LIFE CYCLE ASSESSMENT ANALYSIS OF A REPRESENTATIVE RESIDENTIAL BUILDING IN TÜRKİYE

by

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ABSTRACT

LIFE CYCLE ASSESSMENT ANALYSIS OF A REPRESENTATIVE RESIDENTIAL BUILDING IN TÜRKİYE

As one of most carbon-intensive sectors, construction sector is responsible for significant portion of the global greenhouse gas emissions. To understand and further reduce the carbon emissions of the sector, it is necessary to first identify the emission sources for building construction. This study undertakes a detailed Life Cycle Assessment analysis (LCA) of a representative residential building in Türkiye. The study begins by emphasizing the construction sector's significant contribution to global greenhouse gas emissions and identifies the research gaps in similar LCA studies both from the global and local contexts. The methodology section includes the comprehensive approach taken, including data collection from official sources, and relevant publications. The analysis undertakes detailed LCA modelling to assess the environmental impacts associated with the investigated building's materials and their transportation, operational phase, and end-of-life. Findings of the study indicate that operational phase followed by the production of construction materials are the most significant contributors to the building's overall environmental impact. In addition, the study suggest different reduction scenarios towards decarbonization of the construction industry in Türkiye, such as switching from the use of CEM I to CEM II cement and making buildings more energy efficient. This study contributes to the literature by highlighting the environmental impacts of a representative residential building in Türkiye along with providing approaches on how to reduce the carbon impact of the sector. The findings of this thesis might benefit city planners, architects, and constructors about their material and design choses for the construction of new residential buildings.

ÖZET

TÜRKİYE'DE TEMSİLİ BİR KONUT BİNASININ YAŞAM DÖNGÜSÜ DEĞERLENDİRME ANALİZİ

İnşaat sektörü, en çok karbon salımına sebep olan sektörlerden biri olarak, küresel sera gazı emisyonlarının önemli bir kısmına sebep olmaktadır. Sektörün emisyon noktalarını anlamak ve azaltmak için, yapı malzemelerinin üretiminden, malzemelerin kullanıldığı binaların ömrünün sonuna kadar olan çevresel etkileri kapsayan geniş bir bakış açısıyla, öncelikle emisyon noktalarını belirlemek gerekmektedir. Bu çalışma, Türkiye'deki temsili bir konut binasının detaylı bir Yaşam Döngüsü Değerlendirmesi (YDD) analizini yaparak, incelenen binanın yaşam döngüsü boyunca inşaat malzemelerinin üretiminden yıkımına ve sonrasına kadar geçen süreçteki etkilerini incelemektedir. Çalışma, hem global hem bağlamında benzer LCA çalışmalarındaki eksik noktaları vurgulamaktadır. Metodoloji bölümünde, resmi kaynaklardan ve ilgili yayınlardan elde edilen verilerin toplanıp, nasıl işlendiği detaylıca açıklanmıştır. Yapılan çalışma ile, i) yapı malzemelerinin üretimi ve sevkiyatı, ii) binanın kullanım aşaması, iii) binanın yaşam sonu aşaması kısımlarındaki çevresel etkiler belirlenmiştir. Çalışmanın çıktıları, binanın kullanım aşamasının en çok çevresel etkiye sebebiyet verdiğini ve ardından yapı malzemelerin üretiminin ikincil etki kaynağı olarak öne çıktığını belirlemiştir. Yapılan çalışma ile ayrıca Türkiye'de inşaat sektörünün karbonsuzlaştırılması yönünde farklı azaltım senaryoları önermektedir. Örneğin CEM I'den CEM II çimentosunun kullanımına geçiş ve binaların daha enerji verimli hale getirilmesi gibi. Bu çalışma, Türkiye'deki temsili bir konut binasının çevresel etkilerini belirleyerek ve sektörün karbon etkisinin nasıl azaltılabileceğine dair olası senaryolar sunarak literatüre katkıda bulunmaktadır. Bu tezin çıktıları, özellikle yapılacak olan yeni konut binalarının inşası için malzeme seçimleri ve bina tasarımı noktasında şehir planlamacılarına, mimarlara ve inşaat mühendislerine, ilgili bakanlık ve belediyelere katklı sağlayabilir.

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LIST OF ACRONYMS/ABBREVIATIONS

BENG	Nearly Energy-Neutral Buildings
BIM	Building Information Modelling
BSA	Building Sustainability Assessment
EIO	Economic Input Output
EPD	Environmental Product Declaration
GHG	Greenhouse Gas Emissions
GWP	Global Warming Potential
IEA	International Energy Agency
KGM	General Directorate of Highways
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LULUC	Land Use and Land Use Change
ODP	Ozone Depletion Potential
PM	Particulate Matter
POCP	Photochemical Ozone Creation Potential
TBER	Türkiye Building Earthquake Regulation
TCMA	Turkish Cement Manufacturers' Association
UCTEA	Union of Chambers of Turkish Engineers and Architects
UN	United Nation or United Nations
WLEC	Whole-life Embodied Carbon
WoS	Web of Science

1. INTRODUCTION

One of the biggest problems facing humanity in today's world is climate change. Heavy extrapolation of natural resources and ever-increasing emissions to the soil, water and atmosphere brought the world to such a point that it cannot maintain its delicate balance anymore. The rapid growth of the global population resulted in huge energy demand and especially over the past 65 years, worldwide observed adverse effects of climate change are felt seriously (Olabi and Abdelkareem, 2022) and (Abbass *et al.*, 2022).

Researchers and industries have been looking for ways and developing methods to fight climate change and reduce its adverse effects on nature and human health. Industries are trying to develop technologies to reduce/capture carbon emissions and many set net-zero targets by 2050 (Hale *et al.*, 2021). As one of the biggest sectors across the globe, the construction industry and its activities cause significant emissions and pose enormous environmental danger. As stated by Yılmaz and Seyis (2021) and UN publications (Yılmaz and Seyis, 2021) and (UN and IEA, 2017) around one-third of the global greenhouse gas emissions (GHG) belongs to the construction industry. Similarly, almost 40% of the energy-related total GHG emissions are attributed to buildings and construction when indirect building emissions are accounted for (Rodrigues *et al.*, 2018). Thus, it is inevitable that without reducing the carbon footprint of the construction industry, it is impossible to tackle climate change.

The first step towards reducing carbon emissions is first understanding the current situation. One should first know how much environmental impact a specific activity/product/process/structure causes to reveal any reduction potential and set targets. This study first aims to develop a model to understand where at residential building sector is in Türkiye in terms of environmental impacts. After understanding the current situation, the study suggests a couple of scenarios to reduce the carbon footprint of the building sector in Türkiye. For this purpose, collected data from reliable sources

are analyzed and modeled with a life cycle assessment approach and the results are discussed to discover potential reduction areas. The study is expected to contribute to civil engineers, architects and city planners by making them well-informed about the environmental impacts of residential building construction and in addition revealing carbon reduction scenarios. The following sections explain the research background, gap in the literature, aim and objectives of this thesis, methodology, scope and limitations and organization of the study.

1.1. Problem Statement and Importance of the Study

Even though the construction industry is responsible for a significant percentage of carbon emissions across the globe, (Yılmaz and Seyis, 2021) and (UN and IEA, 2017) and (Rodrigues *et al.*, 2018) the sector has been seen as a challenging area to focus on to reduce its environmental burden. This is due to the complexity of the sector. Regardless of the type/size/location of the construction, it involves the contribution of different people from diverse backgrounds, many different companies working separately or at the same time, etc. In addition, the traditional main objective of any construction activity is to be able to perform within the specified budget and time. As long as the budget and time are the two main objectives, the environmental impacts of the sector went unheeded for many years. As (Isaksson and Linderoth, 2018) mentioned, even though environmental issues have received more attention compared to the past, the adoption is slow and the approaches towards the reduction of environmental impacts lack significant perspectives such as the holistic approach to the environmental challenges, without focusing enough on financial benefits, etc.

Furthermore, as (Baloi, 2003) stated back in 2003, the concern over the environmental impacts of the construction industry was increasing beginning of the 21st century. Throughout the past 20+ years, different legal frameworks were established and advanced technological improvements were made that helped to understand/mitigate the environmental effects of the sector. This is not just only for the construction sector, but also for many other sectors, professionals and academia have put their attention

on understanding the effects of individual activities/products/services on the environment. Thanks to the shift in the focus, many industries have already understood their share of carbon emissions and started to look for ways to mitigate these impacts. As one of the biggest sectors contributing to carbon emissions across the globe (Hossain *et al.*, 2020) and (Borachio *et al.*, 2020), the construction industry also had to understand the impact of its activities and act accordingly. However, the construction industry has traditionally lagged behind other industries in embracing modern technologies and approaches. As highlighted before, this is due to the complexity of the sector. It is hard to monitor/control each activity/process at a construction site, where different people from different companies involve. Even further, the environmental impact of the construction industry is not solely on the activities performed at the site, but more on the production of construction materials and the use of the constructed structure throughout its lifetime (Alvarado and Sanguinetti and Rocamora, 2021) and (Fan and Fang, 2023). Thus, the links and bridges between distinct phases of the construction industry have to be established if one wants to have a clear understanding of the environmental impacts. This requires a comprehensive approach and the contribution of different parties.

All the construction materials that are transferred to the site has already production and transportation-related impacts that typically construction workers/civil engineers are not aware of. This is normal because it is not the responsibility of people working at the site to keep track of each construction material coming to the site and know about their environmental impacts. However, if one wants to understand the impacts of building a structure, this has to be considered. A similar approach applies to the use-phase impacts as well.

People working at the site leave the site when the structure is completed and fully usable. However, the main environmental impacts of any structure come from the impacts during the operational lifetime of the constructed structure (Zhang and Cai and Braun, 2022). Without considering use-phase impacts, total building-attributed environmental impacts cannot be understood. Thus, whole building impacts from

the production of construction materials to the disposal of the structure should be considered to thoroughly investigate the environmental impacts of every structure built.

In recent years, there has been a significant increase in studies assessing the environmental performance of structures (Yılmaz and Seyis, 2021). As data is involved, the quality of these assessments increases. In the initial stages, there was not sufficient focus on the impact of the production of construction materials, because simply there was not enough/high-quality data. Similarly, at different life stages of the buildings, there were substantial data gaps(Sharma *et al.*, 2011). However, currently, these data gaps have been partially filled with quality data published in recent years. Compared to the past, researchers now have more data sources available for them and a better understanding of the environmental impacts of structures. This led to a substantial increase both in terms of the number of papers published on the topic and their quality. There is a various range of studies focusing on different aspects such as assessing the impacts of urban development (Anderson and and Lang, 2015), developing a framework for the pre-use stage of buildings (Li *et al.*, 2015), investigating different construction materials (Pretot and Collet and Garnier, 2014), strategy establishment for sustainability performance of buildings (Hossain and NG, 2020), etc.

Even though there is more focus on sustainability studies within the construction industry perspective by utilizing better data sources, there are still important lacks/limitations of the current studies. Even with better data, it is still challenging to include each life stage impact of a building and also there are still data gaps at some certain points. Thus, the majority of the related studies have focused on only 1-2 life cycle stages of the investigated study. This brings risks to the studies because of non-included impacts. This thesis does not claim to eliminate these risks but by including the majority of the impact stages, it does reduce the risk. The stages that are not included in this study due to high uncertainties and data gaps do not have the potential to alter the study findings significantly.

In addition, environmental analyses are prone to regional/local changes. These changes have to be interpreted and identified to increase the quality of study outputs. For example, a country where the majority of the housing stock is made of wooden structures will have different outputs compared with a country where housing stock is mainly reinforced concrete frame buildings. Some studies use global datasets where utilizing regional/local requirements is not possible. Even if the methodology is correct, that does not properly reflect the real case because a structure cannot be considered without considering where it is located. Throughout this study, attention was given to the local conditions of Türkiye. For this aim, official documents, studies and results for Türkiye are used. For instance, construction materials and their quantities were taken from an official body, 'The Union of Chambers of Turkish Engineers and Architects'. Similarly, to calculate use-phase-related impacts, consumption amounts (electricity, natural gas, water) were taken from government publications/reliable data sources that monitor the conditions in Türkiye. Thus, by including the majority of the life cycle stages of the investigated structure with special attention to Türkiye's condition, this study demonstrates environmental impacts on typical residential buildings in Türkiye. The output of the study helps to understand the impacts of various stages of the residential building sector in Türkiye and establishes a benchmark for where Türkiye is in the globe. In addition, suggested reduction scenarios fill an important gap where the outputs of a typical LCA study are linked with possible areas of reduction.

1.2. Aim, Objectives and Motivation of the Study

This study aims to conduct the life cycle assessment analysis of a representative residential building in Türkiye and highlight the reduction potentials in terms of carbon emissions. The motivation of this study lies primarily in the fact that, there is no existing study that can be taken as reference for determining environmental performance of residential buildings in Türkiye. Many countries, mostly Western countries, have already well-established range of values which show the overall impact of different type of structures such as residential houses, offices etc. Since the quantity and the source of impact is known, those countries were able to set well-adjusted targets towards decar-

bonization of their construction sector. However, this is missing in Türkiye. To deal with the adverse impacts of climate change and reduce the carbon emissions of the building sector in Türkiye, the carbon impact of different types of structures should be known. Since majority of the existing building stock in Türkiye is consists of residential buildings, an attention is given to identifying environmental performance of residential sector in Türkiye. Through the outcomes of this study, one can fill the absent area on having a reference value on the carbon impact of the residential building in Türkiye. This enables to uncover the emission sources and establishes comparison with different residential structures across the globe in order to locate the current position of the sector and point out any possible reduction areas. Furthermore, the study establishes three different scenarios to reduce the environmental impacts of Türkiye's building construction sector with the aim of proposing a road map towards decarbonization of the sector.

The objectives of the study are:

(i) Establishing a benchmark carbon value for the residential housing sector in Türkiye which enables the current position of the sector and enabling comparison with other countries across the globe,
(ii) Establishing possible reduction scenarios towards decarbonization of the sector in line with the Paris Agreement,
(iii) Informing civil engineers, architects and city planners about the environmental impact of the sector and making them more informed during the construction material selection process and deciding on design and energy criteria for the structures,
(iv) Providing a roadmap for the public institutions such as municipalities, relevant ministries in Türkiye to implement regulatory frameworks towards making buildings more energy efficient and less carbon intensive.

1.3. Research Methodology

The initial step was to conduct a thorough literature review of life cycle assessment studies on structures. One of the aims of conducting a literature review was to be able to understand the current status and studies about life cycle analysis on different types of structures (offices, residential houses, etc.). In addition, challenges and limitations faced by researchers during similar studies were examined. Following the literature review, the second step was to determine the scope and boundaries of this study. For this purpose, there were two points of focus. The first one was to determine the type of structure that will be investigated. Since the majority (85%) of the construction stock in Türkiye is for residential houses (Tunc, 2021), the focus is concentrated on the life cycle analysis of a residential building. The second was to determine the life cycle stages that will be investigated in this analysis. Based on the existing data and literature, the scope in terms of including different life cycle stages on the investigated building was kept as wide as possible.

After the scope and system boundaries of the study are determined, a detailed investigation of the impact/emission sources for each included life cycle stage is conducted by making use of available literature, official documents publications, etc. Once all the parameters are gathered, a life cycle assessment analysis for the representative residential building in Türkiye is conducted via the use of databases and software.

After the LCA model was completed and impacts were revealed, detailed analysis and interpretations were made on the numbers and at the end, possible reduction scenarios that might help towards decarbonization of the construction industry were established. Finally, possible positive impacts of these scenarios on carbon numbers were shared and discussed.

1.4. Scope and Limitations

This study investigates the environmental performance of a typical residential building in Türkiye and highlights potential reduction areas to make the construction industry less carbon-intensive. While addressing significant emission sources during the building's life and having a comprehensive analysis, the study also bears some limitations that can be addressed in future research and studies.

Even though the included life cycle stages of the investigated building in this study are comprehensive and cover most of the sources of emissions, there are some stages that are not included in the analysis due to a lack of reliable data. The scope of this study can be further expanded by including these missing LCA stages, such as construction at site and building demolition.

Secondly, construction materials included in the analysis have a wide scope and include all the main construction materials for typical residential housing construction. However, since the included materials and their quantities are taken from an official source that solely aims to provide a practical calculation guide for constructors, there might be additional use of construction materials that can be further investigated and included.

The last limitation of the study is related to the suggestion of potential reduction areas in terms of carbon savings. This study points out three scenarios where a significant reduction in carbon numbers can be achieved. However, there might be more possible potential areas that should be investigated for decarbonization of the Türkiye's construction sector.

1.5. Organization of the Study

This thesis study consists of seven chapters. The first chapter, the introduction, briefly states the background, sets the problem definition and statement and focuses

on the aim and objectives of the study along with the limitations. The literature review chapter first presents the overview of the current status of life cycle assessment analyses on the building level by investigating the available literature grouping into three categories. Secondly, it provides insights about understanding the challenges and limitations that researchers face while conducting similar studies. The third chapter, Research Methodology, step-by-step explains how this study was conducted. In this chapter, detailed information from the data acquisition to the interpretation of the results is discussed. The fourth chapter, life cycle modeling, deeply investigates and points out the parameters/emission sources for each considered life cycle stage of the investigated building. Thus, all the inputs for the LCA model are determined at this stage. Then, the 'results and findings' chapter, demonstrates the outcomes of LCA analysis for each emission source with result tables and figures. The 'discussion and reduction potential' section investigates the results of the study and provides a comparison with similar studies. Also, three possible reduction scenarios with their positive potential on carbon emissions are discussed. Finally, chapter seven, the conclusion, summarizes the outcomes and findings of this thesis along with highlighting the contribution of the study.

2. LITERATURE REVIEW

This chapter presents the literature review on life cycle assessment studies in the construction industry by grouping the current literature into three different areas. These areas are called, general assessment studies, specific focus studies and studies that criticize conducted LCA analysis on a building level. The following sections explain each investigated area in detail.

2.1. Current Literature on Life Cycle Assessment Studies within the Construction Industry

As the effects of climate change are felt more and more every year, researchers and professionals shift their focus on understanding and mitigating the environmental impacts of individual activity / process / product / structure, etc. To first understand the environmental effects of the investigated subject, one should have quantitative measurements to know the amount of impact. One of the most used and advanced methods to have quantitative measurements is called life cycle assessment (LCA) analysis. LCA is an analysis technique for evaluating the environmental effects of materials, products and structures (Seyis, 2020). The analysis involves a whole life cycle view where the impacts from the extraction of raw materials to the final disposal are considered.

Since LCA considers the whole life cycle perspective of the investigated subject and is based on scientific measurements, researchers have been heavily involved in LCA studies within the construction industry perspective in recent years. As can be seen from the figure below, a search on the Web of Science (WoS) yields 6078 publication (4752 articles) on the topic for the last 5 years. The selected keywords were as follows: "life cycle assessment" AND "building". When the research areas are examined, around 51.8 % of the articles belong to 'Engineering' area. This is followed by 'Environmental Sciences' by 35.9% and 'Construction Building Technology' by 23.7%. Figure 2.1 shows that there is a strong interest among the researchers on the topic. Similar findings were

obtained from the study of Yılmaz and Seyis (Yılmaz and Seyis, 2021), (Hou *et al.*, 2015) and (Buyle and Braet and Audenaert, 2013).

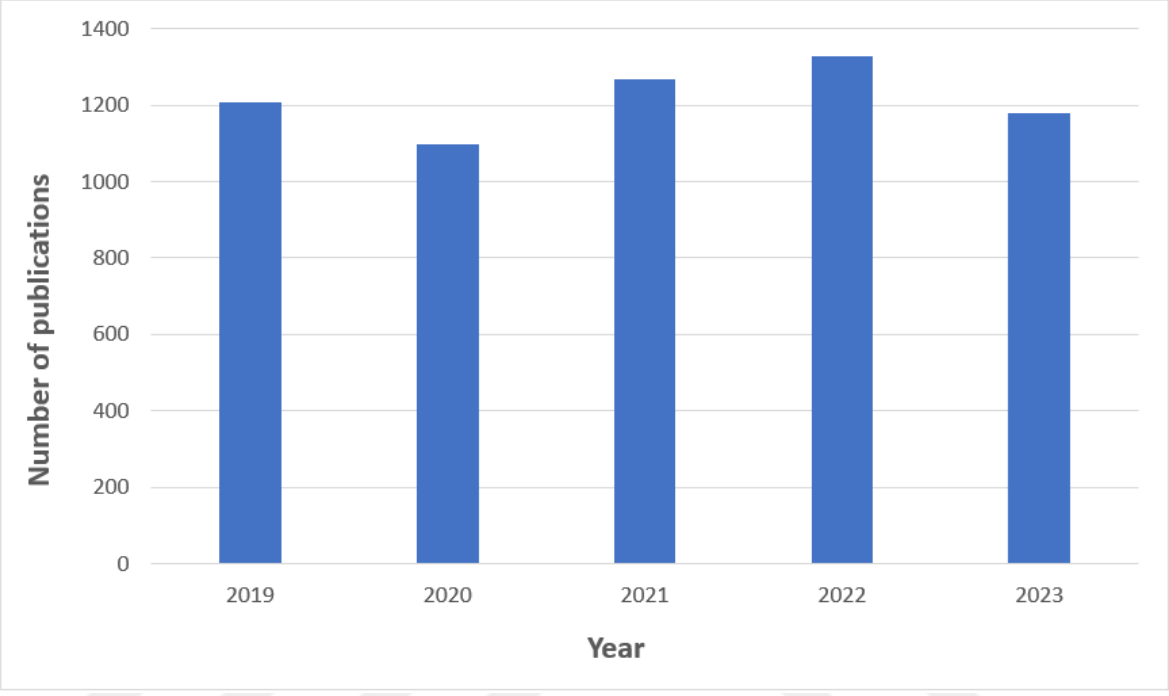

Figure 2.1. Literature search on the investigated topic on WoS for the last 5 years.

Furthermore, the majority of these studies originate from the countries with 'China' being the first country followed by 'USA, 'Italy 'England and 'Spain. Although the West has a high interest in the topic, LCA studies are spread worldwide. When affiliations of the related studies are investigated, the Swiss Federal Institutes of Technology stood first followed by Technical University of Denmark and ETH Zurich. The list includes a significant number of publications from India to Norway. Consequently, it can be concluded that LCA studies in the construction industry have attracted widespread interest from researchers from different backgrounds.

Even though the subjects that researchers focus on in their studies are very diverse, there are a couple of focus areas where large numbers of studies are published. For example, there are a noteworthy amount of studies examining the environmental performance of a specific construction material/s and making comparisons between the investigated products. Moreover, a high number of articles investigate the environmen-

tal performance of a sort of structure to understand where the majority of the impacts come from. When related publications are intensely examined, it is observed that they can be grouped under three main categories except for a few studies. These groups are called general assessment studies, specific focus studies and studies that criticize current literature on the LCA of buildings. The following sections discuss each literature group in detail.

2.1.1. General Assessment Studies

When the current literature is examined, it is observed that a significant amount of studies investigate the environmental performance of a specific structure/building. To do this, most of the time, researchers choose a structure in which they can get/have information about the construction materials, building operation, etc. By setting up system boundaries according to the data they have, they conduct life cycle assessment analysis from a building perspective. Almost none of these studies manage to include each life cycle stage from raw material extraction to the disposal and aftermath since very likely there is a data gap/s at some points.

For example, (Gardner *et al.*, 2020) investigated a three-story, steel-frame, public building located in Pittsburgh, Pennsylvania. The building already had features such as solar panels, geothermal wells, a rainwater collection and purification systems. Their scope of life cycle analysis covered almost all stages except construction. They have found that structural materials dominate the pre-use impacts of the investigated building. Since the building is net-zero, it does not cause carbon emissions during the operational phase but rather contributes carbon offsetting by producing more electricity than needed through installed solar panels.

Gardner's work is one of the most detailed life cycle assessment studies in terms of its high coverage and data quality. There are also similar studies focusing on different types of structures. For example, (Rodrigues *et al.*, 2018) investigated the LCA of constructing an industrial building with a focus on embodied carbon and energy. Their

main focus was on the activities during the construction process. Since it is hard to control/monitor activities at the site, the majority of LCA studies on buildings either do not include the construction stage or use default consumption values. However, since they have the primary data, (Rodrigues *et al.*, 2018 detailly investigated impacts arising from construction activities at the site and found out that diesel use is the main source of emissions followed by electricity and water. A similar study was conducted by (Bilec and Ries and Matthews, 2010) where researchers also focused on modeling the construction process for buildings found that particulate matter emissions are significant in the construction phase.

Similar studies were investigated such as (Kumanayake and Luo, 2018), where researchers conducted the first building scale LCA analysis in Sri Lanka; (Hart *et al.*, 2021) where whole-life embodied carbon (WLEC) comparisons were made between different types of structures; (Franca and Azapagic, 2012) where researchers presented LCA results for the three most common types of house in the UK and highlighted that for all types, use stage is the most dominant stage.

Table 2.1 summarizes some of the investigated literature categorized under general assessment studies. It shows building types, including LCA stages and the data/software used along with the major outputs of the investigated publications. It is evident that the majority of the studies where life cycle assessment is performed on a building scale, try to include as much LCA stage as possible to increase the coverage and quality of the study outputs.

However, since the information is not always available, most of the time, some of the stages are omitted. In addition, as in the case of (Bilec and Ries and Matthews, 2010) sometimes researchers focus only on a single life cycle stage to detailly investigate/reveal any associated impact at that stage. It is also apparent from Table 2.1 that, it is inevitable not to use a data source/software for conducting an LCA. It is observed that among the three categories into which existing relevant studies are grouped, this group has the highest number of publications.

Table 2.1. Life cycle assessment studies on building level.

Publication	**Building Info**	**Included LCA Stages**	**Data source/ Software**	**Major outputs**
Gardner *et al.*, 2020	Three-story, steel frame, mainly office use	A1-A4 and Use phase and End-of-life	Ecoinvent	- Structural materials dominate pre-use impacts - The building is net-zero energy and water, but not net-zero carbon.
Rodrigues *et al.*, 2018	Two-story, Industrial building,	A1-A4 and Construction	Inventory of Carbon and Energy (ICE)	- Building materials contribute most of the total embodied energy and carbon. - More processed materials such as materials concrete, contribute more. - Diesel use is the major impact source during building construction
Bilec and Ries and Matthews, 2010	Six-story, steel frame, Commercial building	Construction	Analytica, EIO-LCA, SimaPro	- PM emissions are significant in the construction phase - Critical to include service sectors in LCAs and EIO-LCA

Table 2.1. Life cycle assessment studies on building level. (cont.)

Publication	**Building Info**	**Included LCA Stages**	**Data source/ Software**	**Major outputs**
Kumanayake and Luo, 2018	Seven-story, University building,	A1-A4 and Construction and Use phase and End-of-life	Literature	- Emissions during the material operation and production significant stages are
Hart *et al.*, 2021	Multistory buildings, steel, concr ete, and timber structures	A1-A4 And Construction and B1 stage and End-of-life	Ecoinvent, SimaPro	- WLEC emissions are mainly governed by the upfront emisssions In the case of timber, significant emissions occur post-construction
Franca and Azapagic 2012	Detached, Semi-detached and terraced-houses	A1-A4 And Construction And Use Phase And End-of-life	GABI	- The main hotspot is the use stage - Benefits from reusing the bricks and recycling the aggregates
Carvalho *et al.*, 2020	A Portuguese Residential house	A1-A4 And Construction And Use phase and End-of-life	Tally	-Integrating BIM-based LCA models Increases quality and comparability
Shirazi And Ashuri, 2020	Single-family Detached Residential Building in Atlanta	A1-A4 And Construction And End-of-life	SimaPro	- 3-5 years in operation for embodied energy payback for pre-1970s buildings and 1.6-3.2 years for post 1970s buildings

Table 2.1. Life cycle assessment studies on building level. (cont.)

Publication	**Building Info**	**Included LCA Stages**	**Data source/ Software**	**Major outputs**
				- No lifetime payback for eutrophication and ozone depletion impacts
Rinne and Ilgın and Karjalainen , 2022	Hybrid, concrete, and timber apartment buildings in Finland	A1-A4 And Construction and Partial use phase and End-of-life	One Click LCA	- For A1-A3, the timber apartment had the lowest carbon footprint however use stages had the highest - Overall, Hybrid Construction Outperforms concrete and timber construction
Kayaçetin And Tanyer, 2020	Residential Housing in Türkiye	A1-A4	GABI	- Around 24 the emissions originate from transportation infrastructure and 9 structural landscape
Airaksinen And Matilainen, 2011	Office building	A1-A4	IDA ICE	- Reduction of electricity use has high importance on CO_2 emissions - Lowest primary energy was achieved when bio-based local energies were used

2.1.2. Specific Focus Studies

Unlike the first category, studies grouped under 'specific focus' have a narrow perspective. These studies do not directly focus on assessing the environmental performance from a building level but focus on the environmental impacts of individual construction materials or processes. In addition, these studies generally make comparisons between different construction materials that can be used interchangeably. Thus, these studies make the readers well-informed about the environmental performance of a specific process/product by making like-to-like comparisons so that decision-makers can benefit during the early designing phase of buildings. The outputs of these studies help reduce the carbon footprint of buildings by utilizing less environmentally harmful construction materials.

For example, (Muneron *et al.*, 2021) compared the environmental performance of ceramic brick and concrete blocks in the vertical seal subsystem in residential buildings. They have pointed out that using alternative energy sources such as biomass during production might significantly reduce CO_2 emissions. In their study, Muneron *et al.* also considered other factors such as the transportation of materials to the site, etc. to provide a comprehensive comparison between the two investigated materials. Similarly, Stafford *et al.*, 2016 focused on the life cycle assessment of the production of cement from a Brazilian context and (Moretti and Caro, 2017) from an Italian perspective. In their papers, environmental impacts on concrete production in Brazil and Italy are investigated and similar to the findings of Muneron, the use of alternative fuels during production is suggested to reduce the CO_2 impacts. Moreover, even though the major concern of the studies under the 'specific focus' group is to investigate the environmental performance of certain construction materials and provide comparison and reduction scenarios, some studies focus on other specific comparable subjects such as wood waste management strategies (Hossain and Poon, 2018) comparison of different life cycle assessment approaches (Hendrickson *et al.*, 1997), etc.

Outcomes of studies under this group can be better utilized towards reducing the carbon footprint of the buildings because these studies are generally more direct than the first category of studies. The main focus is to compare different construction materials and suggest ways to reduce the environmental impact of a specific product/process. Thus, from the outputs of these studies, it is clear which building material is less environmentally harmful compared with its counterpart. Therefore, benefits in terms of carbon emissions can be directly measured and observed if the material with lower carbon emissions is utilized. This is not the main aim of the studies grouped under the 'general assessment' category. The main aim of 'general assessment' studies is to be able to demonstrate the environmental performance of a structure and highlight the hot spots in terms of carbon emissions. A significant portion of these studies only highlight the results from building content and do not focus much on reduction potentials as this is generally outside of their scope. However, determining the current status is only half of the work, the other half is to develop/demonstrate ways to reduce the emissions. Therefore, when the outputs of studies under these two groups are combined, it brings more clarity and coverage. For example, the outputs of a study focusing on determining the carbon impact of a typical house in Italy can be used together with the outputs of (Moretti and Caro, 2017), where researchers investigated the cement sector in Italy. An understanding of the impact of cement types and production on the carbon burden of a typical house in Italy can be established by combining the findings of these two studies. Thus, even though the main focus of these two groups of studies is different, they complement each other and expose further understanding and coverage.

2.1.3. Studies That Criticize Current Literature on LCA of Buildings

The last group of studies among the current literature are grouped as studies that criticize current literature on the LCA of buildings. Rather than investigating the environmental performance of structures or construction materials, these studies critically review the current literature on life cycle assessment analysis in the construction industry. It is crucial to have these critical review studies because they highlight the lacking or problematic sides of studies and provide alternative approaches to overcom-

ing these lacking sides. Moreover, they provide an understanding of the challenges in the area and provide new research directions. Considering the fact that a life cycle assessment analysis requires a holistic approach across different stages (time frames) of the investigated subject and involvement of intensive data, it is prone to different interpretations based on the quality of data sources, complexity of the investigated subject, etc.

For example, in their studies, (Fnais *et al.*, 2022) reviewed the application of life cycle assessment in buildings and promoted the concept of semantic-based, real-time LCA to address variations in the built ecosystem to make LCA studies more effective. In another study, (Anand and Amor, 2017) investigated the recent developments, future challenges and new research directions in LCA of buildings. They have listed some of the problematic sides of LCA analyses such as comparison issues, significant differences in actual and calculated impacts, discrepancies in use-phase impacts, etc. (Nwodo and Anumba, 2019) also stated similar problematic sides such as data intensity and quality, subjectivity in environmental impact characterization, assumptions for building life span, etc.

No ones claim to have a 100% reliable and correct LCA study whether on a product or building level. LCA studies always involve certain assumptions at some points that can alter the results. Data quality and selected data sources substantially alter the results as well. Even though the standards are in place such as ISO 14040/44 and EN 15978, the studies are highly prone to the knowledge of the LCA practitioners and the quality of both the data and emission factors. As these researchers suggest, LCA studies should have the same playing ground to make them more suitable for comparison. Moreover, problems such as choosing the declared/functional unit and lifetime of buildings should be homogeneous across the studies. Furthermore, when making an assumption is necessary, it should be an acceptable one so that it does not affect the results significantly.

2.2. Current Gaps in Life Cycle Assessment Studies within the Building Context

As highlighted in this chapter, current literature on life cycle assessment analysis within the construction industry perspective has gained worldwide interest both among the researchers and the industry. Thus, especially for the last decade, there has been an upward trend in the number of related publications as shown in Figure 2.1. The current chapter investigated the literature thoroughly by grouping the relevant publications into three categories.

It has been found that there is no comprehensive research on the life cycle assessment analysis of a residential building in Türkiye where the study outputs can be also used as a proxy value within the country. Even more, the current literature on the subject within the Türkiye context is limited with only a few publications available. The majority of these publications in Türkiye fall into the category of 'specific focus studies' where researchers focus on the environmental performance of a specific material/process etc. rather than the whole structure. When studies on the building level are examined, the majority of them either lack in terms of comprehensiveness or coverage.

Kayaçetin and Tanyer, (2020) investigated a residential building in Türkiye through A1 to A4, without focusing operational phase and end-of-life emissions. Since the majority of the impacts of the building are at the operational phase, exclusion of this stage results in omitting a significant percentage of the building's total impacts. In another study, (Atmaca A and Atmaca N, 2015), even though the included stages are comprehensive, the study focuses on the comparison of two specific buildings in Gaziantep, Türkiye. Thus, the aims of their study are different and the outputs cannot be taken as proxy values for the Turkish residential sector. Thus, this study fulfills an important gap in the literature by providing environmental performance values for a representative residential building in which the study outputs are not specific to a unique structure but can be representative of the residential housing sector in the

country. Therefore, the outputs of this study can be used as a proxy by civil engineers, architects and city planners. Furthermore, there is no study available within the Türkiye context that investigates not only the CO_2 related impacts but other impacts such as eutrophication potential, land-use impacts, etc. When relevant publications are also examined globally, there are only a few studies that go beyond only considering CO_2 related impacts. In addition, this study goes one step beyond by providing two major scenarios for decarbonization of the building sector that are believed to apply to Türkiye. A high majority of the current literature reveals the environmental performance of the investigated subject but does not establish a link between the numbers and possible reduction schemes. Providing reduction scenarios when considering country-based criteria is another further step that distinguishes this study from the current literature.

In this study, to increase comprehensiveness, all the major stages (in terms of carbon contribution) are included not just focusing on CO_2 impact but also providing an understanding of the other environmental burdens that the building creates. Moreover, the study links the outputs of the LCA analysis to possible reduction scenarios which the author believes can be appropriate for Türkiye's conditions. The outputs of this thesis study can be highly beneficial for the interested parties in terms of both understanding the environmental impacts of the residential building construction sector in Türkiye and the ways how to reduce the impacts.

3. RESEARCH METHODOLOGY

The methodology of this study comprises six distinct yet interrelated parts, aimed at assessing the environmental impacts of a typical residential building in Türkiye and highlighting its reduction potential. These parts are as follows:

- Identifying the inputs for the representative residential building
- Determining the regional and local requirements
- Choosing the data sources
- Life cycle assessment modeling of the investigated building
- Comparison of study outputs with the existing studies in the literature
- Determining possible reduction potentials

3.1. Identifying Material Inputs for the Representative Residential Building

A structure, from its construction to demolition, causes environmental impacts at various life cycle stages. It is possible to divide the entire life cycle of a structure into different phases and to analyze the environmental effects associated with each phase. These stages commence with the production of building materials and extend beyond demolition to encompass end-of-life impacts. When adopting a holistic life cycle perspective of a building, from construction through to demolition and subsequent stages, it becomes evident that the use phase of the building has the highest impact. As noted by (Gardner *et al.*, 2020) and (Junnila and Horvath, 2003) approximately 80% of the total life cycle impacts are attributable to the use-phase stage. Following the use phase, the second most carbon-intensive stage is the impact attributable to construction materials (Khan *et al.*, 2022). Given an average lifespan of 50 years for a building, the environmental impacts during its use stage are anticipated to be considerable. Similarly, the impacts arising from the production of the numerous different construction materials used in the building also have significant effects.

The first aim of the study was to determine the environmental impacts of building materials used in the investigated structure. A review of the literature shows that researchers have either employed average material quantities (Hart *et al.*, 2021, Gervasio and Dimova, 2018) or quantities from specific projects/structures (Kumanayake and Luo, 2018). While many of these studies are comprehensive and detailed, they do not align with the objectives of this study. The purpose of this study is to conduct an analysis representative of the typical residential building stock in Türkiye. To achieve this, the building materials and their quantities should accurately reflect the Turkish housing sector. This implies that input from a unique housing project in Türkiye should not be used, as it may not represent the existing residential building stock. Similarly, global average material consumption figures are also unsuitable due to their high uncertainties and variations, primarily arising from differences in construction methodologies and material types used in various countries. Therefore, it was crucial to precisely acquire construction materials and their quantities that are representative of the housing sector in Türkiye, considering the country's building practices. The necessary data is provided in Table 3.1.

Table 3.1 provides information on material quantities applicable for practical calculation for a typical residential building in Türkiye with a net living area of less than 150 m^2 per independent unit. These calculations have been prepared by the 'Union Of Chambers Of Turkish Engineers And Architects, UCTEA and published as an official document with OB 1303 publication number on 8 June 2016 (Aksu, 2021), (full document can be found in the appendix). The study was requested by the Ministry of Treasury and Finance's Revenue Administration from the relevant trade associations with its circular issued on 11.05.2016. Table 3.1 is prepared at the request of the relevant ministry and has the purpose of being a practical guide for professionals in terms of assessing the construction material quantities for residential projects. The quantities of materials to be used in a residential project vary depending on the design of the construction work, the region, the ground settlement and many other parameters. However, the published study has been prepared and suggested to be a guide to the professionals for practical calculation and included core material inputs for residential

building construction. Thus, the materials and quantities listed in Table 3.1 represent the current housing sector of Türkiye and its inputs are used in this study to assess the number of materials used and their environmental impacts on the representative residential building.

Table 3.1 provides the main construction material inputs and their quantities based on 1 m^2 of construction area, listed under 18 different entries. As seen in Table 3.1, material quantities are given for two types of building structures: masonry and reinforced concrete. Given that the majority of the housing stock in Türkiye constructed as reinforced concrete frame buildings, the quantities specified for reinforced concrete structures were utilized in the analysis

For example, the first material input is 'reinforced concrete'. It has been calculated that for a residential building, approximately 0.380 m^3 of concrete is used per 1 m^2 of building area. Following the list, 34 kg of rebar and 2.6 m^2 of formwork are suggested to be used per the same unit. Following the rest of the table, the main material inputs and quantities used in a representative residential building are determined.

The rationale for quantifying material inputs based on a 1 m^2 area is to neutralize the impact of building size. As the area of a building increases, so does its environmental impact. To facilitate accurate comparisons, environmental impacts are therefore presented and compared on a per-square-meter basis. Given this approach, variables such as the structure's design and the number of floors become less significant. As indicated in Table 3.1, only a few material inputs are influenced by the building's number of floors, namely wooden roofing and metallic coating. In this analysis of residential buildings in Türkiye, data from TÜİK for 2021 (TÜİK, 2021) shows that households predominantly reside in 2-storey buildings. Consequently, for materials whose usage is dependent on the number of floors, a 2-story residential building is assumed in the analysis. Upon reviewing similar studies (Kumanayake and Luo, 2018), it has been determined that the materials listed in Table 3.1 represent the majority of construction materials used in a typical residential building.

Table 3.1. Construction materials and their quantities per 1 m^2 building area.

	Construction Type	Masonry	Reinforced
1.	Concrete	0.250 m^3/m^2	0.380 m^3/m^2
2.	Structural steel	22 kg/m^2	34 kg/m^2
3.	Mold	1.75 m^3/m^2	2.60 m^3/m^2
4.	Falsework	1.90 m^3/m^2	2.80 m^3/m^2
5.	Working scaffold	1.43 m^2/m^2	1.43 m^2/m^2
6.	Brick wall	0.200 m^3/m^2	0.150 m^3/m^2
7.	Interior plaster	2.40 m^2/m^2	2.40 m^2/m^2
8.	External plaster	1.30 m^2/m^2	1.30 m^2/m^2
9.	Ceiling plaster	0.90 m^2/m^2	0.90 m^2/m^2
10.	Whitewash (internal)	3.00 m^2/m^2	3.00 m^2/m^2
11.	Tiles - ceramic	0.30 m^2/m^2	0.30 m^2/m^2
12.	Wooden structure +carcass	0.15 m^2/m^2	0.15 m^2/m^2
13.	Wooden window	0.12 m^2/m^2	0.12 m^2/m^2
14.	Oil painting	0.42 m^2/m^2	0.42 m^2/m^2
15.	Wooden roof, tile cover (over the total construction area)		
	Single story	1.25 m^2/m^2	1.25 m^2/m^2
	Two stories	0.63 m^2/m^2	0.63 m^2/m^2
	Three stories	0.42 m^2/m^2	0.42 m^2/m^2
	Four stories	0.33 m^2/m^2	0.33 m^2/m^2
	Five stories	0.25 m^2/m^2	0.25 m^2/m^2
16.	Metallic Coating (over the Total Construction area)		
	Single story	1.33 m^2/m^2	1.33 m^2/m^2
	Two stories	0.67 m^2/m^2	0.67 m^2/m^2
	Three stories	0.44 m^2/m^2	0.44 m^2/m^2
	Four stories	0.34 m^2/m^2	0.34 m^2/m^2
	Five stories	0.27 m^2/m^2	0.27 m^2/m^2
17.	Mosaic Floor covering	0.90 m^2/m^2	0.90 m^2/m^2
18.	Glass	0.10 m^2/m^2	0.10 m^2/m^2

3.2. Identifying Use-Phase Related Inputs for a Representative Residential Building

At this stage, the environmental impacts arising from the use phase of the representative residential building are considered. As noted earlier, over a typical building lifespan of 50 years, the majority of environmental impacts come from use-phase re-

lated emissions. The environmental impacts during the building's use phase can be categorized into two parts. The first involves the consumption of electricity, natural gas, water, etc. The second encompasses impacts associated with restoration, renovation and maintenance activities that the building may undergo during its operational life. Upon examining these two aspects, it has been observed that environmental impacts resulting from energy source consumption are higher than those attributed to maintenance and refurbishment activities (Kumanayake and Luo, 2018). In this study, the effects of energy usage were included, but emissions related to maintenance and refurbishment were excluded due to the absence of reliable data.

A methodology similar to the one used when assessing the impacts of construction materials has been used to assess the impacts of the use-phase related emissions as well and average values that are valid and representative of Türkiye's conditions were used. The included parameters for the use phase are summarized in Table 3.2. In light of these inputs, environmental impacts of the building due to electricity, natural gas and water consumption during its use were calculated.

Table 3.2. Considered parameters for use-phase impacts.

Emission source	**Unit**	**Quantity**
Electricity	kWh/m^2/year	89.5
Natural gas	m^3/m^2/year	8.63
Water	kg/m^2/year	2410

3.3. Determining The Regional and Local Requirements

After determining the inputs and quantities for construction materials and use-phase emission sources for the representative residential building in Türkiye, the collected data was localized to best reflect the realities of the Turkish building sector. At this stage, each construction material specified in Table 3.1 was modeled to align closely with Türkiye's local requirements. As (Nwodo and Anumba, 2019) stated, it is crucial to conduct building environmental analysis studies in accordance with the conditions of the region and country where the building is located. Such an approach enhances the

accuracy and quality of the study. Although Table 3.1 specifies the building materials and their quantities, it does not provide any further information.

For example, it has been stated that 0.380 m^3 of reinforced concrete per m^2 of building area should be used. However, details such as the strength class of the concrete, the amount of aggregate it contains and the type of cement in the concrete are not specified. These parameters should also be addressed because they directly alter the environmental impacts of the investigated material. Within the scope of this study, the reinforced concrete specified in Table X was modeled as a concrete with C30 strength and produced with CEM I cement to best reflect the Türkiye's conditions. According to TBER, (Resmi Gazete, 2018) the lowest concrete strength class that can be used in building construction in Türkiye is C30. In addition, according to the Turkish Cement and Cement Products Assembly's 2022 data (Türk Çimento İstatistikler, 2022), approximately 51% of the cement produced in Türkiye in 2022 is CEM I Portland cement. When these two data are brought together, it is very likely that the reinforced concrete for residential building construction in Türkiye will be a reinforced concrete with C30 strength, containing CEM I Portland cement. Considering the relevant parameters, the reinforced concrete specified in Table 3.1 was modeled and its environmental effects were assessed.

As another example, the use of reinforcing steel listed in the same table can be considered. Similarly, it is calculated in that it would be appropriate to use 34 kg of reinforcing steel per m^2 of building area, but no details are provided. The major manufacturers of reinforcement steel in Türkiye were examined and their steel production route was modeled and reinforced concrete steel data that best reflects the reality of Türkiye was created. Studies in similar detail were carried out for each building material specified in Table 3.1 and each building material was modeled to reflect the conditions of Türkiye in the most realistic way. Table 3.3 summarizes the 'localization' steps performed for each building material included in the analysis along with the modified datasets.

Table 3.3. Localization steps for included construction materials.

Material	**Localization Steps**
Concrete	30 MPA concrete with CEM I Portland cement is used. Production in Türkiye for both cement and concrete. Supply of raw materials either from Türkiye or nearby regions
Structural steel	Crude steel Production from electric arc furnace Route representative for Türkiye Inclusion of Localized Additional Processes (hot rolling etc.)
Mold	Plywood Production Impact for Türkiye
Brick wall Interior plaster External plaster Ceiling plaster Whitewash (internal)	Inclusion of clay brick and mortar adhesives for Türkiye's conditions Production of cement plaster for interior, exterior And Ceiling application in Türkiye Alkyd paint use, without water for whitewash with Türkiye's conditions
Tiles-ceramic	Production of ceramic tile in Türkiye Production of adhesive and cement mortars in Türkiye Water use During application
Wooden Structure +carcass	Production of Wooden Structural elements, Mostly structural timber in Türkiye
Wooden window + Glass	Production of double- glazing window in Türkiye PVC window frame
Oil painting	Production of oily paint, without water inTürkiye
Wooden roof, tile Cover (two-storey)	Production of roof system consisting of roof slate, steel parts, oriented strand board, polystyrene, sawn wood, polyethylene, and calcium carbonate productions in Türkiye with Needed Additional processes
Mosaic Floor covering	Production of gravel and aggregates used in mosaic floor covering Production of adhesive mortar Water use During application

3.4. Determining the Data Sources and Their Comprehensiveness

Within the scope of this study, the environmental impacts resulting from the production of construction materials, energy consumption during the operational life and end-of-life related impacts of the building were examined. In this section, the

datasets and sources used to determine the environmental impacts of the considered impact sources within the study's scope are detailed. As highlighted in similar studies the quality of data sources used in life cycle analysis studies is of crucial importance. In this study, two main sources were used: the Ecoinvent database and published Environmental Product Declaration (EPD) studies.

3.4.1. Ecoinvent

Based in Zurich, Switzerland, ecoinvent is a non-profit organization committed to making high-quality data for sustainability assessments globally available. The ecoinvent database's beginnings can be traced back to the 1990s during which Swiss Federal Offices and research institutes worked together to create Life Cycle Inventory (LCI) data. These efforts have led to the creation of the ecoinvent database in 2000 with the sole aim of harmonizing, updating and expanding the LCI data available globally (Moreno-Ruiz *et al.*, 2023). After the successful initiation of the database, thanks largely due to public interest, the ecoinvent had major updates from 2000 to 2013. Since 2013, the database has been updated regularly each year with the purpose of increasing the data quality and coverage. (Steubing *et al.*, 2016) states that life cycle inventory analysis (LCIA) databases continue to evolve as the databases get updated. He also points out that version 3 of the ecoinvent database, which was initially published in 2013, features more up-to-date background data than previous versions.

The ecoinvent database currently has more than 18000 individual data for materials and processes. One of the most useful features of the ecoinvent database is its ability for modularity. Each data point in the dataset is constructed and fully documented on 'unit processes' where inputs and outputs are individually quantified. This gives the user the ability to modify the data that has been used and to create even more comprehensive representative datasets. For example, crude steel production data representative for Europe can be modified in a way that it represents crude steel production in Türkiye. To do that, inputs and outputs of the main data can be modified such as using Turkish electricity grid mix and fuels, etc. rather than using Europe

averages. Following this modular approach, each regional and country-based data on ecoinvent can be modified/updated. Within the context of this study, it was important to modify the data based on regional and country-specific conditions to better reflect a representative residential building in Türkiye.

3.4.2. EPD

An Environmental Product Declaration (EPD) is an ISO Type III Environmental Declaration based on the ISO 14025 standard. An EPD transparently reports the environmental performance of products or services from a lifecycle perspective. The preparation of an EPD includes different stages, from acquiring raw materials to the end of life of the final product/service. EPDs are based on international standards and consider the entire value chain. ISO 14025 standard (ISO, 2006) establishes the principles and specifications for developing Type III environmental product declarations.

To publish an EPD document, first, an LCA study must conducted. The environmental impacts of the investigated product/system are determined through this LCA analysis. In addition, Product Category Rules (PCRs) determine the requirements for a specific product category and establish guidelines that must be met when creating an EPD document (Gelowitz and McArthur, 2017). EPD documents are regarded as a valuable primary data source to assess the environmental impact of the investigated product/system because the EPD owner is the manufacturer of the product that has been investigated. (Andersen *et al.*, 2019) listed the advantages of EPDs as having the capacity to communicate objective information, improve the corporate image and communicate large amounts of environmental information. As can be seen in the below infogram (Anderson *et al.*, 2023), the growth in the number of construction product EPDs is exponentially increasing. There were around 200 publicly available construction product EPDs in August 2011 whereas there are more than 16000 registered EPDs publicly available as of January 2023. Since the demand for sustainable and low-carbon construction materials is expected to increase even further in the coming years, this growing trend is expected to continue.

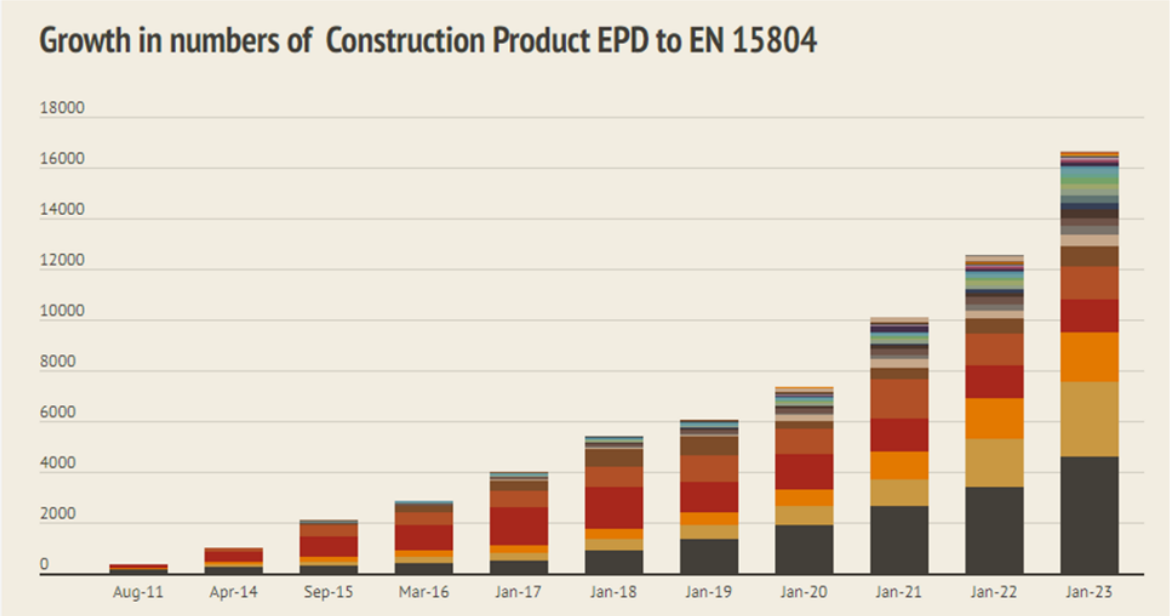

Figure 3.1. Number of registered EPDs across the globe.

Different colors on the bars on the infogram represent several published EPDs by different publishers. The majority of these publishers are based in Europe and the main responsibility of a publisher is to maintain the quality of EPDs. In addition, each EPD document has to be externally verified to have the highest level of quality.

A typical EPD includes several parts. These are namely: Program information, Company and Product Information, LCA Information and LCA Results.

The program information part includes information about the manufacturer, product/service and other general information such as the validity and expiration dates of the EPD, the contact information of the verifier and the following Product Category Rule (PCR). The second part of the EPD includes information about the manufacturer and investigated product. It summarizes the characteristics of the product and provides information such as product material composition and packaging. The LCA information part is one of the most important parts of the EPS as it describes the declared unit, time period of the study, used database(s) and software along with system boundaries. In the LCA result section, the outcomes of the LCA study are presented in a table format. There are several mandatory impact assessment indicators that have to be considered in an EPD. LCA tables show an amount at each life cycle stage to

see the impact of different indicators on different stages.

Similar to the trend described in the infogram (Anderson *et al.*, 2023), the demand for EPDs in Türkiye is also increasing. According to the below statistics from EPDTürkiye as of June 2023, currently, there are 589 EPDs published from 109 different companies in Türkiye (EPD Türkiye, 2023). The below graph shows the number of EPDs published in Türkiye by year. A similar trend with the globe is observed. There are 153 published EPDs on the system but the data is available until June 2023. Projecting an increasing trend, it is expected to have more than 250 registered EPDs in Türkiye for 2023.

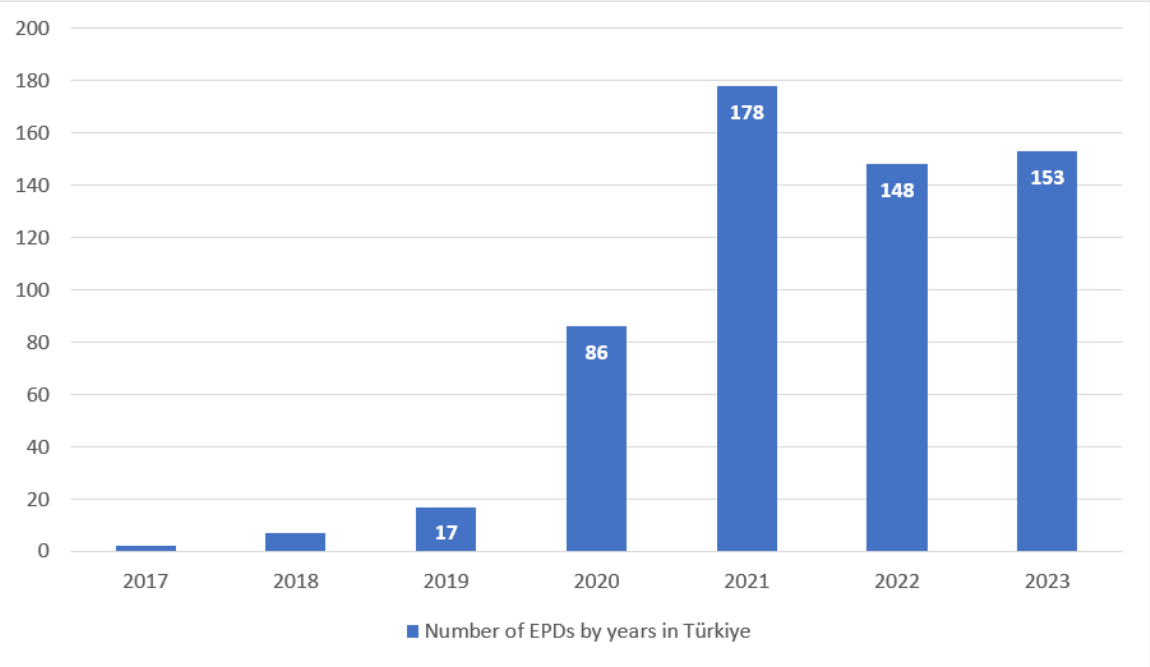

Figure 3.2. Number of EPDs by years in Türkiye.

3.5. Modelling the Investigated Structure

Since this study analyzes the environmental performance of a representative building, there is no actual building considered in this study. Thus, this study and its included life cycle stages are not linked to a real residential building in Türkiye. The aim of this study at first was to be representative for the residential sector in Türkiye, so

that the outputs can be taken as reference within the country. For this aim, a 'hypothetical' residential building in Türkiye is considered. However, couple of parameters about the considered building must be determined prior to modeling. As previously mentioned, the investigated hypothetical structure is a residential building in Türkiye. It has two story with having less than 150 m^2 net living area per independent unit. The structural frame is reinforced concrete that compatible with the latest building standards. In addition, the building materials and their quantities are taken from an official source of Union of Chambers of Turkish Engineers and Architects. Similarly, the parameters used during the operational and end-of-life stages are also taken from official sources/publications.

At this point, the system boundaries of the study are established and data sources are determined. As mentioned, this study includes environmental impacts that are associated with the production and transportation of construction materials, use-phase energy consumption and end-of-life impacts. To better interpret the data and understand the hot spots of the analysis, a software program, SimaPro is used.

3.5.1. SimaPro

SimaPro is a cost-effective, science-based tool that offers solutions for users for Life Cycle Assessment (LCA) modeling and calculation. SimaPro is developed and managed by PRé-Sustainability, based in the Netherlands (SimaPro, 2022). In the market, there are two leading software solutions for LCA-related analyses. These are called SimaPro (SimaPro, 2022) and Gabi (GABI, 2023).

Both these tools include several databases that support life cycle impact assessment methodologies and have user interfaces for modeling different product/process systems (Herrman and Moltesen, 2015). It is possible to have an understanding of the environmental impacts of a product/system without a tool. However, an LCA tool makes the complex models more understandable and graphically visible. In addition, it makes it easier to modify/adjust the LCA data to have better results in terms of

data quality. Three main reasons for utilizing SimaPro in this study are;

- Comprehensiveness of the software along with its strong default LCA databases
- Selection of using SimaPro by scholars for similar studies such as the studies of (Hart *et al.*, 2021), (Shirazi and Ashuri, 2020), (Abd Rashid *et al.*, 2017), (Oladazimi *et al.*, 2020)

3.6. Comparison of the Numbers with the Existing Studies in the Literature

After the study was completed and the environmental impacts of the building were revealed, the figures were compared with the results of similar existing studies in the literature. To do this, one can have an understanding of the range of the impact and make comparisons between different countries, different types of structures, etc. In the following sections, a detailed comparison of the residential buildings between different countries is made. The comparison on the country level demonstrates where Türkiye is in terms of the environmental impact of its residential building sector and also sets upper and lower boundaries toward reducing carbon emissions. Through comparison, it is also possible to determine where most of the impacts come from. Along with providing a bulk number for the investigated structure per m^2 basis, relevant studies also highlight which stages have the most impact. Knowing the high-impact areas is beneficial in terms of determining where the attention should be placed.

3.7. Determining Possible Reduction Points

Another aim of the study is to reveal the reduction potentials for Türkiye's housing construction scheme in terms of environmental impacts and determine the possible areas with reduction potentials. In addition, several what-if scenarios were created to understand the changes in environmental impact numbers with changes in certain areas/applications.

4. LIFE CYCLE MODELLING

Life cycle analysis of the representative residential building in Türkiye has been conducted via SimaPro software with modifying/localizing each data used. The LCA study includes the following life cycle stages of the building:

- Production of construction materials and their shipments to the construction site
- Use-phase (energy-related) emissions during the operational life
- End-of-life emissions of construction materials

The included stages are highlighted in green in Figure 4.1.

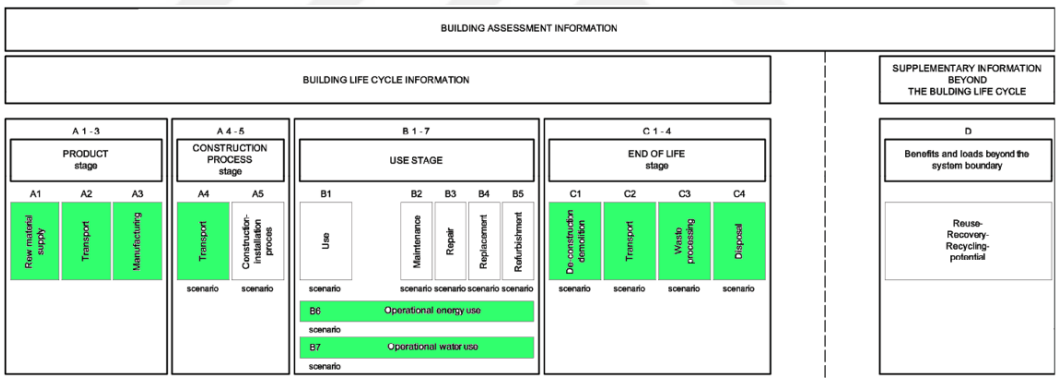

Figure 4.1. Included LCA stages of the study.

Impacts of construction processes at the site and maintenance, repair, etc. related impacts are not within the scope of the LCA analysis due to the lack of reliable data. The majority of environmental impacts for a typical building come from the use-phase (energy-related) and embodied carbon stages. Thus, by including these two stages and an additional end-of-life stage, the majority of the environmental impacts are covered within the scope of the study. The following sections describe each included stage in a comprehensive manner and discuss the outputs of the life cycle assessment study for each stage.

4.1. Production of Construction Materials and Their Shipments to the Construction Site

The first phase of the life cycle assessment study involved scrutinizing the environmental impact associated with the production of construction materials used in the representative building. Every material incorporated in the building, such as concrete, rebar, aluminum, paint, glass, etc., carries an environmental burden even before its use in the structure. These burdens come from the production and preliminary treatment processes of each considered material. For instance, the utilization of steel rebar necessitates the production of crude steel through either primary or secondary steelmaking routes, encompassing all relevant procedures until the rebar is manufactured. By examining each production stage for every construction material, the embodied carbon impact was determined. Materials that are considered in this study are given in Table 3.1 with their quantities per m^2 basis. Each building material was modeled to reflect the conditions of Türkiye in the most realistic way. Table 3.3 summarizes the 'localization' steps for each building material included.

During the 'localization' efforts, available data on ecoinvent is modified to best reflect Türkiye's conditions. These modifications mainly have two aspects. The first is to include Türkiye's conditions and requirements (if there are any) for the production of the considered materials. The second is to localize the energy inputs. For example, for reinforced concrete, the C30 strength class (minimum strength class for residential building by TBER regulation) and the use of CEM I portland cement (the most-used cement type in Türkiye) are the most likely cases. In addition, produced concrete cannot be transported far away from the production site because it is transported as ready-mix via concrete trucks. That means the concrete will most likely be produced in Türkiye and shipped to the construction site. By combining these conditions and constraints, representative reinforced concrete data is modeled. A similar approach is followed for each of the materials listed in Table 3.1 and environmental impacts due to the production of building materials are determined. The impact of falsework and working scaffold was not considered in the analysis even though they are listed in

Table 3.1. The reason is their repetitive use in the industry. Falsework and working scaffolds are modular systems so that they are deconstructed and reused at many construction sites before they reach their end-of-life. Thus, their impact on a single building consideration becomes relatively low and can be neglected.

When the results for this stage are examined and compared, it is seen that studies such as Hart *et al.*, (2021) and Kumari *et al.*, (2019) also have similar outcomes. The substantial use of concrete and rebar in building construction is reflected in their significant contributions to CO_2-related impacts, with concrete alone accounting for approximately 50% of the impact. This prevalence aligns with the material's extensive use in structural applications. Rebar is found to be the third-largest contributor, following 'glass + frame'. This variation is attributed to the dominant use of Electric Arc Furnace (EAF) rebar in the industry. Steel production can occur through two primary methods: the Basic Oxygen Furnace (BOF) and the (EAF). The latter is 3-4 times less environmentally harmful than the former, as it constitutes secondary production from steel scraps, in contrast to the BOF's primary production from iron mines. In Türkiye, the majority, if not all, of the rebar production follows the EAF route, thereby resulting in lower emissions. It is assumed in this analysis that 100% of the rebar is produced via the EAF route. Conversely, the 'glass + frame' category encompasses double-glazing glasses and their framing systems, which typically include materials such as PVC, aluminum and some steel, thus forming a complex system with varied material constituents. When these factors are considered collectively, the impact of 'glass + frame' marginally exceeds that of rebar. The impacts of other materials are detailed in Figure 5.3.

After production-related environmental impacts were determined for building materials, the next step was to consider their transportation to the construction site. To do this, the total weight of transported materials and their transportation distance should be known. Summing the quantities given in Table 3.1, the total weight of the materials was determined. In addition, an average distance of 150 km is assumed for the transportation of construction materials to the site. To make this assumption,

sector practices and the properties of the materials that are being transported are considered. When a 1 m^2 building area is considered, the total weight of the materials that need to be transported to the site is 1259 kg where concrete makes up around 72% (912 kg). To maintain strength and performance, as a rule of thumb, the concrete should be discharged from a truck mixer within two and a half hours (Collins, 2019). Thus, the distance that a concrete mixer can travel in a typical scenario is around 150 km when the maximum speed limit of 60 km in Türkiye (KGM, 2022) is considered. Since the majority of the transportation involves transferring the concrete, the rest of the materials (28% in terms of weight) have less impact on the transport distance. In addition, the study investigates a representative residential building in Türkiye where there is no specific construction location. Thus, a 150 km distance for the rest of the materials is considered to be an average distance. Also, since the majority of the materials are transported to the site via highway, highway transportation is considered to be a good proxy to calculate transportation-related impacts.

4.2. Use-Phase (Energy-Related) Emissions during the Operational Life

Up to this point, environmental impacts generated from the production of construction materials and their shipments to the construction site are analyzed. At this stage, impacts occurring during the operational life of the representative residential building are examined. As discussed by Röck *et al.*, (2020) and Bahramian and Yetilmezsoy (2020), the use-phase of the buildings carries the highest environmental burden. The rationale behind this is relatively straightforward. Except for the use phase, all other impacts are time-independent and typically occur only once. For instance, after the production of all construction materials, their production-related impacts can be calculated and within the specified time frame of the building, they do not impose an additional burden. The same principle applies to shipments; once the products are shipped, their transportation-related environmental burden has already occurred and does not repeat. However, occupants in the building continuously consume energy sources, etc. Considering a 50-year time span for the investigated building, these consumption-related impacts last until the building is demolished. Thus, over the

entire lifetime of the building, use-phase-related impacts emerge as having the highest environmental burden.

Throughout the lifespan of the building, various sources contribute to emissions. These sources can be categorized into two groups: those associated with the energy consumption of the occupants (electricity, natural gas, etc.) and those linked to renovation, repair, replacement, etc., activities. By aggregating the impacts of these two groups, the use-phase emissions of the examined structure can be determined.

This study specifically addresses the impacts related to energy consumption during the operational life of the building and does not consider any repair, maintenance, or similar work that the building might undergo within the specified 50-year timeframe. The effects associated with any repair, refurbishment, or renovation work have relatively minimal impacts on the overall carbon burden of the building. Additionally, there is a lack of reliable data in the literature regarding the materials and energy required for renovation-related activities, given that the need and period for such works can vary significantly from region to region and building to building. Therefore, the study only considers the energy consumption of the occupants during the use phase.

To calculate energy consumption and its environmental impacts during the operational life of the building, the energy sources and their quantities should be known. Table 4.1 shows the energy sources that cause emissions and their quantities considered in this study. The following sections describe how these consumption amounts were derived.

Table 4.1. Use-phase consumption amounts.

Emission source	**Consumption amount**
Electricity	89.5 kWh/m^2/year
Natural gas	8.63 m^3/m^2/year
Water	2410 kg/m^2/year

4.2.1. Electricity Consumption

Concerning the emissions associated with the operational phase of buildings, the primary consideration is electricity consumption. Households regularly use electricity for various purposes, including heating, cooling, lighting and operating appliances. In Türkiye, nearly all households meet this electricity demand through the country's electric grid, contributing to a carbon burden. The Turkish electricity grid carries a carbon burden that fluctuates continually based on the sources of electricity generation. When the energy sources lean towards renewables, the carbon burden is lower; however, when the sources tend towards fossil fuels, the carbon burden is higher.

According to the Republic of Türkiye Ministry of Energy And Natural Resources (Enerji Bakanlığı, 2022), the first source of energy generation in Türkiye is hard coal followed by natural gas and hydro energy. Table 4.2 below, shows energy sources and their percentages for Türkiye's electricity production for 2022.

Table 4.2. Sources for electricity generation for Türkiye.

Source	**Percentage (%)**
Hard coal	34.6
Natural gas	22.9
Hydro	20.3
Wind	10.6
Solar	5.1
Geothermal	3.4
Other sources	3%

As can be seen from Table 4.2, both fossil and renewable sources are used to generate electricity. Considering these production percentages, the carbon burden of electricity production in Türkiye is modeled. The next step was to have an answer to the following question: How much electricity does an average household consume in Türkiye? To answer this question, 'Energy Identity Certificates' are used.

According to the Energy Efficiency Law No. 5627 (Enerji Kimlik Belgesi, 2007) and the Regulation on Energy Performance in Buildings (Enerji Verimliliği Kanunu, 2007), to ensure the effective and efficient use of energy and energy sources in buildings, prevention of energy waste and the protection of the environment, the building's energy need and energy consumption, greenhouse gas emission level, insulation properties and efficiencies of building's heating and cooling systems must be documented and reported. This document is called an "Energy Identity Certificate". It is obliged by law to acquire this document for any residential/office buildings which have more than 50 m^2 of use area and are expected to be in service for more than two years. In simpler terms, energy performance classification for house appliances, such as refrigerators, washing machines, etc., are now valid for buildings as well. The certificate has three pages, with the first page presenting details about the building's address, energy performance class, greenhouse gas emissions, individual consumption calculations and energy performance classes of heating, cooling, hot water, ventilation and lighting systems. Additionally, it includes information on energy production values and rates of renewable energy systems. The second page provides information on the insulation status of the walls, roof, floors and windows, collectively forming the building envelope. Lastly, the third page focuses on the mechanical systems employed in the building, providing data on these systems, as well as information on the lighting system and, if applicable, details about the cogeneration system.

As depicted in the figure below, the classification levels range from A to G, with Class A signifying the most efficient level and Class G indicating the least efficient. In compliance with the law, new or under-construction buildings must be planned and constructed to achieve an energy identity certificate class of at least level C. Buildings that are newly constructed or under construction and fall below a Class C rating are ineligible to receive an occupancy permit.



Figure 4.2. Energy classes according to energy identity certificate.

Thus, this law sets a target for the whole country to achieve at least class C for new or under-construction buildings. According to the Republic of Türkiye Ministry of Environment Urbanization and Climate Change (2020) and (Gündoğmuş, 2023) since this implementation started in 2011, the document has been obtained for more than 1.5 million buildings, 1.16 million of which are new and 340 thousand of which are existing buildings. 1 million and 20 thousand of these certificates were issued in the 'C' class, 368 thousand in 'B', 73 thousand in 'D', 27 thousand in 'E', 10 thousand in 'F' and 2 thousand in 'G' class.

The numbers show that the majority of the existing building stock in Türkiye has a 'C' level energy performance class. As discussed previously, all these levels have a range of electricity consumed in kWh/m^2/year unit. The range for these energy classes is shown in the below table.

Table 4.3. Corresponding energy class electricity consumption ranges.

Energy Class	**Range (kWh/m^2/year)**
A	0 – 39
B	40 – 79
C	80 – 99
D	100 – 119
E	120 - 139
F	140 – 174
G	175 - . . .

As outlined in Table 4.3, the 'C' class corresponds to a consumption range of 80 to 99 kWh/m^2/year. For the life cycle assessment analysis, the median value of this range, which is 89.5 kWh/m^2/year, is used as the electricity consumption for an average household in Türkiye.

4.2.2. Natural Gas Consumption

In Türkiye, another significant source of energy consumption for households is the use of natural gas. The country primarily meets its natural gas demand through imports from nations like Iran, Azerbaijan and Russia. A considerable portion of households predominantly utilize natural gas for heating purposes. Therefore, it is crucial to analyze the carbon impact of burning natural gas. To achieve this, the first step is to determine the average household's natural gas consumption.

The Natural Gas Distribution Companies Association of Türkiye maintains comprehensive statistics on the use and consumption of natural gas. Functioning as a non-governmental organization, it serves as the umbrella entity for natural gas distribution companies operating across Türkiye. The association was established with the primary purpose of monitoring developments in the urban natural gas distribution sector, both in the public and private spheres. Its key activities include ensuring coordination among distribution companies and implementing measures to enhance the service quality for natural gas users (GAZBIR,2023) Each year, the establishment shares statistics about the number of users, their consumption amount and behaviors, related natural gas infrastructure investments and future outlook of the market. Natural Gas Distribution Sector Assessment Report, 2022 (GAZBIR,2023), highlights the consumption amount across the region and cities throughout the year. According to the report, total natural gas consumption in Türkiye was 53.3 billion m^3 in 2022. Consumption amounts vary based on the months and location considered however, the biggest users are cities with high populations such as İstanbul, Ankara, İzmir, etc. The average consumption per household between 2017 and 2021 was 966 m^3 and it will increase to an average of 984 m^3 in 2022 (GAZBIR,2023). Thus, 984 m^3 per year of

natural gas consumption is considered in the analysis. Consequently, it was necessary to obtain a consumption value on a per m^2 basis. To achieve this, the average size of households in Türkiye, as reported by the Turkish Statistical Institute (TSI) in 2019, was used. According to the TSI report (TÜİK, 2019), the average housing size in Türkiye is 114 m^2. Dividing the yearly natural gas consumption of 984 m^3 by 114 m^2, a value of approximately 8.63 m^3/m^2/year was derived. This indicates that an average household in Türkiye consumes 8.63 m^3 of natural gas per 1 m^2 of building area per year. This consumption amount is similar to the findings of Selçuk and Pasinlioğlu (2020) in their studies on natural gas consumption of households in Türkiye. This value is utilized in the analysis accordingly.

4.2.3. Water Consumption

After modeling the environmental impacts of electricity and natural gas consumption for households in Türkiye, the final step in assessing use-phase emissions was to include household water consumption. According to TSI's 2020 statistics (TÜİK, 2020), the average daily water consumption per person was calculated as 228 liters. Extrapolating this value for the entire year and considering an average family size of 3.3 persons (TÜİK, 2020) the total yearly water consumption for an average household was determined to be 274,626 liters. When this figure is divided by the average size of a household (TÜİK, 2019), it equates to 2,410 kg of water consumption per 1 m^2 of area per year. This value was taken into consideration during the analysis. With the consumption amounts of electricity, natural gas and water determined, their environmental impacts were modeled accordingly to derive the operational life-related environmental impacts of the representative residential building.

4.3. End-Of-Life Emissions

The last segment of the LCA analysis involved accounting for the end-of-life emissions of the investigated building. When a building reaches the end of its useful service life, it undergoes demolition and the environmental burden associated with the building

continues during and after the demolition process. Several factors need consideration to account for the end-of-life emissions of buildings, including impacts related to demolition, transportation of construction waste and any recycling, landfilling, incineration, etc., of construction materials. In a typical demolition scenario, heavy machinery is employed on-site. However, due to variations in building types, sizes and other factors influencing the types and numbers of heavy machinery used, establishing an average emission number for the demolition period proves challenging. Consequently, the environmental burdens specifically related to demolition are not considered in this analysis. After the building is demolished, construction waste undergoes transportation to various locations for further processing or landfilling. Calculating this impact requires knowledge of the weight of transported materials and the transportation distance. It is assumed that all the materials considered during the construction period will be transported after the building is demolished, amounting to approximately 1259 kg of construction materials per m^2 of area. Additionally, an average transportation distance of 50 km is considered sufficient for the subsequent processes of the materials. With these values, the impacts related to construction waste transport are calculated. The next step involved determining the fate of different types of construction materials after the building was demolished. From metals to plastics and glass, various types of construction material waste are generated at the site and based on sector practices and the value of the materials, different approaches are taken. In industry practices, for instance, an operator may break the concrete and separate the rebar from it. Since rebar holds economic value, it is not landfilled but rather mostly recycled or reused for other purposes. Table 4.4 lists the types of materials and their end-of-life options as percentages.

Table 4.4. Construction materials and their end-of-life scenarios.

	End-of-Life Option	
Material Type	**Recycle (%)**	**Landfill (%)**
Metal	90	10
Plastic	50	50
Glass	60	40
Wood-based	55	45
Rest (concrete, mortar, paints, etc.)	0	100

Given that most metals used in buildings, such as steel and aluminum, hold economic value, the majority of metal parts are typically recycled. However, the recycling rates for plastic and wood-based products are not as high as metals. According to the provided table, approximately 50% and 55% of plastic and wood-based products, respectively, are recycled, while the remainder is sent to landfills. Based on these end-of-life options and the quantity of materials listed in the table, the end-of-life emissions of the construction materials are determined.

5. RESULTS AND FINDINGS

In this section, the results of a life cycle assessment (LCA) study conducted on a representative residential building in Türkiye are presented. As previously mentioned, the study encompassed three distinct life stages of the building: the impact of construction materials, use-phase-related impacts and end-of-life impacts. The LCA analysis was performed using SimaPro software and the results are presented in accordance with the life cycle assessment indicators detailed in the methodology section. This study extends beyond merely focusing on carbon dioxide emissions, also evaluating the building's impact on various indicators, such as eutrophication potential and ozone depletion potential, among others. Figure 4.1, displayed below, shows the main interface of the constructed LCA model within SimaPro software. In the figure, it is shown that each construction material, process and energy source is individually modeled. Upon completion of the analysis, these impacts are aggregated under the category 'Whole building'. On the left side of the figure, three entries under the 'assembly' section correspond to the three life stages included in the study. The following sections discuss the results for each considered stage separately, then summing up these impacts all together to have the whole carbon impact of the investigated building.

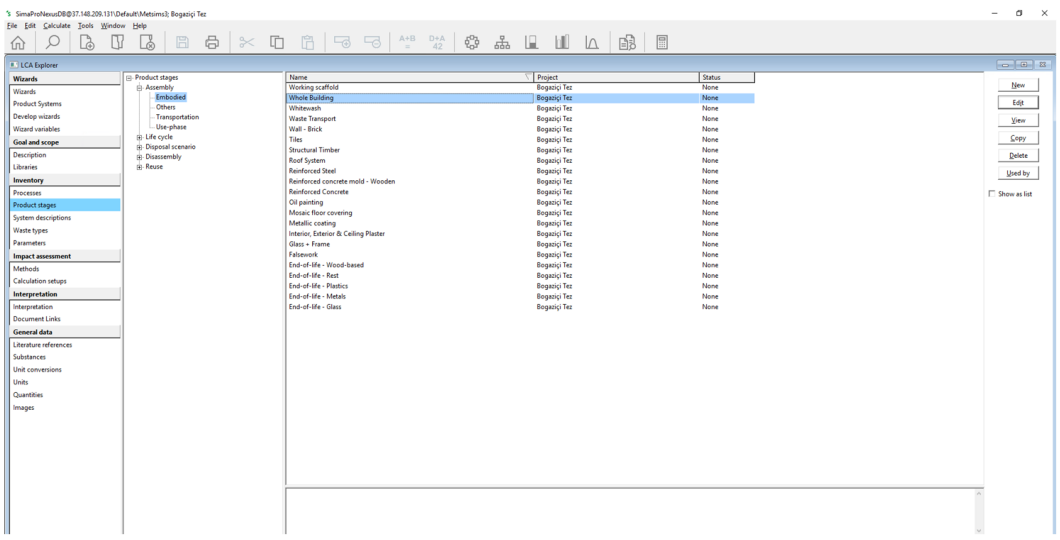

Figure 5.1. General overview of LCA model in SimaPro software.

5.1. LCA Results for Construction Materials and Their Transportation to the Site

The environmental impacts of the construction materials included in Table 3.1 are presented in the table below. As discussed in the methodology section, the LCA results are represented using 13 impact indicators. This approach enables a comprehensive analysis of the environmental impacts of the investigated building, extending beyond a sole focus on CO_2 emissions to include other emissions as well. However, it is noted that the majority of similar studies in the literature predominantly concentrate on CO_2-related emissions. Consequently, specific attention has been given to the CO_2 impacts of the individual stages and eventually the whole building. This approach was adopted to facilitate like-to-like comparisons with existing studies. Therefore, for each considered LCA stage, results are initially presented in tabular forms for all impact indicators. Subsequently, the emphasis shifts to CO_2 emissions and their sources of contribution.

The life cycle assessment impacts of the construction materials used in the building are presented in Table 5.1. The analysis reveals that the Global Warming Potential (GWP)-fossil impact is 257.17 kg CO_2 eq., followed by a GWP-biogenic impact of -39.41 kg CO_2 eq. and a GWP-luluc impact of 0.94 kg CO_2 eq., among others. Given that each impact indicator is unique and follows different calculation methodologies, direct comparisons between indicators are not feasible.

Nevertheless, several interpretations can be made from Table 5.1. The GWP-total indicator represents the aggregate of the other three GWP indicators, which are listed in the top three rows of the table. For consistent comparison with the available literature, the 'GWP-fossil' figures are primarily considered. It is thus concluded that the construction materials included in the analysis contribute to emissions amounting to 257.17 kg CO_2 eq. Furthermore, the appearance of negative numbers indicates carbon capture rather than emission. The negative value for the GWP-biogenic indicator is attributed to the wood-based materials that absorb CO_2 from the atmosphere. This

captured carbon is eventually released back into the atmosphere when the wood-based materials reach their end-of-life stage.

Table 5.1. LCA results for construction materials and their transportation to the site.

Impact category	**Unit**	**Total**
GWP fossil	kg CO_2 eq.	**257.2**
GWP-biogenic	kg CO_2 eq.	-39.4
GWP-luluc	kg CO_2 eq.	0.94
GWP-total	kg CO_2 eq.	218.7
ODP	kg CFC-11 eq	1.0E-05
AcidificationPotential (AP)	mol H+ eq.	1.14
EP-freshwater	kg P eq.	0.07
Eutrophication Marine	kg N eq.	0.26
EP-terrestrial	mol N eq.	2.94
POCP	kg NMVOC eq.	0.82
Abiotic Depletion potential–non-fossil	kg Sb eq.	1.5E-03
Abiotic depletion-fossil (ADPF)	MJ, net cal	2384
Water Deprivation Potential (WDP)	m^3 world eq.	123.4

Figure 5.2 illustrates the main sources of the GWP-fossil indicator for the included materials, represented as a Sankey diagram. In Sankey diagrams, the contribution of each element within the system is displayed from bottom to top. At the top, the cumulative impact on the whole building is shown and one level below, the impacts of construction materials on the GWP-fossil number are detailed. The diagram has a cut-off of approximately 7%, thereby excluding impacts that contribute less than this threshold. It is observed that approximately 50% of the GWP-fossil impact is attributed solely to reinforced concrete. This is followed by 'glass + frame', accounting for 14.4% and reinforced steel, contributing 12.1%. A complete list of materials impacting the GWP-fossil indicator ranked from the highest to the lowest contributor, is presented in Figure 5.3.

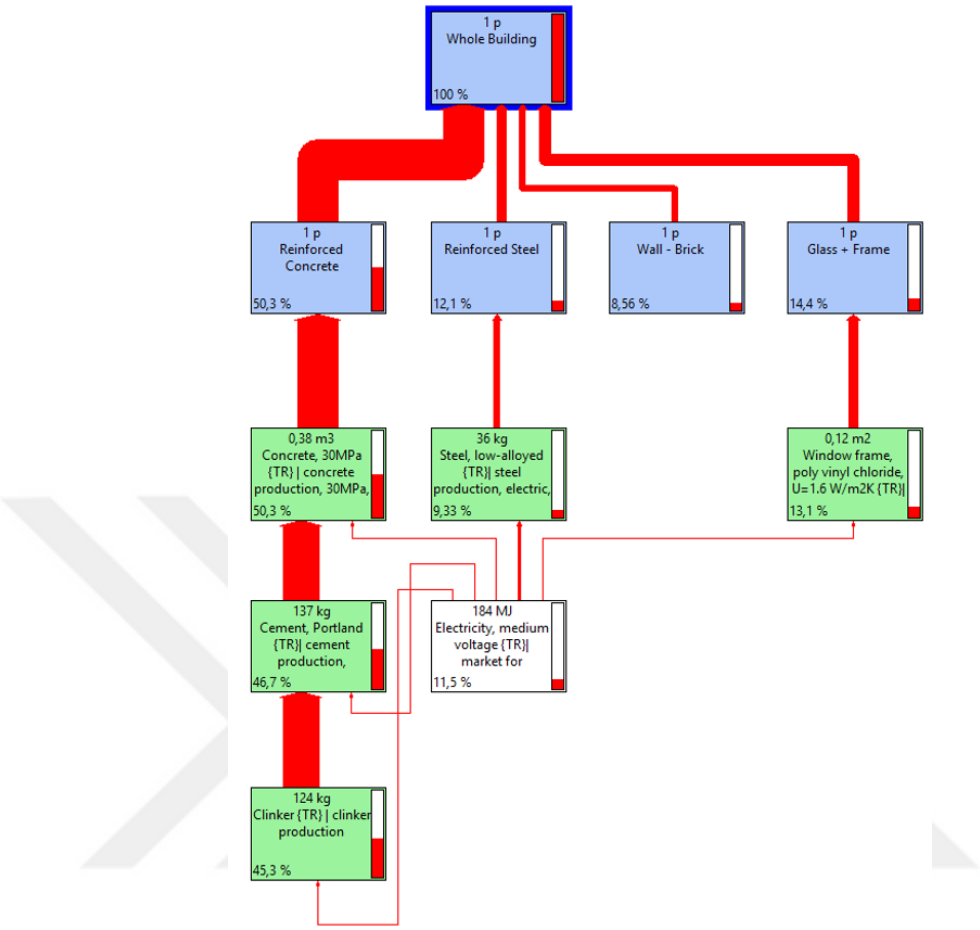

Figure 5.2. Sankey diagram for construction materials' impact.

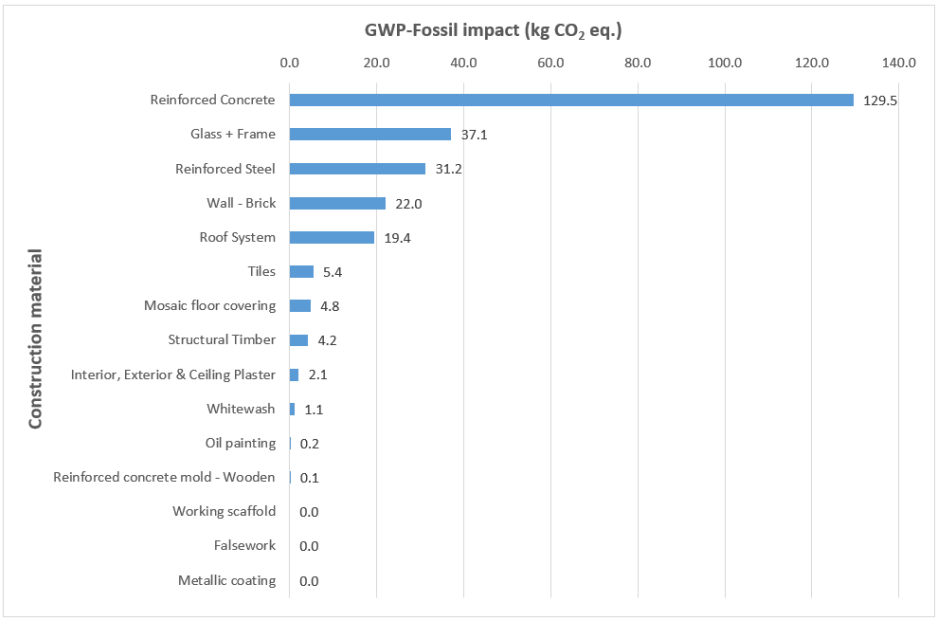

Figure 5.3. Individual impact of construction materials.

In addition to the impacts of construction materials arising from their production and pre-processing, the transportation of these materials to the construction site also contributes to emissions. This study, focusing not on a specific structure but on a representative residential building in Türkiye, does not specify the location of the considered building. Nevertheless, since transportation-related impacts are dependent on travel distance, an average transportation distance is crucial. For this study, an average transportation distance of 150 km is assumed as a conservative estimate for calculating relevant emissions. The total weight of materials listed in Table 2.1, amounting to approximately 1259 kg, is considered. Of this, about 72% (912 kg) is concrete, which is typically transported as ready-mix via mixers and is not suited for long-distance travel. Therefore, the 150 km transportation distance is deemed a representative and conservative estimate. The environmental impacts of transporting these 1259 kg of materials, including concrete, via trucks and mixers to the construction site over a distance of 150 km, are calculated and presented in Table 5.2. Road vehicles equipped with Euro 5 engines are used in the model. According to the analysis, the transportation of materials to the construction site is responsible for 36.3 kg CO_2 eq. of GWP-fossil emissions.

Table 5.2. Transportation related impacts.

Impact category	**Unit**	**Total**
GWP-fossil	kg CO_2 eq.	**36.3**
GWP- biogenic	kg CO_2 eq.	0.01
GWP-luluc	kg CO_2 eq.	0.02
GWP-total	kg CO_2 eq.	36.3
ODP	kg CFC-11 eq	5.43E-07
Acidification potential (AP)	mol H+ eq.	0.13
EP- freshwater	kg P eq.	2.95E-03
Eutrophication Marine	kg N eq.	0.04
EP-terrestrial	mol N eq.	0.45
POCP	kg NMVOC eq.	0.17
Abiotic Depletion potential –non-fossil	kg Sb eq.	1.16E-04
Abiotic depletion-fossil (ADPF)	MJ, net cal	510.6
Water Deprivation Potential (WDP)	m^3 world eq.	2.7

5.2. LCA Results for Use-Phase

In this section, life cycle assessment results related to the operational life of the investigated building are presented. The LCA impacts of construction materials and their transportation to the construction site have been previously discussed and determined. Excluding environmental burdens due to construction-related activities at the site, which fall outside the scope of this study, the focus shifts to the building's longest stage: the use phase. The building in question is a residential structure, expected to house occupants over its estimated 50-year service life. Throughout this duration, the consumption of electricity, natural gas and water by the residents is anticipated. Additionally, the building may undergo renovation-related work during its lifespan. The environmental impacts arising from the use of energy sources and water are incorporated into this analysis, while renovation-related impacts are omitted due to the previously described lack of information/data. When the included impact sources are modeled as described and quantified in the previous section, their impacts have been analyzed and the results were shared in Table 5.3. Numbers in Table 5.3 show the operational-use phase-related impacts of the investigated building per year. Around 79.4 kg CO_2 eq. emissions are generated within a year of use per 1 m^2 of area.

Table 5.3. Use-phase-related impacts.

Impact category	**Unit**	**Total**
GWP- fossil	kg CO_2 eq.	**79.4**
GWP-biogenic	kg CO_2 eq.	0.7
GWP-luluc	kg CO_2 eq.	0.6
GWP-total	kg CO_2 eq.	80.7
ODP	kg CFC-11 eq	1.4E-06
Acidification Potential (AP)	mol H+ eq.	0.4
EP-freshwater	kg P eq.	0.1
EutrophicationMarine	kg N eq.	0.1
EP-terrestrial	mol N eq.	0.7
POCP	kg NMVOC eq.	0.2
Abiotic Depletion potential-non-fossil	kg Sb eq.	9.3E-05
Abiotic depletion-fossil (ADPF)	MJ, net cal	926.0
Water Deprivation Potential (WDP)	m^3 world eq.	127.8

Figure 5.4 shows the contribution of each source to the GWP-fossil number. As can be seen, electricity has the highest impact with 51.8 kg CO_2 eq. followed by 24.7 kg CO_2 eq from natural gas and 3.0 kg CO_2 eq. from water use.

When the annual use-phase impact of 79.4 kg CO_2 eq. is extrapolated over the 50-year life span of the building, it totals 3970 kg CO_2 eq. per square meter over 50 years. Initially, the inclusion of only the first year's impact may appear to contribute less to the carbon burden compared to construction materials. However, once the materials are produced and constructed on-site, their influence on carbon impacts diminishes. In contrast, the impacts associated with the use of electricity, natural gas and water continue for as long as the building remains in active use. Ultimately, the environmental impacts arising from these ongoing activities become significantly higher than those related to the construction materials and their transportation.

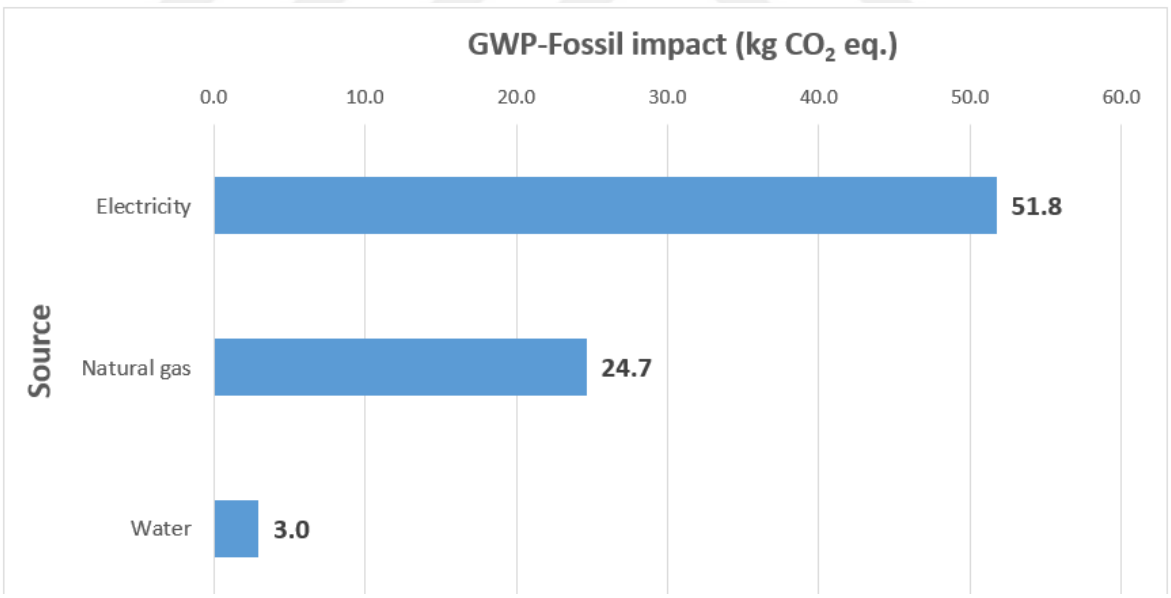

Figure 5.4. Contribution of each consumption during operational phase of the building on carbon emissions.

5.2.1. LCA Results for end-of-life stage

Upon reaching the end of its service life, a building is typically either renovated, restructured if feasible, or more commonly, demolished. In the case of reinforced con-

crete frame buildings, demolition is the usual outcome. The demolition process and subsequent activities exert various impacts on the environment. These end-of-life impacts can be categorized into three groups: demolition, transportation of waste and end-of-life treatment of materials. The impacts of these three categories are aggregated and represented as a singular measure, reflecting the end-of-life impacts of the investigated building. Similar to the construction-related activities at the site, the environmental impacts of demolition-related activities are highly dependent on factors such as location, terrain conditions, building type and sector practices. Consequently, accurately determining the environmental impacts associated with demolition activities is challenging without access to first-hand data. The majority of demolition activities typically involve the use of machinery such as excavators, crushers and carriers. Therefore, the predominant environmental impacts during the demolition phase are attributed to the diesel consumption of these machines. However, due to the absence of reliable data on diesel consumption, demolition-related impacts were not included in the analysis.

Following the demolition of the building, the ensuing construction waste is assumed to be transported for subsequent end-of-life processes or landfilling. This will involve the transportation of approximately 1259 kg of materials for an estimated distance of 50 km. The distance is assumed based on standard sector practices and similar studies (Gardner *et al.*, 2020; Franca and Azapagic, 2012), where construction waste is typically not transported long distances but is instead sent to the nearest waste processing facility or landfilled. Therefore, an average transportation distance of 50 km is deemed appropriate and representative of sector norms.

The third and final source of impact at the end of a building's life cycle is waste processing. As demonstrated in Table 4.4, varying recycling, incineration and landfilling percentages are applied to different types of construction materials, such as metals, plastics and glass. Taking these percentages and potential treatment scenarios into account, the waste processing impacts are calculated.

The combined effects of discarded material transport and waste processing/landfilling processes of the representative residential building are shown in the table below. According to the analysis, the total GWP-fossil impact of end-of-life is 48.6 kg CO_2 eq. as shown in Table 5.4.

Table 5.4. End-of-life related impacts.

Impact category	**Unit**	**Total**
GWP-fossil	kg CO_2 eq.	**48.6**
GWP-biogenic	kg CO_2 eq.	535.3
GWP-luluc	kg CO_2 eq.	0.0
GWP-total	kg CO_2 eq.	584.0
ODP	kg CFC-11 eq	0.0
Acidification Potential (AP)	mol H+ eq.	0.2
EP-freshwater	kg P eq.	0.0
Eutrophication Marine	kg N eq.	1.3
EP-terrestrial	mol N eq.	0.5
POCP	kg NMVOC eq.	0.3
Abiotic Depletion potential-non-fossil	kg Sb eq.	0.0
Abiotic depletion-fossil (ADPF)	MJ, net cal	415.9
Water Deprivation Potential (WDP)	m^3 world eq.	12.3

5.3. LCA Results for the Whole Building

The objective of this study was to perform a life cycle analysis on a representative residential building in Türkiye, with the aim of identifying the environmental impacts and underscoring potential areas for reduction. To achieve this, various life cycle assessment (LCA) stages of the investigated structure were included and analyzed individually. The sources of emissions and their respective contributions were calculated. Ultimately, upon combining these individual impact sources, the total environmental impacts for the entire building were determined.

Table 5.5. Whole building LCA results for 50 years of lifetime.

Impact category	**Unit**	**Total**
GWP-fossil	kg CO_2 eq.	**4312**
GWP-biogenic	kg CO_2 eq.	530.9
GWP-luluc	kg CO_2 eq.	30.7
GWP-total	kg CO_2 eq.	4874
ODP	kg CFC-11 eq	8.05E-05
Acidification Potential (AP)	mol H+ eq.	21.5
EP-freshwater	kg P eq.	5.2
Eutrophication Marine	kg N eq.	6.6
EP- terrestrial	mol N eq.	38.9
POCP	kg NMVOC eq.	11.2
Abiotic Depletion potential- non-fossil	kg Sb eq.	0.006
Abiotic depletion- fossil (ADPF)	MJ, net cal	49610
Water Deprivation Potential (WDP)	m^3 world eq.	6528

Table 5.5 displays the cumulative results for the studied building across 13 life cycle assessment indicators. The results in Table 5.5 encompass all the considered life cycle stages, namely the production of construction materials, their transportation to the construction site, use-phase-related emissions and end-of-life impacts. According to the analysis, the total carbon footprint of the examined building over a 50-year lifespan amounts to 4312.1 kg CO_2/m^2. This indicates that, based on the included parameters and assumptions, a representative residential building in Türkiye is projected to generate approximately 4312 kg of CO_2 emissions per square meter of building area within 50 years. Table 5.6 details the proportion of this total figure attributable to each distinct life cycle stage.

Table 5.6. Impact of each different stage on total building carbon emissions.

LCA stage	**Impact (kg CO_2 eq.)**
Construction materials and Transportation	293.5
Use–phase (for 50 years)	3970.0
End-of-life	48.6
Total	**4312.1**

Around 6.8% (293.5 kg CO_2 eq.) of the total impact is attributed to the construction materials and their shipments to the site. Whereas around 92 % (3970 kg CO_2 eq.) of the impacts are credited to the use phase of the building. It was expected that impacts for the use phase of the building would dominate the results.

Even though it was evident that the impacts of the operational phase would dominate the results, 92 % of the contribution is slightly higher than expected. This study did not consider construction activities, renovation works and demolition phases. Even though, impacts generated at these stages are low and negligible, if included their impacts would lower the share of use-phase-related impacts. Thus, the overall dominance of the use phase would decrease slightly.

6. DISCUSSION AND REDUCTION POTENTIALS

Up to this point, the environmental impacts of a representative residential building in Türkiye have been examined. As highlighted in the previous sections, there are only few available publications from Türkiye such as the studies of Atmaca and Atmaca, (2015) and Kayacetin and Tanyer, (2020) that investigated the environmental impacts of buildings. None of these studies can be taken as a direct proxy for Türkiye's residential sector because they are modeled for specific building/s with specific considerations that are not necessarily suitable to be representing the conditions of the residential sector in Türkiye. This study filled this gap in the literature by modeling a representative residential building with all the parameters reflected not for a specific building or condition but for an average representative of the country's conditions. The types and amount of construction materials used in this study are taken from official sources which at first place prepared to be a practical guide for constructors in Türkiye. In addition, use-phase related emissions represent the average electricity, natural gas and water consumption of a Turkish household based on official statistics. Thus, it is believed that the outputs of this study can be used as a proxy for the residential building sector in Türkiye and help the involved parties (municipalities, government agencies etc.) to make well-informed decisions on their construction material selections and design criteria.

To control and validate the outputs of this study, the LCA results were compared with similar studies both from Türkiye and other parts of the world. As previously mentioned, there are only few publications in Türkiye that can be compared to justify the outputs of this study. For instance, the study of Kayaçetin and Tanyer (2020) from Türkiye have found a value of 409.2 kg CO_2 eq./m^2. Their study focuses on LCA analysis on three neighborhood-scale mass housing projects in Ankara, Türkiye. The output of their analysis is higher than the output of this study (86.2 kg CO_2 eq./m^2). One of the main reasons for this difference lies in the differences of study boundaries. Kayaçetin and Tanyer's study includes emissions that occurs outside of the investigated

buildings such as the impact of structural landscape and transportation infrastructure. According to their study, about 66.6% (272.4 kg CO_2 eq./m^2) of the total emissions are directly attributable to the building itself.

Similar but more relatable study from Türkiye is conducted by Atmaca and Atmaca (2015). In their study, authors conducted life cycle assessment analysis on two residential buildings in Gaziantep region of Türkiye. The CO_2 emissions for the first investigated residential building is found to be 104 kg CO_2 eq./m^2 and the second 129 kg CO_2 eq./m^2. The system boundaries and considered parameters in both studies are close to each other thus, the outputs of their analyses are also close to the output of (86.2 kg CO_2 eq./m^2) of this study.

In addition to the investigated studies from Türkiye, there are more publications conducted in other countries on life cycle assessment analysis of buildings. Some of the publications that are thoroughly analyzed are summarized in table below. Table 6.1 shows the LCA outputs of the investigated building/s for each study based on 1 m^2 area along with some information about the investigated building. For instance, a study by Nadoushani and Akbarnezhad (2015) on 15 alternative steel and concrete structural systems with different structural components has yielded an impact range between 27.6 to 49.9 kg CO_2 eq./m^2, which are lower than the output of this study. Another study by Kumanayake and Luo (2018) on multi-purpose university building of a case study from Sri Lanka has yielded an impact of 31.81 kg CO_2 eq./m^2. Similarly, another comparative study from Finland on different types of structures by Rinne and Ilgın and Karjalainen (2022) has yielded an impact range of 24.3 to 26.0 kg CO_2 eq./m^2.

When the results of the studies in Table 6.1 are examined, it is noticed that the variety in the numbers are high. Carbon dioxide emission numbers per m^2 area in Table 6.1 varies between 20 kg CO_2 eq./m^2 to 600 kg CO_2 eq./m^2. This is expected because the study results are highly dependent on many parameters such as the system boundaries of the LCA analysis, building type, the location of the building etc. The first thing noticed was the difference on the chosen system boundaries for the LCA analyses.

As previously mentioned, some studies focus only embodied carbon of the building whereas some also include operational phase. In addition, the stages considered on the embodied carbon calculation can be different. Sometimes it includes each embodied carbon stage from the impact of construction materials to their end-of-life impact. Sometimes a researchers only focus on the impact of transportation and construction-related activities. Thus, there is no consensus on whether include/not include a certain stage in the analyses. The tendency of researchers is to include as many stages as possible as long as there is enough/reliable data. Therefore, due to the inclusion or exclusion of certain LCA stages in the analysis, the numbers tend to be different.

The second reason for the difference lies in the type of investigated structure. Life cycle assessment performance of a reinforced concrete structure is not the same with a timber or steel structure. This can be directly seen in some studies where researchers compare these parameters. For instance, the study of Hart *et al.*, (2021), compared timber, concrete and steel frame structures and found that between timber and steel, there is around 91% whole-life embodied carbon difference. These type of studies are important to understand the environmental impact of different structural frames so that during the pre-design phase, the structural body of the building can be selected accordingly. However, this selection is highly dependent on the location, design requirements, structural loads etc. so that it is not always possible to select the lowest carbon attributed structural frame for the construction. However, it does provide understanding of different structural frames' environmental performance so that if it is suitable, it can be selected.

Another significant reason for the variances in numbers lies in the location of the investigated building. The location of a structure does have great potential on influencing the impact of the investigated structure. The magnitude of influence is mostly on the operational life impacts. Countries that has low carbon electricity grid has advantages over a country that has carbon dense electricity grid. For this reason, even all the other parameters were kept the same, a same residential house in India would be much more carbon dense than in Sweden during the buildings' operational

phase. The electricity impact during the operational stage is found to have around 65% of the total operational impacts in this study. Thus, it is obvious that countries where the building occupants can use/utilize low carbon dense electricity has significant advantages in terms of carbon savings of the buildings. In addition to the impact of electricity use, the impact of construction materials between different countries do tend to change the results as well. This is mainly due to the fact that most of the developed countries have already better-quality control procedures and give more attention on the construction material selection and design criteria of the structures. Furthermore, many of these countries have already well-established regulatory frameworks towards decarbonization of their construction sector.

The difference in the numbers in Table 6.1 is not solely due to these three points mentioned but the author believes that these three points are the main reasons for such a huge variances in the numbers. When the output of this study is considered, the author believes that the life cycle assessment numbers fit into the reasonable range.

Towards decarbonization of the construction industry, it was crucially important to understand the current situation (in terms of carbon emissions and hot-spots) in Türkiye. The findings of this study provides understanding about the environmental impacts of a representative residential building in Türkiye. However, without targeting the hot spots and then outlining the possible reduction areas and showing how to make the reductions, the study would be incomplete. For this reason, in addition to the current LCA study, three reduction scenarios are suggested in order to help decarbonization of the sector in Türkiye. The considered scenarios are practical and applicable for Türkiye's conditions and shows how much does a carbon reduction would be with implementing these scenarios. Unfortunately, no studies were found in the literature focusing on how to reduce the environmental burden of the investigated buildings in Türkiye and very few found in the globe. Hence, this study fulfills an important gap by first analyzing the carbon emissions of residential building scheme in Türkiye then providing logical scenarios to reduce the impact.

Table 6.1. Similar publications in the literature.

Publication	**Information**	**Study Result**
De Wolf *et al.*, 2016	Analysis of 200 recently Completed buildings	150 to 600 kg CO_2 eq./m^2
Nadoushani And Akbarnezhad 2015	Analysis ofna set of 15 Alternative steel and Concrete structural systems with different structural components	27.6 to 49.9 kg CO_2 eq./m^2
Skullestad *et al.*, 2016	Comparison of Reinforced Concrete structures to Corresponding timber structures in	111 – 121 (mid-rise RC structures); 26 – 94 (timber)
Zhang And Wang 2016	Comparative case studies in China using Alternative methods for embodied emission calculation	400 – 530 kg CO_2 eq./m^2
Hart *et al.*, 2021	Whole-life Embodied carbon of multistory buildings with steel, concrete and timber structures	119 kg CO_2 eq./m^2 for timber 185 kg CO_2 eq./m^2 for concrete, 228 kg CO_2 eq./m^2 for steel
Atmaca And Atmaca, 2015	LCA analysis of two residential buildings in Gaziantep, Türkiye	104 kg CO_2 eq./m^2 for the 1st building 129 kg CO_2 eq./m^2 for the 2nd building
Zhang *et al.*, 2016	LCA analysis of a residential building in China	28.10 kg CO_2 eq./m^2
Roh *et al.*, 2016	Representative Korean building With Characterizations of GBI certification system for 40 years lifetime	51.22 kg CO_2 eq./m^2
Kumanayake and Luo 2018	Multi-purpose University Building of a case study from Sri Lanka	31.81 kg CO_2 eq./m^2

Table 6.1. Similar publications in the literature. (cont.)

Publication	**Information**	**Study Result**
Rodrigues *et al.*, 2018	LCA analysis of two-story Industrial building	508.57 kg CO_2 eq./m^2
Kayacetin and Tanyer, 2020	LCA Analysis of embodied carbon assessment of residential housing at Urban Scale with consideration of impacts of infrastructure and landscape	409.2 kg CO_2 eq./m^2
Zhang *et al.*, 2014	Carbon emission analysis of a residential building in China through life cycle assessment	28.10 kg CO_2 eq./m^2
Ortiz-Rodríguez *et al.*, 2010	LCA analysis of a residential building in Spain	49.33 kg CO_2 eq./m^2
Franca And Azapagic 2012	LCA analysis of Detached, semi-detached and terraced houses in United Kingdom	70 kg CO_2 eq./m^2
Rinne and Ilgın and Karjalainen 2022	Comparative LCA analysis of hybrid, concrete, and timber apartment buildings in Finland	24.3 to 26.0 kg CO_2 eq./m^2

The subsequent phase of this study involved identifying potential strategies to reduce the environmental impacts of residential buildings within the country. As previously noted, various countries have begun setting targets for reducing the carbon impacts of their buildings. For instance, according to a new regulation in Denmark (Nordic Sustainable Construction, 2023), from January 1st, 2023, the Danish building regulation includes climate requirements for all new buildings and sets an upper limit value of 12.0 kg CO_2 eq. per square meters per year. Similarly, Finland has a target of being carbon neutral by 2035 thus, currently developing legislation to make their construction industry low-carbon (Finland Ministry of the Environment, 2022). Also, the Netherlands obligated some environmental requirements for all new types of construction since January 2021, called Nearly Energy-Neutral Buildings (BENG). Other

countries such as France, New Zealand, etc. have already laws/obligations in place to make sure towards low-carbon and decarbonization of their construction industries. It is expected that in the following years, many other countries including Türkiye will set targets for their construction industry to meet their commitment to net-zero carbon.

The very first step towards decarbonizing the construction industry and setting and achieving threshold values to meet is to understand what the current situation is. Without knowing the current emission levels, it is impossible to set targets and work on reduction potentials. Based on the current literature of life cycle assessment studies on buildings across the globe, one can have an approximate range for CO_2 emissions. For example, in their studies on a residential building, (Zhang *et al.*, 2014) found a 28.1 kg CO_2 eq./m^2/year emission value. In another study on a residential building in Spain (Ortiz-Rodríguez *et al.*, 2010) found a 49.33 kg CO_2 eq./m^2/year emission value. For a similar study in Gaziantep, Türkiye on a residential building (Atmaca A and Atmaca N, 2015) researchers have found 104.4 kg CO_2 eq./m^2/year emission value. When the available literature is deeply analyzed, it is found that on average impact values range between 7-10 to 250 – 300 kg CO_2 emission per meter square area of building per year. The wide range of results has several reasons. The results are subject to the type of structure, whether it's a reinforced frame building or a wooden or steel frame. Similarly, results differ between different types of structures like residential, office, campus buildings, etc. In addition, one of the main reasons for differences in results lies in how use-phase impacts are evaluated.

Since the majority of the impacts for the estimated lifetime of structures come from the use phase, it is important to analyze the parameters used at that stage. In this study, use-phase related consumption amounts are taken with consideration of Turkish households' behavior and findings of public documents to be a representative of the residential sector in Türkiye.

For this current study, the total calculated CO_2 related impacts over the 50-year lifetime of the building was found to be 4312 kg CO_2 eq. per one meter square

of building area. When this number is divided by 50, yearly CO_2 impact per meter square of building area is found. The yearly CO_2 emission value per 1 meter square was calculated as 86.2 kg CO_2 eq., which is consistent with the findings of similar studies.

6.1. Reduction Potentials

Identifying reduction potentials and examining possible reductions in emissions is crucial. To this end, two distinct 'what if' scenarios were developed and their impact on the total carbon figure was analyzed individually. Following the assessment of their impacts, a third scenario was conceived, combining the first two to achieve the lowest possible emission figure. In formulating these scenarios, care was taken to ensure their practical applicability in Türkiye. The first scenario concentrated on the concrete used in the building, which has the highest impact among the building materials, specifically examining the reduction potential if CEM II cement was used instead of Portland cement. The second scenario focused on the use-phase impacts, particularly the effect of electricity consumption in buildings if the overall energy class for buildings in the country was to be elevated from class C to class A, as per the energy identity certificate regulation.

6.2. 1st Scenario–Use of CEM II Rather than CEM I for Concrete Production

According to statistics from the Turkish Cement and Cement Products Assembly (Türk Çimento İstatistikler, 2022), CEM I Portland cement is predominantly used in Türkiye's construction industry. Representing over half (51%) of the cement production, CEM I is the most dominant among the 27 cement types specified in the relevant standard (BSI, 2011). Portland cement, known for its high density, low alkali content and good resistance against sulfate attacks, is also relatively inexpensive to produce. These attributes contribute to its widespread availability globally. However, when considering the environmental impacts of different cement types, Portland cement is noted for having the highest carbon dioxide emissions.

The primary component in cement production is clinker. Emissions during clinker production are mainly attributed to the burning of fossil fuels in the kiln and process emissions related to calcination. As CEM I Portland cement has the highest clinker ratio, it consequently incurs the highest environmental impacts. In contrast, other cement types like CEM II have a lower clinker content due to the incorporation of supplementary cementitious materials, rendering CEM II less environmentally harmful than CEM I.

In this scenario, the substitution of CEM II for Portland cement in the construction materials of the investigated building is examined, aligning with Türkiye's decarbonization efforts as outlined in the country's official national contribution declaration. The CEO of the Turkish Cement and Cement Products Assembly (TCMA, 2023) has indicated that a significant pathway to reducing the cement industry's carbon emissions involves the use of alternative raw materials and supplementary cementitious materials instead of clinker. Achieving this requires an increased utilization of cement types other than CEM I. As per the cement standard (BSI, 2011), the production of CEM I cement necessitates a minimum of 95% clinker content. In contrast, for various types of CEM II cement, the clinker ratio varies between 65 – 94%. The reduction in clinker usage is facilitated by the inclusion of supplementary cementitious materials such as fly ash, ground granulated blast furnace slag and minor additional additives.

Statistics from the Turkish Cement and Cement Products Assembly reveal that CEM II/A-M, or Portland composite cement, is the most produced and utilized type of CEM II cement in Türkiye, with a clinker content of 80 – 94%. When the concrete data in the analysis is adjusted to include CEM II/A-M cement instead of Portland cement, there is a noticeable reduction in the overall carbon emissions from the construction material perspective. The original total carbon impact from the production of construction materials was approximately 263 kg CO_2 eq., with about 136 kg CO_2 eq. attributed to the use of concrete alone. The figure below illustrates the reduction achieved when CEM II/A-M cement is factored into the analysis. The study found that the overall impact decreased to 247 kg CO_2 eq., with the impact from concrete

reducing to 120 kg CO_2 eq. This represents approximately a 12% reduction in the concrete impact and a 7% reduction in the total impact of construction materials.

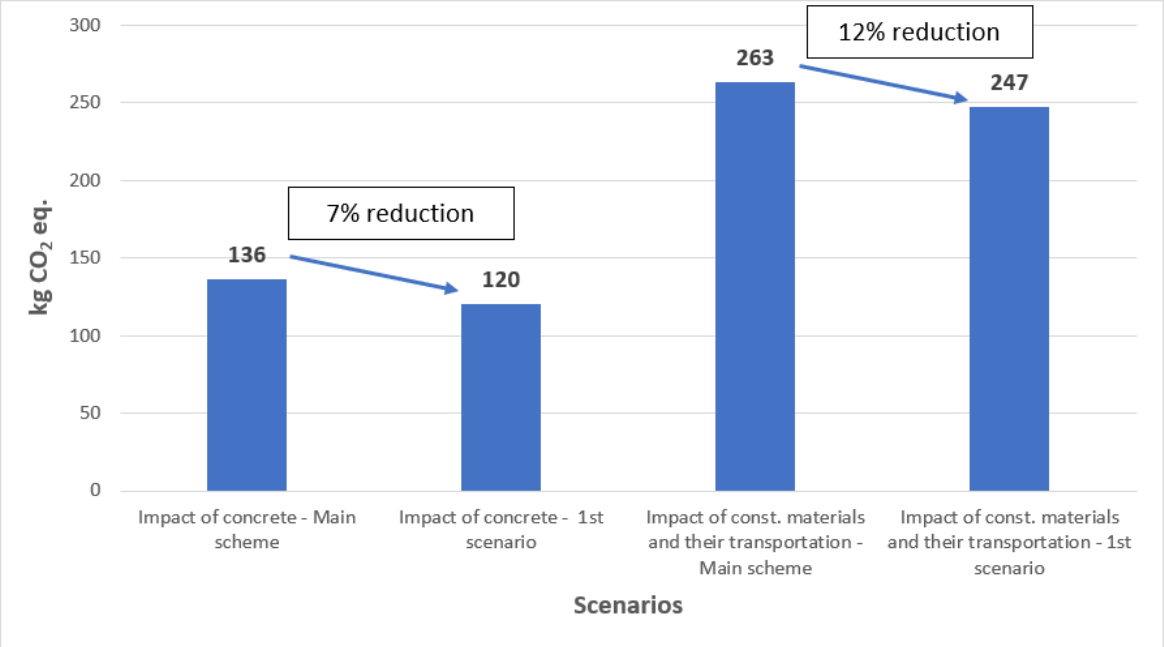

Figure 6.1. Impact of 1st scenario.

The analysis showed that it is possible to reduce the overall carbon impact of the building by switching from CEM I to CEM II/A-M cement. Reduction percentages shown in Figure 6.1, are for a 1 m^2 building area as this is the unit of this study. When the whole building is considered, a 7% decrease in the construction materials and their transportation means tonnes of CO_2 reduction. As explained, this scenario can apply to Türkiye as CEM II/A-M is already the second most produced and sold cement type. In addition, further reduction potentials can be achieved by continuously switching to other CEM II types. CEM II/A-M has a clinker range of 80-94 % (BSI, 2011). Other CEM II types such as CEM II/B-LL and CEM II/B-M have lower clinker ratios. Lower clinker ratios decrease CO_2 emissions thus further reducing the impact of cement and concrete used in the buildings.

6.3. 2nd Scenario-A Class Energy System

It has been previously established that over 1 million out of 1.5 million buildings in Türkiye, possessing an 'energy identity certificate', are rated as C class in terms of energy level. For the modeling of use-phase related impacts, an electricity consumption of 89.5 kWh/m^2/year is assumed, representing the median value for the C-class energy level. The primary objective of the 'energy identity certificate 'is to assess and rank the energy efficiencies and consumptions of buildings, with the ultimate goal of enhancing energy efficiency through progression to B and A classes.

This scenario explores the potential use-phase related impacts for the investigated building, assuming it attained the optimal A-class energy level. As per Table 4.2, the consumption range for the B class is 40 - 79 kWh/m^2/year, while the A class is characterized by a range of 0 – 39 kWh/m^2/year. Adopting the median value of 19.5 kWh/m^2/year for A class, the use-phase related impacts were remodeled, revealing a substantial reduction in carbon emissions.

Previously, the annual use-phase related impacts were estimated at approximately 79.4 kg CO_2/m^2, with electricity consumption accounting for about 65% of this impact. Upon modeling the building as adhering to energy class A, a substantial reduction in these figures was observed, as depicted in the figure below. The annual use-phase related impacts decreased to 38.9 kg CO_2/m^2 and the impact from electricity consumption was reduced to 11.3 kg CO_2/m^2. This represents a 51% annual reduction in carbon emissions for the building's use phase. Given the predominant impact of the use phase over the building's entire lifespan, this reduction holds significant potential.

However, transitioning to an A-class energy level is not a straightforward process and necessitates considerable investment and resource allocation. As previously discussed, (-, 2020) and (Gündoğmuş,2023), the majority of Türkiye's building stock is rated C class, with around 24% of buildings possessing an 'energy identity certificate classified as B class. Data on the number of A-class buildings is scarce, suggesting their

rarity. Achieving an A-class rating for existing buildings is challenging, as it requires specific considerations from the design phase. Nevertheless, for new constructions, targeting an A-class rating is a viable goal. Achieving this requires a comprehensive approach, considering various factors from energy systems (such as solar energy, co-generation and trigeneration) to the architectural design of the structure. Therefore, there is significant potential for decarbonization in the construction industry through the development of energy-efficient buildings.

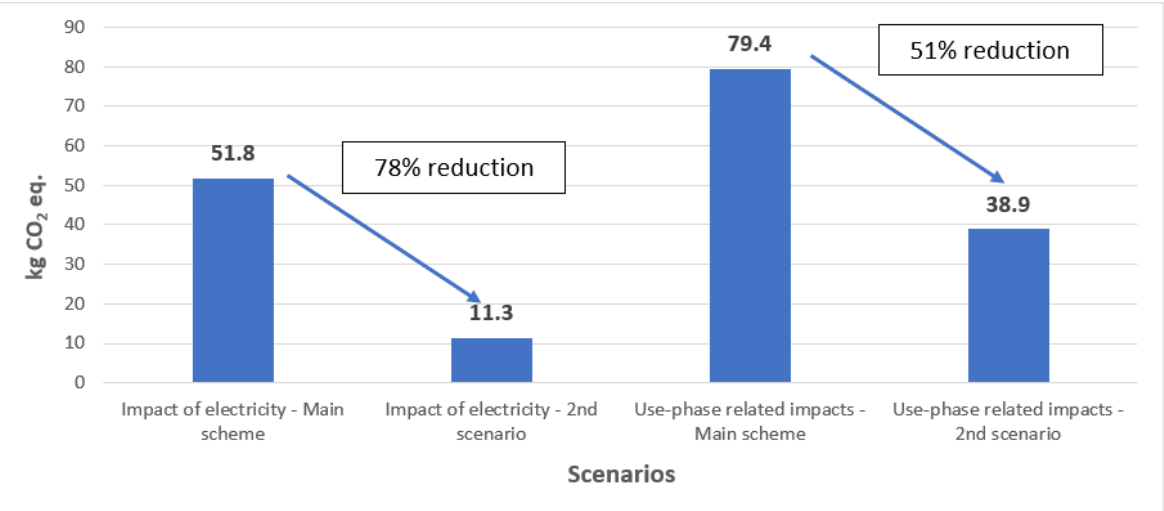

Figure 6.2. Impact of 2nd scenario.

6.4. 3rd Scenario - Combination of Scenarios

This study has highlighted two critical areas where substantial reductions in carbon emissions can be achieved: transitioning from the use of CEM I Portland cement to CEM II cement and constructing buildings with an A-class energy efficiency rating. The impacts of these changes on carbon emissions have been discussed in previous sections. This section combines the first two scenarios to present the life cycle assessment results over the entire lifetime of the investigated building, with the objective of determining the extent of emission reductions. Table 5.5 initially displayed the total carbon emissions for the building's 50-year lifetime. Table 6.1, in contrast, illustrates the results when both scenarios are applied together, exploring the potential for achieving the lowest emission values. The analysis indicates that the total life cycle carbon

impact decreases from 4312 kg CO_2 eq. to 2275 kg CO_2 eq., signifying around 52% reduction. When this impact is amortized annually, it results in the emission of 45.5 kg CO_2 eq. per square meter per year, compared to the previous figure of 86.2 kg CO_2 eq. per square meter per year.

Table 6.2. Impact of each different stage on total building carbon emissions when both scenarios implemented.

LCA stage	**Impact (kg CO_2 eq.)**
Construction materials and Transportation	281.5
Use–phase (for 50 years)	1945
End-of-life	48.6
Total	**2275.1**

7. CONCLUSION

Climate change is a global pressing issue with far-reaching impacts that deeply affect our ecosystems, societies and economies. Its impacts have begun to be felt more greatly in the last decade. The necessity to act against climate change is crucial to keep the global temperature rise within 1.5 0C. Its effects can be reduced/mitigated by decreasing greenhouse gas emissions, transiting towards renewable energies and by adopting more sustainable practices. To fight against climate change, researchers, global industry players and governments look for ways and develop methods. To tackle climate change and reduce its adverse impacts, it is first needed to understand the impact and where it originated. Without understanding where the emissions arise for a specific product/process/flow/structure etc., fighting against climate change would be chasing a tail.

Therefore, especially for the last two decades, different methodologies have been developed to accurately analyze the environmental impacts of materials/ products/ structures/ services etc. Out of these different methodologies, life cycle assessment became a prominent methodology to analyze environmental performance with having strong scientific basis. In addition, LCA analysis is a comprehensive study in that one can determine where emissions occur for the investigated system through not just CO_2 but also different impact indicators. Thus, the outputs of an LCA analysis demonstrate the total impact of the investigated topic by different indicators and provide an understanding of the hot spots (major emission points).

Across different industries, the construction sector is if not first, one of the major sectors with a significant impact on the environment due to its high dependence on natural resources and momentous contribution to greenhouse gas emissions. Construction sector-related activities account for about 36% of global energy use and 40% of CO_2 emissions.

In addition, high dependence on raw materials contributes to the destruction of biodiversity and habitat. Thus, the construction industry stands out as one of the most pressing sectors to tackle climate change.

As previously mentioned, to reduce/mitigate the adverse effects of the sector on the environment, one should first have a clear understanding and knowledge about the environmental impacts and where they arise. The way to do this is to understand the environmental impacts of structures. For this aim, especially for the last two decades, researchers have been conducting life cycle assessment analysis on a variety of structures, from office buildings to mountain houses, from residential houses to campus buildings. The main driver is the same: to be able to understand what causes environmental impacts and how much impact each investigated point has throughout the whole life of a structure from the production of its raw materials to the disposal and hereafter. This is the definite first step towards decarbonizing the construction industry.

To have a more accurate and precise analysis, these life cycle assessment studies have to consider local and regional requirements with broad understanding and coverage. This study aimed to fill the gap in the literature by providing an understanding of the environmental impact of a representative residential house in Türkiye. Firstly, there are not many LCA studies conducted on buildings in Türkiye. Second, the available literature in Türkiye is lacking one or more of the following three points:

- Representativeness
- Comprehensiveness
- Coverage

Current literature in Türkiye, as well as in the majority of the globe, focuses on a specific building where information can be obtained. That's why a high percentage of the relevant studies investigate a unique structure, sometimes a campus building in Philadelphia, sometimes an office complex in London and sometimes a residential

building in Türkiye. Even though the outcomes of these studies are beneficial to understanding the source of impacts and the current situation, they cannot represent/be a proxy for a specific building type in a specific region because the data used solely belong to the investigated structure. Another lacking point in some studies is about not being comprehensible. This might arise due to two reasons: lack of trustable data source/s and lack of included impact indicators. Most of the trusted LCA databases are not easy to reach due to their high cost, thus some researchers prefer to use publicly available data in their analysis. However, the margin of error for publicly available data is high and the coverage is low. Also, a significant amount of related literature focuses on only CO_2 emissions whereas there are other significant impacts of construction activities that are often overlooked such as eutrophication and water depletion. Lastly, some of the current studies are lacking in terms of coverage by only including one or two life stages of a structure, such as raw materials, construction, or use phase. However, it is observed that with the wider availability and accessibility of the data, coverage of LCA studies the literature has increased recently.

7.1. Contributions of the Study

The contributions of this current work lie in the three points mentioned previously; representativeness, comprehensiveness and coverage. The building investigated in this study is a residential building in Türkiye where the outcomes can be taken as a proxy within Türkiye. This is because the majority of the data used during analysis does not belong to a specific residential building but a representative one. To keep the representativeness as high as possible, almost all the data used in the analysis is taken from official sources. For example, raw materials and their quantities are taken from an official source that is in the first place prepared to be a practical guide for residential house construction in Türkiye. Similarly, use-phase-related consumptions, such as electricity, natural gas and water are collected from official sources so that the consumption amounts represent the majority of Türkiye's household consumption. However, representativeness by itself is not enough. The study should be also comprehensive so that the outcomes of the study can be trusted. By using one of the

most trusted life cycle databases, ecoinvent and considering different impact indicators rather than only CO_2 related emissions, the study delivers enough comprehensiveness on the subject. Lastly, the study considers the majority of the life cycle stages of the building and the ones that are not included in the analysis cannot alter the results significantly because not-included stages have around 1-2% of the impact percentage over the whole life cycle impacts.

The study outputs clearly demonstrate environmental burdens of a residential building in Türkiye and highlights the emission sources and hot-spots. By analyzing these outputs, one can have a strong understanding of attributed emissions for different activities across the building life from its construction to demolition. As previously explained, through Paris Agreement, Türkiye has set an official target to become net-zero by 2053. One of the most effective ways to achieve this target is to make the construction industry less carbon intense and transition towards decarbonization of the industry. This is significant because around 40% CO_2 related impacts across the globe are attributed to the construction industry. Thus, without reducing emissions of the construction sector, Türkiye cannot achieve its official net zero target by 2053. Since construction industry is all about constructing structures/buildings, it become crucially important to know/understand the environmental performance of buildings in Türkiye. However, one come up against a brick wall at this point because there are no available study in Türkiye that can be used as reference for determining the environmental performance of buildings. Within a very limited number of studies that investigate environmental performance of specific buildings in Türkiye, none of them can be taken as reference to be representative for the country. This is mainly due to the fact that for all these relevant conducted studies, their environmental performance analysis are on a specific building/s that cannot be taken as representative for the country. This study contributes this significant missing area in the literature by conducting environmental performance analysis of a representative residential building in Türkiye where study outputs can be used/taken as reference values for country's residential sector. This contributes to the relevant bodies (ministries, municipalities, contractors etc.) by providing them understanding about the environmental impacts of Türkiye's

residential sector. With the outputs of this thesis, relevant bodies can start to work on reducing the impacts of hot-spot areas (in terms of emissions). The study outputs can be beneficial in a way that as an example, constructors, civil engineers and architects can be more aware of the environmental impacts of their construction material selections and design criteria so that at the early design stages of residential building construction, they can take the environmental impact of their choices into consideration along with the traditional objectives such as budget and time of the project. The outputs also contribute to the commitment of Türkiye towards becoming a net zero country. Relevant public bodies such as ministries and municipalities can implement the necessary changes in building regulations to assure that future buildings become more energy efficient and less carbon intensive.

Moreover, the study also provided couple of different what-if scenarios to understand the change in the environmental performance of buildings when a specific process/product change is implemented. There are countless points where one can make a change and reduce the emission of a building, but these changes have to be optimized in terms of applicability, timing and cost. The study included two major different scenarios that are in alignment with the current drive of the industry/government in Türkiye. One is switching from CEM I to CEM II cement, which is already aimed and in motion both by industry and government. The other is making the buildings less energy dependent towards having more 'A class' buildings in the future. This is also one of the objectives of the Ministry of Environment, Urbanization and Climate Change in Türkiye. Thus, two possible scenarios that are suitable for the country's conditions and have significant carbon reduction potential were provided.

7.2. Limitations and Future Work

This study bears three main limitations. The first limitation is not including the whole life cycle stages of the investigated building. Even though the study considers the majority of LCA stages from raw material acquisition to the disposal of construction materials after the building is demolished, there are still some stages that are outside

of the scope of the current study. These stages are related to the activities during the building construction at the site and demolition. In addition, any possible activities related to refurbishment and repair during the building service life are not included. Even though the current scope of this study includes the main significant emission sources of the building's life, the inclusion of these stages can further increase the quality and outputs of the study.

The second limitation of the study is not including all construction materials for the investigated building. The study aimed to analyze a representative residential building in Türkiye and as mentioned, construction materials and their quantities per 1 m^2 area are taken from a reliable source. But this source aimed to have a practical document for civil engineers, architects, etc. for their calculation. Thus, it does not include each construction material that is typically used for residential building construction. The list is comprehensive and includes all the major materials, but not 100% completed. More detailed analysis and inclusion of more materials might be a work for future studies.

The last limitation of the study is about including a limited number of reduction scenarios and not testing how hard could it be to implement these changes in reality. The scenarios suggested in this study reveal that significant reduction is possible. However, one can have more scenarios and reduction areas that can also help towards decarbonization of the construction sector. In addition, even though it was thought that the created scenarios are applicable in Türkiye, further investigation on how much effort (both from an individual and country level) is needed to achieve these targets of reduction scenarios can be a future study work.

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Yapı Yaklaşık Maliyeti Hesabı

Pratik hesaplamaya esas olmak üzere yığma ve karkas yapılar için yapı birim alanına isabet eden Yaklaşık metraj birim ölçüleri aşağıdadır.

	İmalat Cinsi	Yığma		Betonarme Karkas	
1.	Betonarme Betonu	0.250	m^3/m^2	0.380	m^3/m^2
2.	Betonarme Demiri	22	kg/m^2	34	kg/m^2
3.	Kalıp	1.75	m^3/m^2	2.60	m^2/m^2
4.	Kalıp iskelesi	1.90	m^3/m^2	2.80	m^3/m^2
5.	İş iskelesi	1.43	m^2/m^2	1.43	m^2/m^2
6.	Tuğla Duvar	0.200	m^3/m^2	0.150	m3/m^2
7.	İç Sıva	2.40	m^2/m^2	2.40	m^2/m^2
8.	Dış Sıva	1.30	m^2/m^2	1.30	m^2/m^2
9.	Tavan Sıvası	0.90	m^2/m^2	0.90	m^2/m^2
10.	Badana (iç)	3.00	m^2/m^2	3.00	m^2/m^2
11.	Fayans - Seramik	0.30	m^2/m^2	0.30	m^2/m^2
12.	Ahşap yapı + Karkas	0.15	m^2/m^2	0.15	m^2/m^2
13.	Ahşap Pencere	0.12	m^2/m^2	0.12	m^2/m^2
14.	Yağlı Boya	0.42	m^2/m^2	0.42	m^2/m^2
15.	Ahşap Çatı, kiremit örtü (Toplam İnşaat Alanı Üzerinden)				
	Tek kat	1.25	m^2/m^2	1.25	m^2/m^2
	İki kat	0.63	m^2/m^2	0.63	m^2/m^2
	Üç kat	0.42	m^2/m^2	0.42	m^2/m^2
	Dört kat	0.33	m^2/m^2	0.33	m^2/m^2
	Beş kat	0.25	m^2/m^2	0.25	m^2/m^2
16.	Metal Örtü (Toplam İnşaat Alanı Üzerinden)				
	Tek kat	1.33	m^2/m^2	1.33	m^2/m^2
	İki kat	0.67	m^2/m^2	0.67	m^2/m^2
	Üç kat	0.44	m^2/m^2	0.44	m^2/m^2
	Dört kat	0.34	m^2/m^2	0.34	m^2/m^2
	Beş kat	0.27	m^2/m^2	0.27	m^2/m^2
17.	Mozaik Döşeme Kaplaması	0.90	m^2/m^2	0.90	m^2/m^2
18.	Cam	0.10	m^2/m^2	0.10	m^2/m^2

Örnek Olarak

Toplam alanı Betonarme karkas ve konut olan 1 500 m^2 bir binanın metraj olarak hesaplanması gerekiyor ise;

Betonarme Betonu = 0.380 x 1 500 = 570 M^3

Betonarme Demiri = 0.034 x 1 500 = 51 ton

Betonarme Kalıbı = 2.60 x 1 500 = 2 600 m^2

Tuğla Duvar =0.150x 1 500 = 150 m^3

Projeden metraj çıkarılması esas olmak üzere yaklaşık pratik kabuller

Tesviye Tabakası alanı = Mozaik döşeme kaplaması alanı 1 m^3 Beton =7-8 m^2 kalıp

Blokaj Alan = Grobeton Alanı = Mozaik Alanı Demirli Beton Hacmine =70 - 90 kg Demir

Kiremit Alanı = Ahşap Çatı Alanı Pencere doğrama alanının = %75 - 80 normal düz cam

Kiremit Alanı = Çatı Yalıtım Alanı Kapı Kanat alanının = %25 buzlu cam

Tavan Sıvası = Tavan Kireç Badana Tüm Demirin = %40 - 45 ince

Badana Alanı = İç Sıva Alanı Tüm Demirin = %55 - 60 kalın

Pencere Yağlı Boya Alanı = Pencere Doğrama Alanı

Figure A.2. Konut inşaatlarının metrekaresinde kullanılan malzeme miktarı 2.

T.C.
MALİYE BAKANLIĞI
Gelir İdaresi Başkanlığı

İVEDİ

Sayı : 64994458-130[5529-1235]-E.50114
Konu : 2015 Yılı Sayıştay Denetim Raporu

11/05/2016

DAĞITIM YERLERİNE

Sayıştay Başkanlığı tarafından Başkanlığımıza gönderilen "Gelir İdaresi Başkanlığı 2015 yılı Denetim Raporu"nda KDV mevzuatı açısından eleştiriye konu olan hususlarla ilgili olarak aşağıdaki açıklamaların yapılmasına ihtiyaç duyulmuştur.

1- Katma Değer Vergisi Genel Uygulama Tebliğinin (III/B-3.1.3.) bölümünde indirimli orana tabi işlemlerden doğan iade taleplerinde, mükelleflerin iade hesabına dahil edebilecekleri ve edemeyecekleri KDV'lere ilişkin olarak örneklere de yer verilmek suretiyle gerekli açıklamalar yapılmıştır. Ancak Sayıştay Başkanlığının söz konusu Raporunda, net alanı 150 m²'nin altında bulunan konut teslimlerinden kaynaklanan KDV iadelerinde, iade hesabına dahil edilecek ve edilmeyecek KDV'lere ilişkin vergi daireleri itibariyle standart bir uygulama olmadığı belirtilmektedir. Bu çerçevede, net alanı 150 m²'nin altında bulunan konut teslimlerinden kaynaklanan KDV iadelerinde, iade hesabına dahil edilemeyecek harcamalara isabet eden KDV'nin tespitinde Tebliğde yer alan açıklamaların dikkate alınması gerekmektedir.

2- Net alanı 150 m²'nin altındaki konut teslimlerine ilişkin olarak yersiz iadeye mahal vermemek amacıyla, yüklenilen KDV listelerinde yer alan demir, çimento, hazır beton gibi inşaata ilişkin temel girdilerin teknik bilgi gerektiren kullanım miktarları konusunda gerekli araştırma ve değerlendirmenin yapılması, ilgili meslek odalarından görüş alınması ve YMM raporlarında bu değerlendirmelere yer verilmesi sağlanmak suretiyle KDV iade taleplerinin sonuçlandırılması gerekmektedir.

3- Katma Değer Vergisi Genel Uygulama Tebliğinin (III/B-3.1.3.) bölümünde indirimli orana tabi işlemlerden doğan iade taleplerinde mükelleflerin iade hesabına dahil edebilecekleri yüklenilen KDV'ye ilişkin açıklamalara yer verilmiş olup, indirimli orana tabi işlemlerden doğan iade taleplerine ilişkin olarak yüklenilen KDV listelerinde doğrudan yüklenim, genel giderler ve ATİK şeklindeki sınıflandırmanın doğru ve mevzuatta yer alan açıklamalara uygun olarak yapılması sağlanmalıdır.

İndirimli orana tabi işlemlerden doğan iade talepleri yerine getirilirken yüklenime konu edilen genel giderler ile ATİK'lerin indirimli orana tabi konut teslimiyle ilgili olup olmadığı ve ATİK'lerin işletme aktifine kayıtlı bulunup bulunmadığı araştırılmalıdır.

4-İndirimli orana tabi konut teslimlerinden kaynaklanan KDV iadeleri yerine getirilirken konutlara ilişkin satış faturalarında yer alan tutarların doğruluğu konusunda tereddüde düşülmesi halinde söz konusu tutarların doğruluğuna ilişkin gerekli araştırmalar yapılmalıdır.

Bu belge, 5070 sayılı Elektronik İmza Kanunu'nun 5. Maddesi gereğince nitelikli elektronik imza ile imzalanmıştır.

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Figure A.3. Konut inşaatlarının metrekaresinde kullanılan malzeme miktarı 3.