), HEB200 steel columns (between 1st and 14th floors), HEB100 steel beams, and TUBO100x100x5.4 steel braces (SS14-low).

In this way, 5- and 14-story steel models are investigated under low and high seismic effects. Table 4.36 shows the sections of 5-story models and Table 4.37 demonstrates 14-story models' sections analyzed in 0.10g and 0.40g. For 5-story models, the change occurs in the column section. It decreases HEB160 from HEB 200 steel columns. For 14-story models, all elements change. Steel columns become HEB220 for the basement floor and HEB 200 for other floors. Steel beams fall to HEB 100 from HEB 120 section. Braces are TUBO100x100x5.4 for all floors at 0.10g where the braces of the basement are TUBO100x100x7.1 at 0.40g.

Table 4.36 Sections of 5-Story Steel Models 0.10g vs. 0.40g

	5-Story Steel Models	
	0.10g (SS5-low)	**0.40g (SS5-high)**
Slabs	8cm Reinforced Concrete	8cm Reinforced Concrete
Columns	HEB160	HEB200
Beams	HEB100	HEB100
Braces	TUBO100x100x5.4	TUBO100x100x5.4

Table 4.37 Sections of 14-Story Steel Models 0.10g vs. 0.40g

	14-Story Steel Models	
	0.10g (SS14-low)	**0.40g (SS14-high)**
Slabs	8cm Reinforced Concrete	8cm Reinforced Concrete
Columns	HEB220 (at the basement floor) HEB200 (between 1st and 14th floors)	HEB300 (between the basement floor and 2nd floor) HEB200 (between 3rd and 14th floors)
Beams	HEB100	HEB120
Braces	TUBO100x100x5.4	TUBO100x100x7.1 (at the basement floor) TUBO100x100x5.4 (between 1st and 14th floors)

Table 4.38 shows the volume of reinforced concrete slabs and the weight of structural steel elements. According to this table, selecting steel material for a 14-story building at low seismicity is quite effective in terms of reducing the material weight.

For the buildings having reinforced concrete shear wall system, there are limitations on minimum dimensions in TEC 2018. Because of these limitations, the wall thickness can not be decreased even if the building is located in a low seismic region. This situation causes over-design reinforced concrete buildings, i.e., buildings containing excessive volumes of reinforced concrete material.

Table 4.38 Quantity of Materials in Steel Models for Low and High Seismicity

	Slabs (Concrete Volume) (m^3)	**Columns, Beams, Braces (Steel Weight) (t)**
SS5-high	102	88
SS5-low	102	78
SS14-high	223	260
SS14-low	223	218

Table 4.39 shows the LCA result of 5-story steel models for high seismicity and Table 4.40 indicates for low seismicity. The LCA values of 14-story models are given in Table 4.41 for high seismicity and in Table 4.42 for low seismicity.

Tables do not include the values of construction/installation process, maintenance and material replacement, energy use, and water use since their results are zero “0” as the previous LCA studies.

Table 4.39 LCA Results of SS5-high

	Result category	**GWP**	**AP**	**EP**	**ODP**	**FOLA**	**TOTAL UPE**
		kg CO_2e	**kg SO_2e**	**kg PO_4e**	**kg CFC11e**	**kg Ethenee**	**MJ**
A1-A3	Construction materials	99,148.84	333.3	49.18	0.00620	32.93	1,315,181.29
A4	Transportation to site	3,156.25	8.53	1.82	0.00057	0.36	64,572.86
C1-C4	Deconstruction	3,396.88	11.46	2.67	0.00064	0.34	85,887.71
D	External impacts (not included in totals)	-19,015.19	-68.67	-23.09	-0.00081	-10.45	-174,705.33
	Total	**105,701.97**	**353.29**	**53.67**	**0.00741**	**33.62**	**1,465,641.86**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	82.32	0.28	0.04	5.785E-6	0.03	1,141.47

Table 4.40 LCA Results of SS5-low

	Result category	**GWP**	**AP**	**EP**	**ODP**	**FOLA**	**TOTAL UPE**
		kg CO_2e	**kg SO_2e**	**kg PO_4e**	**kg CFC11e**	**kg Ethenee**	**MJ**
A1-A3	Construction materials	91,389.18	303.73	44.7	0.00560	29.54	1,183,671.88
A4	Transportation to site	3,014.56	7.88	1.68	0.00054	0.35	60,539.83
C1-C4	Deconstruction	3,319.38	11.15	2.6	0.00062	0.33	83,684.41
D	External impacts (not included in totals)	-17,536.19	-62.28	-20.96	-0.00073	-9.35	-158,347.93
	Total	**97,723.13**	**322.77**	**48.98**	**0.00676**	**30.21**	**1,327,896.12**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	76.11	0.25	0.04	5.272E-6	0.02	1,034.19

Table 4.41 LCA Results of SS14-high

	Result category	**GWP**	**AP**	**EP**	**ODP**	**FOLA**	**TOTAL UPE**
		kg CO$_2$e	**kg SO$_2$e**	**kg PO$_4$e**	**kg CFC11e**	**kg Ethenee**	**MJ**
A1-A3	Construction materials	269,227.94	928.59	137.84	0.0180	94.87	3,764,454.14
A4	Transportation to site	7,858.31	23.07	4.94	0.0014	0.83	168,440.4
C1-C4	Deconstruction	7,950.48	27.14	6.26	0.0015	0.8	202,670.14
D	External impacts (not included in totals)	-51,571.62	-193.28	-64.9	-0.0023	-30.32	-492,542.65
	Total	**285,036.73**	**978.8**	**149.04**	**0.0209**	**96.51**	**4,135,564.69**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	221.99	0.76	0.12	6.446E-6	0.08	3,220.84

Table 4.42 LCA Results of SS14-low

	Result category	**GWP**	**AP**	**EP**	**ODP**	**FOLA**	**TOTAL UPE**
		kg CO$_2$e	**kg SO$_2$e**	**kg PO$_4$e**	**kg CFC11e**	**kg Ethenee**	**MJ**
A1-A3	Construction materials	236,637.38	804.4	119.01	0.0150	80.66	3,212,114.59
A4	Transportation to site	7,263.24	20.33	4.34	0.0013	0.8	15,1501.7
C1-C4	Deconstruction	7,624.98	25.85	5.99	0.0014	0.76	193,416.28
D	External impacts (not included in totals)	-45,359.82	-166.47	-55.94	-0.0020	-25.68	-423,841.57
	Total	**251,525.61**	**850.58**	**129.34**	**0.0177**	**82.22**	**3,557,032.57**
	The result according to the unit floor area (Gross Internal Floor Area = 1284 m^2)	78.36	0.26	0.04	5.584E-6	0.03	1,108.11

As an expectable outcome, LCA results decrease with the fall of the material weights at models. Therefore; the change of LCA results is summarized for all impact categories in Table 4.43 for the 5-story steel model and in Table 4.44 for the 14-story steel model.

Table 4.43 The Change of LCA Results for SS5 at Low Seismicity

Result category	**GWP**	**AP**	**EP**	**ODP**	**FOLA**	**TOTAL UPE**
	kg CO_2e	**kg SO_2e**	**kg PO_4e**	**kg CFC11e**	**kg Ethenee**	**MJ**
SS5-high	105,701.97	353.29	53.67	0.00741	33.62	1,465,641.86
SS5-low	97,723.13	322.77	48.98	0.00676	30.21	1,327,896.12
Change	7,978.84	30.52	4.69	0.00065	3.41	137,745.74
Percentage of Change **(=Change/ SS5-high)**	**0.08**	**0.09**	**0.09**	**0.09**	**0.10**	**0.09**

Table 4.44 The Change of LCA Results for SS14 at Low Seismicity

Result category	**GWP**	**AP**	**EP**	**ODP**	**FOLA**	**TOTAL UPE**
	kg CO_2e	**kg SO_2e**	**kg PO_4e**	**kg CFC11e**	**kg Ethenee**	**MJ**
SS14-high	285036.7	978.8	149.04	0.0209	96.51	4135565
SS14-low	251525.6	850.58	129.34	0.0177	82.22	3557033
Change	33511.12	128.22	19.7	0.0032	14.29	578532.1
Percentage of Change **(=Change/ SS14-high)**	**0.12**	**0.13**	**0.13**	**0.15**	**0.15**	**0.14**

The change is investigated with the percentage of the results that belong to high-seismicity models. For the 5-story model, the LCA results of SS5-low are 9% less than SS5-high for all impact categories except GWP and FOLA. The change percentage is 8% for GWP and the FOLA's change percentage is 10%.

For 14-story models, the change percentage is higher than 5-story models due to the fact that the weight of SS14 declines more than SS5 for low seismicity. GWP's change percentage is 12%, as the minimum percentage. For AP and EP, this value is 13% and the change percentage of TOTAL UPE is 14%. The values of ODP and FOLA are 15% as the maximum change percentage.

When the change is compared, the minimum value of change percentage (12%) in the 14-story sample is 1.5 times the minimum value of change percentage (8%) in the 5-story sample. Therefore, the change, especially, in the 14-story sample is remarkable for low seismicity.

Steel buildings can design with less steel material according to the seismicity of the region since the sections of models for low seismicity are smaller than the sections for high seismicity. This makes the buildings more sustainable. The steel samples show that the selection of steel as the building material affects less negatively nature for a low seismic region.

When reinforced concrete models are examined, the limitation of the regulation and structural system selected by TOKİ causes the construction of the reinforced concrete buildings containing excessive volumes of material.

In this thesis, the results of the low seismicity analysis for steel models show that the weight of structural materials can be dropped by using structural steel, especially for a building located in a low seismic region. Therefore, the structural material selection of the buildings should be made in accordance with the level of seismicity, also.

4.2 Discussion of Research

This part clarifies the question of this thesis, evaluates the results of the analyses, and compares the findings with the previous researches. In this thesis, the potentials of steel as the structural material is examined in terms of sustainability. Three different analyses are conducted to analyze the effect of this selection.

The first analysis compares reinforced concrete to steel models and examines the results according to the building height. The results show that steel is less harmful to nature for the potentials of global warming, acidification, eutrophication, and ozone depletion. However, the potential of ozone formation in the lower atmosphere and the total use of primary energy is higher when steel is used in the models. When building height increases, the difference between the results of the reinforced concrete and steel models goes up considerably in terms of the potentials of global warming and the formation of ozone in the lower atmosphere. For the potentials of acidification, eutrophication, ozone depletion, and the total use of primary energy, the difference between the results rises slightly with the increase of the building height. Furthermore, the results indicate that the production phase of the materials has the highest percentage among the life cycle stages and the percentage of the stages shows a slight change when the floor number increases or decreases.

The second analysis investigates the boundary of the analysis by changing the recyclability percentages of material. For 5-story reinforced concrete and steel models, the comparison of the minimum, typical, and maximum cases indicates that the minimum case of steel models is the most harmful option for the environment in terms of all impact categories. The typical and maximum cases of steel models have lower results rather than reinforced concrete models for the potentials of global warming, acidification, eutrophication, and ozone depletion, but the results are higher than reinforced concrete models for the formation of ozone of lower atmosphere and the total use of primary energy. For this study, the library of OneClickLCA is used and it has the recyclability percentages beginning from zero and ending in a hundred for steel materials. For reinforced concrete materials, the library has the percentages zero to forty. The range for steel materials is larger than reinforced concrete materials and this situation causes that the results of reinforced concrete models change slightly from the minimum case to maximum case.

The third analysis examines the effects of the earthquake forces on steel models. The results of 5- and 14-story steel models are compared for the locations which are under low and high seismic effects. The comparison points out that the change between low and high seismicity models is higher for 14-story steel models than 5-story steel models. For the low seismic effects, using steel as the structural material in high-rise buildings decreases the negative effects of the building in terms of environmental parameters.

In this thesis, the results show that the optimum selection changes according to the impact categories or recyclability percentage of the materials or level of seismicity. The proper option can be selected considering the priority of a specific parameter. Also, another method, multi-objective decision-making, may be applied to define the optimum case. Any multi-objective decision-making method (i.e., AHP, ELECTRE, etc.) can be used to evaluate results. This way, to determine the optimum selection among reinforced concrete and steel models, the relative importance of different parameters decided by the analyst according to the different cases and situations, can be considered implicitly.

In the literature, Moussavi Nadoushani & Akbarnezhad (2015) has a similar study to this thesis. The study uses a square shape plan as a base and it has a set of 15 alternative concrete and steel models including moment resisting frames, braced frames, shear wall systems, and dual systems as their words. The models are designed for 3-, 10-, and 15-story buildings. The carbon footprint of each model is given as the emissions occurred in material extraction, transportation, construction, operation, and end-of-life stages. The results indicate that the overall embodied carbon of 3-, 10-, and 15-story models can be minimized by selecting the steel braced frame for the 3-story model, the concrete reinforced shear wall frame for the 10-story model, and the steel braced frame for the 15-story model. In this point, the results of 3- and 15-story models in the study compromise with the results of 5- and 14-story steel models in this thesis but the results of the 10-story model in the study are different from this thesis. Furthermore, the study specifies that using the result of the carbon footprint incurred in a single life cycle phase may be misleading to select the best structural option and the selected option may not necessarily be the optimal case in terms of total life cycle carbon footprint. Since the results of each life cycle stage change and the percentage of the stages are different from each one for 5-story reinforced concrete and steel models, that issue is observed in this thesis, also.

There is a study that considers sustainability in the selection of structural systems in the literature (Buckley et al., n.d.). A cast-in-place concrete system is compared with a structural steel system in terms of the environmental impacts for an integrated learning center in a university. The researchers express that the selection of construction material becomes an important part of the overall environmental impact. The results of the study show that concrete two-way slabs on stiff supports have lower negative effects on global warming, toxicity, and energy consumption. However, the steel frame system with composite steel decking has less harmful for nature in terms of solid waste emission and the use of required resources. In this study, there is an important point, that the analysis does not include the effect of disposal at the end of the building service life and this may affect the results from life cycle analyses. Also, the study declares that structural steel systems can give better results than concrete structures for certain types of buildings. In that point, this thesis states similar opinions, also. The analysis of other types of buildings rather than residential buildings can result in different outcomes. The investigation of another plan may give different results.

Another study (López et al., 2016) examines a 6-story building modeled with the foundation, structure, and walls, which is designed with three different structural systems: industrialized (as an unconfined masonry system), structural masonry, and confined masonry system. According to the study, the common indicator is the global warming potential or carbon footprint and the results show that the industrialized and confined masonry systems have higher carbon footprints than the structural masonry system for this case study, fundamentally. Also, the results of the other environmental impacts are given in the study and the structural masonry system has lower effects on nature in all categories including the potentials of acidification, eutrophication, global warming, ozone depletion, and, smog formation. The lowest value of primary energy demand is observed in the industrialized system, only. In this thesis, all impact categories are studied in detail not only carbon footprint, and the results are compared for each category. The reinforced concrete models have higher results than steel models in terms of global warming but the highest value of energy need is achieved in steel models in this thesis. Also, the effect of the building height is presented for each impact category. Additionally, the effect of seismicity is studied according to the building height for the steel models of this thesis.

In another study (Petrovic et al., 2019), a case study of a single house is conducted to show the environmental impacts related to building materials from the production and construction phase including the transport, replacement, and deconstruction phase. Energy use and water consumption are not included in the study. That situation is similar to this thesis because the construction and usage stages are not in the scope of this thesis. In the study, the global warming potential result of each material is given such as wood framework, wood panel façade, cross-laminated timber, thermo wood external, cellulose insulation, wood fiber insulation, expanded polystyrene insulation for foundation, gypsum, floor internal plastic details, windows-triple glazed doors, roof-galvanized steel. It means that a completed model involving other building materials is analyzed in the study. However, only structural elements are used for the models in this thesis. Therefore, the analysis results of this thesis may change when other types of building elements or different building materials are added to the models.

Another point is that one type of beam is used in this thesis. Primary and secondary steel beams, as one of the structural elements in the steel models, have HEB100 sections. In the analysis, IPE100 steel section is tried to be used for the secondary beams of the 5-story steel model because this type of section decreases the total steel weight of the model considerably. However, the structural analysis of the model with IPE100 secondary beams can not satisfy the requirements of TEC 2018. As another alternative, HEA100 steel section is put for the secondary beams. This model becomes successful in the structural analysis and it has approximately 2.5% lower steel weight than the steel weight of the model having HEB100 section as secondary beams. However, this decrease does not change the relative results of the comparison between the 5-story steel model and the 5-story reinforced concrete model in terms of LCA results. Also, the reinforcing steel for reinforced concrete models is not included in LCA in this thesis. This may affect the results of reinforced concrete models, and change the position of the models in terms of summer smog formation potential and primary energy use.

The study of Naji (2012) includes the examination of cost, durability, and energy efficiency for a better evaluation of the structures in terms of sustainability. All systems (wood light frame structure, light gauge steel structure, 3D panel system) are rated from 1 to 5 by showing the efficiency of each structure in each issue. The best option is represented with 5 and the others are rated according to this value. The lower values show the inefficiency of the systems in comparison with other systems. The 3D panel system has the highest rate in terms of economic parameters and durability issues while the wood light frame structure is rated with the highest value in terms of energy efficiency. In the study, sustainability is analyzed comprehensively with a rating method but in this thesis, this type of method is not used and the results are given comparatively.

There is a study in the literature belonging to Meral Akgül and Dino (2020), which examines a typical 10-story residential building of TOKİ in terms of the effects of climate change on residential buildings in Turkey. In the study of Sezer (2009), TOKİ projects are investigated in terms of the design process, the linkages of location, sustainability of sites, water efficiency, energy, resources of materials, indoor environmental quality, and education. This is another comprehensive study analyzing the other dimensions of sustainability but this study is prepared for TOKİ projects. In this thesis, the analyses are conducted only for environmental parameters among the structural models. Therefore; future studies may examine the effect of structural material selection on the sustainability of TOKİ projects in terms of other dimensions like social or economic ones.

CHAPTER 5

CONCLUSION

This thesis is a study investigating the potentials of another structural material in terms of sustainability, particularly steel. In order to analyze the potentials, the structural models are created with reinforced concrete and steel material. These models are compared in terms of their impact on nature by using the life cycle assessment method. In this chapter, the summary of the study is given, firstly. Secondly, the implication of the research is clarified. After that, the limitations of the study are defined and then the future recommendation is explained.

5.1 Summary of Research

The study starts with the awareness of the fact that sustainability is an important concern in the construction sector because this sector affects the environment directly with the increasing number of dwelling units. Sustainability is researched in the literature and it is studied in terms of building material alternatives, the selection of structural systems, the methods of the examination, and the programs for analyses. Moreover, the structural systems are studied in terms of the comparison method, the effects of seismicity, and the programs for analyses.

In Turkey, the occupancy permit document of buildings has the values of energy performance class, green gas emission, and sustainable green building data, today. This is one of the indicators emphasizing that sustainability in the construction sector is a significant issue.

In the construction sector, there is an important institution in Turkey due to its percentage, which is The Housing Development Administration (TOKİ). TOKİ wants to meet 5-10% of the building need of Turkey and this ratio is quite remarkable. Generally, TOKİ applies typical housing projects, and also, constructs the buildings by using a specific type of structural system. This system is known as a very fast method, which is the reinforced concrete tunnel formwork system. This is a shear wall system in which reinforced concrete is used as the building material and it provides a very fast construction process. As well as, the number of dwelling units which are produced by TOKİ increases day by day, the typical projects of TOKİ may have undesirable impacts on nature. Since TOKİ has a considerable percentage in the construction sector, its projects are studied in this thesis to investigate the effects on the environment. Therefore, the projects of TOKİ are classified according to their floor number and their plan configuration.

After this classification study, a representable sample is determined to use for the analysis in terms of sustainability. In order to form a similar model with the existing projects of TOKİ, the structural models are created with the shear wall system (called the tunnel formwork system in the sector) by using reinforced concrete, firstly. For analyzing the potentials of another structural material, steel is preferred in the models. Steel models are modeled with the braced frame system to make the structural system comparable to the reinforced concrete shear wall system. Three different height classes are applied to the models which are five-story models, ten-story models, and fourteen-story in ProtaStructure. This is a structural analysis program having the regulations of Turkey and it makes analyses according to new current requirements.

Six models are prepared in ProtaStructure and the results of structural analyses are explained in this thesis. Also, the quantity surveys of these models are investigated so that they can be compared by using the life cycle assessment method. OneClickLCA is used for the life cycle assessment. This program has a web-based interface that data can be uploaded to make the analyses and get the results. Moreover, it presents a material library including several types of reinforced concrete and steel materials. There are different options about the percentage of recyclability for each material. Also, OneClickLCA specifies one of these materials as the typical one.

Firstly, the material selection is applied with the typical options of each material for the models. The results are compared among five, ten, and fourteen-story reinforced concrete and steel models according to the impact categories of the life cycle assessment method. The ratio of each life cycle stage is examined for five-story reinforced concrete and steel models.

After this, five-story models are studied by selecting the least recyclable options of reinforced concrete and steel materials. Then, the most recyclable options are analyzed for five-story models. This analysis shows the comparison of minimum, typical and maximum cases, in this way, the boundary of the analyses is defined.

In the end, the thesis studies low seismicity for five-story and fourteen-story steel models since all models are analyzed in high seismicity. The effect of the seismic region is analyzed with five-story and fourteen-story steel models.

5.2 Implication of Research

In this thesis, the structural models are analyzed in ProtaStructure, firstly, and then the results of the analysis are examined.

- Steel models have higher periods than reinforced concrete models at all classes of building height. The periods of five-story steel models are almost two times the periods in five-story reinforced concrete models. However, the total floor weight of steel models is lower than reinforced concrete models. The ratio reached by the division of total floor weights at reinforced concrete models to steel models is increasing with floor number. For fourteen-story models, the seismic weight of the steel model is approximately equal to one-third of the reinforced concrete model. All models are designed with the equivalent seismic hazard at the same location, but the earthquake loads are higher at reinforced concrete models at both of the directions for all models since the periods of reinforced concrete models are higher than steel models.

After structural results, life cycle assessments are conducted for the models.

- The study of six models with three different heights whose materials are selected from typical materials in the library of OneClickLCA shows that steel models have fewer negative effects in terms of global warming potential, acidification potential, and eutrophication potential at all building heights. In terms of global warming potential, the results of steel models at all height types are almost half that of reinforced concrete models. In terms of ozone depletion potential, the results are very low for the models but reinforced concrete models cause more depletion than other models. Steel models at all heights lead to more summer smog than reinforced concrete models. At all height types, the results for steel models are almost twice that of reinforced concrete models in terms of the ozone formation in the lower atmosphere. The total energy need from the raw resources of the earth is high for all steel models compared to the reinforced concrete models.
- The difference between the results of the reinforced concrete and steel models increases considerably when the building rises in terms of the potentials of global warming and the formation of ozone in the lower atmosphere. For the potentials of acidification, eutrophication, and ozone depletion, the difference between the results goes up slightly with the increase of the building height. The rising of the models affects similarly the results of total use of primary energy, and the difference between the results of reinforced concrete and steel models increases at a slight rate.
- When the results of the studies are examined according to the life cycle stages, the manufacturing of the materials, that is the production stage, has the highest percentage in proportion to the transportation and the end-of-life stage for all impact categories at all models.
- “Minimum-maximum boundary analysis” of the thesis shows the results of the minimum case, typical case, and maximum case of five-story reinforced concrete and steel models. Typical and maximum cases of steel models have lower negative impacts on nature at the potential of global warming, acidification, eutrophication, and ozone depletion potential than the typical

and maximum cases of reinforced concrete models. In terms of the ozone formation of the lower atmosphere, the minimum case of the steel models has the highest value and the results of reinforced concrete models change slightly. The values at total use of primary energy are high for steel models and low for reinforced concrete models even if maximum recyclable material is selected. The maximum case of the reinforced concrete model gives approximately 15% to 25% lower results than the minimum case of the reinforced concrete model according to impact categories. However, the minimum case of the steel model reveals almost 60% to 85% higher results than the maximum case of the steel model. To sum up, the minimum case of steel models has the highest damages to the environment for all impact categories. Since the recyclability of steel materials starts from zero as a percentage and rises to a hundred, the range between minimum and maximum cases becomes very large. Nevertheless, the recyclability of reinforced concrete materials just reaches forty from zero. Hence, the range is narrow for reinforced concrete materials.

- The comparison of the analyses which are conducted for the locations with a peak ground acceleration value of 0.40g and 0.10g (representing the high and low seismicity, respectively) according to the recent Turkish Seismic Hazard Map shows that the weight of the steel material can be decreased greatly by changing the sections of steel models in low seismic regions. As a result, LCA results drop in steel models created for low seismicity. The analysis is studied for five and fourteen-story steel models and the results indicate that the change between low and high seismicity models is higher for fourteen-story steel models than five-story steel models. The change in the results of the fourteen-story steel model is approximately one and a half times the results of the five-story steel model in almost all categories. So, the negative effects of the fourteen-story steel model designed for low seismic regions are decreased remarkably in terms of environmental parameters. Since TEC 2018 has limitations for reinforced concrete models and the wall thickness can not be dropped even if the model is placed in a low seismic region, reinforced concrete models have higher volumes of materials than steel models. It means that it is more advantageous to use steel instead of reinforced concrete as the structural material with the rise of the building for the locations which are under low seismic effects in terms of environmental parameters.

In brief, the results show that reinforced concrete and steel models have different influences on nature and the potentials of the materials change. According to the results, it is aimed to see that another structural material may have a great potential to be applied in a structural system for the typical housing units of TOKİ. Not just changing the material from reinforced concrete to steel, but also changing the recyclability of the material used for buildings is very effective in terms of the ecological approach. Moreover, the selection of structural material in relation to the seismic region affects the sustainability of the models, critically. According to earthquake force at a location, a steel building may be less harmful in terms of sustainability. So, changing the selection of structural material from reinforced concrete to steel may be beneficial for the environment.

The conclusion is that TOKİ buildings may be constructed according to more environmentally friendly projects prepared by evaluating the potentials of alternative materials.

5.3 Limitation of Research

In this thesis, there are some limitations of the studies. Firstly, sustainability is examined only in terms of the environmental dimensions. The economic and social dimensions of the sustainable design principles are not within the scope of this thesis. Therefore, the study is limited to the effects of the models on nature. Also, there are different types of methods to analyze sustainability. This thesis is limited to the method of life cycle assessment. For the life cycle assessment, the data of building materials, building area, and calculation period are given to OneClickLCA. The values about annual energy-water consumption and construction site operations are not included in the study. So, the use stage of the life cycle is not in the scope of the study.

The material quantity of models like the volume of concrete material or weight of steel material affects the results mostly. Moreover, the models consist of just structural materials, reinforced concrete models have walls without any other additional material and steel models have just linear elements. In the life cycle assessment of reinforced concrete models, the amount of the reinforcing steel is not included in analyses. So, this situation affects the result of reinforced concrete models in the comparison. Also, there are only structural steel elements in steel models. There are no infill materials in the models. This may be another parameter affecting the results. Therefore, the thesis is limited to the data consist of the quantity of only structural materials.

Another issue is the structural system that is applied to the models. Since TOKİ generally prefers a tunnel formwork system, models are created with the shear wall system only at reinforced concrete models. For the similarity, the braced frame system is used for steel models. The structural systems are limited with these two systems. Therefore, the results of the analysis may not be applicable to the majority of the existing building stock in Turkey. Additionally, in steel models, one type of slab is used which is the reinforced concrete slab carried by the secondary steel beams since this type of slab is commonly used in the construction sector. Moreover, primary and secondary steel beams are the same in the steel models. Other steel sections are tried as secondary beams in this thesis but the analyses show that the change in the LCA results is limited because of the slight decrease in the steel weight. For other types of buildings (high-rise buildings or buildings with large spans such as office buildings), the selection of secondary beams can significantly affect the LCA results. Also, reinforced concrete and steel are only applied to the analysis as materials for the study. Composite materials or systems as the combination of reinforced concrete and steel are not studied in this thesis. It means that the material is just limited in these two materials in this thesis.

In structural analyses, one location is selected where the peak ground acceleration for rock is estimated as 0.40g which represents regions with high seismic hazard at ProtaStructure. All models are analyzed for one type of load at this selected location. Only five-story and fourteen-story steel models are studied for 0.10g earthquake load at ProtaStructure to see the impact of low seismicity. The analysis is limited between the PGA values of 0.10g and 0.40g. Moreover, only three different heights are applied to the models. It means that the height is restricted with the height of 5-, 10, and 14- story models.

Furthermore, the three plan scheme of TOKİ is defined when the projects are analyzed and one of these schemes is selected for this thesis. In this scheme, a plan is applied as the base plan to create the models. So, the models have the properties of only this plan. Other plans having larger or wider boundaries differently from the used plan may give different results. LCA results are related to the volume of reinforced concrete and the weight of steel. Especially, the volume of reinforced concrete obtained from the slabs of the steel models affects the results considerably. For the results that steel models have lower values than reinforced concrete models, the results of a steel model created from a larger plan can approach the results of reinforced concrete models since the slab area increases. Also, the plan used in this thesis belongs to a housing project and does not represent other types of buildings. Therefore, the analyses of this thesis are limited in the features of this residential floor plan since all models are formed from the same base plan.

5.4 Recommendation for Future Research

This thesis focuses on a plan of one scheme at the housing projects of TOKİ. However, another scheme of TOKİ or a different building plan rather than TOKİ’s plans can be studied. Also, this study is conducted with a residential building plan. In order to see the results of different types of buildings such as offices, hospitals, schools, a non-residential plan can be applied by researchers. At that point, different scales can be applied to the models in terms of height because this thesis uses only three types of building height. Maybe, researchers can analyze the results of tall buildings or models having different floor numbers.

Future studies can form the models with other types of structural systems like rigid frame systems, flat plate or flat slab systems, core systems, and shear walled frame systems rather than reinforced concrete shear wall system and steel braced frame system. Other types of the slab can be applied for the steel models rather than the reinforced concrete slab carried by secondary beams. Also, in the steel models, secondary steel beams can be applied as different from primary beams for future studies. By using smaller (more economical) secondary beams in the models, the negative impacts of the steel models can be tried to decrease in terms of environmental parameters. Moreover, there are other structures such as timber, masonry, etc. buildings especially applied for low-rise blocks. Not only the use of one material but also the composite materials can be studied for the buildings. The potential of different elements, composite materials, and other systems can be examined in future works.

For the earthquake issue, this thesis focuses on high seismicity and looks at low seismicity for steel models. The next studies can analyze the models at different locations representing moderate seismicity. Future research can comprise reinforced concrete models at low and mid seismic regions by considering the reinforcing steel.

For the structural analysis, the recent regulation of Turkey is used to control the models but in order to see the results of other locations, the regulations of different countries can be applied to the models.

If the data about installation into the building, use/application, maintenance, repair, replacement, refurbishment, operational energy use, and operational water use can be defined, the life cycle assessment of the models may be enlarged in terms of the scope. In this way, other parameters can affect the results, and the material volume of models may not become the dominant data for the analysis. Also, another method can be conducted for the analysis rather than the life cycle assessment. Future studies may enlarge the scope of this study and examine the models in terms of the other dimensions of sustainable design principles such as the economic and social dimensions.

Finally, the method of multi-criteria decision-making can be preferred to define the optimum alternatives by considering all these different features, parameters, and dimensions.

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APPENDICES

A. Post Analysis Controls Report of ProtaStructure

ProtaStructure gives a report, called Post Analysis Controls, after the structural analysis is completed. In this report, there are parameters checked in terms of structural properties, and the factors used in the structural analysis. Moreover, the features of the models are shown and there is a summary of the report at the end. The titles of the report are listed below:

- (B2) Control of Rigidity Irregularity Between Neighboring Floors (Soft Floor)
- (B1) Control of Strength Irregularity Between Floors (Weak Floor)
- (A1) Control of Torsion Irregularity
- Control of Building Base and Building Height
- In reinforced concrete models, Control of Shear/Frame System is conducted, differently from steel models.
- Control of Shear Wall Ratio
- Control of Interstory Drift
- Control of The Requirement of Second Stage Effects
- In reinforced concrete models, Control of Floor/ Shear In-Plane Shear Stresses is conducted, differently from steel models.
- Control of Floor In-Plane Stress
- Effective Cross-Section Stiffness Coefficients of Elements
- Floor Mass, Floor Weights, and Diaphragm Definitions
- Centers of Floor Weight
- Earthquake Loads (Upper Section)
- Earthquake Loads (Sub Section)
- Earthquake Overturning Control of Building
- Structural Irregularities
- Summary Result Report

According to the controls listed above, ProtaStructure warns the user about the success status of models. When all controls are checked and they have proper values according to the parameters, the model becomes successful in terms of the regulations.

In ProtaStructure's report, Effective Cross-Section Stiffness Coefficients of Elements are given. It is shown in Table A.1. These coefficients are used in calculations according to the element type.

Table A.1 Effective Cross-Section Stiffness Coefficients of Elements

Element Type	**Modulus of Elasticity**	**Axial Area**		**Flexural Rigidity**	**Slip Area**	**Torsional Rigidity**
Shear Walls (Shell Model)	1.000	0.500	In-Plane	0.500	0.500	1.000
			Out of Plane	0.250	1.000	
Shear Walls (Equivalent Rod)	1.000	0.500	Prime Direction	0.500	0.500	1.000
			Secondary Direction	0.500	0.500	
Basement Shear Walls	1.000	0.800	In-Plane	0.800	0.500	1.000
			Out of Plane	0.500	1.000	
Slabs	1.000	0.250	In-Plane	0.250	0.250	1.000
			Out of Plane	0.250	1.000	
Columns	1.000	1.000		0.700	1.000	1.000
Beams	1.000	1.000		0.350	1.000	0.100
Link Beams	1.000	1.000		0.150	1.000	0.100

In the final part of the report, there is a title of Structural Irregularities showing six irregularities. They are divided into two as "irregularities in plan" and "irregularities at the vertical direction".

“Irregularities in plan” shows three of them, which are:

1. (A1) Torsional Irregularity
2. (A2) Discontinuity of Floor Diaphragm
3. (A3) Finding Protrusions in the Plan

“Irregularities at vertical direction” demonstrates three irregularities, which are listed below:

1. (B1) Control of Strength Irregularity Between Floors (Weak Floor)
2. (B2) Control of Rigidity Irregularity Between Neighboring Floors (Soft Floor)
3. (B3) Discontinuity of Vertical Elements of the Structural System

The report warns if there are any of these irregularities. In the end, ProtaStructure gives a Summary Result Report, which summarizes all results and controls, and it says if the results are proper according to the regulation.