A LIFE CYCLE ASSESSMENT BASED DECISION SUPPORT TOOL FOR EARLY-DESIGN PHASE OF MASS-HOUSING NEIGHBOURHOODS IN TURKEY

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

BY

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

SEPTEMBER 2018

Approval of the thesis:

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ABSTRACT

A LIFE CYCLE ASSESSMENT BASED DECISION SUPPORT TOOL FOR EARLY-DESIGN PHASE OF MASS-HOUSING NEIGHBOURHOODS IN TURKEY

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September 2018, 168 pages

In developing countries such as Turkey, the main driving force of economy is the Architecture-Engineering-Construction (AEC) industry. Hence, rapid urban expansion dramatically increases the pressure on the existing infrastructure which affects buildings, public transportation and overall energy usage. In order to control urbanization, governments facilitate mass-housing projects in increasing numbers. Higher rates in construction require an immediate need for methods of assessing the environmental impacts of these large scale mass-housing projects. Currently, there is not any framework or legislation which regulates the environmental impact of mass-housing projects.

In order to provide a comprehensive response to this need, the study aims to develop a life cycle assessment (LCA) based decision support tool (DST) for early design phase of mass-housing projects in Turkey. DST should take into account several clusters of aspects that are inherit in the urban and typological characteristics. In this context, neighbourhood scale is considered as the suitable scale in order to have more precise results.

This tool is aimed to provide planners with decision support where and when it is most needed. Residential buildings are the most constructed building type in Turkey, and early design phase is when the design preferences have the highest impact.

In the end of the assessments, a reference LCA study which represents the mass-housing projects in neighbourhood-scale in Turkey was developed. Different embodied carbon values were defined for project typologies. Depending on the reference LCA study, a decision support tool (DST) for mass-housing projects in neighbourhood scale was achieved. The DST is capable of introducing several sustainable solutions that are appropriate for mass-housing projects.

Keywords: Life cycle assessment, decision support tool, mass-housing projects, neighbourhood scale, sustainability

ÖZ

TÜRKİYE'DE TOPLU KONUT ALANLARI ERKEN TASARIM AŞAMASI İÇİN YAŞAM DÖNGÜ DEĞERLENDİRME TABANLI KARAR DESTEK ARACI

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Eylül 2018, 168 sayfa

Türkiye gibi gelişmekte olan ülkelerde, ekonominin sürükleyici gücü inşaat endüstrisidir. Bu durumda, hızlı kentsel gelişim; mevcut bulunan altyapı, bina stoku, toplu taşımacılık ve genel enerji tüketimi üzerinde ağır bir yük oluşturur. Kentsel gelişimin kontrolü için ise, hükümetler artan sayıda toplu konut projeleri üretmek zorundadır. Yüksek inşaat oranları, büyük ölçekli toplu konut projelerinin çevresel etkilerinin değerlendirilmesi için acil bir ihtiyaç oluşturur. Bu projelerin çevresel etkilerini düzenleyen bir çerçeve ya da yasal çalışma bulunmamaktadır.

Belirlenen ihtiyaca kapsamlı bir cevap vermek amacıyla, bu çalışma Türkiye'deki toplu konut alanlarının erken tasarım aşaması için yaşam döngü değerlendirme (YDD) tabanlı bir karar destek aracı geliştirmeyi amaçlamaktadır. Bu çevresel değerlendirme aracı, projelerin kentsel ve bina tipolojisi özelliklerinden gelen, birden fazla katmanda bulunan konuları içermesi gerekmektedir. Kullanılan ölçek, bu noktada daha kesin veriler ortaya koyacağı belirlenen mahalle ölçeği olarak kabul edilmiştir.

Çalışmanın amacı, planlamacılara en gerektiği alanda ve aşamada karar desteği sunabilmektir. Konut binaları Türkiye’de en fazla sayıda inşaat edilmekte olan bina tipidir, planlama kararları ise ön tasarım aşamasında sonuç ürün üzerinde en fazla etkiyi gösterebilmektedir.

Yapılan çevresel değerlendirmenin sonucunda, Türkiye'deki mahalle ölçeğindeki toplu konut projelerini temsil eden bir referans YDD çalışması elde edilmiştir. Farklı proje tipoloji için farklı gömülü karbon değerleri tanımlanmıştır. Bu referans YDD çalışmasına dayanarak bir karar destek aracı oluşturulmuştur. Araç, toplu konut projeleri için uygun olan sürdürülebilir çözüm önerileri sunmaktadır.

Anahtar kelimeler: Yaşam döngü değerlendirmesi, karar destek aracı, toplu konut projeleri, mahalle ölçeği, sürdürülebilirlik

To My Wife and Daughter

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my supervisor Assoc. Prof. Dr. Ali Murat Tanyer for his guidance, advice, criticism, encouragements and insight throughout the research.

I would like to thank to valuable jury members for providing continuous input and support during monitoring juries and discussions.

I would also like to thank to Mustafa Pişkin for his great support at the beginning of the study. I am grateful to the Housing Development Administration of Turkey for allowing the usage of information on mass-housing projects and to the Urban Transportation Technology Accessibility Implementation and Research Centre (KUTEM) for sharing their valuable studies on transportation preferences of citizens of Ankara. I also appreciate the manufacturers, architects and experts who have shared their valuable time and knowledge during interviews and communication.

I would like to express my deepest thanks to my family, my parents and my brother and his family, for their enduring love and support, which gave me the inspiration to complete this study.

Finally, I would like to show my gratitude to my wife Berna, from whom I have always received spiritual support and strength all the time by sharing her unique partnership and to my daughter Ada, who has been the source of determination and purpose for my life.

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LIST OF ABBREVIATIONS

AEC - Architecture-Engineering-Construction

DST - Decision Support Tool

GHG - Green House Gas

GWP - Global Warming Potential

IO - Input-Output

LCA - Life Cycle Assessment

LCI - Life Cycle Inventory

TOKİ - Housing Development Administration of Turkey

CHAPTER 1

INTRODUCTION

In this chapter, the argument for and objectives of the study being reported herein are first presented under respective sub-headings. Again under a dedicated subheading, it continues with a brief overview of the general procedure followed in its conduct and ends with a concise description of what is covered in each of remaining chapters, under the sub-heading titled “Disposition”.

1.1. Argument

The focus on sustainability is ever increasing in our daily life, in academic research efforts and in AEC industry. As a point of interest, sustainability has been defined numerous times in the literature. One common definition was introduced in the Brundtland Report (WCED, 1987) as: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.

At the U.N. World Summit in 2005, sustainable development was taken into consideration within three categories; environmental, economic and social. Kohler (1999) introduced a similar categorization for sustainability in built environment. The highlighted term was ‘sustainable building’, which is suggested instead of ‘green building’. Sustainable development concept is illustrated in Figure 1.

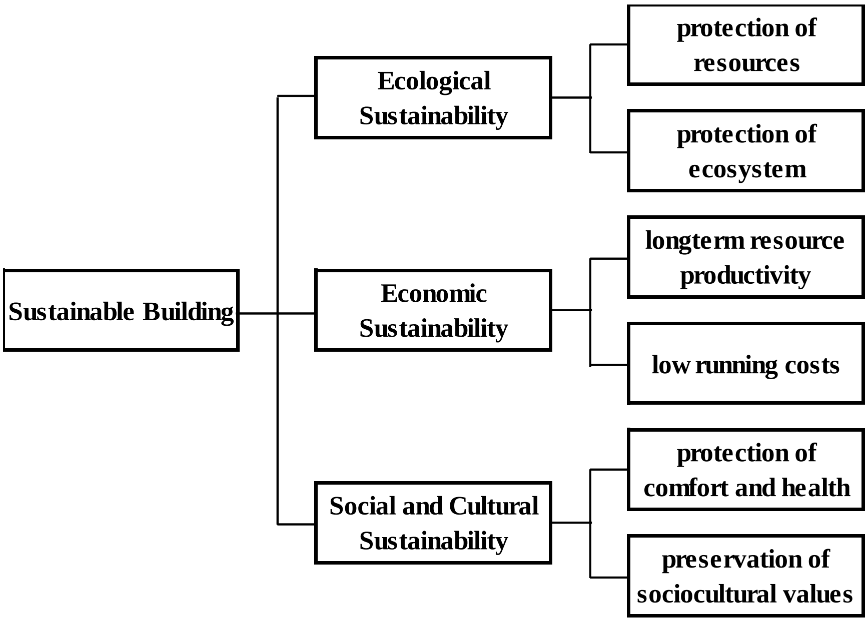

Figure 1. Three dimensions of sustainability concept (Kohler, 1999)

Within this categorization, ecological (environmental) sustainability is likely to take the lead among its social and economic counterparts, as the consequences of the environmental impact on the nature is being revealed. Many parties from differing sectors emphasize on the immediate necessity of taking precautions. Being one of the largest industries, AEC industry is among the candidates that can make the difference.

According to U.S. Energy Information Administration (EIA, 2013), the AEC sector is responsible for more than one fifth of total worldwide consumption of delivered energy (in which ratio of residential energy consumption is 65 percent), one sixth of world's fresh water withdrawals, one-quarter of wood harvests and two-fifths of material and energy flows. Moreover, it is pointed out that increase in energy consumption grows fastest among all other sectors. In the future projections, AEC sector is foreseen to be responsible for setting the trends in energy markets. Currently, buildings alone represent more than 50% of national wealth in U.S. Research efforts suggest that reductions of 24% in energy demand, 33% in gas emissions, 40% in water use and 70% in solid waste can be achieved by applying green solutions in building design. (EIA, 2005)

As in most developing countries, Turkey is experiencing an expansive urban growth. The OECD report on Turkey (2012) forecast a growth rate of 8,5% per year for the next decade. As declared by Turkish Statistical Institute (TÜİK, 2013), an enormous increase from 36 to 153 million m^2 (app. 425%) with large annual fluctuations (75% to -25,9%) in the total floor area permitted for building is being observed in the last decade. With the governmental policies that favor the construction industry to lead the national economy, a greater rate of growth may be witnessed in the following years. This urban growth causes excessive pressure on the existing infrastructure, which affects buildings, public transportation, road networks, water quality, waste collection, public health, and overall energy usage.

Such a demand for development and change in the building industry has brought forward one of the largest revolutions in the construction history which is called as "sustainable building design" or "ecological design". With the means of setting up standards in this development notion, Building Rating Systems such as LEED in U.S, BREEAM in U.K, *etc.*, have been developed and accomplished well enough to become an established standard in the building industry. The rating systems have also managed to create market demand for ecological design and this may be the singular key motivation which facilitates the whole sustainability movement. Moreover, these systems provided the necessary literature defining much of the sustainable building concept.

At early years of sustainable architecture, the promotions on agents such as green roof, recycling, renewable products and applications such as photovoltaic, geothermal panels had influenced the industry and increased the usage of mentioned components. However, neither the application of these green tools solely implies that the design target is achieved, nor it provides the level of success. As it is stated by Athena Sustainable Materials Institute (ASMI, 2013), above mentioned agents are just the means of sustainable architecture, what really matters is the measurement of embodied energy and greenhouse gas (GHG), consumption of raw materials, emissions, etc.

On the other hand, rating systems have been criticized for low sensitivity in rating categories and not including local priorities. Another major argument is about the exclusion of the building life-cycle. While, the operational phase of buildings is proved to have the largest effect on environment in most research efforts, without a comprehensive life cycle analysis (LCA), it is difficult to evaluate the total impact that a particular building has on its surroundings. Hence, it may be misleading to brand a product of AEC as "sustainable" without considering every impact that is done upon environment during its expected life-cycle. Even though substantial knowledge on energy-saving strategies for building operations can be found, there is still less information on the upstream (extraction, manufacturing, transportation) and downstream (deconstruction, disposal) impacts of buildings (Ragheb, 2011).

Moreover, performance of a particular building may be valuable if only the scope of evaluation is limited to building systems. If the scope is enlarged to built-environment, then we can assume that improvement of a single building may have a very little impact on the whole. In this case, impacts of urban scale components such as infra-structure, distance to urban center, means of transportation, *etc.*, must also be included. The meaning of improving building performance could be questioned if the occupant is driving a fossil fueled car for three-hours a day.

In this respect; consideration of embodied energy of buildings, significance of regional priorities, and inclusion of infrastructure have altered the way of evaluating the impact of built environment. Currently, the carbon footprint of Turkey is relatively low when compared to EU average (OECD, 2012). The annual GHG emission per capita in Turkey is 5,3 tons of CO_2 against the EU average of 10,2 tons and the OECD average of 15 tons. However, under existing energy consumption rate, GHG emissions are set to rise rapidly. Therefore, OECD (2012) advised Turkey to set quantitative mitigation targets for greenhouse gas emissions. Within this context, it is crucial to know the amount of impact done upon environment up to now and to foresee the amount of impact mitigation may be achieved in the following years.

The solution for this need can be supplied by the means of a decision support tool (DST) which provides planners and designers with output on environmental impact of different design scenarios. Currently, there is no mandatory legislation intact in Turkey which regulates the environmental impact of mass-housing projects. Planners refer to ÇED reports. ÇED reports require assessment of natural resources (water, land) and waste amount from industrial and large-scale developments (MoEU, 2013). However, it is only mandatory for residential buildings when a mass-housing project has more than 2.000 dwellings and it is not needed for projects with less than 200 dwellings. Between 2.000 and 200 dwellings, mass-housing projects are processed with ÇED only when it is considered necessary by local authority. Hence, ÇED procedure does not guarantee an environmental impact assessment for residential developments. Moreover, these reports do not cover embodied and operational carbon emissions of a mass-housing projects.

Furthermore, when the procedure for ÇED reports is investigated (MoEU, 2014), even if it is suggested by regulation that ÇED procedure should start in the early phases, it is seen that planners are not an integrated in the process. ÇED procedure is initiated after the planning is completed and tender process is conducted with a result of a winner contractor. Hence, it is complicated and impractical to apply revisions when the tender process is over, which may as well be demanded according to conclusion of ÇED reports.

Solutions for environmental impacts of built-environment should be available for designers and planners at early design stage when it is most needed and effective. In order to set up quantitative targets, a tool for environmental analysis of the current condition and potential solutions must be facilitated. In this study, it is suggested that life-cycle assessment of built environment at urban scale may provide a better perspective in taking necessary actions against environmental impacts by planning future settlements. The solutions should be aimed at the largest group of buildings in order to have a significant effect. According to TÜİK (2013), about 69 million m^2 of occupancy permit was given in 2013, and 52 million m^2 of these new construction buildings were residential. Most of the residential housing projects are realized by a single governmental authority, Housing Development Administration of Turkey (TOKİ). Furthermore,

1.2. Aim and Objectives

In this context, the aim of the study is to develop a comprehensive tool which provides environmental assessment of and sustainable solutions in early design stages for mass-housing projects in neighbourhood scale. Neighbourhood scale is considered as the appropriate level to implement and monitor sustainable developments regarding mass housing projects.

The primary objective to achieve this goal is developing a LCA-based DST for early design phase of mass-housing projects. The DST is necessary to support the designers and planners with adequate information in early design phases for achieving significant effect on environmental impact of the projects.

The secondary objectives determined for this goal are originating from the urban and typological characteristics of DST. In order for the tool to perform properly, the secondary objectives below should be achieved:

- Analysis of environmental impact of buildings and building components,
- Analysis of environmental impact of urban transportation,
- Assessment of environmental impacts and benefits of sustainable solutions,
- A link to a 'reference LCA study' which represent environmental impact of the mass-housing projects in Turkey,

The 'reference LCA study' herein implies a hypothetical mass-housing project at an urban scale which represents and identifies a mean for environmental impact of mass housing projects in Turkey. By determining variables and parameters for this reference study, the DST can provide output for planners about environmental impact of different design scenarios.

On the other hand, there are side objectives which are fulfilled by default during the study. There is a lack of available data regarding the environmental impact of built environment and building components in Turkey. While environmental LCA of mass housing projects is performed and interpreted, a valuable contribution to the literature of environmental assessment of built environment is achieved by collecting and generating new data. The data acquired in this study is validated through a data quality system integrated in the proposed methodology. In the end of this study, the data clusters may enable other researchers to conduct similar assessments in Turkey. Hence, it may also contribute to a national database which, as a concept, is considered as an important component of any LCA study. Moreover, life-cycle assessment studies are mainly focused on single buildings. Investigating the possibilities of applying LCA at urban scale is another valuable objective.

This study sets to respond to the immediate need for adopting environmentally conscious construction methods in AEC industry, especially in mass-housing projects in Turkey. It is supposed that the residential building sector may be the key for facilitating significant changes in relatively short-medium time periods. The author believes that the term sustainability in this study may also mean sustainability for a nation, as many factors depend on the performance of AEC industry in this developing country.

1.3. Procedure

The milestones of this study are shown in Figure 2. Research objectives were identified under sub-headings such as environmental assessment, neighbourhood scale and decision support. Then, respective research areas were determined in order to refine these objectives.

A comprehensive literature review was conducted, mainly focusing on LCA and environmental assessment of neighbourhood scale built environment. According to the findings of the literature review, a research methodology that is based on a hybrid LCA framework with three-clustered database was developed. The significance of the database clusters was that the characteristics of a sustainable neighbourhood development were represented in a systematic manner.

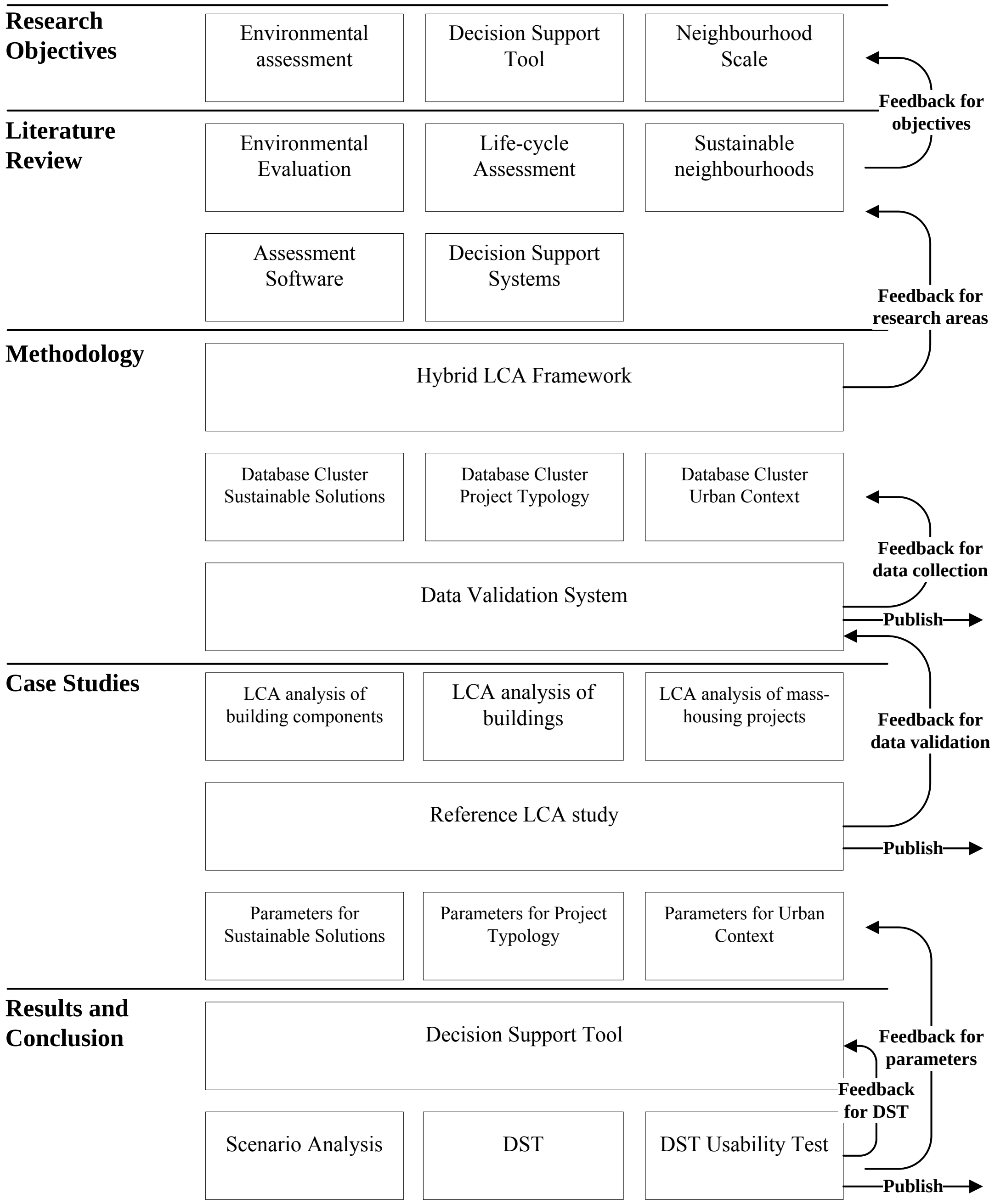

Figure 2. Framework of the research

Considering the paramount importance of data for an LCA framework, a data validation system which integrates data quality into impact assessment methodology was introduced for enhancing the precision of outputs of the study. It utilized a prioritization method to select primary and secondary component from an environmental point of view. The validation system also included comparison of generated data in different levels of scale.

As the methodology was completed with a validation system, it was necessary to test the hybrid LCA framework and collect data on an adequate number of mass-housing projects. LCA assessments were conducted on component, building and neighbourhood scales in three different case studies. The findings of the case studies were used to develop a reference LCA study that represents mass-housing projects in Turkey. The tasks for the case studies were as follows:

- Conducting hybrid LCAs of mass-housing projects realized by TOKİ in the last 10 years in the city of Ankara,
- Identify the data sources and availability of necessary documents to provide the due precision and certainty of LCA analysis,
- Collecting data from architectural projects, bill of quantities and an interview should be conducted with site or project architect,
- Identify primary components of mass-housing projects realized by TOKİ,
- Conduct the hybrid LCA framework for TOKİ mass housing projects in which primary components are taken into consideration with process LCAs, whereas rest of the components are taken into consideration with the generic data in literature,
- Preparing the reference LCA study which yields the necessary output (environmental impacts) of typical mass-housing projects and defining design criteria and parameters.

At the final stage, the DST was developed according to defined parameters and database model linked to the reference LCA study. The DST provides initial environmental estimations for planners in the early design phase regarding different scenarios of a mass-housing projects in neighbourhood scale. In order to mitigate environmental impacts, DST also introduces several sustainable solutions that can be integrated to the mass-housing projects. For demonstrative purposes, a simplified software was developed and was tested for usability with a number of relevant experts from public and private sector.

1.4. Disposition

There are five chapters to this report. This first, containing the argument, the objectives and the procedure of the investigation, along with this disposition which summarizes what follows in the remaining chapters, gives a broad view of its most main aspects. The second chapter consists of a literature review on sustainable development, environmental evaluation frameworks, life-cycle assessment and related techniques and related studies. The third chapter provides a thorough description of study material and methods used in both data collection and in its analysis. Here, the sample population which is considered as mass-housing projects are explained and the LCA methodology is put forward. The fourth chapter then explains the specific result of the study; including findings of sample project LCAs, together with a discussion of these in terms of its objectives and relevant aspects introduced in the literature, are given. The fifth chapter concludes the study by summarizing its findings and offering relevant recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

The literature review introduces the topics related to the use of life-cycle assessment (LCA) in the built environment. Concepts such as sustainable development and environmental evaluation frameworks are given in order to reveal the context in which LCA methodology is referred. Then, standards about the LCA methodology and related research and application areas of this methodology are given in brief. General LCA approaches and applications of LCA in urban scale and in literature are discussed. Most common software that are used in LCA are given and compared. Related LCA studies are presented as a final subheading just after the general terminologies are recognized, for a better reading experience.

2.2. Sustainable Development

Sustainable development is considered as one of the key areas for developing the context for this study. Lack of environmental assessment efforts on neighbourhood scale built environment increases the significance of this research area. In the following sub-headings, the concept is given in detail for sustainable buildings and then, larger scale effects are analyzed under 'sustainable neighbourhood' sub-section.

Bruntland Report (WCED, 1987) has underlined the basic concepts on which sustainability stands upon. Sustainability concept has gain popularity as the public opinion towards environmental issues and global climate change grows sensitive. Several initiatives at international level have been contributing to enhance the recognition of sustainable development such as Agenda 21 at Rio Summit, Habitat II

Agenda at 1996 in İstanbul, 5th Environmental Action Programme of the European commission and Paris Agreement at 2015.

In Agenda 21, (CIB, 1999) several definitions of sustainable development are given, but the Kibert definition is underlined:

> "The creation and responsible management of a healthy built environment based on resource efficient and ecological principles."

The principles that now governs the sustainable development are facilitated under concepts such as sustainable architecture, green architecture and ecological architecture.

2.2.1. Sustainable Buildings

According to U.S. National Institute of Building Science (WBDG, 2013) the main objectives of sustainable design are "to reduce, or completely avoid depletion of critical resources like energy, water, and raw materials; prevent environmental degradation caused by facilities and infrastructure throughout their life cycle; and create built environments that are livable, comfortable, safe, and productive". Williams (2007) leverages sustainable design as it creates solutions that solve the economic, social, and environmental challenges of the projects simultaneously, which are powered by sustainable energies.

Stang and Hawthorne (2005) explain sustainable architecture as a "flexible and holistic" approach that includes careful and conscious decisions at every phase of design and construction. More specifically, they add that design of sustainable residential buildings should at least be as small as possible, well positioned according to sun and located as close to public transportation and activity centers as possible. Without these features, it may be futile to increase energy efficiency and utilize eco-friendly products.

Bauer *et al.* (2007) emphasizes that the intended use of a given building plays an important role in the design of sustainable buildings. The author also draws attention to the relationship between user comfort levels and building resource handling.

> "While there is careful handling of the humans that occupy the building – through creating a high indoor comfort level and through using non health-hazardous materials – care also needs to be taken that energy and water requirements are minimized."

Williams (2007) underlines in-depth analysis of the project site. The author champions the term 'place-based design' in accordance with sustainable design. By studying the site, a designer can determine form and size, orientation, opening layout, building materials and low-maintenance strategy for upkeep and operational costs. It must be noted that there is an immense research effort on sustainable buildings which is beyond the content of this paper.

2.2.2. Sustainable Neighborhoods

According to UN (2016), an estimated 54.5 percent of the world population lived in urban settlements in 2016. It is stated that cities are accounted for 65 percent of total global energy consumption and 70% of energy-related carbon dioxide (CO_2) emissions (IEA, 2016). In the Rio +20 conference, cities have received great attention as over half of the world population is living in one. A framework for action was introduced which includes four general strategies; foster green communities and neighbourhoods, achieve sustainable and affordable housing, build green schools and pursue resiliency as part of the sustainable environment. Later in Paris Agreement at 2015; cities were called to increase and upscale their efforts for both mitigation and adaptation actions, reducing the emission and building resilience.

Williams (2007) refers to AIA principles for livable communities. These principles include; design on human scale, provide choices in housing, employment and social activities, encourage mixed-use development, preserve urban centers, vary transportation options, build vibrant public spaces, create neighbourhood identity, protect environmental resources, conserve landscape and design excellence.

U.S. Green Building Council (USGBC, 2011) claims that neighbourhood and community scale provides the right size to develop sustainable growth rapidly. Neighbourhoods are small enough to innovate quickly and suitable for testing new implementations. A green community should include strategies connected to sustainable land development, such as;

- clustering of growth around existing infrastructure,
- increased density, and investment in transit infrastructure;
- measures to enhance community revitalization such as walkability
- promotion of green space like parks and plazas;
- concrete agendas to reduce the environmental impacts of construction and operation of buildings and infrastructure

There are frameworks for monitoring sustainable development, such as LEED for neighbourhood development (ND), the STAR community index, etc. Case studies such as Pedra Branca in Brazil and Twinbrook Station in United States are two examples of which are certificated by LEED ND (USGBC, 2011). There are also sustainable urban and community case studies such as Belle Glade in Florida, Rio Nuevo Master Plan in Arizona and Great River Park in Minnesota (Williams, 2007).

On the other hand, there are researchers focusing on urban settlements. Aste *et al.* (2010) examined the project Borgo Solare in Italy, from a detailed techno-economic analysis. Glaeser and Kahn (2010) investigated carbon emission rates associated with new construction in varying locations in United States. Burch (2010) analyzed the socio-cultural and institutional barriers to actions on climate change at the local level in three cities of Canada. Dhakal (2009) sought answers for the amount of urban contribution to energy usage in China and how energy uses and CO_2 emissions have transformed. The author suggested a better understanding of urban energy uses is necessary for decision-makers at various levels to address energy security, climate change mitigation, and local pollution abatement. Rickwood *et al.* (2008) examined the embodied and operational energy in construction and use of residential buildings and reviewed the relationship between urban structure and private travel behaviour.

2.3. Environmental Evaluation Frameworks

In literature, several frameworks can be found for environmental evaluation of built environment. Background information regarding such frameworks are given in below sub-sections. Comparison between frameworks are given together with the reasons for preference for LCA over other methods.

2.3.1. Environmental Impact Assessment (EIA)

EIA as it is practiced today is being used as a decision support tool rather than decision making tool. Almost all EIAs address the direct, on-site effects alone. A significant disadvantage of EIA is that it is too generic and uses a broad scale of analysis.

2.3.2. Rating or Certification Systems (RS)

The common problem with RSs is that the requirements are not adaptable to the situational context of the building. The non-inclusion of context of the building is one major criticism against rating systems. Nevertheless, it has to be acknowledged that RSs are powerful tools from education, public image, and even marketing point of view. Below in Figure 3, is a list of well-known rating systems:

System	BREEAM	LEED	Minergie	CASBEE	GREEN STAR	DGNB
Country	UK	USA	Switzerland	Japan	Australia	Germany
Initiation	1990	1998	1998	2001	2003	2007
Key Aspects of Assessment	Management Health & Well-being Energy Water Material Site Ecology Pollution Transportation Land consumption	Sustainable sites Water Efficiency Energy & Atmosphere Material & Resources Indoor Air Quality Innovation & Design	Building Envelope Heating System Ventilation Air Tightness Appliances Ecological Construction	Energy Efficiency Resource Consumption Building Environment Building Interior	Management Indoor Comfort Energy Water Material Ecology Emissions Transport Land consumption Innovations	Ecological Quality Economical Quality Social Quality Technical Quality Process Quality Site Quality
Versions	Courts Ecohomes Education Industrial Healthcare Multi-residential Offices Prisons Retail	New Construction Existing Buildings Commercial Interiors Core and Shell Homes Neighborhood Dev. School Retail	Minergie Minergie-P Minergie-Eco Minergie-P-Eco		Offices - Existing Offices - Interior Offices - Design	Existing Buildings Offices Industrial Retail Portfolios Schools
Level of Certification	Pass Good Very good Excellent Outstanding	LEED Certified LEED Silver LEED Gold LEED Platinum	Minergie Minergie-P Minergie-Eco Minergie-P-Eco	C (poor) B B+ A S (excellent)	4 Stars, Best Practice 5 Stars, Excellence 6 Stars, World Leadership	Bronze Silver Gold

Figure 3. Comparison of different rating systems (Bauer *et al.*, 2007)

2.3.3. Life Cycle Assessment (LCA)

LCA is a scientifically defensible tool for environmental assessment. It is based on mass and energy balance method and assesses buildings using a consistent framework. It measures all inputs to a building and all outputs (emissions) released to the environment.

Due to the comprehensive approach in LCA approaches, it was adopted as one of the main components for the proposed methodology in this study. One of the main advantages of LCA over other evaluation frameworks is the integration of embodied energy and emissions of production phase beside the operational phase. In the following section, detailed information regarding the LCA methodology are given under respective sub-headings.

2.4. Life Cycle Based Assessment

LCA studies the environmental aspect and potential impacts throughout a product's life from raw material acquisition through production, use and disposal. While LCA has been a methodology that is mainly developed by the Society for Environmental Technology and Chemistry (SETAC) and EPA, it may be the initial research by Kohler (1987) that triggered a thorough and comprehensive understanding of life-cycle building impacts. Life cycle based assessment is a rather new approach in environmental assessment of built environment. It is intended as a comprehensive approach and championed for integrating the strengths of LCA and bridging the inadequacies of rating systems (Ragheb, 2011). In the literature, LCA is often acknowledged as a science based, fairly comprehensive, and standardized environmental assessment methodology (Tsai *et al.*, 2011).

2.4.1. LCA Framework Standards

As stated in ISO 14040 (1997E), there is no single method for conducting LCA studies. However, the International Standards Organization ISO 14040 series on how to conduct a LCA study was released in Geneva as a development of the ISO 14000 Environmental Management Standards. These include the four steps of a LCA study which are: goal and scope definition, inventory analysis (ISO 14041); impact assessment (ISO 14042); and interpretation (ISO 14043). A general introductory framework was also introduced (ISO 14040, 1997E).

As can been seen in Figure 4, following items and requirements shall be considered at each phase;

- Goal and scope definition;
  - The function of the system
  - The functional unit
  - The system boundaries
  - Type of impact assessment methodology and interpretation to be performed
  - Data requirements and quality
  - Assumptions and limitations
- Inventory analysis (LCI);
  - Data retrieval, management and quantification

- Impact assessment (LCIA)
  - Classification (environmental loads are classified with impact categories)
  - Characterization (calculation of category indicator loads)
  - Valuation (linking category indicators to a standard)
  - Grouping (ranking impact categories)
  - Weighting (subjective weighting of impacts according to the project context)
  - Data quality analysis (reliability)
- Interpretation

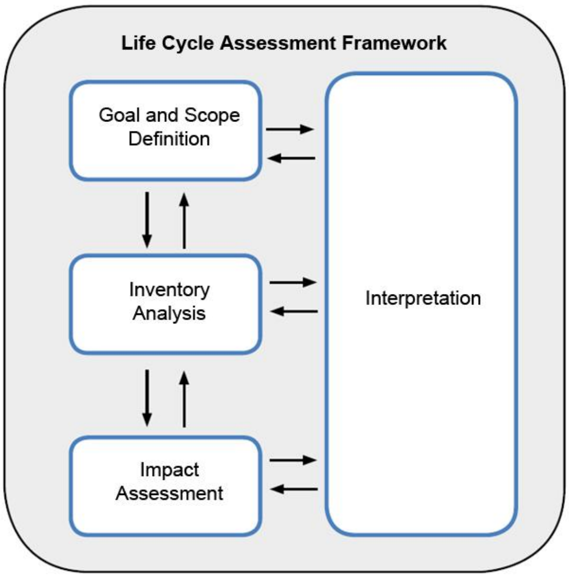

Figure 4. Phases of a life-cycle assessment (ISO 14040, 1997E)

Currently, there are various LCIA methods available to calculate under impact categories. According to EN 15804 and EN 15978, the chosen LCIA impact assessment indicators are:

- Global warming potential (GWP)
- Ozone depletion (ODP)
- Acidification for soil and water (AP)
- Eutrophication potential (EP)
- Photochemical ozone creation (POCP)
- Depletion of abiotic resources: elements (ADP-elements)
- Depletion of abiotic resources: fossils (ADP-fossils)

2.4.2. Life-Cycle of the Whole Building

According to further development in EN 15978 (BS, 2011), the method considers environmental impacts of a particular building component or system or the whole building, during its life-cycle. The expression 'life cycle of a building' refers to the following phases as displayed in Figure 5; manufacture of building materials, transport, construction of the building, occupancy/renovation, and finally demolition and removal.

Building Life Cycle Information													
Production Stage			Construction Process Stage		Use Stage					End-of-life Stage			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4
Raw material supply	Transport	Manufacturaing	Transport	Construction process installation	Use	Maintenance	Repair	Refurbishment	Replacement	Demolition	Transport	Waste processing	Disposal
					B6 Operational energy								
					B7 Operational water								

Figure 5. Four life cycle phases of buildings (EN 15978, BS 2011)

- **Production Phase (A1-A3):**

The life cycle inventory starts with accounting energy use and emissions to air, water and land per unit of extracted resource. In addition to the actual harvesting, mining or quarrying of a resource, the extraction phase includes the transportation of raw resources to the mill or plant gate, which defines the boundary between extraction and manufacturing.

Manufacturing accounts for the largest proportion of embodied energy and emissions associated with the life cycle of a building product. This stage starts with the delivery of raw resources and other materials at the mill or plant gate and ends with the delivery of building products to retailer.

- **Construction Phase (A4-A5):**

This stage starts with the transportation of individual products and subassemblies from distribution centers to building sites within each city. The average or typical transportation distances to building sites are used in the LCA process. Significant amount of waste is generated in this stage. In addition to above, the on-site construction activity stage includes such items as the transportation of equipment to and from the site, concrete form-work, and temporary heating and ventilation.

- **Operation / Use Phase (B1-B5)**

During the occupancy stage, functions like heating, cooling, lighting and water use, as well as the introduction of new products such as paints, stains, floor coverings and other interior finishes are taken into account. Renovations are also included in this stage, with changes to interior partitions and possibly the addition of new products or systems.

- **End-of-Life Phase (C1-C4)**

In this stage, demolition energy use for different structural systems is examined under different climatic conditions assuming 100% recycling and 100% reuse of the structural components. This is the final stage in the life cycle of the individual components or products comprising a building. It is an especially difficult area for building's LCA, since the reuse or recycling is an unknown for most components. Consequently, assumptions are made regarding the final fate of the materials.

In the literature, there is a well-established structure for the assessment of building components and buildings as a whole. It was also observed that the number of researches on LCA of single buildings is significantly more than those on urban areas (see Section 2.6). On the other hand, assessment frameworks for large-scale built environment are still in development. In the next section, these frameworks are investigated.

2.4.3. Life-Cycle of an Urban Area

In order to evaluate life cycle of a group of buildings, new concepts have been introduced into standard LCA assessments. One of the recently developed methodologies considered cities as urban metabolisms (UM), were used in a number of research studies (Kennedy *et al.*, 2007, Chester *et al.*, 2010, Goldstein *et al.*, 2013). It is an input-output material or energy assessment of cities. The focus is on energy, water, waste, etc. There are also, extended frameworks such as urban building energy models (UBEM) which follows the same principle (Doğan and Reinhart, 2017).

A significant addition of these methodologies is inclusion of the environmental impact of infrastructure necessary for buildings. The notion that implies high density urban areas are performing better than suburbs originates from optimum sharing of infrastructure. The impact of maintenance of infrastructure throughout the building life time should also be included for more precise results.

Another issue arising from assessment of large scale built environment is the location of new settlements. Besides the necessary infrastructure to be extended for settlements, the means of transportation gains a critical role. Unless there is a nearby public transportation line, it is almost impossible to maintain sustainability due to dependency on private transportation.

2.4.4. Life-Cycle Assessment Approaches

In the literature, LCA can be grouped in two conceptually different approaches; process-based LCA (SETAC-EPA approach) and economic input-output analysis based LCA (EIO-LCA) (Hendrickson *et al.*, 1998, 2006). As shown in Table 1, major difference between the two approaches is that while process-based LCA focuses on the individual phases that are used to make a product or generate a service, the latter uses a macro economic framework that includes all the monetary changes generated in a country's economy by the production of a product or by the offer of a service.

Table 1. Comparison of LCA approaches (Hendrickson *et al., 2006)*

	Process Based LCA	Economic Income-Outcome LCA
Pros	▪ Results are detailed, process specific ▪ Allows for specific product comparisons ▪ Identifies areas for process improvements, weak point analysis ▪ Provides for future product development assessments	▪ Results are economy-wide, comprehensive assessments ▪ Allows for systems-level comparisons ▪ Uses publicly available, reproducible results ▪ Provides for future product development assessments ▪ Provides information on every commodity in the economy
Cons	▪ Setting system boundary is subjective ▪ Tend to be time intensive and costly ▪ Difficult to apply to new process design ▪ Use proprietary data ▪ Cannot be replicated if confidential data are used	▪ Product assessments contain aggregate data ▪ Process assessments difficult ▪ Must link monetary values with physical units ▪ Imports treated as products created within economic boundaries ▪ Availability of data for complete environmental effects ▪ Difficult to apply to an open economy (with substantial non-comparable imports) ▪ Uncertainty in data

Process-based LCAs

Process LCA is the most traditional way of conducting a LCA. The method is based on local and current process data that is used to convert amounts of materials and energy into carbon emissions. In a process-based LCA, one documents the inputs (materials and energy resources) and the outputs (emissions and wastes to the environment) for a given step in producing a product (CMU, 2008). This process must be performed for all life cycle steps. The carbon emissions of each process in the product life cycle are analyzed separately according to the boundary definition of the modeling. Because of the difficulty in estimating resource consumption and environmental wastes produced by processes associated with the life cycle of a product, the scope of a process-based LCA analysis is limited with the boundary definition. The process LCA method is suitable in comparing similar products within one product category (Saynajoki *et al.*, 2012).

Input-Output LCAs

Input-output (IO) LCA uses economic input-output tables coupled with data on resources consumption, environmental emissions and wastes to calculate out the various economic transactions, resource requirements, and environmental emissions required for a particular product or service (CMU, 2008).

IO-LCA is based on converting monetary costs into carbon emissions based on matrices that use industry average data. Performing IO-LCAs is also time-effective and assessment models are often available free of charge. According to Hendrickson *et al.* (1998), advantages of IO-LCA originate from the comprehensive economy that is used which resolves analysts from drawing arbitrary boundaries. Analyses can be performed rapidly and inexpensively. This property is extremely important in design applications in which approximate but rapid results are needed. On the other hand, IO-LCA, is unreliable because of assumptions and the homogeneity and proportionality of sectors. Even though, the IO system boundary is practically complete, the results of IO analyses are only representative of the national average case (Treloar, 1997). Hence, IO-LCAs suffer from the aggregation error (due to dependency on average values) and lacks representativeness of the different processes. As a result, IO-LCA is not a suitable method for comparing different products within one industry (Saynajoki *et al.*, 2012).

Hybrid LCAs

Hybrid analysis is the combination of both techniques. It consists of using available process data and filling the systemic gaps with input–output data in order to assess the entirety of the supply chain of a product (Stephan *et al.*, 2012).

The two approaches above are integrated to provide a more accurate or cost-effective LCA or to provide alternative estimates for comparison purposes. In particular, the EIO-LCA can be applied for the materials extraction and manufacturing-stage assessments to advantageously use an economy-wide boundary; and to advantageously use its focus on specific processes, the SETAC-EPA LCA approach can be utilized in product-use and end of- life phase assessments (Hendrickson *et al.*, 1998). Treloar (1997) proposed a hybrid LCA method that integrates traditional process LCA and IO LCA data within the IO model. The proposed model enables reliable comparisons of construction products with less work and costs compared to the process LCA.

2.4.5. Data Quality in Life-Cycle Assessment

Data quality is one of the key aspects of an LCA which may facilitate or hinder the validity of the study. Several characteristics of data in LCA determine the quality of the assessment, including data types, uncertainty of data, variety, etc.

According to the acquisition method, LCA data can be grouped into two basic categories; (i) process data which is provided by the producer or directly derived from the production line, and (ii) generic data which includes input-output values that are based on national economic frameworks (Dahlstrom *et al.*, 2012). In literature, process data implies high quality data from the source whereas generic data is the average value of similar products which may represent the target. Uncertainty plays an important role for LCA studies, especially when it is used for decision-making. It is natural that LCA practitioners seek for quality and credibility in their works. Uncertainty may originate from several sources in an LCA (Lloyd and Ries, 2007) and it can be referred to as lack of knowledge: no data is available, or the data that are available are wrong or ambiguous. The available methods for tackling data gaps aim to either reduce the uncertainty level or explicitly incorporate it (Heijungs and Huijbregts, 2004).

While there are several issues which may hinder the credibility of an LCA study, most of the studies refrain from declaring data quality properly. In their study, Junnila *et al*. (2006) declared that out of 30 components assessed only four in the European Union and seven in the U.S. case study were considered to have average or lower-than-average data quality. This lowers the possibility of comparing or adopting the outputs. As Heijungs and Huijbregts (2004) put forward the interest in data quality has not been common practice since the development of LCA and the rise of its use. Even though the quality of LCA results should be considered at an early stage of LCA development, assessment of this quality is still not a standard step and a holistic method has not been introduced within the LCA literature.

One of the most common methods on determining /displaying data quality of LCA data has been proposed by Weidema and Wesnaes (1996). As given in Figure 6, the pedigree matrix based method displays a set of pre-determined characteristics of data that are evaluated in a semi-quantitative 1-5 scale. The characteristics are categorized as 'data quality indicators' according to acquisition, independence, representativeness and temporal, geographical and technological correlation. Indicator scores of 1-5, where 1 implies the best and 5 implies the worst condition, are assigned to a pre-determined qualitative description.

Indicator Category	Indicator Score				
	1	2	3	4	5
Acquisition Method	Measured Data	Calculated data based on measurement	Calculated data partly based on assumptions	Qualified estimate (by industrial expert)	Non-qualified estimate
Independence of data supplier (Reliability)	Verified data from public or other independent source	Verified information from enterprise interested in the study	Inpedendent source, but based on non verified information from industry	Non-verified information from the industry	Non-verified information from enterprise interested int he study
Representitiveness of the study (Completeness)	Representitive data from sufficient sample of sites over an adequate period to even out normal flactuations	Representitive data from a smaller number of sites but for adequate periods	Representitive data from adequate number of sites, but for shorter periods	Representitive data from a smaller number of sites but for shorter periods	Representitiveness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal Correlation (Data Age)	Less than 3 years of different to year of study	Less than 6 years difference	Less than 10 years difference	Less than 15 years difference	Age of data unknown or more than 15 years difference
Geographical Correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Technological Correlation	Data from enterprises, process and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

Figure 6. Pedigree matrix (Weidema and Wesnaes, 1996)

The pedigree matrix has been utilized in previous LCA research (Weidema and Wesnaes, 1996; Junnila and Horvath, 2003, Heijungs and Huijbregts, 2004; Ciroth, 2009; Koffler et al., 2016). In these studies, pedigree matrix is used for determining the level of uncertainty. Depending on this level of uncertainty, a coefficient of variation (CV) is generated which implies the amount of variation as percentage. For ensuring the credibility, LCA data are modified by multiplying the results with an overall CV (combination of CVs from all quality indicators). In this sense, it is useful for reviewing data quality, pinpointing areas to improve data collection method but it does not have an effect on the selection of impact assessment method. In study of Kayaçetin and Tanyer (2018), pedigree matrix is utilized as a part of determining impact assessment method depending on the quality of data available.

2.4.6. Life-Cycle Assessment in Design Process Phases

In the literature, building LCA studies are mainly conducted at late stages of the design process, as LCAs are considered as complete representation or analysis of a construction product. On the other hand, there is also a wide-spread acknowledgement on the fact that decisions at early stages are more effective and easier to implement. Designers need feedback at early stages in order to create environmentally friendly buildings and settlements, as shown in Figure 7. In this context, it is necessary to investigate the LCA process with respect to phases of a design process.

In the construction industry, the design process is described by the phases of pre-design, conceptual design, design development, and final design. The building life cycle process can be considered in two phases of construction and building operation. It is crucial to identify the right type and level of information that is needed within each phase to create the most value out of a LCA study.

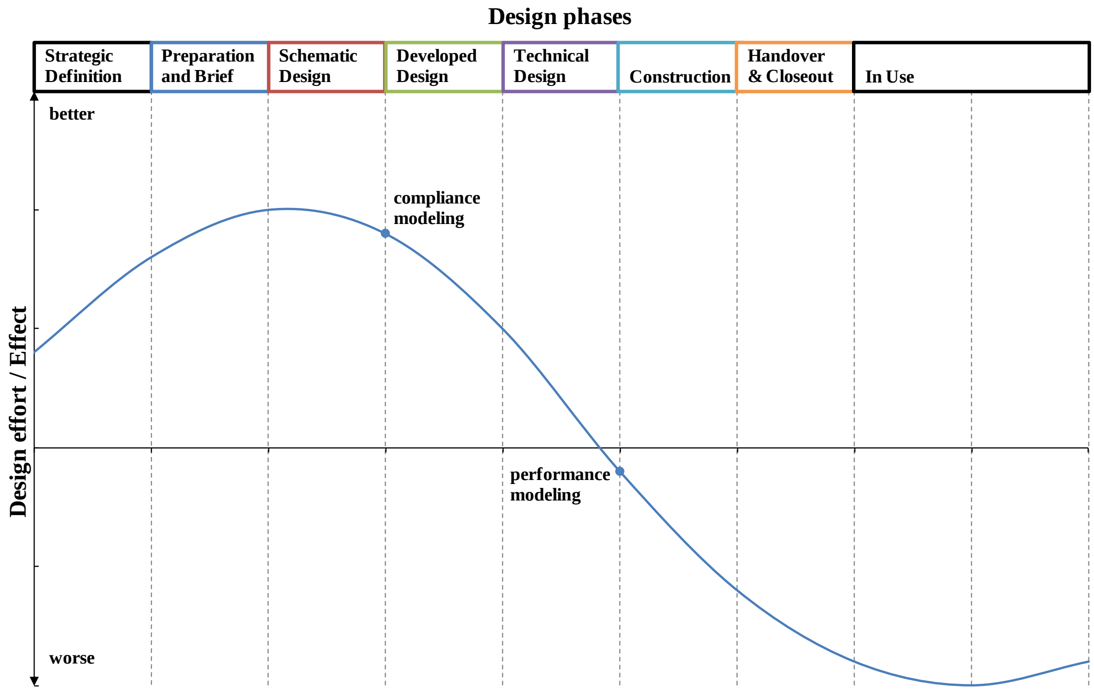

Figure 7. Design stages and effort / effect curve (adopted from RIBA, 2013)

For an effective management of the design process in a project workflow, the industry has adopted a formal language of describing the completeness of a project model at a given point in time. The Level of Development (LOD) Specification is a reference that enables practitioners in the AEC Industry to specify and articulate with a high level of clarity the content and reliability of project data (i.e. Building Information Models (BIMs)) at various stages in the design and construction process. In this respect, specific development or detail levels are assigned to each design phase with due contents and characteristics, which can be seen in Figure 8.

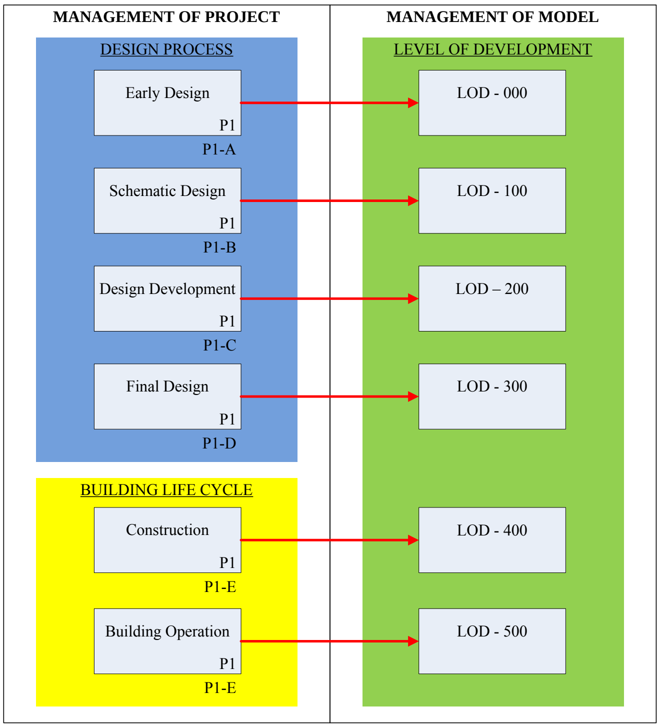

Figure 8. Building design phases and information level

For each design phase, AIA sets descriptions consisting of two perspectives; outcomes and primary responsibilities. Outcomes are where necessary data and information can be identified for each phase. By utilizing these descriptions, it is possible to group the inputs and outputs and draw the limitation any LCA study accordingly. By doing so, the relationship between Level of Development and project phases can be developed. However, it should be emphasized this relationship is not empirical.

By combining, LOD framework and project phases defined by AIA (2007), necessary project inputs and outputs can be determined for each project phases, which can be seen above in Figure 9. This can be utilized in a LCA study to focus the life cycle inventory to a specific project phase.

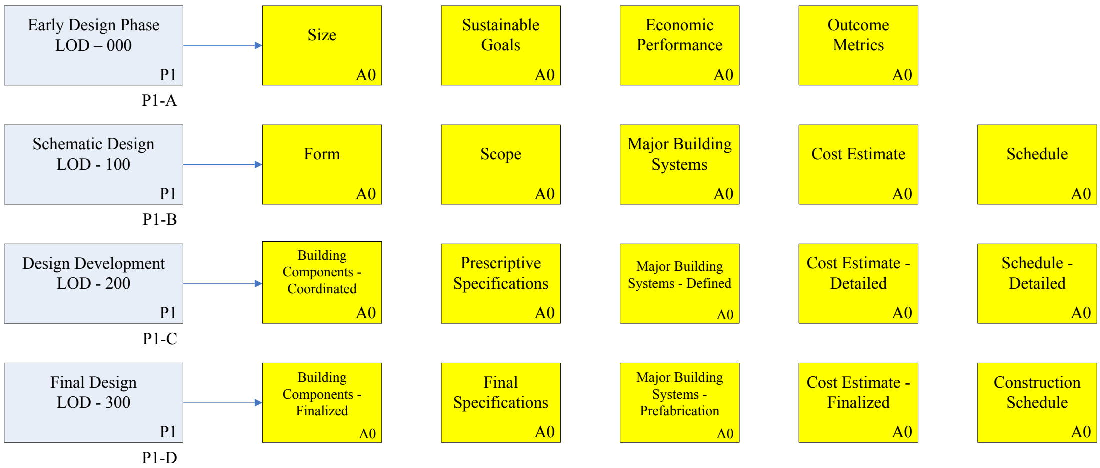

Figure 9. Building design phases and outcomes (AIA, 2007)

2.5. Life-Cycle Assessment Software

In this section, LCA software that is available for building life cycle assessment was investigated. Software programs were examined under certain categories according to the purpose of use, calculation methods, and data base preferences and were compared according to strong and weak points (Lee *et al*., 2009).

First, general overview of software is introduced. In Table 2, programs are listed based on the intended usage. The aim of this examination is to define the LCA software that suits the regional requirements in Turkey and fits for the purpose of this specific study. The selected software was introduced with detailed information with the reasons why it was preferred.

2.5.1. Overview

In developing of the research areas considering building environmental assessment tools and sustainability in building construction, several national and international projects have been initiated. Among several issues, the lack of common ground of these sustainability and LCA projects is considered as the greatest handicap for academicians and practitioners. Moreover, building environmental assessment tools have rather been analyzed individually than as groups. Neither shared aspects and common features, nor differences have been emphasized in the studies. Disadvantages or limitations have not been pointed out explicitly.

Whatever differences they display, as they may, all LCA programs should at least meet some basic requirements. These basic requirements can be listed as:

- Inclusion of all life cycle phases of a building or built-environment,
- Capability of displaying the outputs of LCA in various formats, depending on what is being analyzed (energy consumption, or emissions, *etc.*),
- Adaptability in defining the goal and scope of the assessment.

The scope to be included in the life cycle process of a building should be limited to the construction material resources required for the building, construction activities for modification & repair, lighting and energy requirements, and demolition & dismantling requirements. An LCA program must include a building's life cycle, and be devised to permit input and output of LCI database for the respective stages of this life cycle. Furthermore, it is necessary to allow comparison between alternatives, and to show the results of analyses in a quantitative format. For this purpose, it should be able to present the results of analyses not only as aggregate quantities, but also as a function of base unit dimensions of floor area.

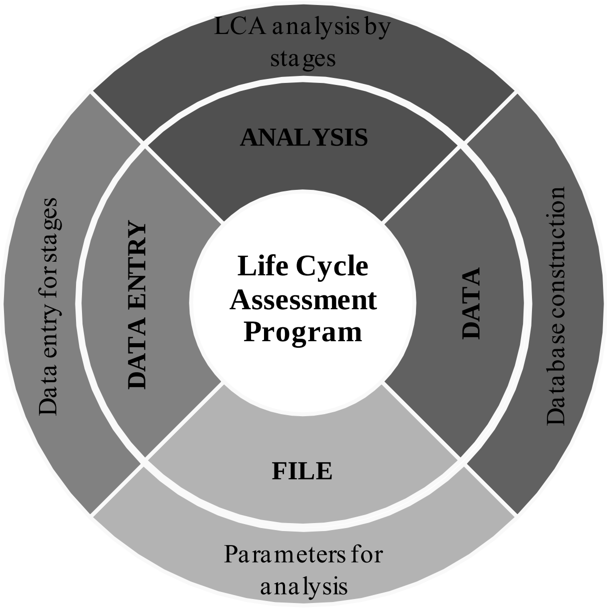

Figure 10. Composition of a LCA software (adopted from Lee *et al.*, 2009)

LCA programs that are used on buildings and built environments can be divided into three main categories. First, a program should be capable of performing Life Cycle Assessment (LCA). Second, it should facilitate analysis and assessment of energy consumption, where such programs are utilized during planning and design stage of a building for simulations to assess energy consumption. Third is an assessment scheme for reducing environmental emissions, and a program used as a decision making tool during design stages, as can be seen in Table 2.

Table 2. LCA programs according to intended usage

LCA Software	Energy Use Assessment Tools	Design & Decision Making
BEES (US)	Athena (CAN)	BREEAM (UK)
Boustead (UK)	BREGains (UK)	Building Design Advisor
Eco Quantum (NL)	BUNYIP (AUS)	ECOTECT (AUS)
Gabi (DE)	CanQuest (CAN)	Equer (FR)
KCL-ECO (FIN)	Cheetah (AUS)	Green Building Advisor
LCAid (AUS)	DOE2 (US)	LEED (US)
LCAit (SW)	Energy Plus (US)	
LISA (AUS)	Envest (ULC)	
PEMS (UK/US)	eQuest (US)	
SIB LCA (DE)	Firstrate (AUS)	
SimaPro (NL)	NatHers (AUS)	
TEAM (FR/US)	Optimize (CAN)	

They can also be categorized according to the methods used to build LCI database for construction materials. As introduced previously, process-based methods construct a database by directly observing entire process for building materials. Input-output based methods build databases by analyzing related industries and present data. Hybrid methods utilize above data construction techniques.

Table 3. Calculation methods for database construction

LCA Software	Input / Output	Others
Boustead (UK)	EIOLCA (US)	Adv. Building Technologies
Eco Quantum (NL)	NIRM (JP)	Harris Directory (US)
SIB LCA (DE)		Oikos
SimaPro (NL)		Energy Audit (AUS)

Besides the systematic characteristics, there are also different features of programs according to the software programming. These various LCA programs show differences in terms of their development entity, and their ease of program operation. Comparison of the programs for their purpose and speed, data handling capacity, handling of uncertain variables, sensitivity analysis, and ease of operation are shown Table 4.

Table 4. Comparison for LCA programs (adopted from Lee *et al.*, 2009)

Software	Intended Purpose	Speed	Computational Capacity	Uncertainty Handling	Sensitivity Analysis	Ease of Handling
SimaPro	Inventory / Impact Analysis	-	Average	None	None	Average
KCL-Eco	Inventory Analysis	-	-	Average	-	Average
EcoPro	Inventory / Impact Analysis	-	Bad	-	-	Average
GaBi	All purpose	Average	-	-	-	Average
TEAM	All purpose	Superior	Superior	-	-	Bad
TEMIS	Energy Analysis	-	-	-	-	-
EcoPack K2000	Packaging Analysis	-	-	-	-	-
LCAiT	All purpose	Average	-	-	-	Average

2.5.2. GaBi Life Cycle Assessment Software

GaBi a software for Life Cycle Assessment (LCA), Life Cycle Engineering (LCE), Green House Gas Accounting, Benchmarking and Energy Efficiency of products, and is widely used for LCA studies and decision support in industry but also used in LCA research institutes.

GaBi allows creating models based on physical process chains. Next to the basic functions of LCI modeling, data analysis, impact calculation, it has fully integrated parameter functionality to create flexible systems including circularity effects. It also eases the process of selecting the best dataset for the kind of data documentation required, and utilizes its embedded database documentation to aid the user in the design process. With GaBi's process recording feature, data can be collected from any point of the design process and determine precisely where efficiencies occur. GaBi presents its database documentation in accordance with International Life Cycle Database formatting.

Calculation Methods:

Implemented methods are as follows; CML 96, CML 2002, Ecoindicator 95, Ecoindicator 99, Ecological scarcity, EDIP 97, EDIP 2003, Impact 2002+, Traci. The user can however define own methods; this possibility is made available in line with the flexibility principle of GaBi.

For interpretation, GaBi balance is the starting point for the extensive analysis and interpretation capabilities. GaBi balance view allows switching between percent shares or absolute numbers, weak points in the modeled system are determined with colors, tracing them back top-down. Normalizations and valuations are easily applicable; own weighing patterns can be added by the users. Users benefit from evident and meaningful results for decisions on materials, processes, and usage or disposal scenarios. For a detailed analysis the GaBi analyst offers scenario analysis, parameter variation, sensitivity analysis and a fully user controlled, very performance Monte Carlo analysis.

Database preferences:

GaBi comes along with one of the globally most comprehensive, consistent and especially high quality database system of the GaBi databases, also including the data from the European Commission's ELCD database. Data updates are done remotely; for in-house data exchange, professional database management features are made available. In addition to the provision of LCI related information the GaBi professional database will provide information on social aspects as well.

GaBi's central database manager supports users in keeping a good overview over his database; it provides a structure for the database content while drag and drop and export/import functions help in maintaining even large databases well structured. (Wolf *et al.,* 2002) The GaBi proprietary database has 4.500 datasets, and the software also works with Ecoinvent.

The "GaBi web questionnaire" allows easily to organize web-based data collection e.g. within industrial associations or for global players: Parameterized systems are set-up in GaBi and a special functionality allows to automatically create web based questionnaires for easy and effective data collection. The received data can be imported into GaBi, what is supported by consistency checks, etc.

Strong and Weak Points:

With the extension functions "GaBi i-report" and "GaBi reader", interactive reports can be generated using all objects defined in GaBi to created powerful Ecodesign models to be used for e.g. Eco-Design or EPD purposes. With this functionality LCA experts can generate complex parameterized systems, which are then transferred into ready to use applications to support product development or communication or other applications.

GaBi life cycle assessment software's tools, including iReport, often need to be downloaded and updated independently of the main program. The software has a steep learning curve, appearing to still be on their original codebase, which is more than a decade old. Much of the background documentation for the included datasets is empty and lacks transparency, requiring reliance on their support staff.

2.5.3. Conclusion

GaBi is a complicated LCA tool that enable users to define life cycle processes of any material or product. It also has the capacity to deal with complex building models. The software is of appropriate choice, if the processes are to be studied in detail. However, it is time consuming to learn to build models in GaBi. In case of a more general analysis, software such as BEES and Athena IE can be utilized, which would significantly save time in the modeling stage.

For a specific study in Turkey, most important aspect that significantly affects the result of the analysis is the characteristic of database. Even though, most databases are collateral to each other due to the global trade system and such, European reference Life Cycle Database (ELCD) is considered as the most appropriate database for this study. It is pointed out in many studies that, most of the variations on the results originate from errors in creating system boundaries and uncertainties in the data. While, lowering the uncertainty with applying process-based analysis, the author is not to raise it with a wrong choice of database.

It is observed that GaBi is a software of high quality and methodology. It is capable of covering all purposes that a LCA program may provide and the database construction is slightly larger than other LCA tools.

2.6. Related Studies

In literature, there are some distinct approaches to research studies regarding the LCA methodology. A group of studies put emphasis on a few components of buildings with a detailed life-cycle analysis, whereas other studies attempt to perform a whole building LCA with limited impact categories.

At another perspective, the scale of research studies differs from building specific to urban scale. As the scale of the study expands, consequently the assumptions and uncertainty of the results tend to increase, though they present a greater picture on the environmental evaluation. Under respective sub-headings, these studies are presented in brief.

2.6.1. LCA Studies on Building Components

Some studies have investigated on limited number of lifecycle phases or building components in their calculations. Klunder (2001) suggests that building assessments should focus on components that stand for large quantities of material, such as foundation, floors and walls.

Salazar and Meil (2009) examined the influence of wood use on the carbon footprint of a typical single family house. They compared two alternatives of wooden houses of different wood intensities. Results show that wood-intensive house yields one-third of a typical house, showing great reduction at the manufacturing phase emissions.

Kellenberger and Althaus (2009) attempted to determine the relevance of materials and processes often neglected in simplified LCA of building components that aim to provide results of similar quality as comprehensive assessments with less effort. There is also an effort for identifying the most significant components regarding environmental impact by analyzing different combination of components on different levels of simplification. They compared results between a fully detailed LCA study and a LCA study simplified to only main materials such as wall component.

Kim (2009) evaluated a transparent composite façade system (TCFS) that is developed at the University of Michigan from structural and life-cycle perspectives. The environmental performance of this façade system was compared to a glass curtain wall system (GCWS) and it was found that total life cycle energy was 93% of GCWS and CO_2 emission was 89% of GCWS. The methodology was defined as a comparative life-cycle assessment process. A similar study can be seen from Glick (2007) who examined two types of residential heating systems on a 280 m^2 well-insulated house, for his doctoral thesis work. He conducted comparative LCA studies. According to the results of an analysis of the life-cycle cost and life-cycle assessment data initially indicated, the gas forced air system was the better choice both environmentally and economically.

Grant (2010) examined the material longevity in the building envelope by conducting LCA. In this doctoral thesis study, a total of thirty-six roof and wall combinations were analyzed by using five different alternative service life models. Results were presented in three environmental impact categories (global warming potential, atmospheric eco toxicity and atmospheric acidification).

2.6.2. LCA Studies on Single Buildings

Other studies have undertaken the analysis of buildings as a whole. There is an extensive research on analyzing single buildings by applying LCA methodologies. The key points of these studies are the consideration of embodied building energy, manufacturing and demolition phases and ratio between the effect of embodied and operational energy consumption. Comparisons are often made with popular building certification systems. In general, the impact of the construction phase is often considered minor (Scheuer *et al.*, 2003, Junnila and Horvath, 2003). However, some recent studies show that the production phase of an energy efficient passive house may account for more 50% of the building's total life cycle primary energy use (Saynajoki *et al.*, 2012). This is due to the improved building energy efficiency, increasing the relative importance of the construction phase. Criticisms on the exclusion of one or more life cycle phases can be seen and comprehensive LCA studies which include all phases are highlighted. Some of the studies are briefly given below:

Junnila *et al.* (2006) conducted two detailed LCA studies by quantifying the significant environmental aspects of a new high-end office building in Europe and United States over 50 years of service life. A comprehensive environmental life-cycle assessment, including data quality assessment, was conducted to provide detailed information for establishing the connection between the different life-cycle elements and potential environmental impacts. The results show that most of the impacts are associated with electricity use and building materials manufacturing.

Scheuer *et al.* (2003) conducted a LCA on a six story building of 7.500 m^2 in University of Michigan campus for a projected 75-year life span. The significant feature of this study was presented as the comprehensiveness of the methodology compare to previous work. Also, it was aimed to examine differences that might arise between results from a complete inventory LCA of a building, and the results from partial LCAs. It was concluded that the optimization of operations phase performance should still be the primary emphasis for design (83% of overall phases), until it is evident that there is a significant shift in distribution of life cycle burdens. It was also added that, detailed life cycle models are necessary for representing unique feature and requirements, which is in this case, the inclusion of potable water consumption.

Pushkar *et al.* (2004) used LCA methodology to group design variables into four clusters then show each variable's environmental impact bounds for each phase in a building's life cycle. It was aimed that each of the studied variables would be optimized with respect to the relevant life cycle stage where it has largest environmental impacts. When compared to typical categorization of building components such as energy usage-related and manufacture-related, this would enable an overall optimization.

In a master thesis study prepared by Dahlstrom (2011), two complete cradle-to-grave life cycle assessments were conducted for the comparison of a house built after building standard, TEK07, and a passive house built after the Norwegian Standard NS 3700:2010. Both houses are constructed with a wooden framework, where passive house has a different foundation and better insulation. For the LCA, generic data from Ecoinvent 2.0 database was used with some modifications to better suit Norwegian production information. For 50 years of life cycle, passive house has about 10-20% lower impact values. The ratio of operational phase is 76% for TEK07, and 67% for the passive house.

Medineckiene *et al.* (2011) performed a multi-criteria decision making method by using LCA and analyzed two types of apartment buildings by comparing different heating scenarios. This study highlights that a simplified LCA methodology can easily be used instead of detailed LCAs for comparing different design scenarios as problems such as lack of information, uncertainty in data and problems originating from bias can be dealt within a good description of system boundaries and limitations.

On the other hand, Stephan *et al.* (2012) presented a comprehensive life-cycle energy analysis framework for residential buildings. Comparing two case studies in Brussels and Melbourne, they confirmed that embodied, operational and transport requirements are of equal importance. This result is significantly important as previous research studies have heavily been focused on operational energy. It is also in accordance with findings of Blengini and di Carlo (2010) who confirmed that improvements made on low energy buildings may change the relative importance of LCA stages.

Moreover, same authors at another study (Stephan *et al.*, 2013a) investigated this issue by performing the same methodology on passive houses in which impact of operational energy are aimed to be minimized. Consequently, the previous result of their study becomes more significant as the ratio of operational energy to overall energy demand decreases. The authors put forward that the operational energy of passive houses can represents less than 40% of the total energy consumption of the house. They argued that certifications such as the passive house standard can lead to an increased overall energy demand by only addressing operational stage of the life cycle of a building. They conclude that a passive house building can result in the same life cycle energy demand as a new standard house when whole life cycles phases are taken into account. In line with this study, Ibn-Mohammed *et al.* (2013) also evaluated the impact of embodied carbon against the operational carbon emissions in buildings. The authors examined existing studies in the literature for the understanding of the trends and their reasons in different countries and regions. It was concluded that embodied carbon is responsible for an increasing ratio of life cycle emissions associated to new buildings and is subject to rise due to the improvement of building regulations for better operational performance.

It is interesting to see how consideration of life phases has shifted within 10 years from Scheuer *et al.* (2003) to Stephan *et al.* (2013a) and other authors. Optimizing the performance of buildings has been a focal point of sustainable architecture for almost two decades. While boosting insulation and performance, operational energy output has indeed decreased, but on the other hand, embodied energy has increased within or without our awareness. Thus, it is very important to see whether total energy for the life time of a building is higher or lower than the standard applications.

De Wolf *et al.* (2016) analyzed data from over 200 buildings to evaluate the embodied carbon through the development of a database of building structures. The results were given, for example, according to building typologies, size, *etc.* which includes offices, commercial, residential and other building types. It was found out that the GWP potential of buildings ranged between 150-600 $kg_{CO_2\text{-}eq}/m^2$.

Pomponi and Moncaster (2016) applied a systematic critical review on academic knowledge regarding the existing approaches to reduce embodied carbon. 17 mitigation strategies were identified and concluded that these strategies were not able to tackle the problem alone. Also, an analysis on 77 studies displayed that most of the studies include construction phase and exclude the following life cycle phases such as operational, end-of-life and recycle/reuse. Same authors (Pomponi and Moncaster, 2018) applied a similar methodology and compared the methodologies and the results of several LCA studies on embodied carbon for each life cycle phase in a statistical manner. It was found out that LCA results on main structural building materials display a variation between 280 - 1000%. This condition was considered as a second-wave 'performance-gap' in building assessment. The authors emphasized that more objective and transparent impact assessment methodologies should be adopted by LCA practitioners.

2.6.3. LCA Studies at Urban Scale

From a larger point of view, the assessment of environmental impacts of single units, such as buildings, within the built environment is not sufficient and is indeed incomplete. There is a solid literature on how to apply LCA on a complex product as a building. Alas, the complexity tends to increase as the scale of the study includes an urban area. The effect of necessary infrastructure for facilitating a building and occupant transportation are two of the highlighted aspects of investigating the urban scale with LCA methodology.

Junnila and Heinonen (2011) investigated the influence of metropolitan areas on carbon consumption by analyzing two metropolitan areas in Finland. They questioned the general belief which implies high density metropolitan areas produce less carbon emission per capita than same area of less density. The methodology is an input–output-based application of a tiered hybrid LCA that combines the comprehensiveness of the input–output approach with the accuracy of the process LCA approach. According to their results, there is no clear correlation between urban density and the carbon consumption. The factors such as; (i) the growth of living space and high frequency of private transportation in low density metropolitan areas, and (ii) economical sharing of infrastructure in high density areas are overruled by following conditions. First, after the inclusion of communal building energy to the energy consumption per capita, the differences in the energy consumption and emissions between two different metropolitan areas decrease radically. Second but more interestingly, there is a high correlation between income per capita and carbon consumption. As the income increases, the effect of occupant behaviour on carbon emission becomes more significant. In this respect, occupant behaviour is also an influential factor in LCA as mentioned by other authors such as Verbeeck and Hens (2010) and Aste *et al.* (2010).

The findings of the above study were also supported by the study of Du *et al.* (2015). The authors provided a comparison of life-cycle energy consumption of a high-rise downtown area and a low-rise suburban area. It was estimated that life-cycle energy per capita in downtown area was 25% more than suburban area. The study also combined LCA of buildings and transportation. In total life-cycle energy, building operational energy was the largest contributor, followed by vehicle operational energy. Embodied energy was observed to be even less effective in high-rise buildings since the long lifespan increases the operational energy.

In the study of Saynajoki *et al.* (2012) buildings with different energy efficiency levels (low energy building, passive house) were compared with a similar hypothetical area of buildings of the average existing building stock and with a renovation of an area with average buildings from the 1960s. The study questioned whether the climate change mitigation goals can be achieved by the means of construction new energy efficient buildings. The authors discussed this question from the temporal perspective of their approach on the allocation of the emissions while analyzing the life-cycle of the building. The most interesting finding of the study was that the construction phase emissions seem to dominate the life cycle emissions beyond the currently set mitigation goals. They concluded that, renovating current building stock should be preferred if short-termed mitigation goals are to be reached. Their results are in line with the article of Sartori and Hestnes (2007).

While previous study by Saynajoki *et al.* (2012) considered low energy and passive house buildings, Stephan *et al.* (2013b) aimed to provide a detailed life cycle energy assessment of a new suburban neighbourhood that complies with standard building code and energy efficiency regulations. The authors reasoned that at urban scale, most development does not comply with new emerging green building standards. The methodology utilized a representative low-density neighbourhood in Melbourne, Australia, assessed its energy consumption and greenhouse gas emissions over 100 years and examined different scenarios related to house size, transport technology, housing typology and the temporal evolution of parameters. One of the analyzed scenarios revealed that replacing half of the built area of the suburb with apartment buildings reduces the total energy consumption per capita by 19,6%, compared to a typical single storey detached house layout.

As mention prior, Ceron-Palma *et al.* (2013) investigated sustainable strategies for social neighbourhoods in Mexico. These strategies include utilization of eco-technology (efficient air conditioning equipment) and green spaces (sedum and food production). The study used a previous work as a reference data for energy habits and consumption. It was found that due to poor construction quality and climatic conditions, the air conditioning was responsible for 48% of the energy consumption and associated GHG emissions. For eco-technology strategy, the results projected a 31% reduction in the total annual of energy consumption and GHG emissions in housing with air conditioning. By utilizing green spaces (green roof and plot) for production of food and increasing the roof insulation, decreasing the heat island effect, a reduction of 20-30% of carbon emission is achieved. This study supported the importance of integrating environmental quantitative tools in planning cities.

2.6.4. LCA as a Decision-Making Tool

LCA is commonly used in such industries as automotive design, equipment manufacturing, and consumer product design. Adoption of LCA methods in AEC projects has been limited due to features such as uniqueness of buildings, their very long lifespan, multi-functionality and being locally assembled. In addition, LCA methods typically require significant time and effort for implementation. The difficulties in applying LCA to the AEC industry have been noted by others, including obtaining complete environmental impact data for building components, tracking material flows, and clearly defining system boundaries. In addition, building information modeling (BIM), which is increasingly used by AEC designers to digitally represent a facility during the early design stages, currently lacks interoperability with LCA software. Another challenge of performing LCA during the early stages of a building project is the complexity and large number of decisions that a designer faces. Balancing between completeness and simplicity of use is one of the challenges in developing an effective and efficient environmental building assessment tools.

Moreover, numerous researchers have shown that the earlier decisions are made in the design process and the fewer the changes to these decisions at later stages, the greater is the potential for reducing the building's environmental impact. Some research examples are as follows:

Nicholson (2009) examined analytical variations in valuation method and treatment of recycling by exploring allocation methods that affect product end-of-life. The author sought for the answer for whether the end-of-life allocation methods can lead to different materials selection decisions in early stage product development cycles. Results indicated that the choice of analytical method as well as its underlying parameters can have substantial impact on individual metrics that determine environmentally preferred material.

Mereb (2008) presented a tool titled 'GREENOMETER-7' to measure and subsequently improve the sustainability performance of a building over its entire life-cycle while still at the conceptual design stage. It is a LCA tool and it evaluates the projected building at two levels: micro- and macro-assessment. These micro and macro LCA assessments are structured into sub-categories which are derived from the LEED scoring system. Macro-assessment implied for 'sustainable sites' category and micro-assessment implied for the rest of the categories of LEED. By doing so, the tool is incorporated with rating systems as well. A proposed one-story residential building in Columbus, Ohio was selected for this case study. The developed tool is championed for its implementation at conceptual design stage, its incorporation with LEED and capable of offering alternative design selections. Although, the LCA is limited to building site only, gate-to-gate, not a cradle-to-grave perspective, for the sake of time and effort saving.

In their study, Tsai *et al.* (2011) aimed to adopt life cycle assessment (LCA) in order to assess CO_2 emission costs at bidding stage and apply a mathematical programming approach to allocate limited resources to maximize profits for construction companies. Decreasing the cost of CO_2 emissions consequently meant less CO_2 emission. In this respect, building project cost is structured as direct costs such as material, labor, machinery, and indirect cost as CO_2 emission. Depending on assumptions such as deriving accurate energy information from producers, LCA methodology is utilized to calculate the amount of emission. The findings imply that the CO_2 emission costs are the key factor for construction companies in selecting building projects.

Basbagill *et al.* (2013) introduced a method for applying LCA to early stage decision-making in order to inform designers of the relative environmental impact importance of building component material and dimensioning choices. The methodology utilizes UniFormat 2010 classification (Substructure, Shell, Interiors, and Services) for structuring building components. By allowing users to alter two parameters, thickness and material, the proposed tool provide designers with an impact allocation scheme, which shows the minimum and maximum embodied impacts possible for each of the building components across different design considerations. The results are given as CO_2 equivalents using 100-year global warming potential and displayed in histogram format. A second goal of the methodology is claimed to create an automated or semi-automated process that provides environmental impact feedback on many building designs. The author further explains the application with a case study on a mid-rise residential development.

Peuportier *et al.* (2013) also put emphasis on the fact that decisions having the largest influence on building performance are made in early design. The authors claimed an eco-design tool should therefore be usable in this phase and also have a user-friendly interface which is essential to professional use. The contradiction between usage in early design and data requirements of a detailed LCA was another concern for the authors. It was claimed that generic data and default values from databases can be used for typical impacts of materials, end of life processes, and impact of transportation. A case study was performed on two attached houses which are also the first Passive Houses in France. Ventilation, occupancy and internal heat gains are modeled by scenarios, considering two types of occupants' behaviour, such as economical, and spendthrift. It was concluded that detailed LCA could be used in early phases of a project. LCA provides a useful contribution by quantifying environmental impacts using present knowledge. Moreover, an extension of the eco-design tool for studying urban blocks, open spaces and networks was under development. Comparison of alternatives, regarding morphologies or technical choices, can help decision makers to reduce environmental impacts of building and urban projects.

2.6.5. Sensitivity Tests

Sensitivity analysis is typically used to check either the significance of changing key parameters contributing to the overall LCA or key assumptions governing the methodology of the LCA itself. Although sensitivity analysis is a recommended part of an LCA study, it is still not a standard practice.

The sensitivity has been assessed in some building LCA studies. For example, Adalberth *et al.* (2001) have assessed the effects of three alternative scenarios for a multi-family building in Sweden. The study found that the energy mix used could have a considerable influence on the result (25-45%), but only a minor influence by the material data and the amount of operational energy of around 15%. In another study, Peuportier (2001) performed a sensitivity analysis for a single-family house in France. The author tested four alternative scenarios and found that the type of heating energy used has a major influence on the result (around 40%); alternative building materials used having a minor influence on the results (18%).

2.7. Discussion

Assessment of the environmental impact of large-scale built environment is one of the key research areas, from which, strategies for optimizing resource management can be developed. As seen in the literature, there are several aspects to take into consideration which are highly complex and unique, such as; buildings, urban context and transportation. These aspects should be analyzed and integrated properly while considering a number of critical points, given below.

Currently, there is no mandatory legislation intact in Turkey which regulates the environmental impact of mass-housing projects. Planners refer to ÇED reports which includes assessment of natural resources (water, land) and waste amount, in certain cases if it is considered as necessary by local authority (MoEU, 2013). However, it is only mandatory for residential buildings when a mass-housing project has more than 2.000 dwellings and it is not needed for projects with less than 200 dwellings. Between 2.000 and 200 dwellings, mass-housing projects are processed with ÇED only when it is considered necessary by local authority. In practice, very few projects have conducted ÇED process. Moreover, ÇED reports do not cover embodied and operational carbon emissions of a mass-housing projects. On the other hand, carbon emissions are being used as the most common and mandatory indicator for sustainability concepts in EU (such as nearly-zero carbon buildings) and other countries (BPIE, 2015).

Furthermore, when the procedure for ÇED reports is investigated (MoEU, 2014), even if it is suggested by regulation that ÇED procedure should start in the early phases, it is seen that planners are not an integrated in the process. ÇED procedure is initiated after the planning is completed and tender process is conducted with a result of a winner contractor. Hence, it is complicated and impractical to apply revisions when the tender process is over, which may as well be demanded according to conclusion of ÇED reports.

It was seen that there is a need for decision-making regarding assessment of carbon during planning of large-scale mass housing projects and urban areas. Regional and country priorities, temporal perspective of environmental impacts and uncertainty originating from immature or even non-existing databases are points of interest in such an assessment, which is the focus of this study. Inclusion of impacts of manufacturing phase in environmental assessment is one of the significant improvements for refining the results. These issues should be addressed and dealt accordingly in this study.

In this context, LCA is a method of great potential for realizing a framework for achieving sustainable urban development. The methodology is capable of responding to priorities. It also enables researchers to assess impacts in any specific duration. LCA takes into account all life cycle phases, both manufacturing and operational processes. Embodied impacts originating from manufacturing phase are the focus of several research studies (Scheuer *et al.*,2003, Stephan *et al.*, 2012, 2013a, 2013b, Ibn-Mohammed *et al.*, 2013) in the literature.

While, LCA is a comprehensive methodology, it is also possible to apply it for assessing environmental impact of large-scale developments. On the other hand, it is necessary to be aware of the fact that the complexity further increases and methodological errors have significant effects on the results. Lack of data, complexity and heavy labor demand of LCA methodologies prevent the wide-spread usage in the AEC industry, especially when the results should be at hand in short terms. Heavy labor demand of LCAs can be lessened by using simplified and hybrid LCA methods. Lack of data can be dealt with better data validation systems.

In the end of the literature review, this study was refined in such a way to tackle these issues by introducing a simplified LCA framework for early design phase which provides a focus on significant components of a neighbourhood scale urban development that is complemented by a data validation system and a user-friendly decision support tool.

Below, discussion points in the literature are given in detail under three categories:

- **Environmental assessment of large-scale urban development**

There is a lack of LCA studies at urban scale. It must be added that conducting LCA on single buildings may not provide sufficient feedback for taking actions at strategic levels. The knowledge that has been gained at LCA studies on single buildings should be utilized in an extended scope at large-scale studies for more precise and realistic results.

Another issue about LCAs is the cumulative environmental impact. When impacts are taken into consideration from temporal perspective, first five years of any LCA studies is significantly more important than the rest of the life cycle. This is a vital decision from author perspective. It means that the sudden impact of any new construction process should have an increased impact on overall values. According to Saynajoki *et al.* (2012), in some cases, this implies constructing high-performance buildings with larger embodied energy may be less preferable than renovating existing buildings for better performance. In the example of Turkey and other developing countries where large amount of new constructions take place, this aspect may gain a critical implication. In the literature, most studies neglect this aspect while interpreting LCA results.

- **Lack of environmental data / databases**

One of the obstacles in doing research on LCA is the lack of information. High rates of new construction activities dramatically increases the importance of evaluating environmental impacts. The development is too fast to comprehend the limits of how further it may go and the research efforts have been insufficient to create a literature and a database about the impacts of built environment. Knowledge on product information, material quality management, waste management and energy management are missing. Again, the problems enhance the importance of research.

LCA methodologies depend on the inventory databases created by governmental or non-governmental institutions. Turkey is cooperating with the EU and attempting to abide the EU standards. At this point, an EU referenced database may give the leverage for providing data on the significant inventory items that embodies the highest environmental impact. There are studies on LCA in which, missing data is not significantly important for the analysis, so the weighted impact of the item can be omitted. The critical issue is to identify the top priority environmental impacts. For example, in a study on sustainable strategies on social housing in Mexico, Yucatan by Ceron-Palma *et al.* (2013), due to climatic conditions and construction quality, the greatest impact was originating from air-conditioning devices. Moreover, the electricity generation is depended on fossil fuels (by 79%) which deal a very heavy impact on carbon emissions. Hence, it is very important to define the environmental impact category according to conditions of country the LCA is being conducted.

Moreover, the general databases on environmental data are dependent on US or EU databases, which creates bias on the calculations. Significant differences occur between countries due to the national electricity mix. Countries that produce electricity from fossil-fuel are significantly more affected by sustainable buildings. For the example of Turkey, the heating systems and transportation are depending on outsourced natural gas and oil resources. This fact adds upon the LCA frameworks which enable prioritization of different aspects according to regional or country conditions.

- **Methodological Errors**

In the literature, it is observed that studies that utilize a single LCA method, either process-based LCA or EIO-LCA, display technical errors by nature of the methods. Studies that rely on one LCA technique suffer from technique-related problems, such as truncation error in process-based LCA, and aggregation error in EIO-LCA. As stated by Stephan *et al.* (2013a) quantification of embodied energy is one of the controversial issues in the literature. It is claimed that process-based LCAs may omit a large portion of embodied energy due to truncation error. As a result, number of studies that benefits from both methods tend to increase.

Definition of system boundary is a significant phase of LCA where results may differ due to preferences which includes heavy assumptions. An example for that may be the situation of passive houses in some north Europe countries. Most of the certified houses are single-family detached houses in suburban areas whose occupants rely on private transportation. In such a case, focusing on the building system and performance may prove the success of manufacturers and practitioners. On the other hand, not considering occupant transportation would lead to a misleading result as the overall emission of the building may be higher than a conventional building.

Similarly, evaluating built-environment over singular building cases is not giving an overall view about the environmental impact. Limiting calculations within ‘building site’ omits the impact of construction of infrastructure and road network. There is need for further research on evaluation of urban scale developments.

CHAPTER 3

MATERIAL & METHOD

3.1. Introduction

This chapter presents the research material and the methodology used in collecting and analyzing the data. In order to have a clear explanation of the concepts, material and method themes are given separately.

In material section, sampling method and characteristics of chosen projects are explained briefly. Overview of mass-housing projects in Turkey, characteristics of the selected projects are also given in this section. Also, literature on the building sample is given for additional information.

In method section, the LCA framework and methodology which was developed for this study is given in details. First, LCA framework development within ISO 14040 and EN 15978 standards is introduced. Beginning with goal and scope definition (including system function and unit, boundaries, life cycle assessment method, etc.) and followed by life cycle inventory analysis (including necessary data, means of data collection and management and data validation system), the whole life cycle analysis is explained. At the end of the analysis, an environmental impact database with three main clusters on mass housing projects at neighborhood scale was achieved. By grouping the inputs and outputs according to the clusters, it is aimed to evaluate the mass housing projects at different scales. These three main clusters are:

- Environmental impact by building typology
- Environmental impact by urban context
- Environmental impact by sustainable solutions

At the next stage, the development of the tool for decision support is explained. The framework of the tool is presented in IDEFØ language, and possible features of user-friendly software is introduced.

In the guidance of the proposed methodology, this study aimed to analyze mass housing projects in Ankara. According to the results of a specific number of analyses, a reference LCA model was established which was utilized in a DST for aiding planners and designers at the early design stages of mass-housing projects, and supporting clients in their decision-making for carbon emission mitigation.

3.2. Material

This study was conducted on mass housing projects in Ankara, Turkey. The sample population was defined as mass-housing projects built with tunnel formwork system facilitated by TOKİ within last 10 years in Ankara.

The projects were evaluated through major elements defined in LCA, such as;

- Construction materials (including residential buildings, utilities and roads)
- Building operations (operational energy) and,
- Transportation (private automobiles and public transit).

Bill of quantities, architectural drawings and interviews with responsible staff (construction manager, site architect, etc.) were utilized for necessary data. Data management for the proposed framework is presented in Table 11, in Section 3.3.3.

3.2.1. Mass-Housing Projects in Turkey

According to Housing Development Administration of Turkey (TOKİ, 2015), TOKİ provides 5-10% of the housing needs of Turkey, which concludes to a number around 50.000 dwellings a year. The total number of dwellings realized by TOKİ was 805,000 by last quarter of 2017 (TOKİ, 2017).

These dwellings are being provided under a specific development typology called mass-housing projects, which generally represents a design and construction standard for multiple domestic dwellings that are utilized with the same scheme in several geographical locations. These projects are also considered as social housing projects, even if there are specific categorization regarding the cost of the dwellings.

Mass housing projects are categorized according to the 'target market'. 40,57% of these projects are consisting of those for middle-income groups. As to the 22,92% portion of the projects, they consist of projects toward the low-income group and the poor. The urban transformation projects, which have recently become increasingly significant, have a ratio of 13%.

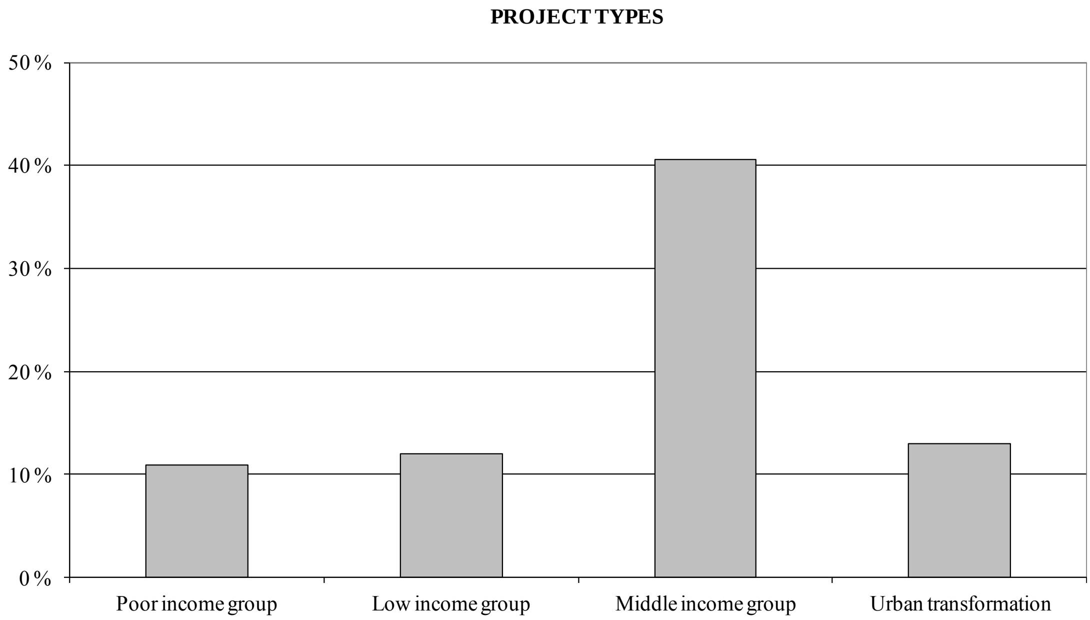

Figure 11. Project types implemented by TOKİ until 2017 (adopted from TOKİ, 2017)

Quality and cost margin also varies according to this categorization. As TOKİ puts forward; approximate m^2 cost and sale price for the poor group houses is equal being between 700-800 TL; m^2 cost of low-income group houses m^2 is between 800-930 TL; m^2 cost of middle-income group houses is 900-1.050 TL, respectively.

Category	Area	Cost (per m^2)
Poor income	45 – 65 m^2	700 – 800 TL
Low income	65 – 87 m^2	800 – 930 TL
Middle-High income	85 – 146 m^2	900 – 1500 TL

Figure 12. Housing area and cost figures (adopted from TOKİ, 2015**)**

Living area of dwellings is also a parameter in this regard. It is reported that poor group houses are constructed with a dwelling area of 45 - 65 m^2; low–income group houses with an area of 65 - 87 m^2 and narrow- and middle-income group houses with an area of 85-146 m^2.

The housing projects are generally constructed using the 'tunnel form' technique. The major motive for this preference is observed as fast and quality production. Also, the system is claimed to be earthquake-resistant, smooth geometric spaces with better building safety. On the other hand, problems such as noise insulation and inflexibility for renovation are also facts about tunnel form constructions.

3.2.2. Sample Projects

As given in the introduction, the sample population was defined as at least three housing estate applications built with tunnel formwork system facilitated by TOKİ within last 10 years in Ankara.

Sample selection was conducted according to the types of mass housing projects facilitated by TOKİ. There are three potential building quality class that could be chosen for this study; poor, low-income and middle income. Luxury housing projects was omitted due to low ratio to overall housing project number. It was considerably reasonable to select all of the projects among a single group, rather than picking limited number from each. In order to have a control group for comparison between projects, it was more suitable to have similar projects with a few differing parameters, like location (i.e. distance to city centre).

After an evaluation regarding the building groups, middle-income group was selected for its high proportion among all buildings with 40.57%. Another reason for this selection was the fact that it has the highest approximate m^2 cost. As depicted in the literature, higher costs imply higher environmental impacts. It also means higher inspiration for sustainability solutions and increased shareable cost for applying these solutions. Choosing a low-cost building would hamper the variety of this study.

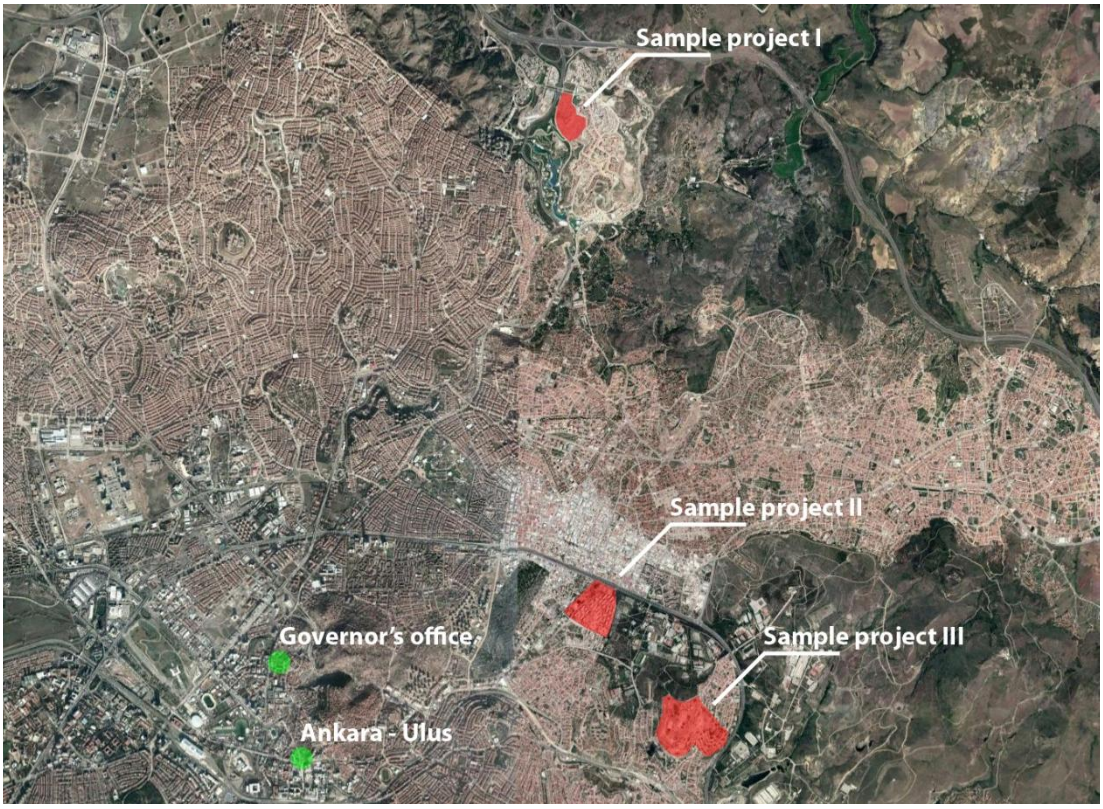

Figure 13. Location of sample projects in Ankara

The sample projects are; (i) Mass Housing Project with 277 dwellings in Mamak, (ii) Mass Housing Project with 889 and 330 Dwellings in Gülseren and (iii) Mass Housing Project with 415 Dwellings in Karaağaç. Project drawings and bill of quantities were provided by TOKİ at 09.09.2015. The projects were under construction at time of inspection and were planned to be completed at 2018. Location of the projects can be seen in Figure 13. After the collection of data in digital format (dwg, xls), semi structured interviews were conducted with construction managers in order to verify the data collected from the project documents with the actual realized construction. The structure of the interviews can be seen in Table 5.

Table 5. Interview questions

	General Information
1	Please confirm the number of dwellings and project area that are provided in the table as an annex to this questionnaire.
2	In the material list provided to you, what would be overall percentage (%) of materials that are depicted as those that have highest measurement/cost.
3	In the material data sheet, what percentage of necessary data can be reached?
	HVAC
4	What is the percentage of mechanic and electrical installations to the project overall?
5	What is the energy source for heating in the project?
6	Is heating system individual or central?
	Water consumption
7	How is domestic hot water being heated?
8	Is there any water treatment system?
	Landscape / Urban
9	What is the percentage of landscaping works to the project overall?
10	How is water and electricity for landscaping being provided?
11	Are there any current studies for mass-transportation for this project?
	Renewable Energy
12	Are there any renewable energy sources in the project?
13	Does the project have an energy performance certificate?
14	How could renewable energy investment, which is a requirement in BEP-R, of 10% over the total cost of projects that are above 20.000 m^2 be achieved?

3.2.2.1. Project 1 - Mass Housing Project with 277 Dwellings

The first project is located at Mamak, Ankara, with a distance from the city center of 10 km. Project 1 is within middle-income group type according to its cost per m^2.

It is built upon three separate plots as 70140/7, 70140/4, 70140/6 with a total area of 45.812 m^2. The total area of mass housing project is 60.128,33 m^2. The project is a 277 dwelling mass housing project which is consisting of 14 blocks, with two building types; A1 and 10A. There are also three children playground distributed to each plot, and walkways for pedestrian entrances and vehicle roads between and around the plots. Open car parking is provided for each plot according to the municipality legislations.

Figure 14. Layout of sample project 1

Figure 15. Site photo of sample project - 1

In the project, there are;

- 10 blocks of type A1, which is a 7-storey building with a gross area varying between 2.685 - 2.715 m^2. Type A1 provides 12 dwellings of 172,19 m^2 with 4+1 plan layout.
- 4 blocks of type 10A, which is a 11-storey building with a gross area of 8.257,37 m^2. Type 10A provides 40 dwellings of 167,00 m^2 with 4+1 plan layout.

Table 6. Data chart for sample project - 1

01-KUZEY ANKARA 277 DWELLING MASS HOUSING PROJECT														
Plot No.	**Plot Area**	**Block Code**	**Block No.**	**Block Type**	**Block Count**	**Block Story**	**Story No**	**Story Area**	**Block Area**	**Total Area**	**Dwell. No.**	**Total Dwell.**	**Dwell. Area**	**Room No.**
70140/7	9.185,00	A1	1	A	1	1B+Z+5	7	382,74	2.685,81	2.685,81	12	12	172,19	4+1
70140/7		A1	2	B	1	2B+Z+4	7	383,10	2.706,12	2.706,12	12	12	172,19	4+1
70140/7		A1	3	C	1	3B+Z+3	7	383,10	2.715,78	2.715,78	12	12	172,19	4+1
70140/7		A1	4	B	1	2B+Z+4	7	383,10	2.706,12	2.706,12	12	12	172,19	4+1
70140/4	17.475,00	A1	5	C	1	3B+Z+3	7	383,10	2.715,78	2.715,78	12	12	172,19	4+1
70140/4		A1	6	C	1	3B+Z+3	7	383,10	2.715,78	2.715,78	11	11	172,19	4+1
70140/4		A1	7	C	1	3B+Z+3	7	383,10	2.715,78	2.715,78	12	12	172,19	4+1
70140/4		A1	8	C	1	3B+Z+3	7	383,10	2.715,78	2.715,78	12	12	172,19	4+1
70140/4		A1	9	C	1	3B+Z+3	7	383,10	2.715,78	2.715,78	12	12	172,19	4+1
70140/6	19.152,00	A1	10	B	1	2B+Z+4	7	383,10	2.706,12	2.706,12	10	10	172,19	4+1
70140/6		10A	1	D	1	1B+Z+9	11	743,19	8.257,37	8.257,37	40	40	167,00	4+1
70140/6		10A	2	D	1	1B+Z+9	11	743,19	8.257,37	8.257,37	40	40	167,00	4+1
70140/6		10A	3	D	1	1B+Z+9	11	743,19	8.257,37	8.257,37	40	40	167,00	4+1
70140/6		10A	4	D	1	1B+Z+9	11	743,19	8.257,37	8.257,37	40	40	167,00	4+1
Total	**45.812,00**				**14**		**114**			**60.128,33**		**277**		

3.2.2.2. Project 2 - Mass Housing Project with 889 and 330 Dwellings

The second project is located at Gülseren, Mamak, Ankara with a distance from the city center of 6,1 km. Project 2 is within low-income group type according to its cost per m^2.

It is built in two stages on two plots as 2B 1st District and 2B 2nd District with a total area of 67.597 m^2. The total area of mass housing project is 176.505,61 m^2. The project is two staged mass housing project with 889 and 330 dwellings which is consisting of 32 blocks, with six building types; A, L, M, N, R and S. An area of 5 blocks footprint is dedicated for car parking and 1 block footprint for technical facilities. There are also 6 recreation areas providing children playground, semi-closed seating area, 3 basketball courts and 3 main squares, utilizing the structure above underground car parking areas.

In the project, there are;

- 4 blocks of type A, which is a 13 storey building with a gross area of 4.743,63 m^2. Type A provides 26 dwellings of 155,90 m^2 with 4+1 plan layout,
- 5 blocks of type L, which is a 17 storey building with a gross area of 10.356,36 m^2. Type L provides 77 dwellings of 80,7 m^2 and 127,9 m^2 with 2+1 and 3+1 plan layout,
- 6 blocks of type M, which is a 15 storey building with a gross area of 4.419,97 m^2. Type M provides 28 dwellings of 115,9 m^2 and 126,8 m^2 with 3+1 plan layout,
- 3 blocks of type N, which is a 15 storey building with a gross area of 4.250,5 m^2. Type N provides 28 dwellings of 115,9 m^2 with 3+1 plan layout,
- 10 blocks of type R, which is a 13 storey building with a gross area of 3.746,44 m^2. Type R provides 36 dwellings of 68,0 m^2 and 80,1 m^2 with 2+1 plan layout,
- 4 blocks of type S, which is a 13 storey building with a gross area of 4.780,98 m^2. Type S provides 36 dwellings of 68,0 m^2 and 118,8 m^2 with 2+1 and 3+1 plan layout,

Figure 16. Layout of sample project 2

Figure 17. Site photo of sample project - 2

Table 7. Data chart for sample project - 2

02-ANKARA MAMAK GULSEREN 889 DWELLING MASS HOUSING PROJECT														
Plot No.	**Plot Area**	**Block Code**	**Block No.**	**Block Type**	**Block Count**	**Block Story**	**Story No**	**Story Area**	**Block Area**	**Total Area**	**Dwell. No.**	**Total Dwell.**	**Dwell. Area**	**Room No.**
2B 1. BÖLGE	49.097,00	A		1	1	2B+Z+11	14	357,99	5.111,19	5.111,19	26	26	155,90	4+1
2B 1. BÖLGE		A		2	2	B+Z+11	13	357,99	4.743,63	9.487,26	24	48	155,90	4+1
2B 1. BÖLGE		L		1A	1	2B+Z+14	17	603,55	10.356,36	10.356,36	77	77	80,7 - 127,9	2+1 - 3+1
2B 1. BÖLGE		L		2	3	B+Z+15	17	603,55	10.355,74	31.067,22	78	234	80,7 - 127,9	2+1 - 3+1
2B 1. BÖLGE		M		1	2	2B+Z+13	16	288,73	4.718,05	9.436,10	30	60	115,9 - 126,8	3+1
2B 1. BÖLGE		M		2	2	B+Z+13	15	288,73	4.419,97	8.839,94	28	56	115,9 - 126,8	3+1
2B 1. BÖLGE		N		1	1	2B+Z+13	16	277,43	4.537,35	4.537,35	30	30	115,90	3+1
2B 1. BÖLGE		N		2	1	B+Z+13	15	277,43	4.250,52	4.250,52	28	28	115,90	3+1
2B 1. BÖLGE		R		1	2	2B+Z+10	13	282,62	3.746,44	7.492,88	36	72	68,0 - 80,1	2+1
2B 1. BÖLGE		R		2	4	B+Z+10	12	282,62	3.463,82	13.855,28	33	132	68,0 - 80,1	2+1
2B 1. BÖLGE		S		1	3	2B+Z+10	13	362,16	4.780,98	14.342,94	36	108	68,0 - 118,8	2+1 - 3+1
2B 1. BÖLGE		S		1A	1	2B+Z+10	13	362,16	4.780,98	4.780,98	36	36	68,0 - 118,8	2+1 - 3+1
Total-1a					**23**		**327**			**123.558,02**		**907**		
2B 1. BÖLGE		TEC		1	1				220,80	220,80				
2B 1. BÖLGE		GRG		A	4				1.383,60	5.534,40				
2B 1. BÖLGE		GRG		D	1				1.249,60	1.249,60				
Total-1b	**49.097,00**									**130.562,82**				
02-ANKARA MAMAK GULSEREN 330 DWELLING MASS HOUSING PROJECT														
Plot No.	**Plot Area**	**Block Code**	**Block No.**	**Block Type**	**Block Count**	**Block Story**	**Story No.**	**Story Area**	**Block Area**	**Total Area**	**Dwell. No.**	**Total Dwell.**	**Dwell. Area**	**Room No.**
2B 2. BÖLGE	18.500,00	A		2	1	B+Z+11	13	357,99	4.743,63	4.743,63	24	24	155,90	4+1
2B 2. BÖLGE		L		2	1	B+Z+15	17	603,55	10.355,74	10.355,74	78	78	155,90	4+1
2B 2. BÖLGE		M		2	2	B+Z+13	15	288,73	4.419,97	8.839,94	28	56	115,9 - 126,8	3+1
2B 2. BÖLGE		N		2	1	B+Z+13	15	277,43	4.250,52	4.250,52	28	28	115,90	3+1
2B 2. BÖLGE		R		1	1	2B+Z+10	13	282,62	3.746,44	3.746,44	36	36	68,0 - 80,1	2+1
2B 2. BÖLGE		R		1A	3	2B+Z+10	13	282,62	3.746,44	11.239,32	36	108	68,0 - 80,1	2+1
Total-2a					**9**		**127**			**43.175,59**		**330**		
2B 2. BÖLGE		GRG		A	2				1.383,60	2.767,20				
Total-2b	**18.500,00**									**45.942,79**				
Total-1+2	**67.597,00**				**32**		**454**			**176.505,61**		**1237**		

3.2.2.3. Project 3 - Mass Housing Project with 415 Dwellings

The third project is located at Karaağaç, Mamak, Ankara with a distance from the city center of 7,5 km. Project 3 is within middle-income group type according to its cost per m^2.

It is built upon three separate plots as 8, 9, 11 with an total area of 35.518,36 m^2. The total area of mass housing project is 58.228,10 m^2. The project is a 415 dwelling mass housing project which is consisting of 13 blocks, with five building types; A, C, D, L and S. An area of 1 block footprint is dedicated for car parking and also for technical facilities. There are also 2 recreation areas providing children playground, semi-closed seating.

In the project, there are;

- 2 blocks of type A, which is a 7 storey building with a gross area of 2.491,40 m^2. Type A provides 12 dwellings of 155,20 m^2 with 4+1 plan layout,
- 3 blocks of type C, which is a 7 storey building with a gross area of 2.312,65 m^2. Type C provides 18 dwellings of 70,6 m^2,102,5 m^2 and 116,1 m^2 with 2+1 and 3+1 plan layout,
- 1 blocks of type D, which is a 7 storey building with a gross area of 2.463,90 m^2. Type D provides 20 dwellings of 70,6 m^2 and 116,1 m^2 with 2+1 and 3+1 plan layout,
- 1 blocks of type L, which is a 15 storey building with a gross area of 9.274,42 m^2. Type L provides 68 dwellings of 81,6 m^2 and 128,1 m^2 with 2+1 and 3+1 plan layout,
- 6 blocks of type S, which is a 15 storey building with a gross area of 5.706,91 m^2. Type S provides 42 dwellings of 80,9 m^2 and 116,0 m^2 with 2+1 and 3+1 plan layout,

Figure 18. Layout of sample project 3

Figure 19. Site photo of sample project - 3

Table 8. Data chart for sample project - 3

03-ANKARA MAMAK KARAAĞAÇ ALTIAĞAÇ 415 DWELLING MASS HOUSING PROJECT														
Plot No.	**Plot Area**	**Block Code**	**Block No.**	**Block Type**	**Block Count**	**Block Story**	**Story No.**	**Story Area**	**Block Area**	**Total Area**	**Dwell. No.**	**Total Dwell.**	**Dwell. Area**	**Room No.**
8	13.417,70	A		1	2	3B+Z+3	7	337,70	2.491,40	4.982,80	12	24	155,20	4+1
8		C		1G	1	3B+Z+3	7	319,85	2.312,65	2.312,65	18	18	70,6 - 102,5 - 116,1	2+1, 3+1
8		D		1	1	Z+6	7	337,30	2.463,90	2.463,90	20	20	70,6 - 116,0	2+1, 3+1
8		S		1GK	1	3B+Z+11	15	370,01	5.706,91	5.706,91	41	41	80,9 - 116,0	2+1, 3+1
9	2.335,40	S		1G	1	3B+Z+11	15	370,01	5.706,91	5.706,91	42	42	80,9 - 116,0	2+1, 3+1
11	19.765,26	C		1	2	3B+Z+3	7	319,85	2.312,65	4.625,30	18	36	70,6 - 102,5 - 116,1	2+1, 3+1
11		S		1	1	3B+Z+11	15	370,01	5.706,91	5.706,91	42	42	80,9 - 116,0	2+1, 3+1
11		S		1K	2	3B+Z+11	15	370,01	5.706,91	11.413,82	41	82	80,9 - 116,0	2+1, 3+1
11		S		2	1	2B+Z+12	15	370,01	5.693,68	5.693,68	42	42	80,9 - 116,0	2+1, 3+1
11		L		1	1	2B+Z+12	15	606,70	9.274,42	9.274,42	68	68	81,6 - 128,1	2+1, 3+1
Total					**13**		**147**			**57.887,30**		**415**		
8		TEC		1	1				170,40	170,40		0		
11		TEC		1	1				170,40	170,40		0		
Total	**35.518,36**									**58.228,10**				

3.2.3. Sample Project Inventory Analysis

A brief of sample projects is put forward in this section before conducting LCA study. In Table 9 below, main features of sample projects are put forward as such:

Table 9. General characteristics of sample projects

	Location	Distance to city centre (km)	Site area (m2)	Total Construct. area (m^2)	No. of blocks	Number of storeys	No. of dwelling	Other facilities
Project I	Mamak, Ankara	10.0	45,812	60,128	14	A:7 10A:11	277	– 3 children playground, – walkways for pedestrian, – vehicle roads, – open car parking
Project II	Gülseren, Mamak, Ankara	6.1	67,597	166,733	32	A:14 L:17 M,N:16 R,S:13	1,219	– 6 children playground, – semi-closed seating area, – 3 basketball courts, – underground car parking
Project III	Karaağaç, Mamak, Ankara	7.5	35,518	57,887	13	A,C,D:7 L,S:15	415	– 2 children playground, – semi-closed seating

The main purpose of LCA of the sample project is to develop an environmental impact database on mass housing projects at neighborhood scale. Hence, it is important to put forward similarities and differences between sample projects to conduct a proper analysis and make sure the result is representative. The comparison of the characteristics of the sample projects are compared in table below:

Table 10. Comparison of general characteristics of sample projects

Characteristics	**Project 1**	**Project 2**	**Project 3**
Total Area	60.128,3	176.505,6	58.228,1
Cost per m^2	1.117,40 ₺	807,63 ₺	918,16 ₺
Number of dwellings	277	1. 237	415
Number of storey	114	454	147
Number of blocks	14	32	13
Average Dwelling Area	217,1	134,8	139,5
Average Block Area	4.294,9	5.362,6	4737,6
Average Storey Area	4.85,9	357,6	377,1
Average Storey No	8,1	14,4	11,8

It is apparent that Project 1 and Project 3 are significantly similar whereas Project 2 differentiates among the others. Total area, cost per m^2, number of blocks and average block area are adequately close which enables a robust comparison between Project 1 and 3.

3.3. Method

In this section of the study, research methodology and the proposed framework for LCA of mass-housing projects at neighborhood scale are explained. The research methodology for the study is justified by explaining the research requirements and appropriate methods adopted. The LCA framework, then is introduced according to LCA steps defined in related standards.

3.3.1. Research Methodology

For this specific study, the author adopts an explanatory case-study approach for two main reasons. As Yin (2009) stated, case study is preferred in investigating contemporary events on which the author has no control or cannot manipulate. In this study, environmental behaviour of mass housing projects are examined. The appropriate method to derive tangible outputs from this examination is suggested as analyzing adequate number of sample project, building statistical data and utilizing this information in the proposed LCA model.

The first reason is the lack of statistical data regarding building materials and performance that is available in Turkey. Building statistical data is necessary for each and every component of a working LCA model for mass housing projects in Turkey. By investigating at least three cases, it is supposed that sufficient amount of information can be gathered on the building type under specified system boundaries. Moreover, it is required to compare the results of this study with a similar work that is conducted upon of a building of same typology or in a similar geography. Due to the lack of national databases, the comparison was performed with similar studies in other countries.

The second reason to adopt an 'explanatory study-case' approach is directly related to the research objectives of this study. The aim of the study is to answer the following questions:

- What is the amount of overall environmental impact that mass housing projects have in Turkey?
- How can planners and architects reduce the environmental impact while planning new settlements of mass housing projects?

Based on the above explanations, the proposed framework is explained in following sub-headings as depicted in ISO 14040 and EN 15978. Presentation of framework is provided by relationship models which are generated by using the IDEFØ modelling methodology (IDEF, 2017). IDEF is the abbreviation of **I**ntegrated **DEF**inition language which was commissioned by the United States Air Force to develop a function modelling method for analyzing and communicating the functional perspective of a system (IDEF, 2017). In the study, IDEFØ was adopted to clearly explain the relationships between systems and components in the proposed framework.

3.3.2. Definition of the Goal and Scope

The goal and scope of a LCA study must be put forward clearly at the beginning. In this study, the aim is to develop a DST for early-design phase including possible sustainable solutions appropriate for the project typology. For this purpose, three mass housing projects were evaluated and a reference database which includes data in three main clusters, namely (i) building typology, (ii) urban context and (iii) sustainable solutions, was built. The main framework for decision support system is given in Figure 20.

The secondary objective is to form scenarios depending on the identified parameters for each cluster. The parameters are identified which are suitable for pre-design and schematic design phases.

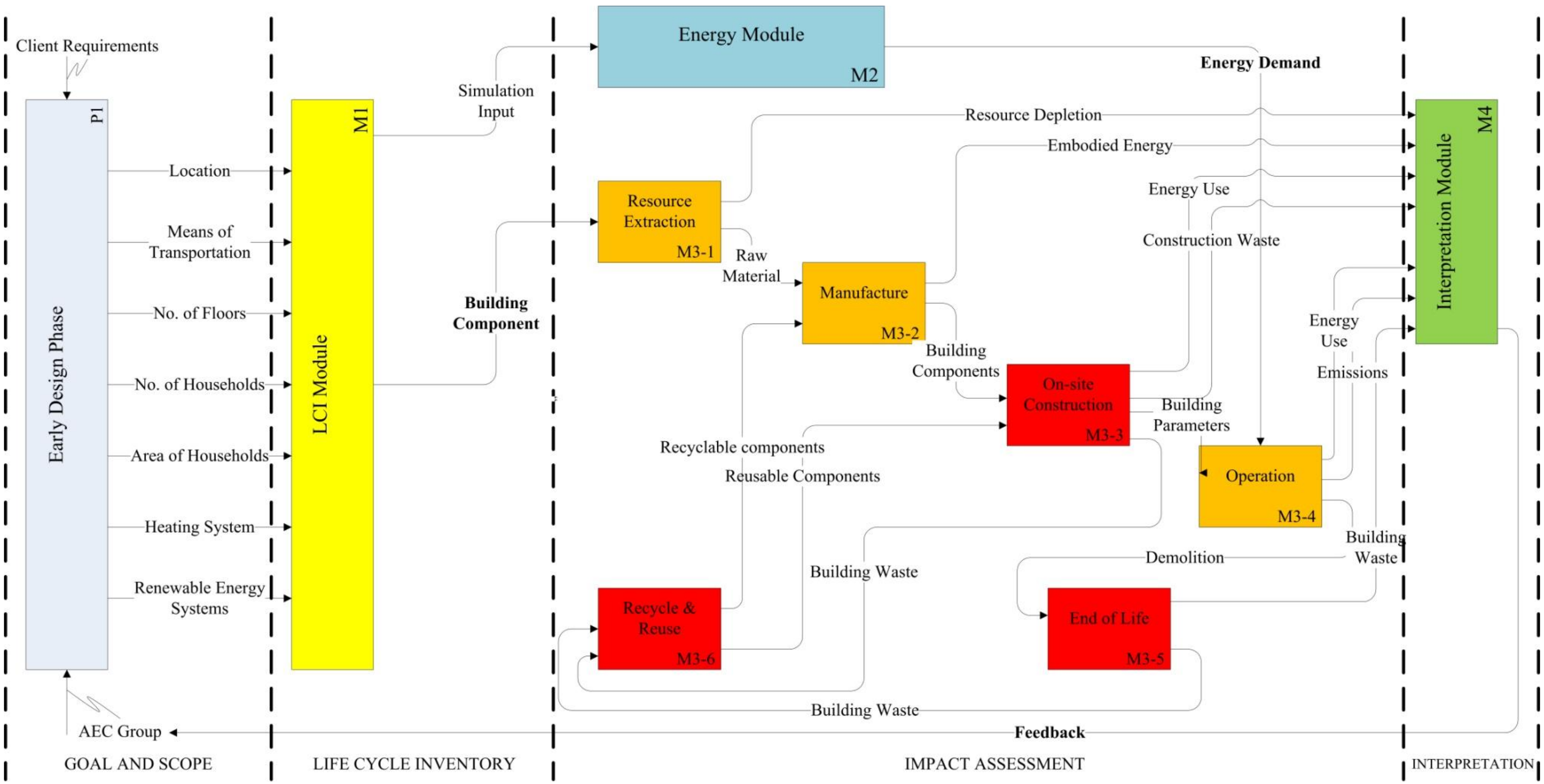

Figure 20. Proposed LCA framework for decision support tool

At the first stage of LCA, the goal and scope is defined, including subsets as such;

- The function of the system and functional unit
- The system boundaries
- Data requirements and quality
- Limitations and assumptions

3.3.2.1. Function of the System and Functional Unit

Function of the system is defined as the total of the CO_2 or equivalent greenhouse gases emitted to the atmosphere as a result of facilitating a mass housing project which includes several building blocks of differing functions (housing, public, services, etc.), along with the necessary infrastructure, and the total of all emissions that are produced during 50 years of service life. Functional unit is one square meter of useful area. The environmental impacts are calculated according to CML 2001 assessment methodology and the results are given in $kg_{CO_2\text{-}eq}/m^2$ which corresponds to global warming potential impact category (GWP) which was defined by the Intergovernmental Panel on Climate Change (IPCC, 2014).

3.3.2.2. System Boundaries

The boundaries of the study includes the mass-housing project site area with an inclusion of transportation of the residents to the city centre. However, there are limitation to the scope of the study due to lack of data, purpose of the study and time constraints. As seen Figure 21, construction of buildings and infrastructure, maintenance and end-of-life processes are excluded due to lack of data.

Assessment of energy and carbon during construction is considered as hard to achieve, as it is necessary to monitor the energy consumption from the beginning of construction (ideally with a separate generator for the site). Alternatively, if the construction company is collecting the consumption, which is not common in Turkey, then the data can be analyzed. It is even harder for end-of-life processes, where there is no waste management scenario for the demolition of the buildings.

After the mention life cycle phases are excluded, such an assessment is defined as 'cradle-to-gate' in the literature, in which the life cycle is being partially investigated.

There are also some specific assumptions which are related to the sample that is being assessed, which is the mass-housing projects in Turkey. Limitations and assumptions regarding the LCA of a mass-housing project are given in Section 3.3.2.4.

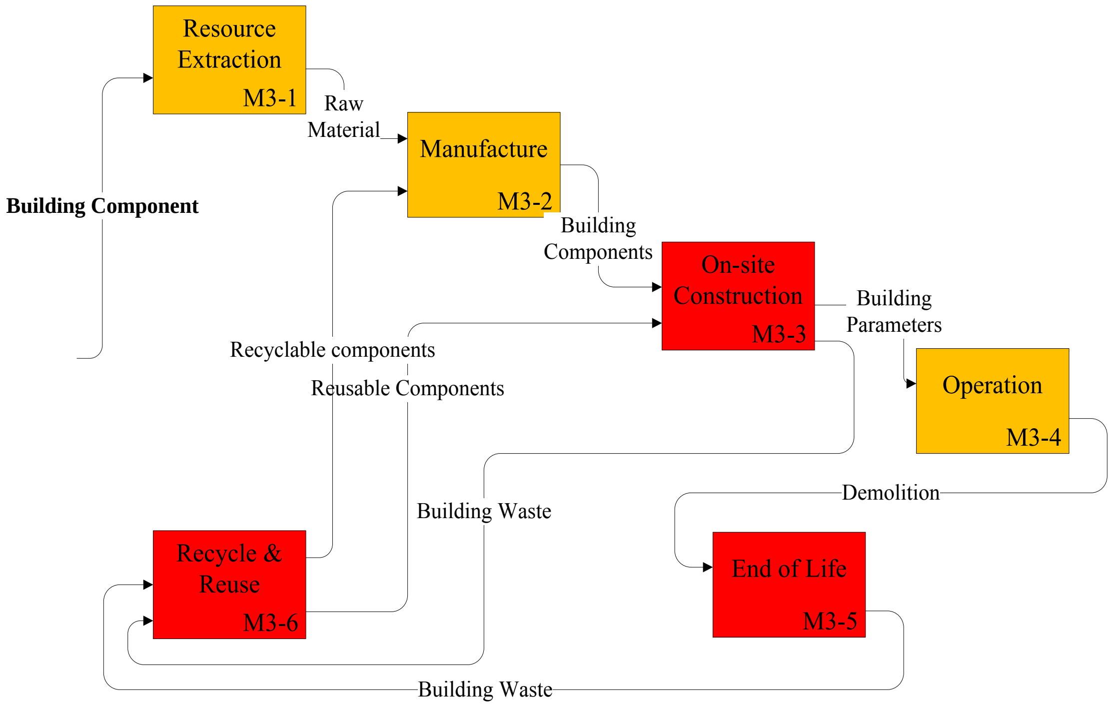

Figure 21. LCA phases included in proposed framework

Due to the scope of this study, the LCA includes inputs that are available at early stages of a project. In Figure 22, the necessary goals of each phase can be seen. Level of Development for this specific study is selected as 100 in order to represent the level of information at early project stages. The parameters derived from projects goals above are given in detail in Section 3.3.3.1 Life Cycle Cluster Databases.

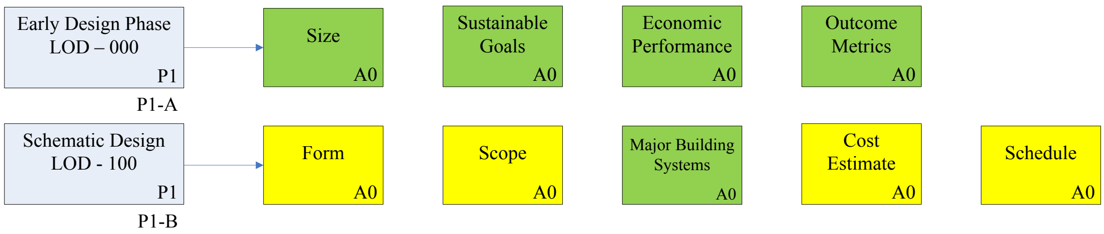

Figure 22. Building design phases included in the framework

3.3.2.3. Data Requirements and Quality

Data requirements and quality is a critical sub-step for this model. In ISO standards, there are already pre-defined data requirements of a component. The interpretation of these requirements are to be made by the LCA practitioner according to the goal and scope of a study. As put forward by Kayaçetin and Tanyer (2018), data requirements determine the method to be used in life cycle environmental impact assessment step in this study.

First data requirement is related with the building components which build up the life cycle inventory. It is assumed that components which builds up the inventory can be categorized and treated differently according to two parameters; (i) embodied carbon of functional unit and (ii) total amount of the component. In this regard, the components can be considered as primary or secondary. Components with higher embodied carbon and amount are defined as primary component whereas the other components are considered as secondary components. By doing so, the study may focus on the crucial products which may comprise 70-80% of the total environmental impact. This may provide a higher ratio of time/effort vs. efficiency. The benchmark for embodied carbon and total amount of component is given in Section 3.3.3.

Second data requirement takes data quality into consideration. The LCA model utilizes six different data quality indicators to evaluate data quality which can be seen in Figure 23. Data quality indicators are derived from the pedigree matrix (Weidema and Wesnaes, 1996) which assesses the quality of data regarding its source, qualitative or quantitative aspect, date, geographical context.

The data quality is determined according to the sources of data, which is displayed in Table 12. According to different sources such as; EPDs, average of EPDs, EPDs of similar products, generic LCA data and process data, five levels of data quality are assigned. These data quality levels are utilized in the data validation system that is shown in Figure 29.

PROJECT					PEDIGREE MATRIX (1-5)						
Building Cluster	Building Component	Component ID	Amount	Unit	Acquisition Method	Independence of data supplier (Reliability)	Representitiveness of the study (Completeness)	Temporal Correlation (Data Age)	Geographical Correlation	Technological Correlation	Average Rate
Roof	Roof Cladding	Y.18.201		m^2	1	2	2	1	1	1	1,33
	Roof Heat Insulation	Y.19.061/004		m^2	1	2	3	1	2	2	1,83
	Roof Waterproofing	Y.18.461/005		m^2	1	2	3	1	2	2	1,83
Exterior Walls	Brick Wall 25 cm	Y.18.001/C08		m^2	1	2	3	1	2	2	1,83
	Brick Wall 20 cm	Y.18.001/C06		m^2	1	2	3	1	2	2	1,83
	Exterior Paint	Y.25.004		m^2	1	2	2	1	1	1	1,33
	Exterior Heat Insulation			m^2	1	2	2	1	1	1	1,33
	Exterior Cladding			m^2	1	2	3	1	2	2	1,83
	Exterior Plastering	27.525/1		m^2	1	2	2	1	1	1	1,33
Interior Walls	Brick Wall 13,5 cm	Y.18.001/C04		m^2	1	2	3	1	2	2	1,83
	Brick Wall 10 cm	Y.18.001/C02		m^2	1	2	3	1	2	2	1,83
	Ceramic Wall Tile 40x40cm	Y.26.008/405B		m^2	1	2	2	1	1	1	1,33
	Interior Paint	Y.25.003		m^2	1	2	2	1	1	1	1,33
	Interior Plastering	27.531		m^2	1	2	2	1	1	1	1,33
Windows & Doors	Window Profile	Y.23.244		kg	1	1	2	1	1	1	1,17
	Window Glass	Y.28.645		m^2	3	2	3	2	3	2	2,50
Floors&Ceiling	Ceramic Floor Tile 40x40cm	Y.26.008/405A		m^2	1	2	2	1	1	1	1,33
	Stone Tile			m^2	3	2	3	2	3	2	2,50
	Laminated Wood			m^2	3	2	3	2	3	2	2,50
Basement	Foundation Concrete	Y.16.050/03		m^3	1	2	2	1	1	1	1,33
	Foundation Steel Reinforcement	Y.23.014-015		ton	2	2	3	2	2	2	2,17
	Basement Heat Insulation	Y.19.056/013		m^2	1	2	3	1	2	2	1,83
	Basement Waterproofing	Y.18.461/005		m^2	1	2	3	1	2	2	1,83
Structure	Structural Concrete	Y.16.050/06		m^3	1	2	2	1	1	1	1,33
	Structural Steel	Y.23.101		ton	1	1	2	1	1	1	1,17
	Structural Steel Reinforcement	Y.23.014-015		ton	2	2	3	2	2	2	2,17

Figure 23. Data quality displayed with Pedigree matrix (Weidema and Wesnaes, 1996)

At this point, the necessary action is to determine the level of data quality at which the study should differentiate high, average and low. This critical level of data quality is called quality benchmark. For certain benchmarks, different life assessment methods are assigned which are explained in detail in the Section 3.3.4.

The data required to conduct this study is presented in Table 11. Most of the data rely on the bill of quantities and architectural drawings. Interviews with either site manager or project architect are to be arranged.

3.3.2.4. Limitations and Assumptions

LCA methodology has its limitations, which are important to recognize while initiating the study and interpreting the results. In the literature, the inventory analysis stage is considered to have the least uncertainty. The most of the weaknesses are related to the scope definition, impact assessment, and interpretation stages.

In this study, there are certain limitations that are originating from the complex parameters that are related to urban scale. The limitations can be grouped under project typology, urban context and sustainable solutions.

For project typology, mechanical systems and electrical equipment are excluded from the assessment as well as the building infrastructure. Consumption data in Turkey are derived from Building Energy Performance Regulation (BEP-Y) (Ministry of Environment and Urbanization, 2008). It must be noted that this data is a reference value which is calculated rather than measured. It is assumed that efficiency of the building systems is constant through the life cycle.

For urban context, due to the fact that data on embodied impacts of transportation is not available in Turkey, necessary data on emissions from transportation are derived from a foreign source. However, transportation preferences are adopted from a study of a research centre in Ankara. Ankara is considered as a single-centered city, hence the distance of projects to city center are calculated from the same center. Urban growth and development are ignored for the simplicity of the study.

For sustainable solutions, only three renewable energy systems are included due to availability in Turkish market.

3.3.3. Life Cycle Inventory Analysis (LCI)

In this section, data collection and calculation procedures to quantify relevant inputs and outputs are given. After the life cycle framework is created, data management process is facilitated in order to build up a database from which the LCA framework retrieve necessary quantitative input. The sample projects are evaluated through three major clusters which define the mass-housing projects and given in detail in Section 3.3.3.1. Each cluster is assessed in two phases; construction (A1-A4) and operation (B1). Clusters are given as below;

- Urban context (transportation, infrastructure, landscape).
- Project typology (construction and operation of buildings)
- Sustainable solutions (renewable energy systems)

For urban context, construction includes the environmental impact of realizing the necessary infrastructure for specific means of transportation such as road, train ways, stations, etc. It also includes the structural landscape for the mass-housing projects. Operation includes the carbon emissions during the operation of specific vehicles such as private cars, buses and metro trains.

For project typology, construction includes the environmental impact of realizing the buildings of mass-housing projects. Major components of buildings are included in the assessment. Operation includes the carbon emissions during the use phase of buildings, including heating, cooling and lighting systems.

For sustainable solutions, construction includes the environmental impact of implementing the necessary infrastructure for specific renewable energy systems. Operation includes the carbon emissions during the use phase of buildings with specific renewable energy systems.

Bill of quantities, architectural drawings and interviews with responsible staff (construction manager, site architect, etc.) are utilized for necessary data. Data management framework is presented in Table 11.

Table 11. Data Management for LCA framework

Data Management Framework						
LCA Phases	**Project Typology**		**Urban Context**		**Sustainable Solutions**	
	Components	**Data Source**	**Components**	**Data Source**	**Components**	**Data Source**
A1-Resource Extraction / **A2-Transportation** / **A3-Manufacturing**	**Basement**		**Structural Landscape**		**Solar Thermal**	
	Foundation	Bill of quantities, process	Pavement	Bill of quantities, generic	Structure	Generic data
	Basement Walls	Bill of quantities, generic	Playgrounds	Bill of quantities, generic	Panels	Generic data
	Shell		Pathways	Bill of quantities, generic	Insulation	Generic data
	Floor Construction	Bill of quantities, process	Parking lots	Bill of quantities, generic	**Solar Panel**	
	Exterior Walls	Bill of quantities, process	**Transportation**		Structure	Generic data
	Windows&Doors	Bill of quantities, process	Roads	Generic data	Panels	Generic data
	Roof	Bill of quantities, process	Vehicles	Generic data	Insulation	Generic data
	Interiors		Stations	Generic data	**Wind turbine**	
	Partitions	Bill of quantities, process	Lighting	Generic data		
	Finishes	Bill of quantities, generic	Energy production	Generic data		
A4- Transport	**Transportation of Materials**	Generic data	**Transportation of Materials**	Generic data	**Transportation of Materials**	Generic data
B1- Operation	**Operation of buildings for 50 years**	Statistical data for GHG emissions for heating systems	**Operation of transportation for 50 years**	Statistical data for GHG emissions for kilometer per travelled	**Operation of systems for 50 years**	Statistical data for GHG emissions for renewable systems
Location	**Construction plot or area**	Distance	**Brownland Development**	Yes / No		
Functional unit	per building useful area (m2)					
Metrics	GHG emissions (CO2 equivalent - kgCO2-e)					

In the process of building life cycle inventory, it is important to define which building components have larger or smaller impact for any LCA study. Specifically, for simplified LCAs, it is crucial to be able to define priorities among evaluated components in order to increase the efficiency of assessment.

Components are considered as primary components if they have environmental impact per functional unit and if they are higher in quantity when compared to total building components. In this approach, secondary components can be omitted and system boundaries can be redefined for the sake of simplicity and efficiency of the study. Primary components can also be utilized for sensitivity analysis.

Environmental energy of commonly used materials can be seen in Figure 24. For demonstrative purposes, components with higher than 5% of total amount and embodied carbon with more than 1 $kg_{CO_2\text{-}eq}/kg$ are considered as primary components in this study.

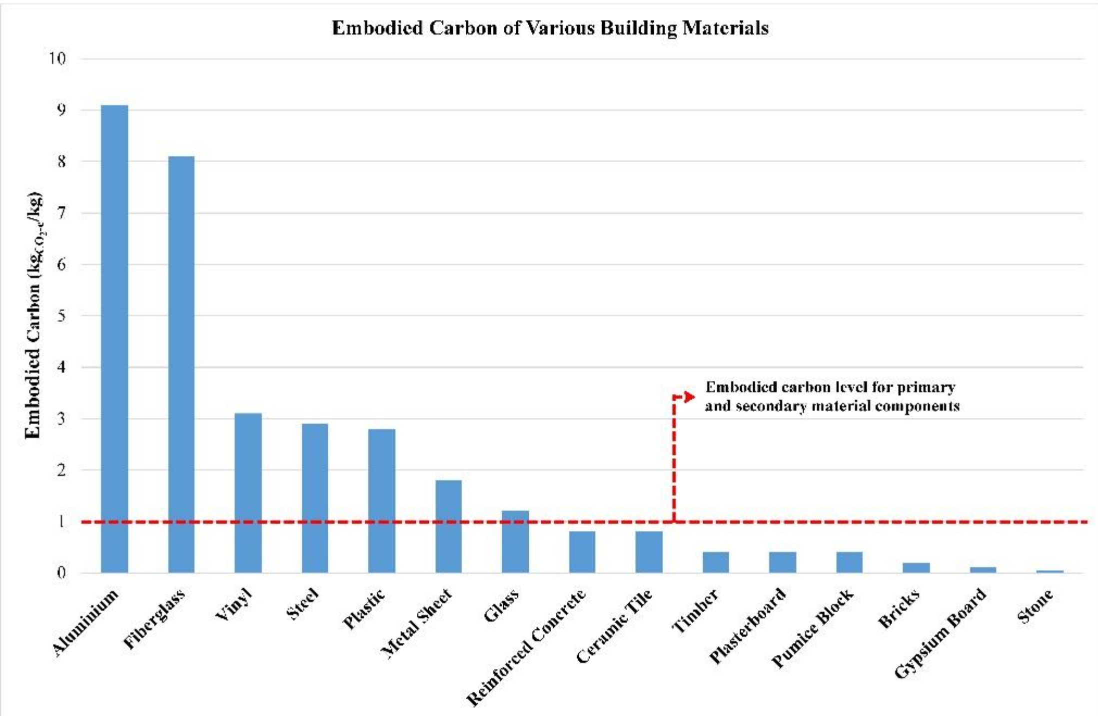

Figure 24. Embodied carbon of building components (adopted from Hammond and Jones, 2011)

PROJECT					ENVIRONMENTAL IMPACT					
Building Cluster	Building Component	Component ID	Amount	Unit	Acidification Potential	Eutrophication Potential	Global Warming Potential	Ozone Depletion Potential	Abiotic Depletion, Elements	Abiotic Depletion, Fossil
Roof	Roof Cladding	Y.18.201		m^2	9,61E-03	1,41E-03	1,10E+00	2,15E-08	1,99E-06	1,09E+02
	Roof Heat Insulation	Y.19.061/004		m^2	2,94E-02	1,09E-02	6,62E+00	1,92E-07	6,15E-06	1,43E+02
	Roof Waterproofing	Y.18.461/005		m^2	8,82E-03	4,34E-03	1,73E+00	4,71E-07	3,35E-06	6,17E+01
Exterior Walls	Brick Wall 25 cm	Y.18.001/C08		m^2	3,95E-01	9,37E-02	1,87E+02	1,02E-01	6,52E-01	1,42E+03
	Brick Wall 20 cm	Y.18.001/C06		m^2	3,95E-01	9,37E-02	1,87E+02	1,02E-01	6,52E-01	1,42E+03
	Exterior Paint	Y.25.004		m^2	6,53E-03	1,82E-03	1,33E+00	9,51E-08	2,30E-06	2,51E+01
	Exterior Heat Insulation			m^2	6,15E-02	3,23E-03	7,65E+00	1,64E-10	3,50E-06	1,15E+02
	Exterior Cladding			m^2	5,18E-03	3,86E-02	1,04E+01	3,62E-07	1,11E-03	8,65E+01
	Exterior Plastering	27.525/1		m^2	9,50E-04	2,00E-04	1,90E-01	7,00E-08	4,10E-08	2,90E+00
Interior Walls	Brick Wall 13,5 cm	Y.18.001/C04		m^2	3,95E-01	9,37E-02	1,87E+02	1,02E-01	6,52E-01	1,42E+03
	Brick Wall 10 cm	Y.18.001/C02		m^2	3,95E-01	9,37E-02	1,87E+02	1,02E-01	6,52E-01	1,42E+03
	Ceramic Wall Tile 40x40c	Y.26.008/405B		m^2	5,37E-01	2,72E-02	8,61E+01	2,98E-02	6,46E-05	0,00E+00
	Interior Paint	Y.25.003		m^2	1,86E-02	2,91E-03	1,88E+00	1,59E-07	1,10E-05	3,21E+01
	Interior Plastering	27.531		m^2	9,50E-04	2,00E-04	1,90E-01	7,00E-08	4,10E-08	2,90E+00
Windows & Doors	Window Profile	Y.23.244		kg	1,39E-01	1,15E-02	1,74E+01	9,29E-03	4,21E-03	1,72E+02
	Window Glass	Y.28.645		m^2	1,43E-01	1,43E-02	1,72E+01	1,49E+00	4,39E+00	2,03E+02
Floors&Ceiling	Ceramic Floor Tile 40x40c	Y.26.008/405A		m^2	5,37E-01	2,72E-02	8,61E+01	2,98E-02	6,46E-05	0,00E+00
	Stone Tile			m^2	5,92E-02	8,64E+00	2,17E+01	3,25E+00	4,30E+00	3,13E+02
	Laminated Wood			m^2	7,96E-02	1,60E-02	1,81E+01	6,21E+00	7,31E+00	4,77E+02
Basement	Foundation Concrete	Y.16.050/03		m^3	1,00E-01	6,29E-02	1,07E+02	4,31E-03	1,30E-05	3,07E+02
	Foundation Steel Reinforc	Y.23.014-015		ton	4,26E+00	3,91E-01	8,50E+02	1,14E-06	1,41E-04	1,02E+04
	Basement Heat Insulation	Y.19.056/013		m^2	6,15E-02	3,23E-03	7,65E+00	1,64E-10	3,50E-06	1,15E+02
	Basement Waterproofing	Y.18.461/005		m^2	8,82E-03	4,34E-03	1,73E+00	4,71E-07	3,35E-06	6,17E+01
Structure	Structural Concrete	Y.16.050/06		m^3	1,00E-01	6,29E-02	1,07E+02	4,31E-03	1,30E-05	3,07E+02
	Structural Steel	Y.23.101		ton	1,51E+00	1,50E-01	3,14E+02	3,72E+00	2,42E+00	3,61E+03
	Structural Steel Reinforce	Y.23.014-015		ton	4,26E+00	3,91E-01	8,50E+02	1,14E-06	1,41E-04	1,02E+04

Figure 25. Project inventory template

All information regarding the construction materials are recorded according to the project inventory template which can be seen in Figure 25. The materials are presented in respective building clusters according to Uniformat II (ASTM, 1997). The environmental impacts of each component are derived from the building component template. The detailed breakdown of material information is shown in building component template in Figure 26.

BUILDING COMPONENT INFORMATION		
Database Cluster		
Product Name		
Product Code		
Company		
Contact		
Phone no.		
Address		
Web address		
E-mail		
DOCUMENTATION		
Production Period		
Process Description		
Percentage Supply Covered		
Completeness of Data		
Country		
Production Area		
Distance to Construction (km		
Functional Unit		
Product Weight		
SYSTEM DATA		
Data Type	**Quantity**	**Units**
Raw Material Composition		
x		
y		
z		
Energy Input		
Electricity		
Heat		
Other		
OUTPUT		
Data Type	**Quantity**	**Units**
End Product		
Waste		
ENVIRONMENTAL DATA		
Method: CML 2001 – Nov. 2010	**Quantity**	**Units**
Acidification Potential		kg SO_2-eq.
Eutrophication Potential		kg PO_4^{3-}-eq
Global Warming Potential		kg CO_2-eq.
Ozone Depletion Potential		kg R11-eq.
Abiotic Depletion, Elements		kg Sb-eq.
Abiotic Depletion, Fossil		MJ
PROJECT VALUES		
Data Type	**Quantity**	**Units**
Quantity in the Project (ton)		
Notes:		

Figure 26. Building component template

While creating the building component template, GaBi simulation result formats and data request templates are utilized. Information and documentation parts of the template is to keep the required data in order; input and output values are utilized in life cycle modeling and calculations. Environmental impacts of a single functional unit of selected component will be multiplied by the quantity of respective component in the sample projects.

In this stage, beyond gathering statistical data for all items included in LCA, it is aimed to determine which components of mass-housing projects have the most significant environmental impact. By doing so;

- System boundaries can be redefined and secondary components can be omitted for the sake of simplicity and efficiency of the framework.
- Parameters are created for primary components for sensitivity analysis and for different user/building scenarios.

Sources for the environmental data of building components are; environmental product declaration (EPD) documents, process data from manufacturers and generic data from an LCA software database (Thinkstep, 2017). The main source for the environmental data of building components was the EPD documents published by the manufacturers. For most of the building components (10 out of 26 building components), the EPD of the exact product could be found. In several cases, EPD documents of similar building component (9 out of 26 building components) or average values from EPD documents of similar build components (2 out of 26 building components) were utilized. In some cases, the authors developed LCA models according to the process data provided by manufacturers (see Appendix A) for LCA models by author). In case of the unavailability of any data, generic data from the LCA database (Thinkstep, 2017) was used. The sources and data quality of the environmental data on building components are presented in Table 12.

Table 12. Sources of the environmental data for building components

Environmental Data Sources	Building Components	Data Quality
Process data from manufacturer	Window profile, structural steel	High
Product EPD	Roof cladding, exterior paint, interior paint, exterior heat insulation, exterior plastering, interior plastering, ceramic floor tile 40x40cm, ceramic wall tile 40x40cm, foundation concrete, structural concrete	High
EPD of similar product	Brick wall, basement heat insulation, exterior cladding, basement waterproofing, roof heat insulation, roof waterproofing	Average
Average of similar EPDs	Foundation steel reinforcement, structural steel reinforcement	Low
Generic data from LCA database	Window glass, stone tile, laminated wood	Low

Statistical data for energy consumption and GHG emissions are retrieved from Building Energy Performance Regulation (BEP-Y) (Ministry of Environment and Urbanization (MoEU), 2008). Data regarding transportation infrastructure and operational transportation are derived from the study of Chester and Horvath (2009). Data regarding the transportation statistics for Ankara are derived from Urban Transportation Technology Accessibility Implementation and Research Centre (KUTEM, 2014)

In the end of prepared LCAs, average values on the basis of per square meter of living area are achieved. By defining variables on these values; cost, operational and transportation expenses, total energy demand and CO_2 emissions can be calculated for varying scenarios. Parameters are grouped under main clusters of the LCA framework are further explained in following section.

Calculations on life cycle impact assessment are based on the main clusters as given in detail in Section 3.3.4.

3.3.3.1. Life Cycle Cluster Databases

For LCA studies, national databases are of utmost importance (Trusty and Horst, 2003). In the scope of this study, proposed methodology was customized according to the accessibility of data; information was stored on processes and materials that have significant environmental impact. By performing this study, a new environmental impact database with three main clusters for mass-housing project analysis was created. The main clusters are as follows and can be seen in Figure 27;

- **Cluster-I: Environmental impacts based on Urban Context**

Mass housing projects possess different environmental loads depending on the available means of transportation and location. There are also other aspects such structural and non-structural landscape works which depend on project site area. Defining LCA parameters and creating a database for private/public transportation will enable the planners to compare the environmental loads of urban planning options.

- **Cluster-II: Environmental impacts based on Project Typology**

Housing estate applications built with tunnel formwork system are selected as the project typology in this study. Height and heating system are set as varying features of this typology. The structural system with varying building height has differing environmental loads. This database cluster is beneficial for planners to compare the loads creating by low, medium and high building; central and individual heating system options during the design stage.

- **Cluster-III: Environmental impacts based on Sustainable Solutions**

Sustainable solutions for buildings are widely used for lowering energy demand and utilizing renewable energy sources. It is possible to integrate a holistic sustainable system for projects at larger scales, such as mass-housing projects. Photovoltaic panels, grey water treatment systems, biogas energy are several options that can be utilized in this study and their environmental impact may be analyzed as well.

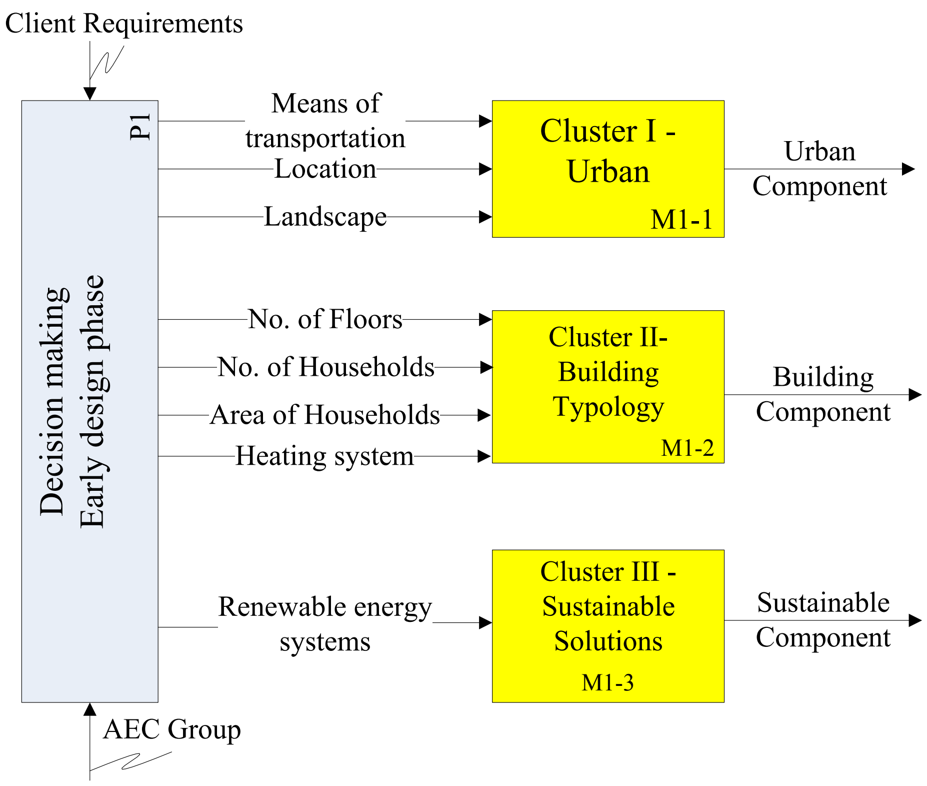

Figure 27. LCI database clusters

Parameters are briefly displayed in below;

- Cluster-I: Urban context
  - Parameter I-a: Location
  - Parameter I-b: Means of transportation
  - Parameter I-c: Landscape
- Cluster-II: Project typology
  - Parameter II-a: Heating system
  - Parameter II-b: Number of floors
  - Parameter II-c: Number of households
  - Parameter II-d: Area of household
- Cluster-III: Sustainable solutions
  - Parameter III-a: Renewable energy systems

Relationship between parameters are given in detail in Section 3.3.5.1.

3.3.4. Life Cycle Environmental Impact Assessment (LCIA)

As the necessary data is prepared and parameters are defined, impact assessment is performed according to the clusters given in previous section. The initial output of the assessment is used to refine the LCA framework and for defining primary components of high environmental load. The output data is integrated with decision support system. Assessment methodology for each cluster (project typology, urban context, and sustainable solutions) is given in the following sections.

3.3.4.1. Project Typology LCIA

Under project typology cluster, buildings in the sample projects are evaluated. The environmental impacts of following components are in the scope of this study:

- embodied carbon of buildings during construction phase (A1-A4),
- operational carbon of buildings during operational phase (B1).

For construction materials and building components, hybrid LCA methodology is utilized for enhancing the accuracy of the analysis where data is available; whereas missing data is compensated with generic data. GaBi software (Thinkstep, 2017) is utilized for preparing the LCA models of components with available data from manufacturers. GaBi software system is a tool for life cycle assessment, creating life cycle modeling and environmental balances. The assessments are conducted according to CML 2001 assessment methodology (Guinee *et al*., 2002).

CML 2001 is an impact assessment method which restricts quantitative modelling to early stages in the cause-effect chain to limit uncertainties. Results are grouped in midpoint categories according to common mechanisms or commonly accepted groupings. Midpoint modeling is referred as the traditional approach with a relatively good level of certainty at the level of characterization modeling with respect to the reach of the endpoints involved (Bare *et al*., 2012). CML 2001 assessment methodology is used since (i) it contains most commonly used impact categories such as; acidification, global warming potential, depletion of abiotic resources, ecotoxicity, euthrophication, ozone layer depletion and photochemical oxidation and (ii) enables providing consistency with the EPD documents utilized, which were also generated with CML 2001 methodology. The results are given in $kg_{CO_2\text{-}eq}/m^2$ for embodied carbon which corresponds to global warming potential impact category.

As suggested in study of Kayaçetin and Tanyer (2018), the primary components of the housing projects are defined at initial steps of data collection stage, and these main components are focused as the points of attraction of the study. In Figure 28, assessment framework for this study can be seen.

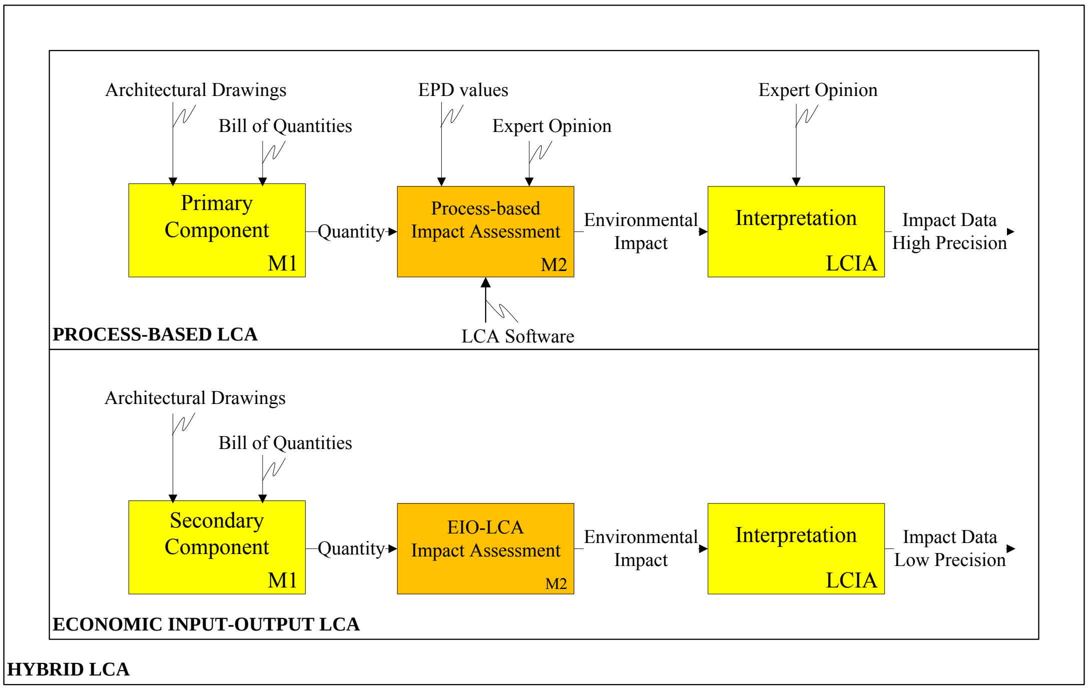

Figure 28. Hybrid LCA methodology

In process-based LCA, utilization of software for assessment is suggested. For primary components, it is advised to collect process data from the manufacturers. It is important to focus on these components and to have outputs with high precision. As these components are supposed to have higher ratio of environmental impacts, it will directly increase the certainty of the whole study. For primary components with partially complete data, generic databases are utilized to fill in the gaps. While making use of generic data, the data quality should be clearly displayed and evaluated accordingly.

For secondary components, EIO-LCA is advised where generic economy-based data are utilized with low precision. The assessment with this method should take minimum effort whereas the main focus is on the primary components.

As shown in Figure 29, primary components with data quality between 1-2 are assessed with process LCA, 2-3 are assessed with generic LCA, 3-5 are assessed with EIO-LCA after a literature check. Secondary components are directly assessed with EIO-LCA.

Components with;

- (i) embodied carbon higher than 1 $kg_{CO_2\text{-}eq}/kg$ and (ii) ratio of total quantity in the building above %5 are considered as primary components,
- (i) embodied carbon lower than 1 $kg_{CO_2\text{-}eq}/kg$ and (ii) ratio of total quantity in the building above %5 are considered as secondary components,
- (i) embodied carbon lower than 1 $kg_{CO_2\text{-}eq}/kg$ and (ii) ratio of total quantity in the building below %5 are not considered in LCA.
- Primary components with data quality indicator score of;
    - 1-2 are assessed with process LCA,
    - 2-3 are assessed with generic LCA,
    - 3-5 are assessed with EIO-LCA after a literature check

Secondary components were assessed with EIO-LCA.

In the study, it was found out that there is a relationship with the embodied carbon of the buildings with building height. According to the statistical studies, higher buildings should have relatively less embodied carbon. Depending on height threshold of low (5 storey), medium (10 storey) and high (15 storey), specific embodied carbon values of 290, 274 and 271 $kg_{CO_2\text{-}eq}/m^2$ are determined according to findings in the sample projects. The details of this aspect is given in Section 4.2.1.2.

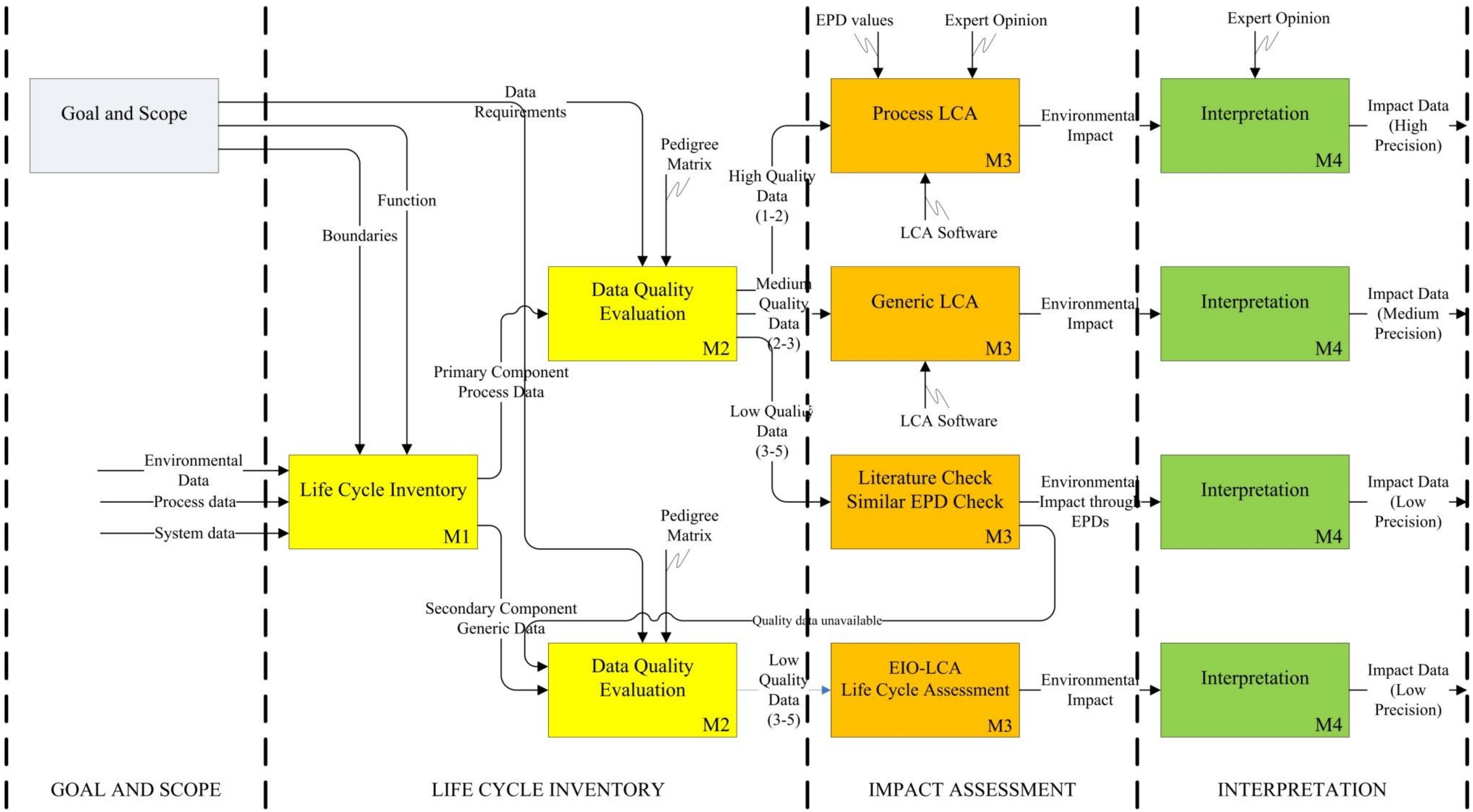

Figure 29. Data quality framework (Kayaçetin and Tanyer, 2018)

Operation of the buildings are evaluated according to the energy consumption per m^2, project area and GHG emissions of available heating system. Available heating systems in all three sample projects are gas-boilers.

Annual primary energy demand of residential housing in climate zone 3 in Turkey is defined as 300 kWh/m^2.year according to Building Energy Performance Regulation (BEP-R) (MoEU, 2008) and final energy consumption is estimated as 190 kWh/m^2.year. Difference between primary energy and final energy consumption is originating from the losses in the energy transmission and during the operation of energy systems. The values given in BEP-Y are reference values which are not measured actual data but are calculated by a simulation program. GHG emissions of gas-boiler is defined as 295 $gr_{CO_2\text{-eq}}/kWh$ as shown in Figure 30 (UK Parliament, 2016). This implies that residential housing in climate zone 3 has GHG emission of 56,05 $kg_{CO_2\text{-eq}}/m^2$.year, which is also parallel with the GHG reference value of 50 $kg_{CO_2\text{-eq}}/m^2$.year that is given in BEP-Y. Formula 1 which is used for calculating GWP of building operation can be seen below:

$$GWP_{\,(operational)} = Project\ area * \ Energy\ Consumption_{(residential)} * \text{Emission per kWh} \quad (1)$$

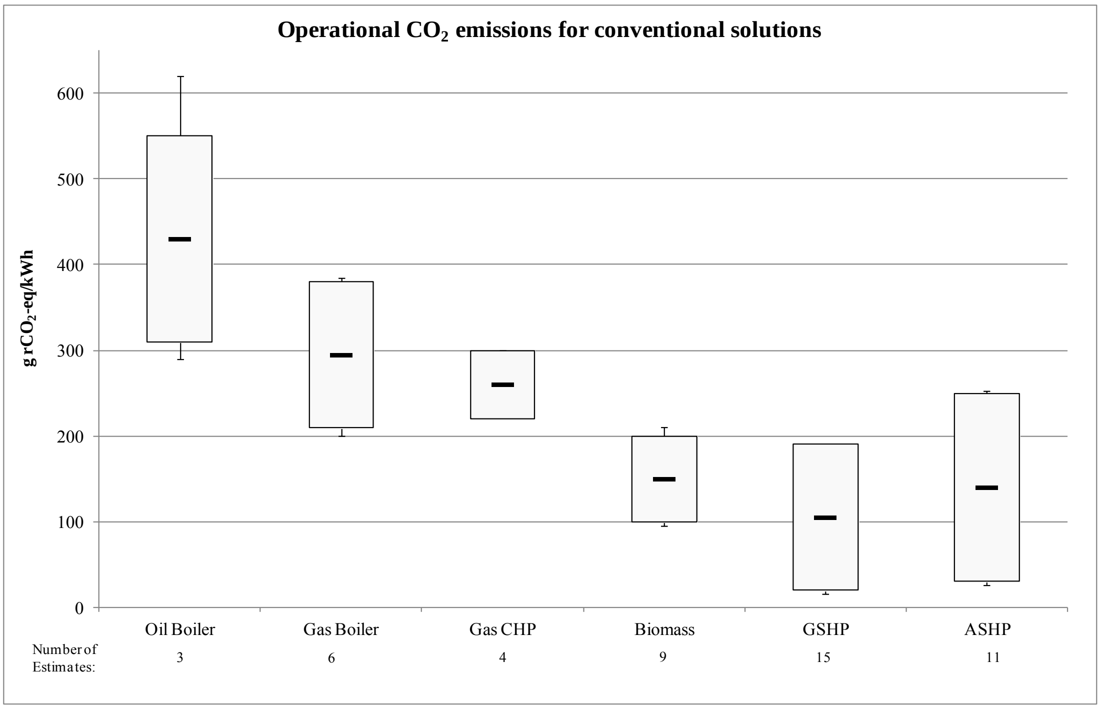

Figure 30. Operational carbon emissions for conventional solutions (UK Parliament, 2016)

3.3.4.2. Urban Context LCIA

Under urban context cluster, sample projects are evaluated on the basis of landscape area, urban location and available means of transportation. The environmental impacts of following components are in the scope of this study:

- embodied carbon of landscape design,
- embodied carbon of transportation infrastructure,
- operational carbon of transportation.

Evaluation of structural landscape works in LCA framework reveals one of the main contributions of neighbourhood scale development to GWP impact. The structural landscape works include pathways, playgrounds, parking lots and small-scaled technical areas.

Evaluation of transportation infrastructure and operational transportation investigates another contributor to the neighbourhood level GWP. The impact of transportation infrastructure includes infrastructure construction, vehicle construction and energy/fuel production for vehicles. The impact of operational transportation includes the emissions that are caused by vehicles during travels. The calculations are conducted depending on the number of dwellings, distance to city centre in km, number of travels and $kg_{CO_2\text{-eq}}$ emissions for transportation infrastructure and operational transportation on a passenger kilometre travelled (PKT) basis. The impact of the transportation infrastructure and operational transportation are calculated for a period of 50 years. Modes of transportation are given as; private car, bus and metro. Transportation preferences in Ankara (KUTEM, 2014a, 2014b) and their impact on GWP (Chester and Horvath, 2009) can be seen in Table 13.

Table 13. Transportation data for Ankara (KUTEM, 2014a and Chester and Horvath, 2009)

Modes of Transportation	**Usage Ratio**	**Infrastructure GWP per PKT** ($gr_{CO_2\text{-eq}}$)	**Operational GWP per PKT** ($gr_{CO_2\text{-eq}}$)
Pedestrian	27.98%	0.00	0.00
Private	22.75%	90.30	144.15
Bus	43.44%	62.31	176.52
Metro	5.64%	61.14	42.71

According to KUTEM (2014a), number of travels in weekday per dwelling for mid-high rise residential areas in Ankara is 4.75. This coefficient is a fixed number regardless of the area of dwellings. GWP data for the transportation infrastructure was derived from the study of Chester and Horvath (2009) and adapted to Ankara. The data for the occupancy rates of buses in Ankara was specified as %51.7 (KUTEM, 2014b). The impact of transportation infrastructure per PKT is 90.3 $gr_{CO_2\text{-eq}}$ for private car, 62.3 $gr_{CO2\text{-eq}}$ for bus and 61.1 $gr_{CO_2\text{-eq}}$ for the metro system. GWP data for the operational transport per PKT is 144.1 $gr_{CO_2\text{-eq}}$ for private car, 176.5 $gr_{CO_2\text{-eq}}$ for bus and 42.7 $gr_{CO_2\text{-eq}}$ for the metro system. Formulas 2 and 3 which are used for calculating GWP of transportation infrastructure and operational transportation can be seen below:

$$Number\ of\ travels\ = \text{Number of dwelling} * 4.75 * \text{Number of working days/year} \quad (2)$$

$$GWP_{\ (mode)} = Number\ of\ travels * \ Ratio_{(mode)} * \text{Distance to city centre} * \ GWP\ per\ PKT_{(mode)} \quad (3)$$

3.3.4.3. Sustainable Solutions LCIA

Under sustainable solutions cluster, renewable energy (RE) systems that are commonly utilized in residential houses were evaluated. In the scope of this study, three renewable energy systems are included as such; solar panel, solar thermal and wind turbine. The environmental impacts of following components are in the scope of this study:

- embodied carbon of renewable energy systems,
- contribution of renewable energy system on carbon saving in operational phase.

The environmental assessment of the RE systems are conducted on the basis of a single unit of kWh that is generated on-site. For each kWh generated, there is a specific positive impact of the systems on the operational phase, and negative impact on construction phase due to embodied carbon.

For calculation of the energy generation capacity (kWh) of solar systems (both panel and thermal), the roof area of mass-housing projects are calculated, and %40 of the area is considered as the application area due to restrictions such as building orientation and other installations on the roofs. For assessment of wind turbines, a standard size turbine which is suitable for the landscape area of the sample projects is selected. Annual energy generation capacity (kWh/year) of each system is estimated according to the size and the application of area. Then, this annual amount is multiplied by the life-time of the projects, specified as 50 years in this study, which yields the overall kWh contribution of renewable energy systems during the operational phase.

The embodied carbon of RE systems is calculated with multiplication of total energy generation and embodied carbon per kWh ($gr_{CO_2\text{-}eq}$/kWh). The sources for environmental data on embodied carbon of RE systems are a collection of LCA studies (UK Parliament, 2011, Finnegan, 2018). Emissions per kWh sustainable solutions are shown in Figure 31. Formulas 4 and 5 which are used for calculating impact of RE systems on embodied and operational carbon can be seen below:

$$Energy\ generation\ = \text{area of system} * \text{capacity of system} * \text{working hours/year} \tag{4}$$

$$Embodied\ GWP_{\ (system)} = kWh\ per\ year * \ GWP\ per\ kWh_{(system)} \tag{5}$$

For each RE system, specific generation values (kWh/m^2.year) for operational phase are given as such;

- for solar panel, 174,4 kWh/m^2.year
- for solar thermal, 480 kWh/m^2.year,
- for wind turbine, 2.700 kWh/year per small wind turbine

Specific generation value for solar panel system is calculated by multiplying three factors; annual average irradiation (kWh/m^2.year) for Ankara, efficiency of solar panel (%) and performance ratio of the system (%) which includes losses (shading, inverter losses, etc.). For solar panels in Ankara, annual average radiation is 1.550 kWh/m^2.year (Aksoy, 2011), efficiency is 15% (EIA, 2018) and performance ratio is 75% (Mangan and Oral, 2016) which yields 174,4 kWh/m^2.year.

Specific generation value for solar thermal system is adopted from the study of Ayompe and Duffy (2013) as 480 kWh/m^2.year. Despite high efficiency of the solar water heating system, the energy output of system can only increase as much as the 14% of the total energy demand of mass-housing project, due to the fact that share of domestic hot water in overall consumption in dwellings is given as 14% by Eurostat (2018). It is suggested to utilize solar thermal systems in an optimum size which does not exceed the water heating energy demand.

Specific generation value for wind turbine system is dependent on two main factors; average wind speed and height. Average wind speed for Ankara at 50 meters height for urban areas is between 3.5 - 4.5 m/s (MGM, 2018). In this study, a number of small or medium wind turbines are envisaged on the rooftops of each apartment block. The average of story level in the sample projects is around 12-15, which implies around 50 meters that allows for a better wind conditions. Bilir *et al*. (2015), investigated the potential of wind power in Ankara and small wind turbines were found to be more feasible than large turbines. Their study concluded that a small wind turbine in Ankara can generate between 1.878 - 3.740 kWh/year. For this study, it is proposed to utilize 5 small wind turbines, each with a capacity of 2.700 kWh/year on an apartment block.

For each RE system, specific embodied carbon values per kWh ($gr_{CO_2\text{-eq}}$/kWh) for construction phase are given in Figure 31 (UK Parliament, 2011, Finnegan, 2018);

- for solar panel, 75 $gr_{CO_2\text{-eq}}$/kWh,
- for solar thermal, 22,5 $gr_{CO_2\text{-eq}}$/kWh,
- for wind turbine, 35 $gr_{CO_2\text{-eq}}$/kWh for average wind speed of 4.5 m/s.

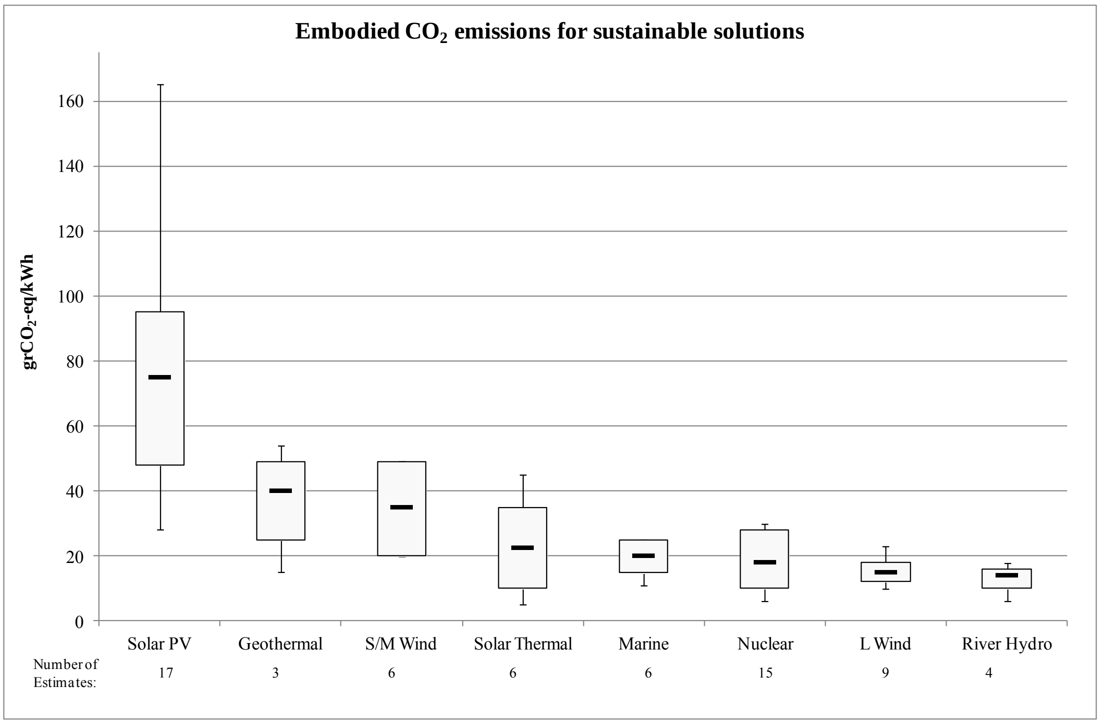

Figure 31. Embodied carbon emissions for sustainable solutions (UK Parliament, 2011)

Evaluation of RE systems cannot be performed in sample projects as there is no such application in these mass housing projects. In order to display how the projects can be optimized, RE systems are taken into consideration in Section 4.6.

3.3.5. Interpretation

Interpretation of the life cycle inventory analysis (LCIA) is conducted through the main clusters. By altering parameters, different scenarios can be built and compared for achieving an optimized design solution.

For optimization of the environmental impacts due to typological, urban and sustainable solution clusters, a decision-making tool based on selected parameters is utilized. First, parameters in each cluster are optimized among each other, then clusters are compared for better solutions by the system. The optimization system is displayed with a mock-up Scenario X, after the actual condition of sample projects are put forward.

By separating environmental solutions, net impact decrease can be seen clearly. Different solutions can be compared and results can be analyzed with ease. The framework in detail can be seen in Figure 32. The detailed description of parameters and their relationship among each other are given in the next section, 3.3.5.1.

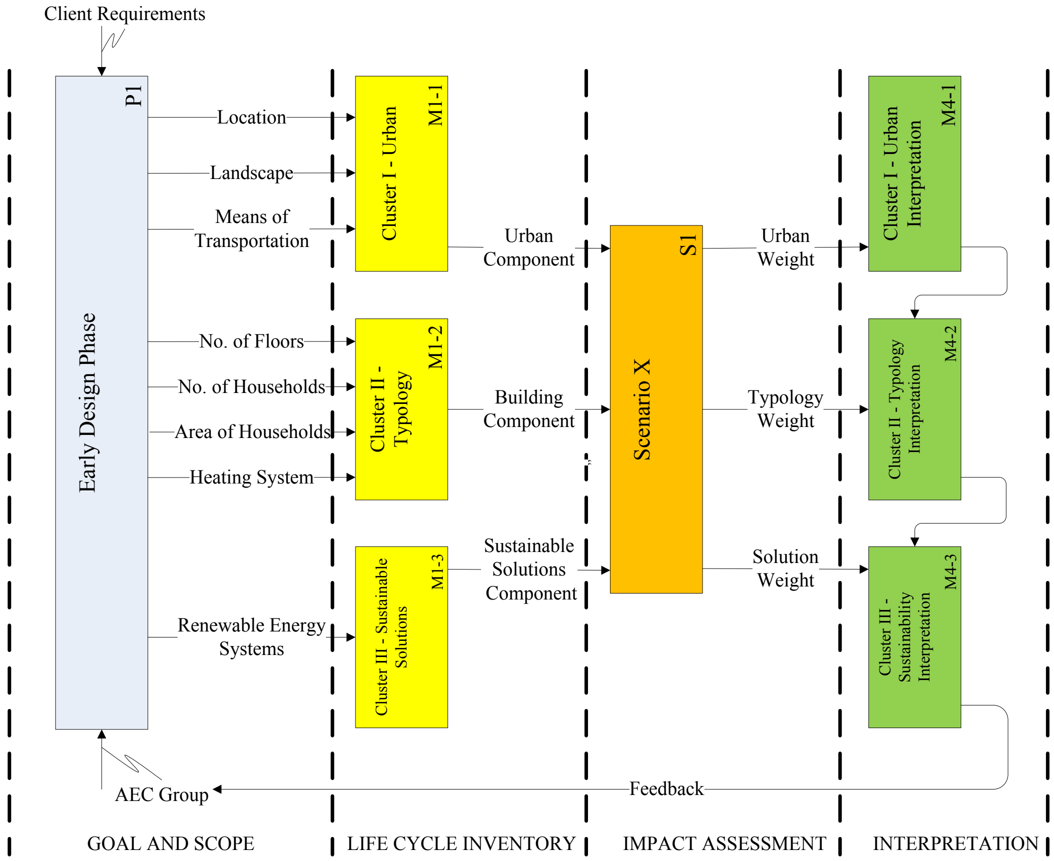

Figure 32. LCI-LCIA to interpretation module

3.3.5.1. Parameters for Decision-Support

In this section, parameters for early design phase which are defined for each cluster are explained in detail. It should be emphasized that the number of parameters should be optimum for providing a working tool in the early design phase, where project information is low. For each parameter, descriptions for available options are given. At the end of each cluster, relationship among the parameters are provided. The general flow of the parameters can be seen in Figure 33.

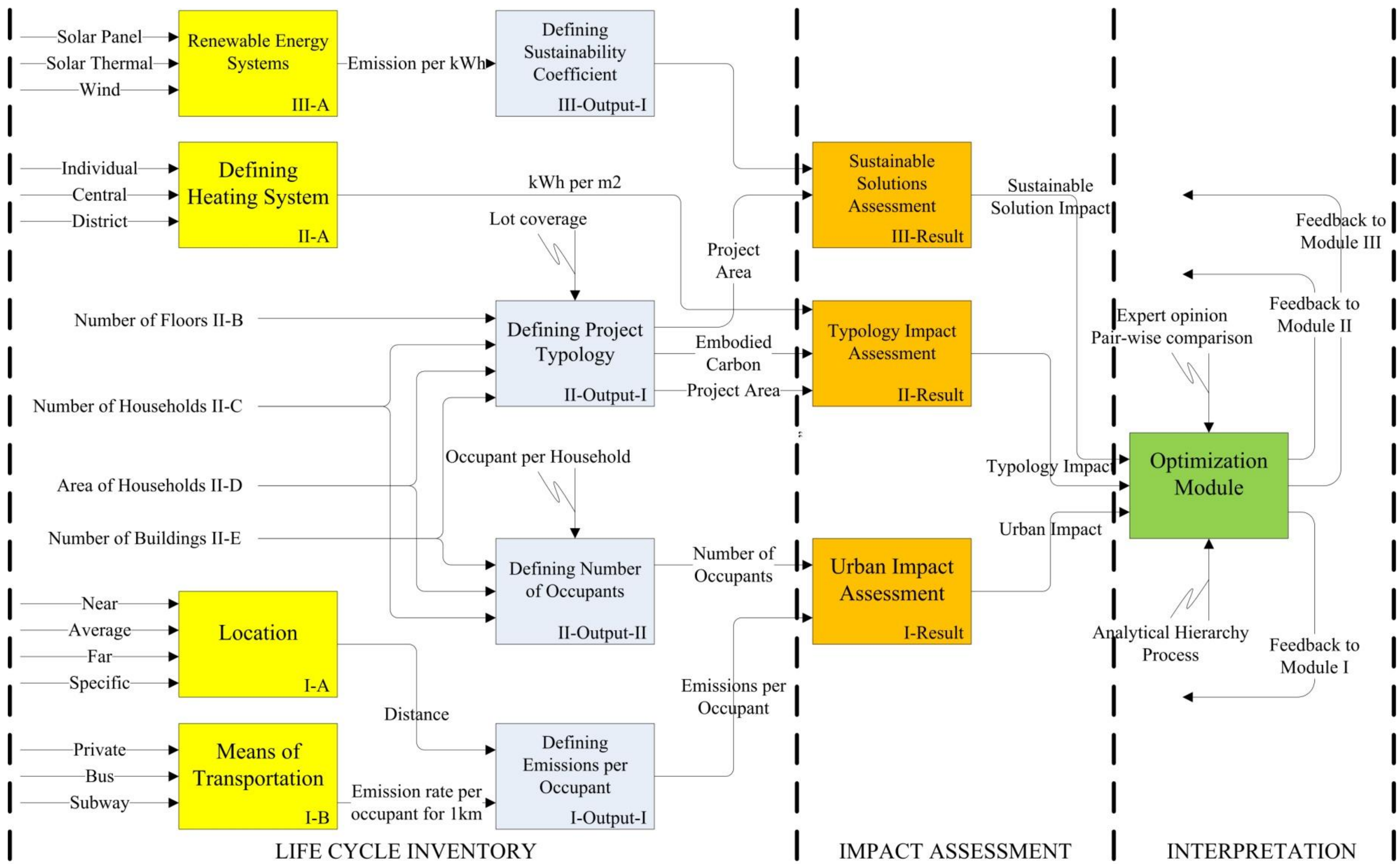

Figure 33. Parameter flow chart

- **Parameter I-a: Location**

Location of the projects is measured according to the official center of the city (Governor's Office). This parameter provides different options to determine the location of the project depending on zoning of the city according to the distance (Zone-I: 5km, Zone-II: 10km, Zone-III: 15km, etc.). This may allow users to assess projects which have not been appointed with a specific building lot and a precise distance to city centre. If location is already selected, specific distance can also be appointed manually.

- **Parameter I-b: Means of Transportation**

Means of transportation determines whether mass-transportation is or will be provided for the project. If available, it depicts the type of transportation system. Finally, this parameter provides the amount of CO_2 emissions for both infrastructure and operation of transportation system per PKT.

Options for the parameter are; private-focus, bus-focus and metro-focus. For each option, usage ratio for each transportation changes. For bus-focus, actual usage ratio of Ankara average is adopted. For other options, the usage ratio of a similar district in Ankara (İncek) is used for private-focus and the usage ratio of a similar district in Ankara (Batıkent) is used for metro-focus. Actual ratios can be seen in Table 14.

Table 14. Usage ratios for options for Parameter I-b

Options for Parameter I-b	**Means of transportation**		
	Private	**Bus**	**Metro**
Bus-focus	22,75%	43,26%	5,82%
Private-focus	42,75%	28,44%	0,64%
Metro-focus	17,75%	23,40%	30,68%

Specific carbon emissions per PKT for each means of transportation that are used during assessment are shown in Figure 34.

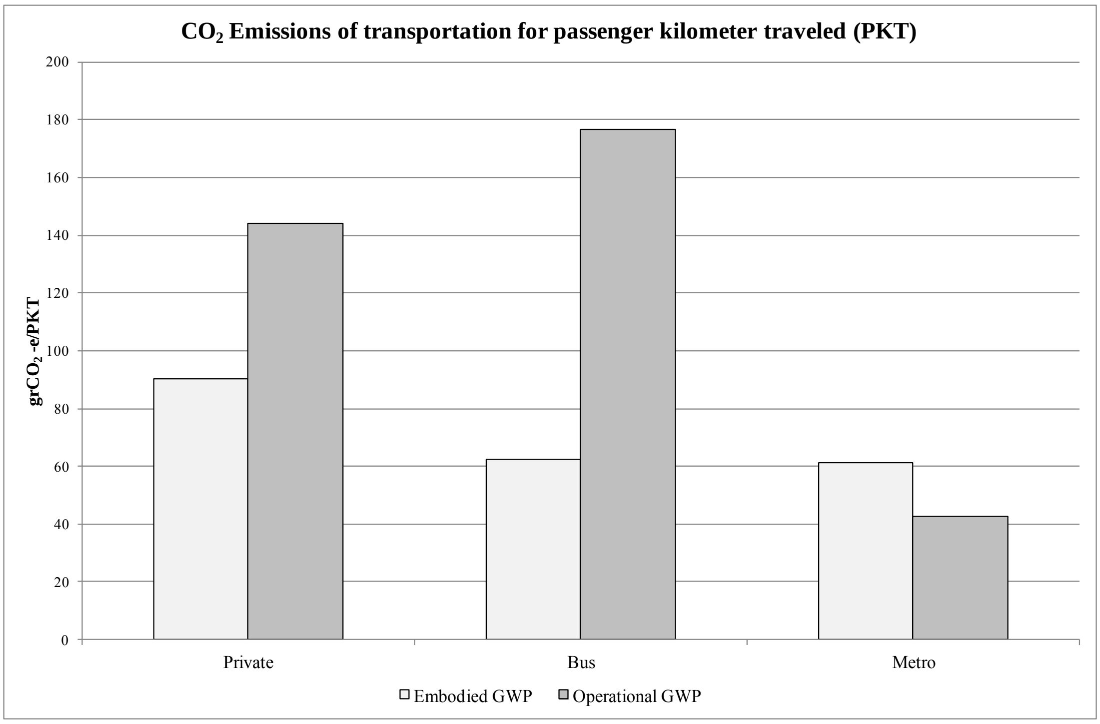

Figure 34. Carbon emissions per passenger/km (adopted from Chester and Horvath, 2009)

Relations between Urban Cluster Parameters:

Parameters I-a and I-b are related with each other and these two parameters are multiplied to calculate the amount of annual carbon emission from projects due to urban context. Parameter II-c, number of dwellings, is a key parameter for this calculation as it determines the number of travels per year.

Calculations in Urban Context Cluster:

For calculation of urban impact; Parameter II-c, number of dwellings, is multiplied with 4,375, number of travels a day per dwelling (KUTEM, 2013) and number of working days in order to calculate the total number of travels a year per project. Parameter I-a, location, is utilized to calculate the total number of PKT of the project. Finally, Parameter I-b, means of transportation which provides emissions per PKT, is multiplied by total PKT. The formula is given below:

$$Number\ of\ travels = number\ of\ dwellings * 4{,}375 * working\ days \quad (6)$$

$$Urban\ Impact = number\ of\ travels\ x\ distance\ \ x\ GHG\ emission\ per\ PKT \quad (7)$$

- **Parameter II-a: Heating System**

Heating system enables selecting the type of heat generator. This parameter provides the amount of CO_2 that selected heating system emits for each kWh generated. The total energy demand (kWh) of the project is determined according to the total area of households that are connected to the system and final energy demand of per household, which is estimated as 190 kWh/m^2 for Ankara depending on 300 kWh/m^2 primary energy demand given in BEP-R (MoEU, 2008).

Options for the parameter are; individual, central and district. For each option, amount of carbon emissions per kWh provided.

- **Parameter II-b: Number of Floors**

This parameter provides different options according to the categorization of the building height such as low (5), medium (10) and high (15). This may allow users to assess projects which have not been completely defined. If the storey level is defined, specific storey level can also be appointed manually. Number of floors parameter defines the building height, amount of material used, number of households (indirectly number of occupants).

Parameter II-b has a relationship with the embodied carbon of the buildings due to height. According to each height threshold of low (5 storey), medium (10 storey) and high (15 storey), specific embodied carbon values of 290, 274 and 271 $kg_{CO_2\text{-}eq}/m^2$ are determined according to findings in the sample projects. Findings imply that higher buildings should have relatively less embodied carbon.

- **Parameter II-c: Number of Dwellings**

Number of dwellings is defined through Parameter II-b. As default, it is accepted that each storey has four household. This parameter directly effects the number of occupants. Number of occupants in the sample projects are calculated by multiplying the number of households (parameter II-c) with a coefficient of 3,3 (which is the average number of occupants per household for Ankara, Nüfus ve Konut Araştırması, TÜİK, 2011).

- **Parameter II-d: Area of Household**

Area of household is defined manually and directly determines the project area together with Parameter II-c. Project area is a result of several parameters which is of critical importance for Project Typology and Sustainable Solutions Clusters.

<u>Relations among Typology Cluster Parameters:</u>

Parameters II-b, II-c and II-d are parameters which defines the area of the project. Parameter II-b defines the number of storey, Parameter II-c implies the number of households in each storey and Parameter II-d determines the area of the household. These parameters form the basis for all environmental impacts.

Parameter II-a is a coefficient for heating systems multiplied with all other parameters in Typology cluster. This provides the amount of energy demand and emissions related to heating for the whole project.

<u>Calculations in Project Typology Cluster:</u>

$$Area\ of\ the\ project = number\ of\ floors * \ number\ of\ dwellings * dwelling\ area \tag{8}$$

$$Energy\ demand\ of\ the\ project\ (kWh) = area\ of\ the\ project * 190\ kWh/m^2 \tag{9}$$

$$Typology\ impact = energy\ demand\ (kWh) * emissions\ per\ kWh\ (grCO2/kWh) \tag{10}$$

- **Parameter III-a: Renewable Energy Systems**

Sustainable Solution parameters are considered as measures to alter the efficiency of the projects. So, they are taken into account as an additional element. Renewable Energy Systems considers whether there is an energy generation through a source of renewable energy source.

Options for the parameter are; solar panel, solar thermal and wind. For each option, relevant characteristics of area, number or capacity of the system is provided as input. Efficiency coefficients provided in Section 3.3.4.3 for each unit of passive energy systems are multiplied by number or area of the systems. With the same approach, the environmental impact of implementing these systems is also calculated by embodied carbon values for each system.

3.3.5.2. Decision-Support Tool

In this section, the parameters and their relationships are shown by using an entity relationship (ER) diagram (See Figure 35). The decision-support tool (DST) utilizes the calculation methodology provided in the previous sections and integrates findings of the LCA studies conduction on sample projects to provide adequate information for planners and designers in the early design phases of projects.

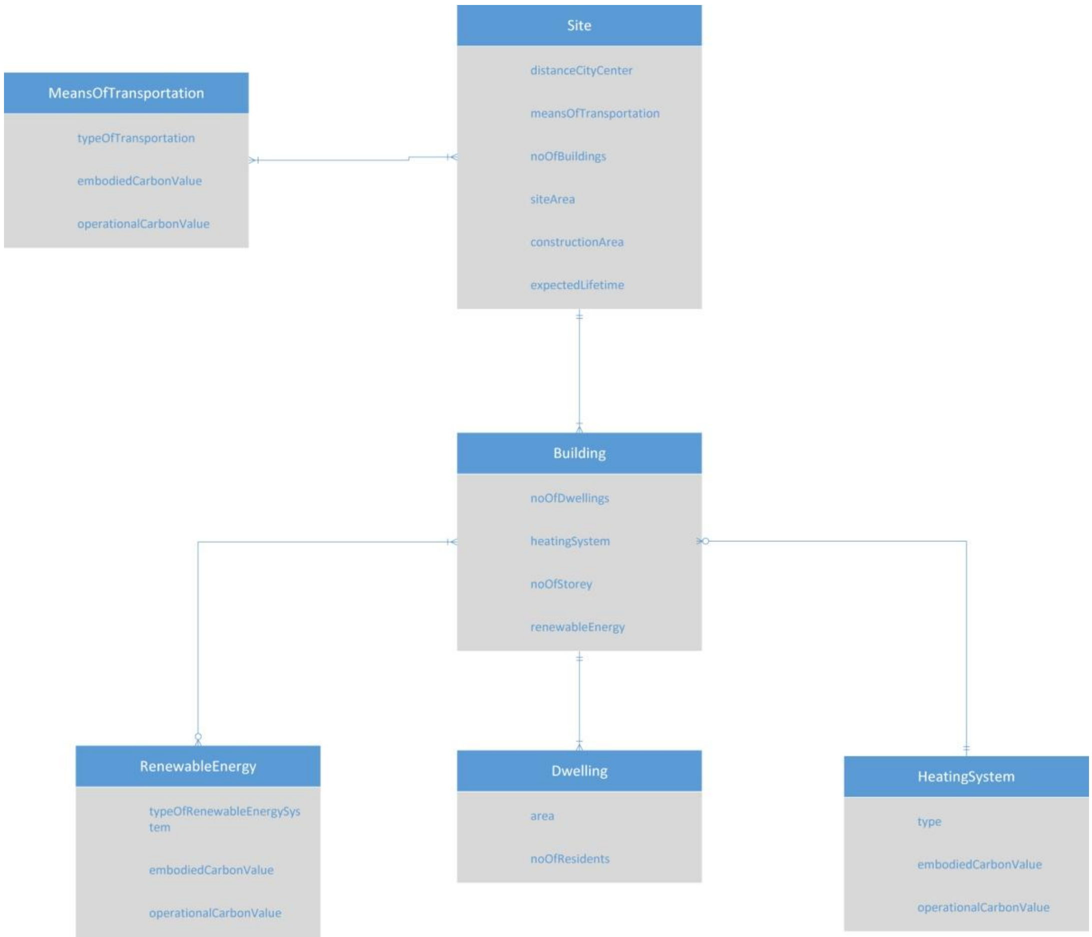

Figure 35. Entity relationship diagram for decision support tool

ER diagram models were first introduced by Chen (1976) for database design. The ER diagram displays the main entities of the model with their relevant attributes. Each attribute represents a necessary input for DST to achieve the expected outputs.

The diagram also demonstrates the hierarchical structure which is initiated by definition of a single dwelling and evolves into a neighbourhood site. By using the relationships shown in the diagram, the LCA calculations mentioned in previous sections are transferred into Excel format (.xsl). Hence, it is possible to display how the DST works in a software.

Parameters				Option	Value	Unit
I	Urban	a	Location			km
		b	Transportation focus			%
II	Typology	a	Heating System			$grCO_2/kWh$
		b	Number of Floors			#
		c	Number of Households (per floor)			#
		d	Area of Households			m^2
		e	Number of Buildings			#
		f	Number of Households	Calculated		#
		g	Number of Occupants	Calculated		#
		h	Energy demand per m2	Fixed		$kWh/m^2.a$
		i	Embedded carbon per m2	Calculated		$kgCO_2/m^2$
III	Sustainable Solutions	a	Renewable Energy Systems			
			Solar Panel			$grCO_2/kWh$
			Solar Thermal			$grCO_2/kWh$
			Wind			$grCO_2/kWh$
	Duration					year
	Project Area			Calculated		m^2
	CO_2 emission per m^2			Calculated		$kgCO_2.50.a/m^2$

Figure 36. Interface of decision support tool

In Figure 36, the interface for the DST can be seen, which is developed in Excel. By using the interface and having selections for parameters given in previous section, different scenarios for mass-housing projects can be generated.

The framework developed in this study is utilized in Section 4.6 for generating of different scenarios and exploration of these scenarios for decision-making.

3.3.6. Validation of Decision-Support Tool

In order to validate the usability of the DST, the tool was introduced to a number of experts and a session for feedback was performed by using the Delphi technique (See Section 4.7). The technique was initially designed for obtaining the most reliable opinion consensus of a group of experts by providing them a series of questionnaires with controlled opinion feedback (Dalkey and Helmer, 1963). The Delphi technique is recognized as a widely used and accepted method for collecting data from a number of experts (Hsu and Sandford, 2007).

The process of technique can be considered as a number of rounds or iterations of questionnaires which are answered by each participant and returned to researcher. In return, researcher collects and provides the position of whole group and participant's own status. This transparent environment enables the participants to reassess their opinion according to information provided in previous rounds. As a result, the technique is well-suited for consensus-building (Ludwig, 1997, Hsu and Sandford, 2007). In literature, it is suggested that three iterations are sufficient in general to collect the necessary data to reach a consensus (Custer *et al*. 1999). The general characteristics of each round are given below:

In the first round, an open questionnaire or, in case of a well-defined problem, a structured questionnaire is used for soliciting specific information about the content area. First round can be considered as the survey instrument for second round of data collection. In the second round, participants receive a second questionnaire and are required to reviews items summarized by the researcher based on the results of first round. The aim is to identify the areas of agreement / disagreement. The participants are also expected to rank or rate items to establish priorities with rationale behind them. In this round, consensus begins to form. In the final round, participants receive a third questionnaire items and ratings collected by the researcher and are asked to specify the reasons for remaining outside the consensus. The final round provides opportunity for participants to revise their judgment by making further clarifications.

3.3.7. Summary of the Chapter

In this chapter, the material and case studies that this study is based on and the methodology of the research have been presented. These include the sample mass-housing projects and its characteristics, the LCA framework and the methods of collecting and assessing the data.

For simplicity and a better reading experience, the definitions and calculations that are used for LCA are briefly given in this sub-section.

- **Function of the system:**

$$GWP_{total} = \sum GWP_{buildings} + \sum GWP_{transportation} + \sum GWP_{renewables} \quad (11)$$

- **Life Cycle Impact Assessment - Project Typology:**

$$GWP_{buildings} = \sum GWP_{building\ embodied} + \sum GWP_{building\ operation} \quad (12)$$

$$GWP_{building\ embodied} = \sum_{i=1}^{n} (GWP_i * \ quantity_i) \quad (13)$$

where:

n = Number of building components

$$GWP_{building\ operation} = GWP_{kWh} * \ kWh_{m2} \ * project\ area \quad (14)$$

- **Life Cycle Impact Assessment - Urban Context:**

$$GWP_{transport} = \sum GWP_{transport\ embodied} + \sum GWP_{transport\ operation} \quad (15)$$

$$GWP_{transport} = \sum_{i=1}^{n} (GWP_i * PKT_i * number\ of\ travels_i * distance) \quad (16)$$

where:

n = Means of transportations (private, bus or metro)

$$Number\ of\ travels = \#\ of\ dwelling * RD * \#\ of\ \ working\ days/year \quad (17)$$

where:

RD = Number of travels per dwelling (4,375 for Ankara)

- **Life Cycle Impact Assessment - Sustainable Solutions:**

$$GWP_{renewables} = \sum GWP_{renewables\ embodied} - \sum GWP_{renewables\ operation} \quad (18)$$

$$GWP_{renewables\ operation} = \sum_{i=1}^{n}(area_i * \ capacity_i \ * working\ hours/year\ ) (19)$$

$$GWP_{renewables\ embodied} = \sum_{i=1}^{n}(kWh/year_i * \ GWP/kWh_i\ ) \quad (20)$$

where:

n = type of renewable system (solar panel, solar thermal or wind turbine)

CHAPTER 4

RESULTS

4.1. Introduction

In this chapter, results of the LCA studies on the sample projects are presented in three sub-sections as; project typology, urban context and sustainable solutions. At the end of the chapter, the results are interpreted and a mock-up sample is generated in order to explain the decision support system.

4.2. Project Typology

Under project typology cluster, buildings in the sample projects were evaluated. The environmental impacts of following components were in the scope of cluster:

- embodied carbon of buildings during construction phase (A1-A4),
- operational carbon of buildings during operational phase (B1).

4.2.1. Embodied Carbon of Project Typology

Analysis on embodied carbon on three mass-housing projects according to CML-2001, GWP category was conducted. Focus of the analysis was construction phase which includes A1-A4 life cycle stages. Results were prepared in three levels:

- component,
- building,
- neighbourhood,

GWP values in $kg_{CO_2\text{-}eq}$ for total and per m^2 on these three levels were calculated. Statistical analysis on project and component level was conducted. Results were also compared with related databases and studies in literature to ensure overall validity.

4.2.1.1. Component Level

Categorization of the building components have been prepared by adopting the Uniformat-II classification system. A list of components for detailed analyses was prepared according to the bill of quantities of each project. Some of the building components which had low embodied carbon per unit and low quantity in project were omitted as their effect to the overall results were considered as insignificant. The list of components for the embodied carbon analyses includes 26 different components. The methodology and data sources utilized for the analyses for building components were given in Section 3.3.3. The embodied carbon of each component were calculated on per kilogram basis ($kg_{CO_2\text{-}eq}/kg$). Results can be seen in Figure 37.

COMPONENT INFORMATION			ENVIRONMENTAL IMPACT					
Building Cluster	**Building Component**	**Component ID**	**Acidification Potential**	**Eutrophication Potential**	**Global Warming Potential**	**Ozone Depletion Potential**	**Abiotic Depletion, Elements**	**Abiotic Depletion, Fossil**
Roof	Roof Cladding	Y.18.201	9,61E-03	1,41E-03	1,10E+00	2,15E-08	1,99E-06	1,09E+02
	Roof Heat Insulation	Y.19.061/004	2,94E-02	1,09E-02	6,62E+00	1,92E-07	6,15E-06	1,43E+02
	Roof Waterproofing	Y.18.461/005	8,82E-03	4,34E-03	1,73E+00	4,71E-07	3,35E-06	6,17E+01
Exterior Walls	Brick Wall 25 cm	Y.18.001/C08	3,95E-01	9,37E-02	1,87E+02	1,02E-01	6,52E-01	1,42E+03
	Brick Wall 20 cm	Y.18.001/C06	3,95E-01	9,37E-02	1,87E+02	1,02E-01	6,52E-01	1,42E+03
	Exterior Paint	Y.25.004	6,53E-03	1,82E-03	1,33E+00	9,51E-08	2,30E-06	2,51E+01
	Exterior Heat Insulation		6,15E-02	3,23E-03	7,65E+00	1,64E-10	3,50E-06	1,15E+02
	Exterior Cladding		5,18E-03	3,86E-02	1,04E+01	3,62E-07	1,11E-03	8,65E+01
	Exterior Plastering	27.525/1	9,50E-04	2,00E-04	1,90E-01	7,00E-08	4,10E-08	2,90E+00
Interior Walls	Brick Wall 13,5 cm	Y.18.001/C04	3,95E-01	9,37E-02	1,87E+02	1,02E-01	6,52E-01	1,42E+03
	Brick Wall 10 cm	Y.18.001/C02	3,95E-01	9,37E-02	1,87E+02	1,02E-01	6,52E-01	1,42E+03
	Ceramic Wall Tile 40x40cm	Y.26.008/405B	5,37E-01	2,72E-02	8,61E+01	2,98E-02	6,46E-05	0,00E+00
	Interior Paint	Y.25.003	1,86E-02	2,91E-03	1,88E+00	1,59E-07	1,10E-05	3,21E+01
	Interior Plastering	27.531	9,50E-04	2,00E-04	1,90E-01	7,00E-08	4,10E-08	2,90E+00
Windows & Doors	Window Profile	Y.23.244	1,39E-01	1,15E-02	1,74E+01	9,29E-03	4,21E-03	1,72E+02
	Window Glass	Y.28.645	1,43E-01	1,43E-02	1,72E+01	1,49E+00	4,39E+00	2,03E+02
Floors&Ceiling	Ceramic Floor Tile 40x40cm	Y.26.008/405A	5,37E-01	2,72E-02	8,61E+01	2,98E-02	6,46E-05	0,00E+00
	Stone Tile		5,92E-02	8,64E+00	2,17E+01	3,25E+00	4,30E+00	3,13E+02
	Laminated Wood		7,96E-02	1,60E-02	1,81E+01	6,21E+00	7,31E+00	4,77E+02
Basement	Foundation Concrete	Y.16.050/03	1,00E-01	6,29E-02	1,07E+02	4,31E-03	1,30E-05	3,07E+02
	Foundation Steel Reinforcement	Y.23.014-015	4,26E+00	3,91E-01	8,50E+02	1,14E-06	1,41E-04	1,02E+04
	Basement Heat Insulation	Y.19.056/013	6,15E-02	3,23E-03	7,65E+00	1,64E-10	3,50E-06	1,15E+02
	Basement Waterproofing	Y.18.461/005	8,82E-03	4,34E-03	1,73E+00	4,71E-07	3,35E-06	6,17E+01
Structure	Structural Concrete	Y.16.050/06	1,00E-01	6,29E-02	1,07E+02	4,31E-03	1,30E-05	3,07E+02
	Structural Steel	Y.23.101	1,51E+00	1,50E-01	3,14E+02	3,72E+00	2,42E+00	3,61E+03
	Structural Steel Reinforcement	Y.23.014-015	4,26E+00	3,91E-01	8,50E+02	1,14E-06	1,41E-04	1,02E+04

Figure 37. List of building components chosen for LCA analysis

Embodied impact of materials were analyzed depending on the data quality framework given in Figure 29.

For the analyses of the components, GaBi software (Thinkstep, 2017) was utilized with process and generic data. Also, environmental product declarations (EPD) were preferred for components without available process data. For components without process data and EPD, average of EPD values for similar building components were adopted. Data sources for environmental impacts can be seen in Table 12. The results of analyses of each component on per kg basis can be seen in Figure 38.

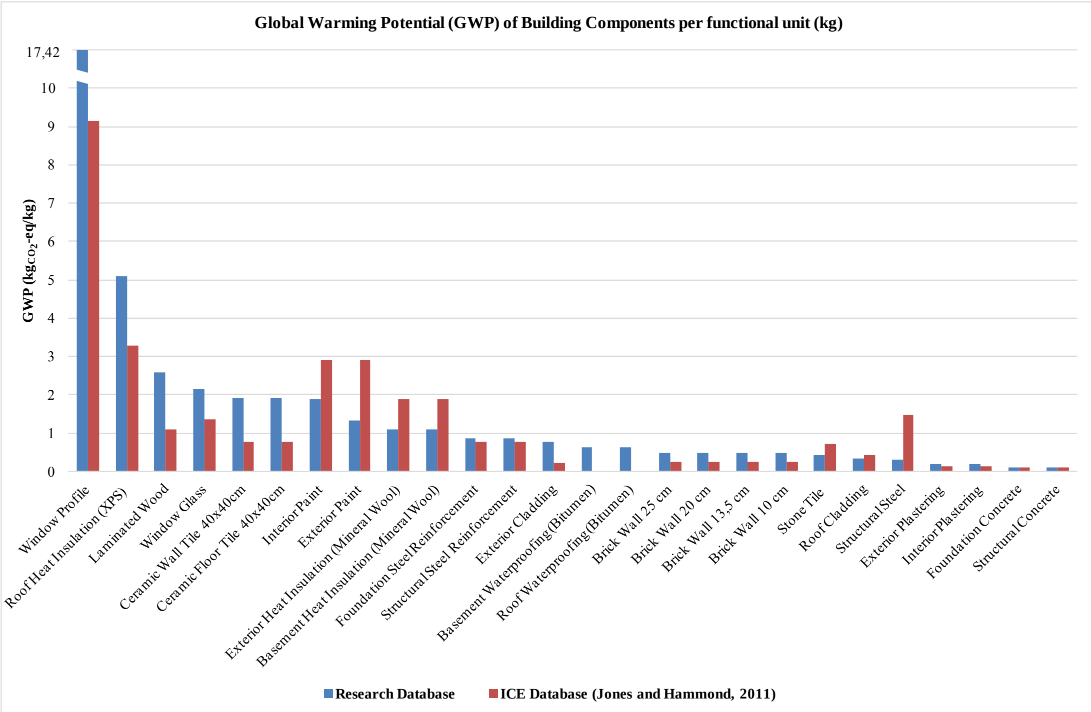

Figure 38. Embodied carbon of building components (adopted from Jones and Hammond, 2011)

The results of embodied carbon of each component per kg was compared with the embodied carbon and energy database, ICE (Jones and Hammond, 2011). It was seen that only one of the components had significantly different GWP value. In this study, the GWP value of aluminium window profile was found to be 17.42 where the ICE database displayed 9.16 $kg_{CO_2\text{-eq}}$.

The main reason for this difference was observed as the impact of transportation during the export of the aluminium. The material was transported mainly from the manufacturers in Greece and partially from Italy to Turkey, which includes both transportation means by ship and trucks. The distance of the main production site to the construction site is 1,100 km. The generic distance given in the LCA software program (GaBi) was 100 km. This implied more than 11 times of emissions from transportation to construction site, when compared to that of local materials. The impact of transportation for the aluminium window profile was 3.14 $kg_{CO_2\text{-eq}}$. The remaining difference was within the range of ICE database which has a tolerance of +/- 30%.

4.2.1.2. Building Level

After the analyses on components were completed, the GWP of 13 different apartment blocks in three sample project sites were calculated based on the GWP of the components and amounts in the bill of quantities. GWP per kg or m^2 calculated in previous section were multiplied by the specific quantity in the building, measured for each component.

The apartment buildings differ in height (number of storeys), total area and consequently GWP values. GWP/m^2 for individual buildings ranges between 227-319 $kg_{CO_2\text{-eq}}/m^2$. The average GWP/m^2 for these buildings has been calculated as 274 $kg_{CO_2\text{-eq}}/m^2$ (see Figure 39). A statistical study on the GWP of individual buildings was conducted in order to assess the correlations between the number of storeys, total area and GWP.

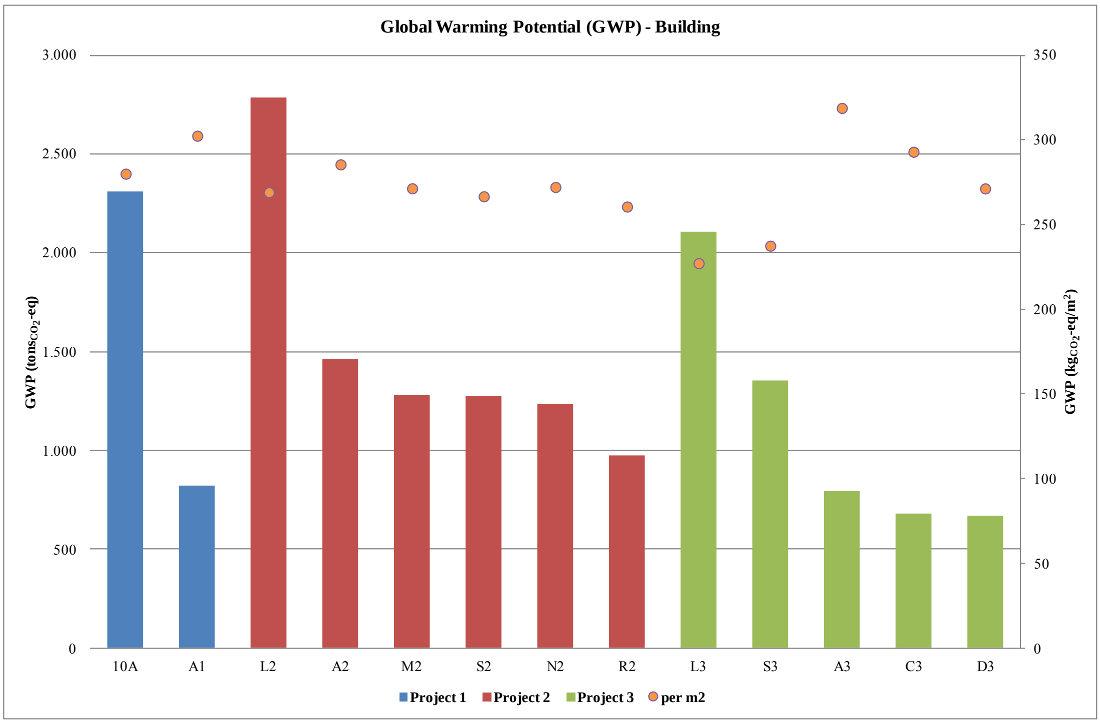

Figure 39. Global warming potential analysis of individual buildings

It was observed that there is an inverse relationship between the GWP/m^2 and the total number of storeys each block has. As can be seen in Figure 40, buildings with higher net floor area due to the number of storeys tends to have lower GWP per m^2. When the relationship between the number of storeys and the GWP/m^2 has been examined with a simple linear regression analysis, it was revealed that the model is meaningful ($f = 5.516$; $p = 0.039$). According to this model, the increase in the number of storeys (beta = -0,0578) decreases the GWP/m^2 (t = -2,349). In other words, the addition of one storey decreases the GWP/m^2 by 3.94 kg$_{CO_2\text{-eq}}$. The reason behind this fact was interpreted as the fact that the impact of roof and basement components remains the same even if number of storey increases, thus decreases the GWP per m^2.

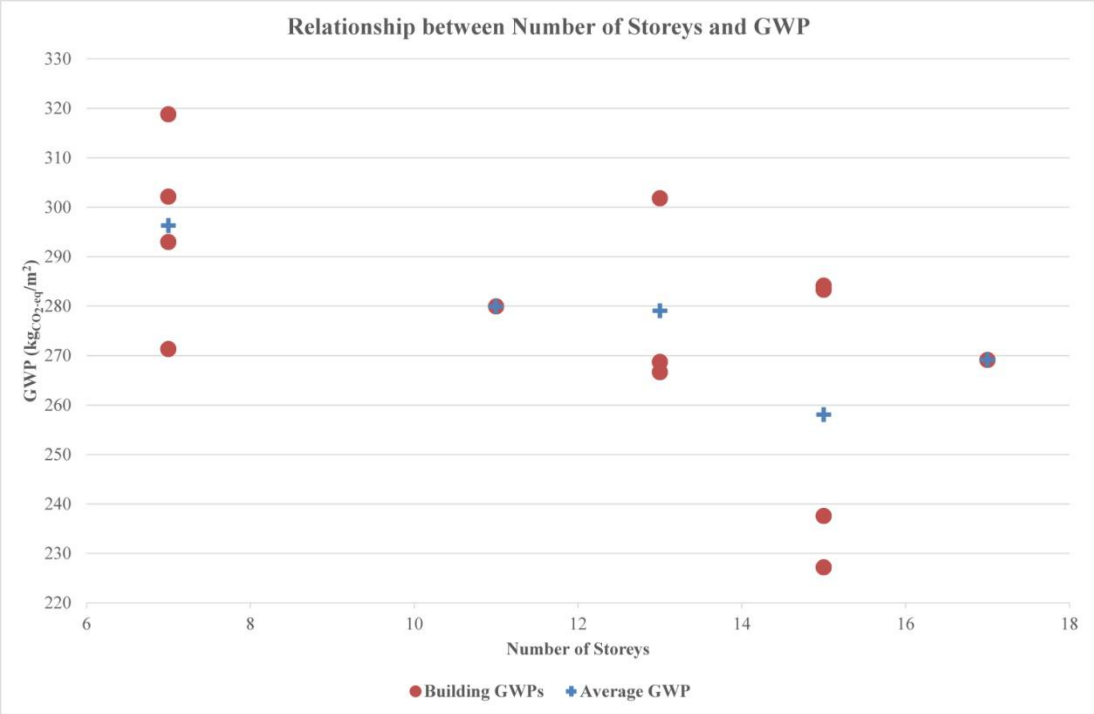

Figure 40. Relationship between number of storeys and GWP/m^2

In literature, there are studies which may be providing differing with this result. Treloar *et al.* (2001) and Oldfield (2012) concluded that the embodied energy of the structural elements is associated and increased with the building height. On the other hand, this association could only be observed when significantly different cases, such as 3 storey and 15 storey buildings, were compared. According to their research, the increase of embodied energy per m^2 with each additional storey in high-rise building group was insignificant. In the study of Du *et al.* (2015), GWP/m^2 for high-rise buildings was found out to be higher than of low-rise buildings. However, the correlation between the embodied energy and the building height was considered as weak for low rise and very weak for high-rise buildings by the same researchers. On the other hand, the results of Treloar *et al.* (2001) displayed a decreasing impact of building substructure on GWP/m^2 when number of storey increases which was parallel with the results provided in this study.

Although this research provides different result with these studies, it must be noted that the research efforts in literature compared buildings of different typologies (*e.g.*

low-rise vs. high-rise) with diverse architectural characteristics (*e.g.* different facade systems). In this study, the comparison was conducted between the buildings with exactly the same characteristics, but with different storey count. Moreover, the studies above utilized average values from other sources, whereas detailed LCA models were conducted in this study. Consequently, the conducted research is believed to provide a more focused and more precise information on the GWP and building height relationship in residential buildings.

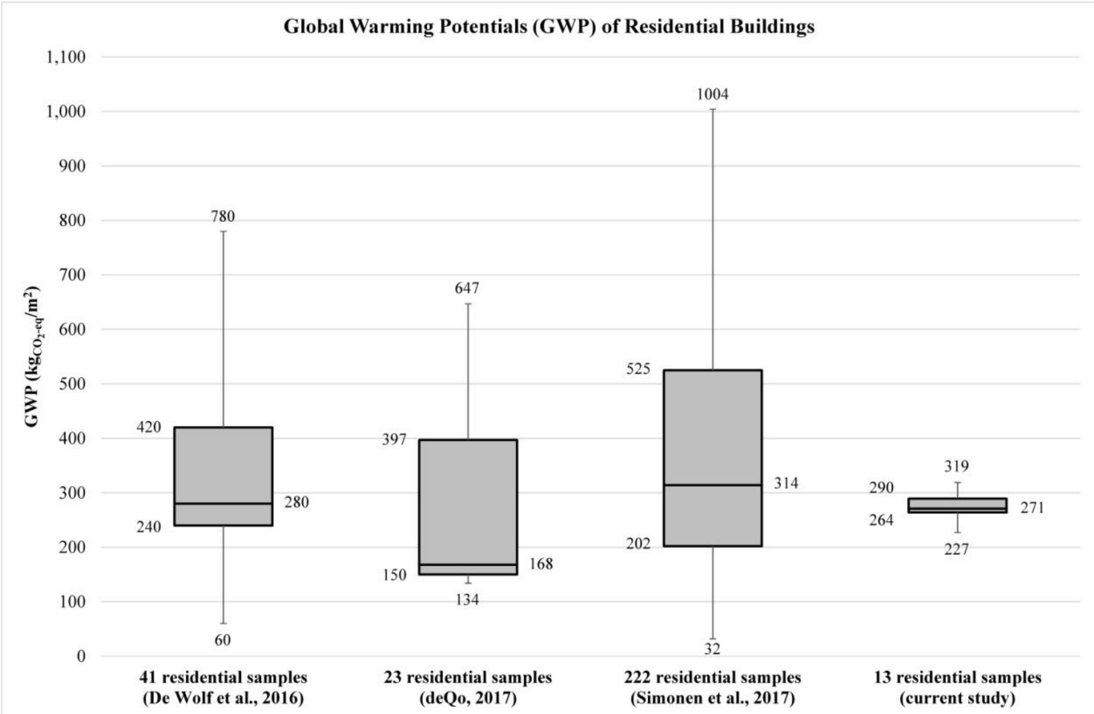

Figure 41. Comparison of embodied carbon in residential buildings (adopted from De Wolf et al., 2016, deQo, 2017, Simonen et al., 2017)

As can be seen in Figure 41, results for GWP per m^2 were also compared to study of De Wolf *et al.* (2016), in which 200 buildings were evaluated and 41 of them were residential buildings with different characteristics. The range for the residential buildings are observed to be between 240-420 kg$_{CO_2\text{-eq}}$/m^2. According to a more recent analysis (deQo, 2017), the embodied carbon outputs of 23 residential buildings (6-15 storey) is between 150-397 kg$_{CO2\text{-eq}}$/m^2. The study of Simonen *et al.* (2017) on embodied carbon benchmark demonstrated a range between 202-525 kg$_{CO_2\text{-eq}}$/m^2 among 222 residential buildings.

4.2.1.3. Neighbourhood Level

At neighbourhood level, the GWP of the individual buildings (see Figure 39) were multiplied by the block number specified for each building type in the project (see Section 3.2.2) they have. As shown in Figure 42, when the projects at neighbourhood scale were investigated for each building component, the largest share on GWP was originating from structural concrete (between 30-40%). Concrete has low GWP per unit but its quantity in buildings are often the highest. Components with high GWP per unit and average quantity in buildings, such as ceramics (17-21%), were second. The following components were varying between structural steel reinforcement, aluminium window profile and foundation concrete.

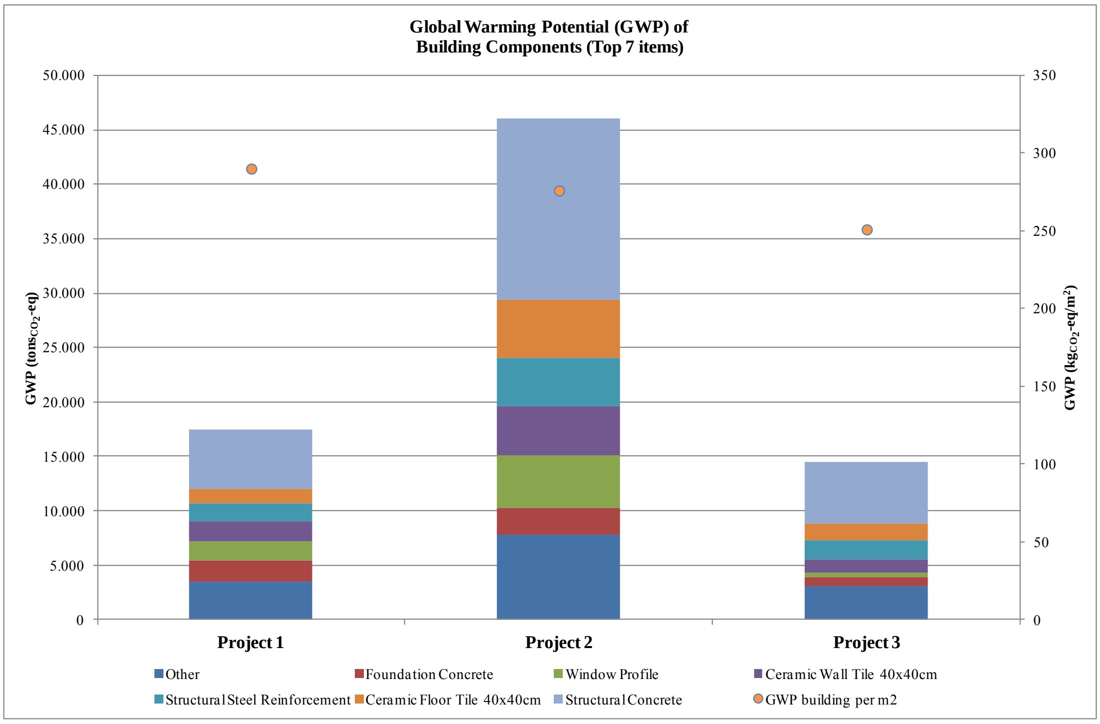

Figure 42. Global warming potential analysis of building components in neighbourhood level scale

When project typology components were evaluated;

- Project 1 with 14 blocks and 60,128 m^2 has the medium value of GWP with 17,442 $tons_{CO_2\text{-eq}}$,
- Project 2 with 32 blocks and 166,733 m^2 has the highest value of GWP with 46,023 $tons_{CO_2\text{-eq}}$,
- Project 3 with 13 blocks and 57,887 m^2 has the lowest value of GWP with 14,529 $tons_{CO_2\text{-eq}}$.

As displayed in Figure 42, the carbon emissions of the building components in the sample projects were calculated as 290, 277 and 251 $kg_{CO_2\text{-eq}}/m^2$ respectively with an average value of 272 $kg_{CO_2\text{-eq}}/m^2$.

4.2.2. Operational Carbon of Project Typology

Analysis on operational carbon on three mass-housing projects according to CML-2001, GWP category was conducted. Focus of the analysis was operational phase which includes B1 life cycle stage.

Operation of the buildings in the sample projects were evaluated according to the energy consumption per m^2, project area and GHG emissions of available heating system for a period of 50 years. Available heating systems in all three sample projects are gas-boilers.

Data on building operation related emissions was derived from Figure 30 and Figure 31 and Formula 3 in Section 3.3.4.3 was utilized. While calculating the operational energy and carbon, factors such as orientation, solar and internal gains and passive heating were not taken into account.

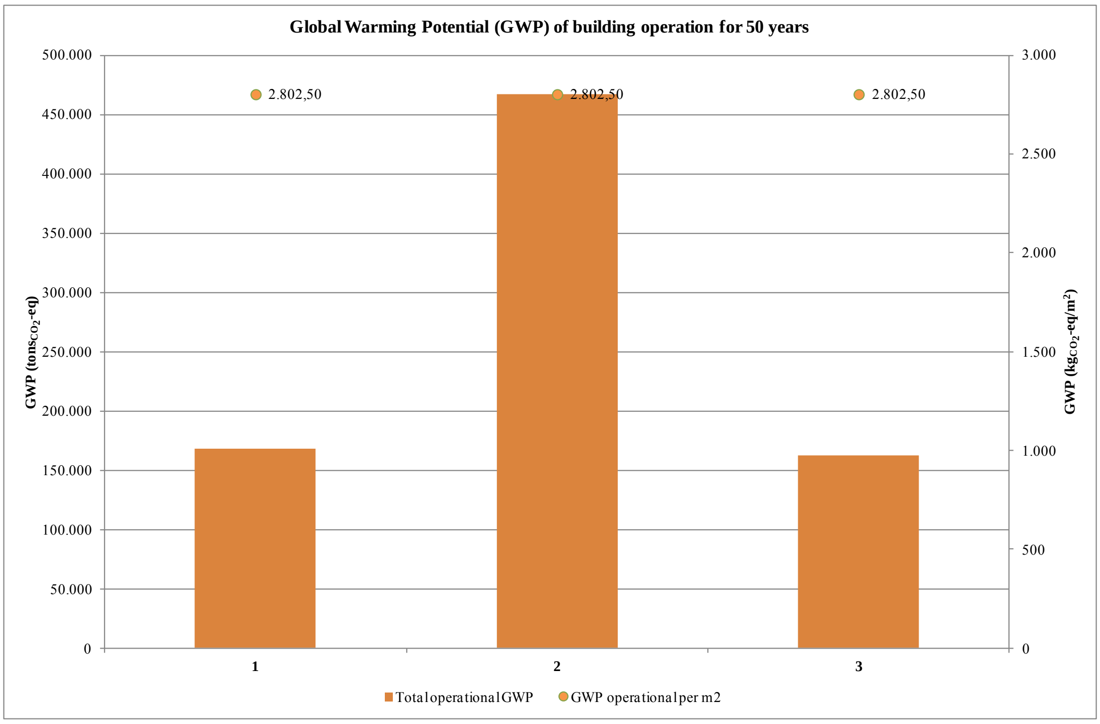

Figure 43. Global warming potential analysis of sample projects in building operation

When emissions regarding building operation were evaluated, as shown in Figure 43;

- Project 1 with 60,128 m^2 area and gas-boiler system, has the medium value of GWP with 168,509 tons$_{CO_2\text{-eq}}$,
- Project 2 with 166,733 m^2 area and gas-boiler system, has the highest value of GWP with 467,270 tons$_{CO_2\text{-eq}}$,
- Project 3 with 57,887 m^2 area and gas-boiler system has the lowest value of GWP with 162,229 tons$_{CO_2\text{-eq}}$.

As, all parameters related to operational emissions for each project were identical, the carbon emissions of the building operation in the sample projects were the same and calculated as 2.802 kg$_{CO_2\text{-eq}}$/m^2.

4.3. Urban Context

For calculating GWP of mass housing projects in urban context, impact of below components were taken into consideration. Impact of structural landscape works and transportation (infrastructure and operation) has been given in total and also been attributed to GWP per building m^2 for comparison among these components:

- embodied carbon of landscape design,
- embodied carbon of transportation infrastructure,
- operational carbon of transportation.

Integration of structural landscape works to LCA revealed one of the contributions of neighbourhood scale development to embodied carbon. The structural landscape works include pathways, playgrounds, parking lots and small-scaled technical areas. In this study, the effect of structural landscape on GWP of sample projects in urban context was observed between 9.6 - 11.2%, as can been seen in Figure 44. Landscaping adds an additional 37.4 $kg_{CO_2\text{-eq}}$ per building m^2.

For analyzing impact of embodied and operational impacts of transportation, calculations were conducted depending on the number of dwellings, number of travels, distance to city centre in km, and $kg_{CO_2\text{-eq}}$ emissions for transportation infrastructure and operational transportation per passenger kilometre travelled (PKT). Data on transportation in Ankara was derived from Table 13 and Formulas 1 and 2 in Section 3.3.4.2 were utilized.

The impact of the transportation infrastructure can be seen in Figure 44. In this study, the effect of the transportation infrastructure on GWP of sample projects in urban context was observed as 28%. Transportation infrastructure contributed an additional 93-111 $kg_{CO_2\text{-eq}}$ per building m^2.

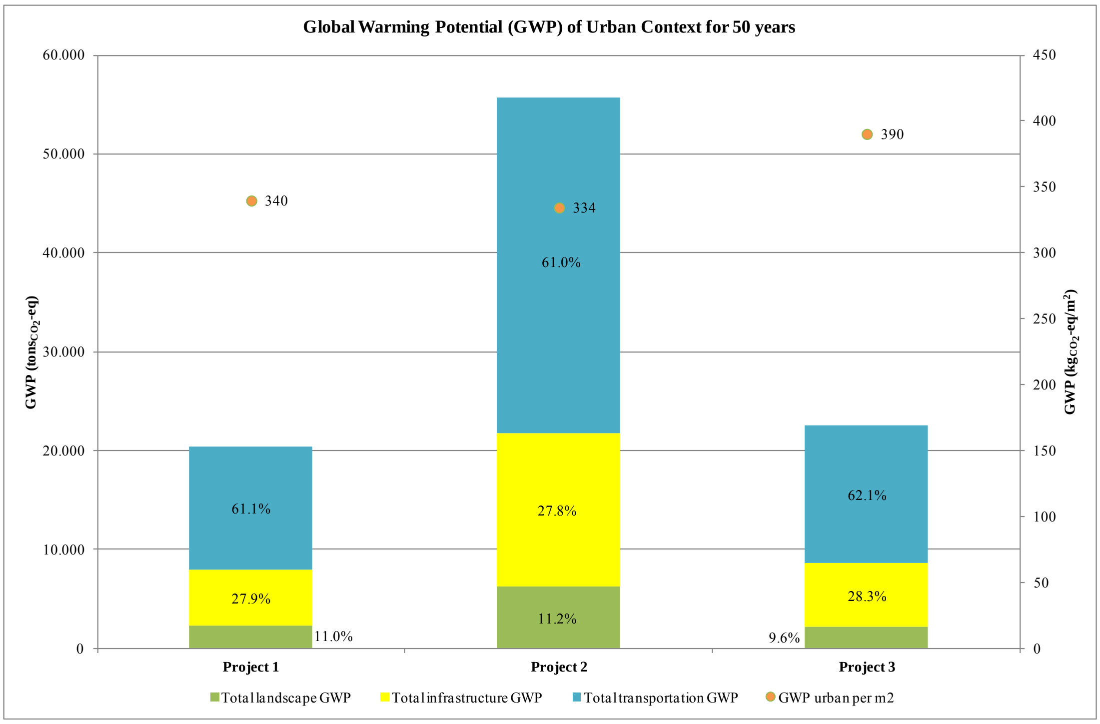

Figure 44. Global warming potential analysis of sample projects in urban context

The impact of operational transportation was observed to be highest among urban context components. In this study, the effect of the operational transportation on GWP of sample projects in urban context was observed as 61%. Operational transportation contributed an additional 204-242 kg$_{CO_2\text{-eq}}$ per building m^2.

When urban context components were evaluated;

- Project 1 with 277 dwellings which is located within 10 km to city centre has the medium value of GWP with 20,426 tons$_{CO_2\text{-eq}}$,
- Project 2 with 1237 dwellings which is located within 6.1 km to city centre has the highest value of GWP with 55,753 tons$_{CO_2\text{-eq}}$,
- Project 3 with 415 dwellings which is located within 7.5 km to city centre has the lowest value of GWP with 22,590 tons$_{CO_2\text{-eq}}$.

As displayed in Figure 44, the carbon emissions of the urban context components in the sample projects were calculated as 340, 334 and 390 kg$_{CO_2\text{-eq}}$/m^2 respectively with an average value of 354 kg$_{CO_2\text{-eq}}$/m^2.

4.4. Sustainable Solutions

As, there was no sustainable solutions in the existing condition of sample projects, no results were introduced in this section. In order to display how the projects could be optimized, sustainable energy systems were taken into consideration with the methodology provided in Section 3.3.4.3 and presented in Section 4.6 for additional information for decision-making process.

4.5. Interpretation of LCA of Sample Projects

In this section, results on three clusters are aggregated together and the overall findings are presented and interpreted. The total GWP of the sample projects were directly related with the total building area and distance to city centre.

- Project 1 with 14 blocks, 277 dwellings and 60,128 m^2 which is located within 10 km to city centre has the medium value of GWP with 206,379 $tons_{CO_2\text{-eq}}$,
- Project 2 with 32 blocks, 1237 dwellings and 166,733 m^2 which is located within 6.1 km to city centre has the highest value of GWP with 569,048 $tons_{CO_2\text{-eq}}$,
- Project 3 with 13 blocks, 415 dwellings and 57,887 m^2 which is located within 7.5 km to city centre has the lowest value of GWP with 199,348 $tons_{CO_2\text{-eq}}$.

As displayed in Figure 45, the carbon emissions of the three neighbourhood-scale mass housing projects for the lifetime period of 50 years were calculated as 3.432, 3.413 and 3.444 $kg_{CO_2\text{-eq}}/m^2$ respectively with an average value of 3.430 $kg_{CO_2\text{-eq}}/m^2$.

It was observed that the operational phase of the sample projects, which included building and transportation operation, was the greatest GWP contributor. Building operation was the highest with 82% and was followed second by embodied carbon of buildings with 8% among all components. The amount of time in which operational carbon overtakes embodied carbon was calculated between 5-6 years for the sample projects. In a study of Ibn-Mohammed *et al.* (2013), the overtake time for a typical office building was found to be 5 years, which is similar to finding of this study.

Even if the embodied carbon of developments has an immediate effect on GWP, in the period of 50 years, the overall effect of embodied carbon, including buildings, landscape and transportation infrastructure, dropped down to 12%.

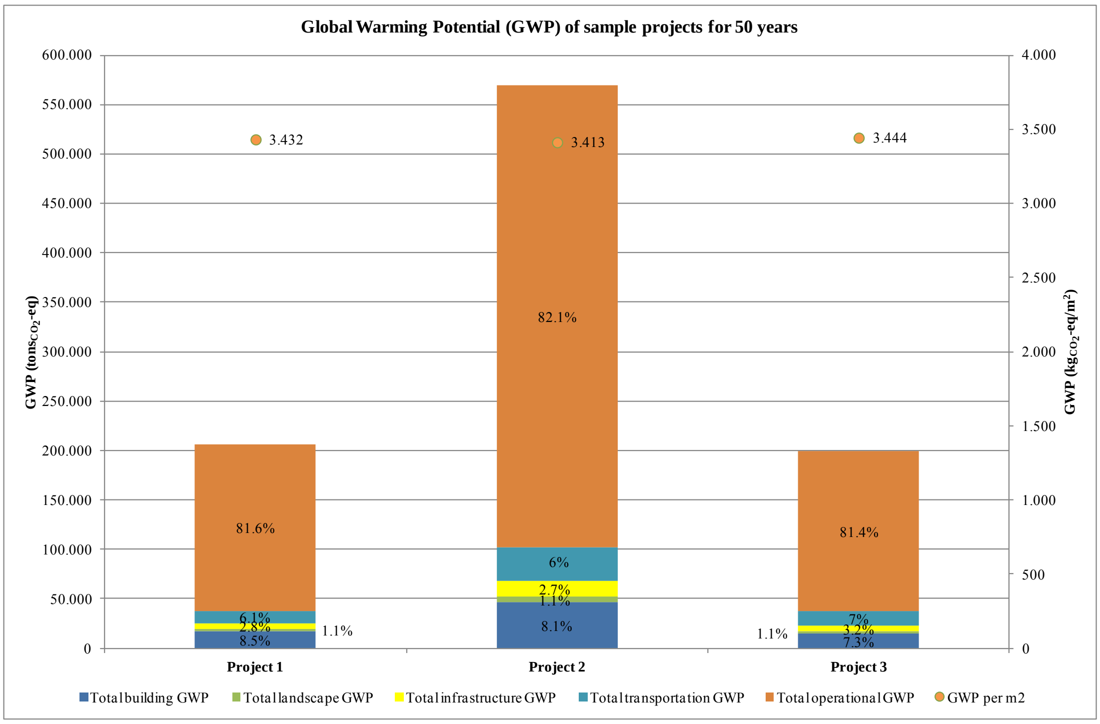

Figure 45. Global warming potential analysis of sample projects for 50 years

Among the embodied carbon contributors, the building components were highest and followed by that of the transportation infrastructure. The ratio between these two neighbourhood-scale component were depending on the number of dwellings and the distance to the city centre. As can be seen in comparison between Project 1 and 2; even if Project 1 had a longer distance to city centre than Project 2, it also had higher dwelling area. This implied less passenger travel number for Project 1 which even out the effect of distance. So, the impact of transportation infrastructure was around 6% for both projects. On the other hand, Project 2 and Project 3 had similar dwelling area whereas Project 3 was further away from the city centre than Project 2. So, this increased the effect of transportation infrastructure to 7% for Project 3. The effect of structural landscape was around 1% as the lowest contributor to GWP.

As the result of case studies, a representative LCA study for mass-housing projects in Turkey was developed, with an average embodied carbon of 272 $kg_{CO_2\text{-}eq}/m^2$. The overall ratio between clusters and components was compared with the studies in the literature and it was in line with the study of Du *et al.* (2015).

4.6. Decision-Support Tool - LCA of Scenario X

In this section, the DST system is displayed with a mock-up Scenario X (with baseline and improved parameters) which is given in detail in sub-sections below. Also, the use of sustainable solutions is provided in the improved Scenario X.

4.6.1. Description of Scenario X

Scenario X is located at Ankara, with 15 km distance from the city center. The project is within middle-income group type according to its cost per m^2.

It is built upon a lot with a total area of 80.000 m^2. The total area of mass housing project is 120.000 m^2. The project is a 600 dwelling mass housing project which is consisting of 30 blocks, with 5 storey blocks. There are also children playground and walkways for pedestrian entrances and vehicle roads around the plot. Open car parking is provided according to the municipality legislations.

Table 15. General characteristics of Scenario X

	Location	Distance to city centre (km)	Site area (m2)	Total construction area (m^2)	No. of blocks	No. of dwelling	Other facilities
Scenario X	Ankara	15	80,000	120,000	30	600	– children playground, – walkways, – vehicle roads,

In the project, there are 30 blocks with 5-storey and 20 dwellings that have 200 m^2 area with 4+1 plan layout. In Figure 46, parameters for Scenario X can be seen on the DST interface. As can be seen, no renewable energy systems are selected for the baseline state of the project.

			Parameters	Option	Value	Unit
I	Urban Context	a	Location	Far	15	km
		b	Transportation focus	Bus focus	43,44%	%
II	Project Typology	a	Heating System	Individual	295	$grCO_2/kWh$
		b	Number of Floors	Low	5	#
		c	Number of Households per floor	Manual	4	#
		d	Area of Households	Manual	200	m^2
		e	Number of Buildings	Manual	30	#
		f	Number of Households	Calculated	600	#
		g	Number of Occupants	Calculated	1980	#
		h	Energy demand per m^2	Fixed	190	$kWh/m^2.a$
		i	Embedded carbon per m^2	Calculated	327	$kgCO_2/m^2$
III	Sustainable Solutions	a	Renewable Energy Systems			
			Solar Panel	No	0	$grCO_2/kWh$
			Solar Thermal	No	0	$grCO_2/kWh$
			Wind	No	0	$grCO_2/kWh$
	Duration			Medium	50	year
	Project Area			Calculated	120.000,00	m^2
	CO_2 emission per m^2			Calculated	3.621,70	$kgCO_2.50.a/m^2$

Figure 46. Scenario X with baseline parameters (S1)

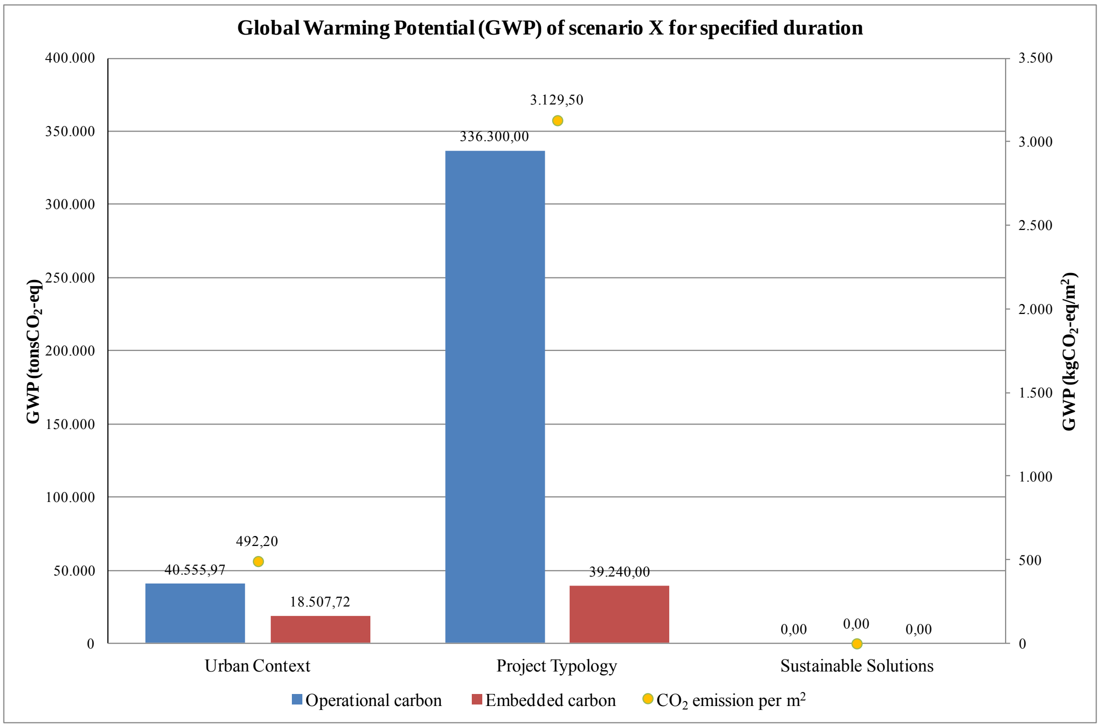

Figure 47. Results for Scenario X with baseline parameters (S1)

Results for Scenario X with baseline parameters can be seen in Figure 47. GWP of this mock-up scenario is given in three-clusters and for each cluster, embodied and operational carbon are provided.

In project typology cluster; for a building area of 120.000 m^2 which was composed of low-rise blocks that are heated by individual system, the total amount of GWP for 50 years was calculated as 375.540 $tons_{CO_2\text{-}eq}$. GWP per m^2 was 3.129,5 $kg_{CO_2\text{-}eq}/m^2$.

Share of embodied carbon of buildings was 34.800 $tons_{CO_2\text{-}eq}$ with 290 $kg_{CO_2\text{-}eq}/m^2$. Total amount and GWP/m^2 value were higher than average of sample projects (274 $kg_{CO_2\text{-}eq}/m^2$) due to lower building height. Embodied carbon of landscape was 4.488 $tons_{CO_2\text{-}eq}$. Total amount of embodied carbon for project typology cluster was 39.240 $tons_{CO_2\text{-}eq}$.

Share of operational carbon of buildings was calculated as infrastructure is 336.300 $tons_{CO_2\text{-}eq}$ with 2.802,5 $kg_{CO_2\text{-}eq}/m^2$. The average value was the same with sample projects, as operational carbon was dependent on heating system and it was the same as individual heating system for Scenario X.

In the urban context cluster; with 15 km distance to the city centre and a bus-focused transportation, the total amount of GWP impact for 50 years was calculated as 59,064 $tons_{CO_2\text{-}eq}$. GWP per m^2 was 492,2 $kg_{CO_2\text{-}eq}/m^2$. Total amount and GWP/m^2 value were higher than average of sample projects (354 $kg_{CO_2\text{-}eq}/m^2$) due to having higher distance to the city centre.

Number of travels to the city centre in a year was calculated around 483.000, according to Formula 2. Share of operational carbon of transportation is 40.556 $tons_{CO_2\text{-}eq}$ with 337,97 $kg_{CO_2\text{-}eq}/m^2$. Share of embodied carbon of transportation infrastructure was 18.507 $tons_{CO_2\text{-}eq}$ with 154,23 $kg_{CO_2\text{-}eq}/m^2$.

The total amount of embodied and operational carbon for 50 years for Scenario X was calculated as 434.604 $tons_{CO_2\text{-}eq}$ with 3.621,7 $kg_{CO_2\text{-}eq}/m^2$.

4.6.2. Scenario X with Improved Parameters

In this section, the purpose is to display the effect of certain parameters on the calculations by using DST. Scenario X was improved in certain parameters whereas geometry and distance to city centre remained the same.

The parameters were altered in each cluster as such (see Figure 48):

- Transportation focus was changed from bus focus to metro focus.
- Heating system was changed from individual to central.
- Solar panels and wind turbines were applied to the project.

Parameters				Option	Value	Unit
I	Urban Context	a	Location	Far	15	km
		b	Transportation focus	Metro focus	30,64%	%
II	Project Typology	a	Heating System	Central	260	$grCO_2/kWh$
		b	Number of Floors	Low	5	#
		c	Number of Households per floor	Manual	4	#
		d	Area of Households	Manual	200	m^2
		e	Number of Buildings	Manual	30	#
		f	Number of Households	Calculated	600	#
		g	Number of Occupants	Calculated	1980	#
		h	Energy demand per m^2	Fixed	190	$kWh/m^2.a$
		i	Embedded carbon per m^2	Calculated	327	$kgCO_2/m^2$
III	Sustainable Solutions	a	Renewable Energy Systems			
			Solar Panel	Yes	75	$grCO_2/kWh$
			Solar Thermal	No	0	$grCO_2/kWh$
			Wind	Yes	35	$grCO_2/kWh$
	Duration			Medium	50	year
	Project Area			Calculated	120.000,00	m^2
	CO_2 emission per m^2			Calculated	2.995,42	$kgCO_2.50.a/m^2$

Figure 48. Scenario X with improved parameters (S2)

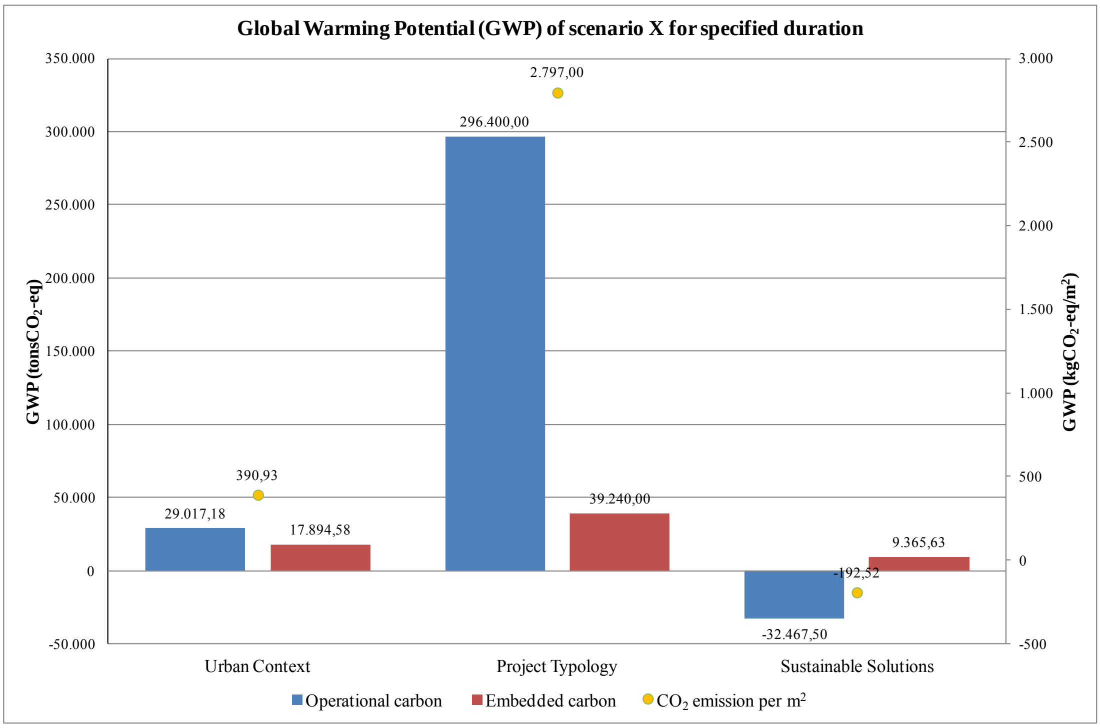

Figure 49. Results for Scenario X with improved parameters (S2)

In project typology cluster, with 120.000 m^2 building area which is composed of low-rise blocks. The heating system was changed to central system which has lower emission value per kWh. The total amount of GWP for 50 years was calculated as 335.640 $tons_{CO_2\text{-eq}}$. GWP per m^2 was 2.797 $kg_{CO_2\text{-eq}}/m^2$.

Share of embodied carbon of buildings is 34.800 $tons_{CO_2\text{-eq}}$ with 290 $kg_{CO_2\text{-eq}}/m^2$. Embodied carbon of landscape was 4.488 $tons_{CO_2\text{-eq}}$. Total amount of embodied carbon for project typology cluster was 39.240 $tons_{CO_2\text{-eq}}$. These values remained the same as geometry of the project was not altered.

Share of operational carbon of buildings is 296.400 $tons_{CO_2\text{-eq}}$ with 2.470 $kg_{CO_2\text{-eq}}/m^2$. With the change to the heating system, emission per kWh dropped from 295 to 260 $gr_{CO_2\text{-eq}}/kWh$. Its effect on total carbon of the project typology is around 11% decrease during 50 years of lifetime.

In the urban context cluster, distance to the city centre remained the same as 15 km and transportation was changed to metro focus. The ratio of metro usage was increased from 5% to 30%. The total amount of GWP impact of urban cluster was calculated as 46,911 $tons_{CO_2\text{-}eq}$ for 50 years. GWP per m^2 was 390,3 $kg_{CO_2\text{-}eq}/m^2$.

Number of travels to the city centre in a year was calculated around 483.000. Share of operational carbon of transportation is 29.017 $tons_{CO_2\text{-}eq}$ with 241,81 $kg_{CO_2\text{-}eq}/m^2$. Share of embodied carbon of transportation infrastructure was 17.894 $tons_{CO_2\text{-}eq}$ with 149,12 $kg_{CO_2\text{-}eq}/m^2$. A drastic 30% decrease in the amount of operational carbon was observed due to low emission of metro system.

In sustainable solutions cluster, integration of RE systems such as solar panels and wind turbines decreased the amount of operational carbon by 27.203 $tons_{CO_2\text{-}eq}$, meanwhile contributed to embedded carbon by 7.847 $tons_{CO_2\text{-}eq}$. Additional systems included solar panel application with a capacity of 1.800 kWp on 12.000 m^2 roof area and 5 medium-sized wind turbine per block which implies a total of 150 wind turbines. Each wind turbine is capable of producing 2.700 kWh per year.

The total amount of energy produced by wind turbines was 405 mWh/year. The amount of carbon emission saving per year was 105 $tons_{CO_2\text{-}eq}$ and 5.265 $tons_{CO_2\text{-}eq}$ for 50 years. The embodied carbon contribution of the system was 1.519 $tons_{CO_2\text{-}eq}$. The total of energy produced by solar panels was 2.093 mWh/year. The amount of carbon emission saving per year was 544 $tons_{CO_2\text{-}eq}$ and 27.203 $tons_{CO_2\text{-}eq}$ for 50 years. The embodied carbon contribution of the system was 7.847 $tons_{CO_2\text{-}eq}$.

The total amount of embodied and operational carbon for Scenario X with improved parameters was calculated as 359.450 $tons_{CO_2\text{-}eq}$ with 2.995,4 $kg_{CO_2\text{-}eq}/m^2$. The impact of sustainable solutions was a decrease of 23.101 $tons_{CO_2\text{-}eq}$ of carbon emissions.

As an additional revision to the assessment conditions, the duration for LCA was decreased to 30 years in order to display the environmental impacts in a temporal perspective.

Parameters				Option	Value	Unit
I	Urban Context	a	Location	Far	15	km
		b	Transportation focus	Metro focus	30,64%	%
II	Project Typology	a	Heating System	Central	260	$grCO_2/kWh$
		b	Number of Floors	Low	5	#
		c	Number of Households per floor	Manual	4	#
		d	Area of Households	Manual	200	m^2
		e	Number of Buildings	Manual	30	#
		f	Number of Households	Calculated	600	#
		g	Number of Occupants	Calculated	1980	#
		h	Energy demand per m^2	Fixed	190	$kWh/m^2.a$
		i	Embedded carbon per m^2	Calculated	327	$kgCO_2/m^2$
III	Sustainable Solutions	a	Renewable Energy Systems			
			Solar Panel	Yes	75	$grCO_2/kWh$
			Solar Thermal	No	0	$grCO_2/kWh$
			Wind	Yes	35	$grCO_2/kWh$
	Duration			Short	30	year
	Project Area			Calculated	120.000,00	m^2
	CO_2 emission per m^2			Calculated	1.928,05	$kgCO_2.50.a/m^2$

Figure 50. Scenario X with improved parameters with 30 years life-time (S3)

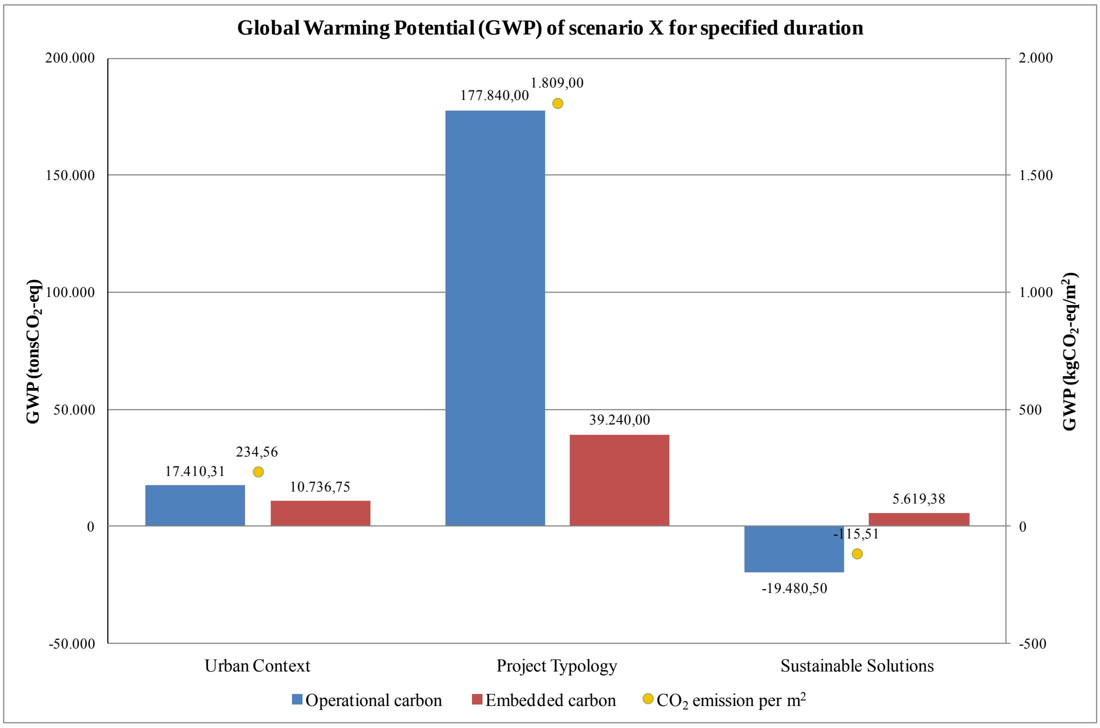

Figure 51. Results for Scenario X with improved parameters for 30 years of duration (S3)

The result was a sudden decrease in the operational outputs in all clusters. On the other hand, decrease in embedded carbon was observed for urban context cluster, as shorter life-time implied lower use of transportation infrastructure and less constructions. Also, embodied carbon of sustainable solutions also decreased due shorter life-time and maintenance.

Although, the operational emissions of buildings decreased from 296.400 $tons_{CO_2\text{-}eq}$ with 2.470 $kg_{CO_2\text{-}eq}/m^2$ to 177.840 $tons_{CO_2\text{-}eq}$ with 1.482 $kg_{CO_2\text{-}eq}/m^2$, embodied carbon remained the same for project typology cluster. The ratio of embodied carbon to operational carbon in project typology cluster changed from 13% to 22%. This example clearly showed that the immediate impact of embodied carbon should be carefully assessed along with the total emissions for 50 or 100 years.

4.6.3. Findings on Decision-Support Tool

According to the results of Scenario X with different parameters (see Figure 52), the largest contributor for carbon emissions is project typology cluster in any generated scenario. As the study provided a comprehensive LCA of building components, the DST performs well with precise results for the largest carbon contributor.

The impact of providing different transportation means on environmental impact of urban cluster was substantial for scenario generation. Switching means of transportation from bus-focus to metro-focus had an effect of 11% decrease on both embodied and operational carbon. RE systems in sustainable solutions cluster can provide savings over 10% for operational emissions and about 6% for whole life cycle emissions. It was significant to see the impact of embodied carbon of RE systems to the overall carbon emissions. Almost a quarter of carbon savings was negated due to the embodied carbon of the systems.

It was seen that the duration of lifetime had a significant effect on the ratio of embodied carbon to operational carbon. The immediate impact of embodied carbon of projects should be taken into consideration during LCA studies.

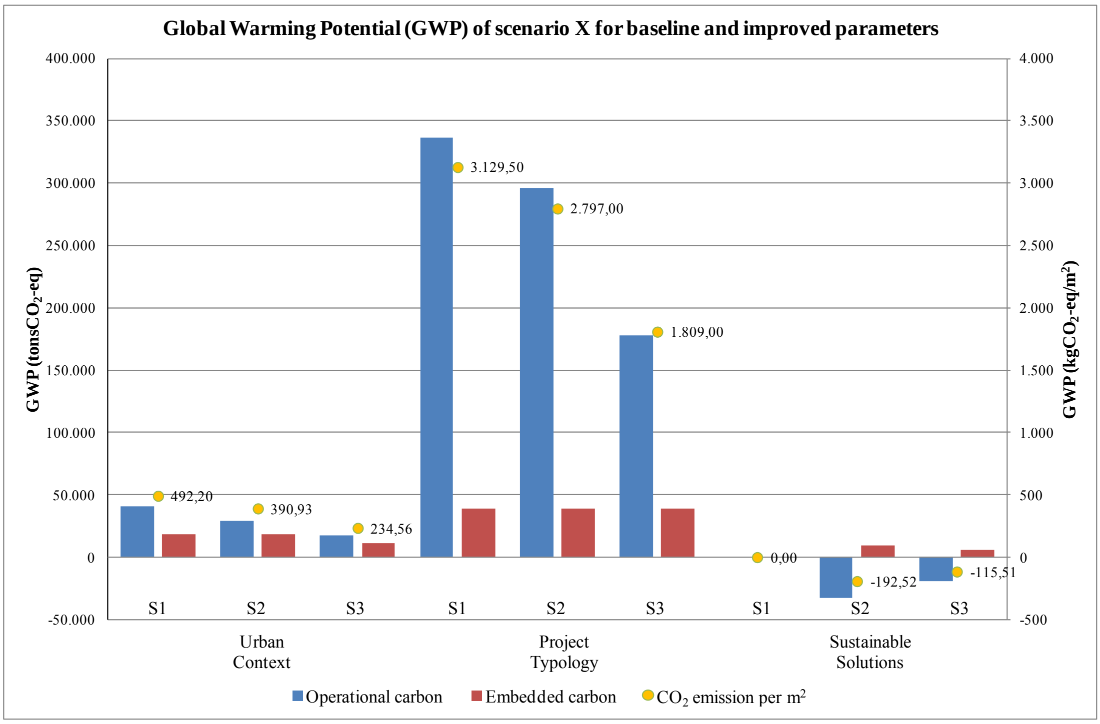

Figure 52. Comparison of Scenario X with different parameters

4.7. Validation of Decision-Support Tool with the Delphi Method

According to the methodology in Section 3.3.6, the Delphi method was conducted with 8 experts. The experts were selected among the respective institutions that are likely to make use of DST in daily professional tasks. It was aimed to form a group of diverse professions. In Table 16, characteristics of the participants can be seen.

Table 16. Participants of the Delphi Method

Expert	Profession	Title	Experience	Institution
1	City planner	Branch Manager	20	Ministry
2	City Planner	Branch Manager	15	Ministry
3	City Planner	Branch Manager	15	Ministry
4	City Planner	Expert	15	Private sector
5	Architect	Expert	11	TOKİ
6	City Planner	Expert	11	TOKİ
7	Architect	Expert	10	TOKİ
8	Architect	Designer	11	Private sector

The documentation for the questionnaire and answered received from the participants can be seen in Appendix B. A likert-scale from 5 to 1 was utilized for recording the answers in a structured and quantifiable manner. Indicator scores of 5-1 were used, where 5 implies the highest and 1 implies the lowest importance or impact. In the following sub-section, an analysis of the structured usability test is also given.

4.7.1. First questionnaire - General overview

The participants were provided a brief of the context of the study and the reasons why and how the Delphi methodology was conducted. Then, the questionnaire for the first round was provided to the participants (Table B.1). They were expected to rate general concepts with six questions regarding DST for environmental assessment of mass-housing projects, before they were introduced to the actual DST proposed in this study.

The first three quests were targeted to general concept of environmental impact of mass-housing project. The remaining three questions were about a hypothetical DST for assessment of this concept. The rationale behind the first round was to investigate the planning process from the perspective of decision-makers and experts.

The results of the first round (see Table B.2) were evaluated under two main categories given below. The first category is regarding the general concepts regarding environmental impacts of mass-housing projects. The second category of is regarding the use of a DST for planning sustainable mass-housing projects.

- **Environmental impacts of mass-housing projects**

The need for a DST on environmental impact assessment was approved by participants with a significant score of 4,3. All participants were aware of the sustainability concept due to their working environment. None of the participants shared the same work tasks with another, so they expressed the reasons for this need from different perspectives.

Among the characteristics that have impact on environment of a mass-housing project; carbon emissions and transportation shared the greatest emphasis from participants with scores of 4,6 and 4,5. It must be added that, all other characteristics received scores above 4. When these characteristics were clustered; urban context received the highest score with 4,4 where it was followed with sustainable solutions with 4,0 and the lowest score was for project typology as 3,8.

When the answers to second and third question was compared, it was seen that the participants were consistent in their perception of project typology and its features. Impact of project typology cluster was the least important with 3,8 whereas individual features such as construction area and number of dwellers received slightly higher scores such as 4,1 and 4. As the difference was not above 1 full point, the answers were considered as sufficiently consistent in between different questions. In Figure 53, the distribution of ratings for characteristics of mass-housing projects can be seen.

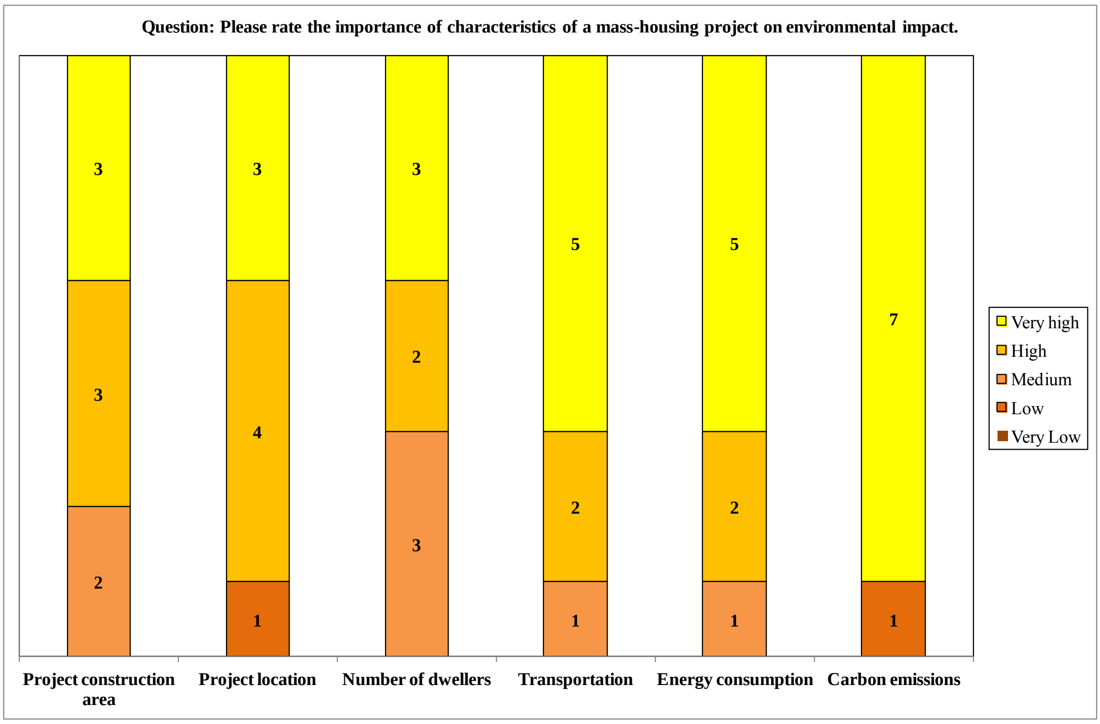

Figure 53. Results of first round of usability test - Characteristics of mass-housing projects

- **A DST for sustainable mass-housing planning**

When participants were asked to identify most important characteristics of a hypothetical DST regarding environmental impacts of a mass-housing project, comprehensiveness was fully agreed as the most significant feature, with a score of 5. Being multi-disciplinary was considered as very importance with 4,8. Accuracy of DST was identified as the least important with 3,3 as the tool is supposed to be used in the early design phase. In Figure 54, the distribution of ratings for importance of characteristics of DST can be seen.

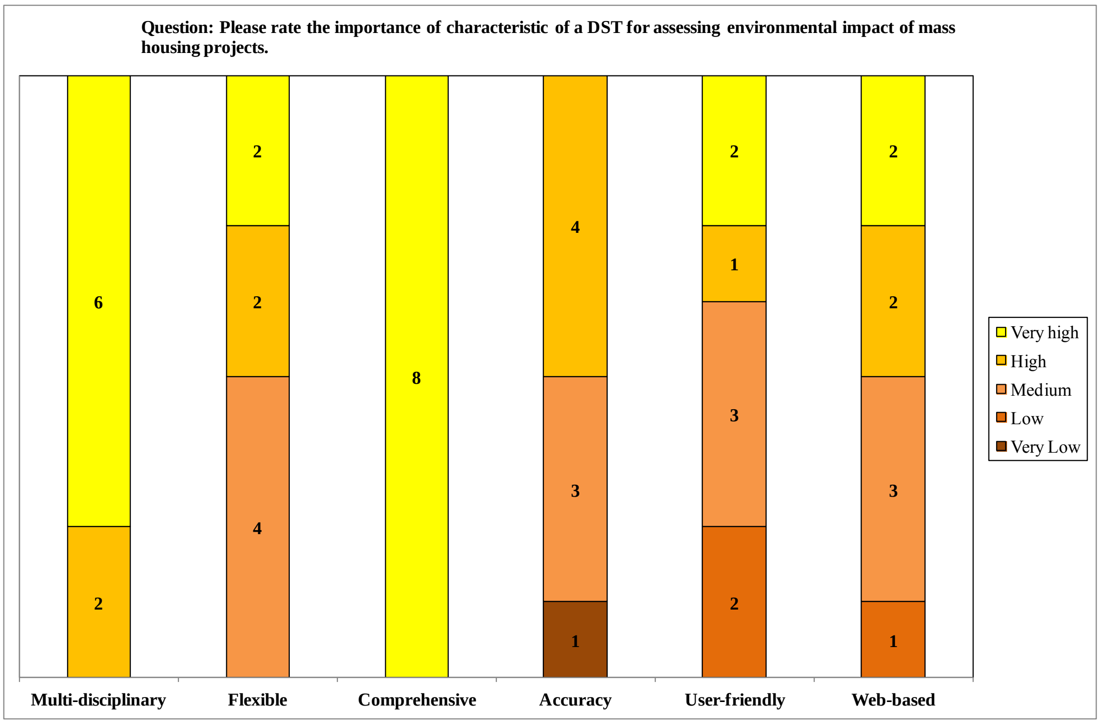

Figure 54. Results of first round of usability test - Characteristics of DST

The most important output of a hypothetical DST was considered as calculation of energy consumption and carbon emissions which was followed by feedback for transportation and integration of RE systems. It was agreed that the city planners and governmental institutions would benefit most and residents would benefit the least from using a DST on environmental impact assessment. In Figure 55, the distribution of ratings for importance of outputs of a DST can be seen.

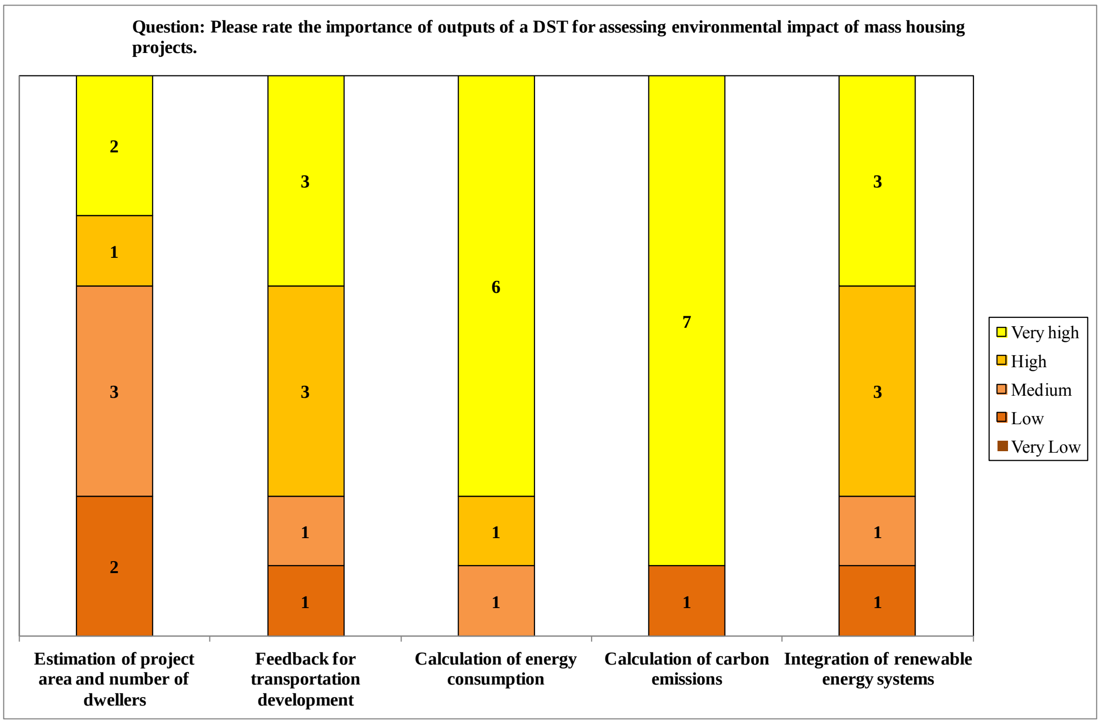

Figure 55. Results of first round of usability test - Outputs of DST

4.7.2. Second questionnaire - Beta-test of DST

For the second round, the participants were asked to use the DST and conduct a beta-test in a pre-defined scenario which is explained below. For the consistency of the outputs at the second round, all participants were requested to:

- generate a mass-housing project that includes 200 households. Each household should have 150 m^2, number of storeys for blocks should be 5 and the blocks should be heated with individual heating systems.
- explore preferences in urban context and sustainable solutions in order to have a carbon emission below 2.800 $kg_{CO_2\text{-}eq}/m^2$ for a lifetime of 50 years.
- revise the project preferences to generate a mass housing project which is located at 10km distance to city centre, have a private transportation focus and have only solar panel as sustainable solution.
- explore preferences in project typology in order to have a carbon emission below 3.100 $kg_{CO_2\text{-}eq}/m^2$ for a lifetime of 50 years.

The thresholds for carbon emissions given at the pre-defined scenario were defined in such a way that users need to make use of all parameters, for a better judgement of the tool. The first threshold of 2.800 $kg_{CO_2\text{-}eq}/m^2$ was low enough to necessitate the usage of at least two RE systems, and even then the participants would have to alter the means of transportation to achieve this value. The second threshold also was low enough, so that the participants would need to alter the heating system and may need to choose high building type to benefit from low embodied carbon.

After the participants performed the necessary tasks with the DST, they were provided with the second questionnaire. In Table B.3, the second questionnaire is displayed. The questions for the second round was prepared according to results of the first round. The results of the second round is given in Table B.4.

- **Features of the DST according to beta-test**

In the end of the second round, it was seen that the participants found the DST to be multi-disciplinary, with a score of 4,1. It was also agreed that the tool was adequately comprehensive and significantly easy to use, with scores of 3,8 and 4, to achieve feedback on environmental impacts of a mass-housing projects. On the other hand, all participants emphasized that the tool can be improved and extended.

However, the accuracy of the tool was considered as the feature to be least appreciated. When participants were asked about the reason for this, it was put forward that they did not find the need for a high accuracy for such a tool. It must be noted that the importance of accuracy was considered as least important in the first round. On the other hand, the proposed DST received a slightly higher score for accuracy than the first round. In Figure 56, the distribution of ratings for importance of outputs of the proposed DST can be seen.

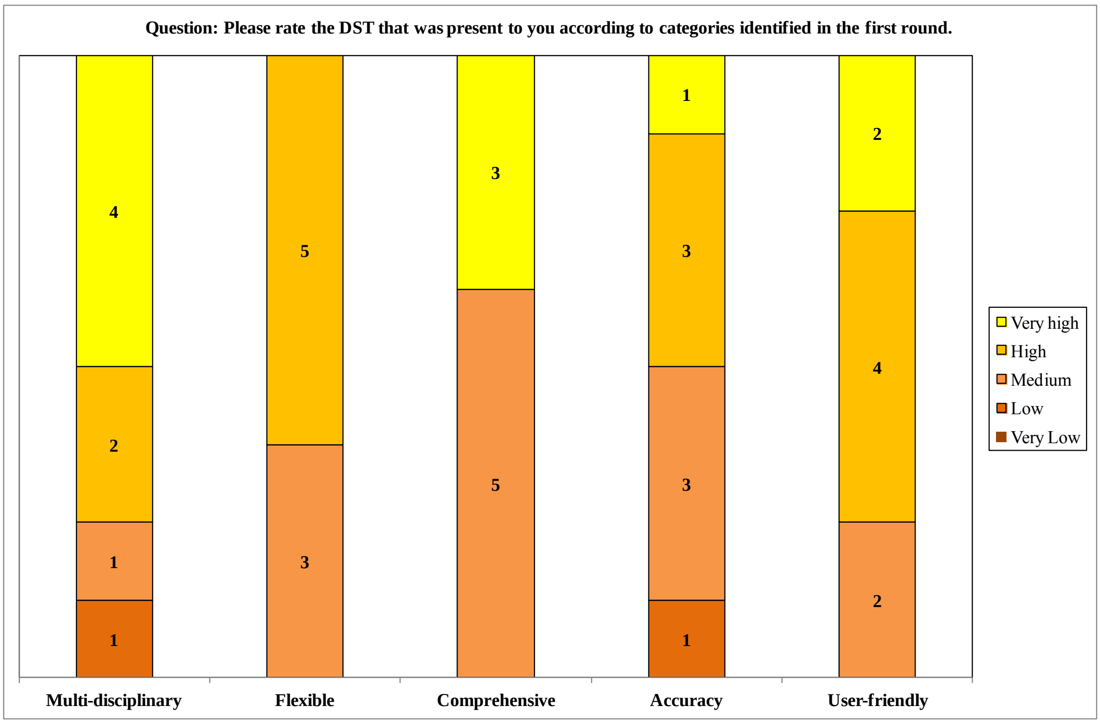

Figure 56. Results of second round of usability test - Characteristics of DST

- **Outputs of the DST**

When the outputs of the DST were discussed in the second question, it was found out that the most important outputs for the participants were integration of RE systems to the planning of mass-housing projects and calculation of energy consumption, with significant scores of 4,4 and 4,6. The least important output was introduced as estimation of construction area and number of dwellers, with a score of 3,6.

It was seen that the scoring for the importance of outputs of the DST was in line with the perception of a decision support system in the first round. It was important to see that the integration of RE systems was recognized by the participants with a high score, as this integration was one of the main objectives of this study. In Figure 57, the distribution of ratings for importance of outputs of a DST can be seen.

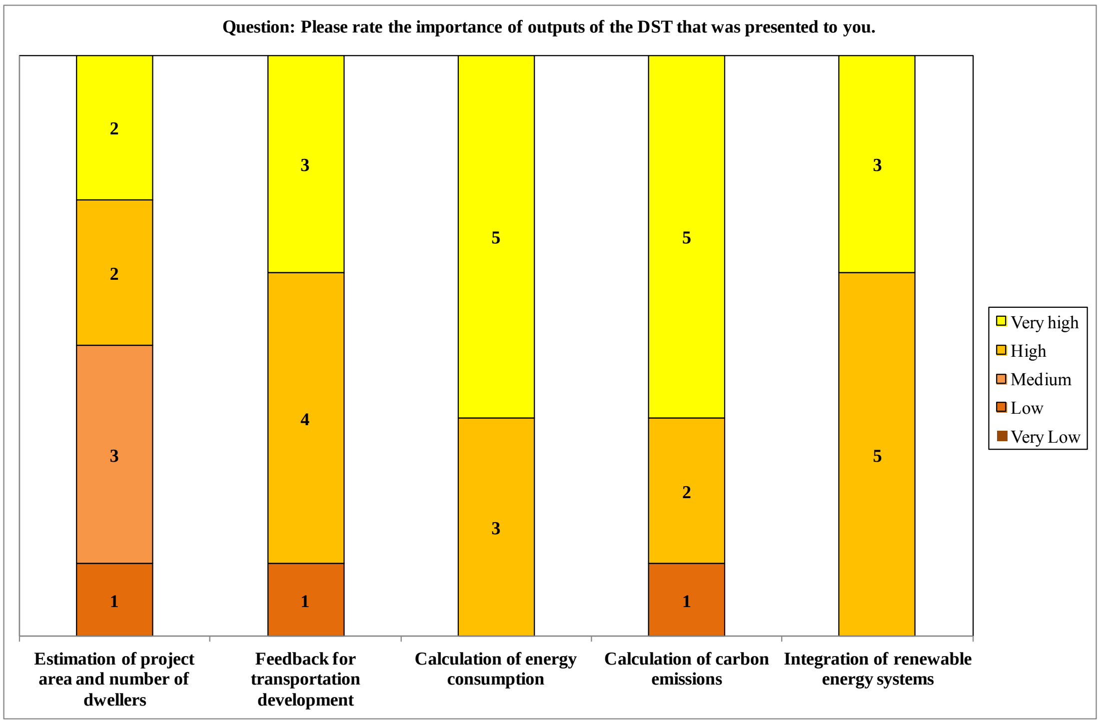

Figure 57. Results of second round of usability test - Outputs of DST

4.7.3. Third questionnaire - Consensus

In the final round, the participants were provided with a third questionnaire which can be seen in Table B.5. The participants were presented with the average grades of the previous rounds. The aim was to enable participants revise their grades to have a consensus according to the general opinion. It was observed that, there was a clear difference in perspectives due to the participant's profession. Architects generally assigned higher scores for features regarding project typology and RE systems than features regarding urban context, such as project location and number of dwellers. The situation for city planners was vice-versa.

When participants were asked to review their scores for first questionnaire, Participant 8 decided to increase the rating for project location from 2 to 3, claiming that location may be more important when distances over 30-40 km are considered. Participant 1 refused to have any changes on scores for energy consumption and carbon emissions, claiming that these are consequences of other features, hence they are less important. Participant 1 also agreed to change score for accuracy of a DST from 1 to 2, claiming that DST should have some basis on the calculation of outputs and agreed with majority that accuracy should be the least important feature.

When participants were asked to review their scores for second questionnaire, Participant 1 refused to revise score of 2 for multi-disciplinary of the DST, claiming that the urban context should have had more parameters. There was no other revisions regarding the characteristics of the DST. In Figure 58, the distribution of revised ratings for importance of characteristics of the proposed DST can be seen.

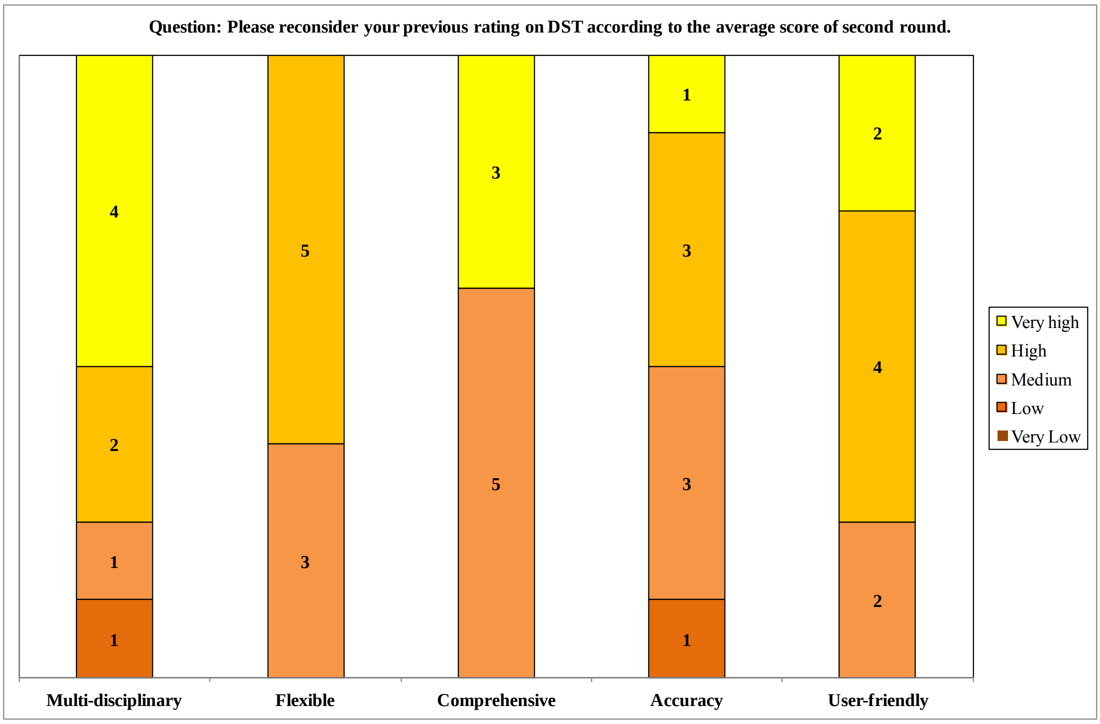

Figure 58. Results of third round of usability test - Characteristics of DST

Participant 1 decided to increase the rating for feedback for transportation from 2 to 3, claiming that Participant 6 refused to revise score of 2 for estimation of construction area and number of dwellers, claiming that there is an existing tool which generates the same output. In Figure 59, the distribution of revised ratings for importance of outputs of the proposed DST can be seen.

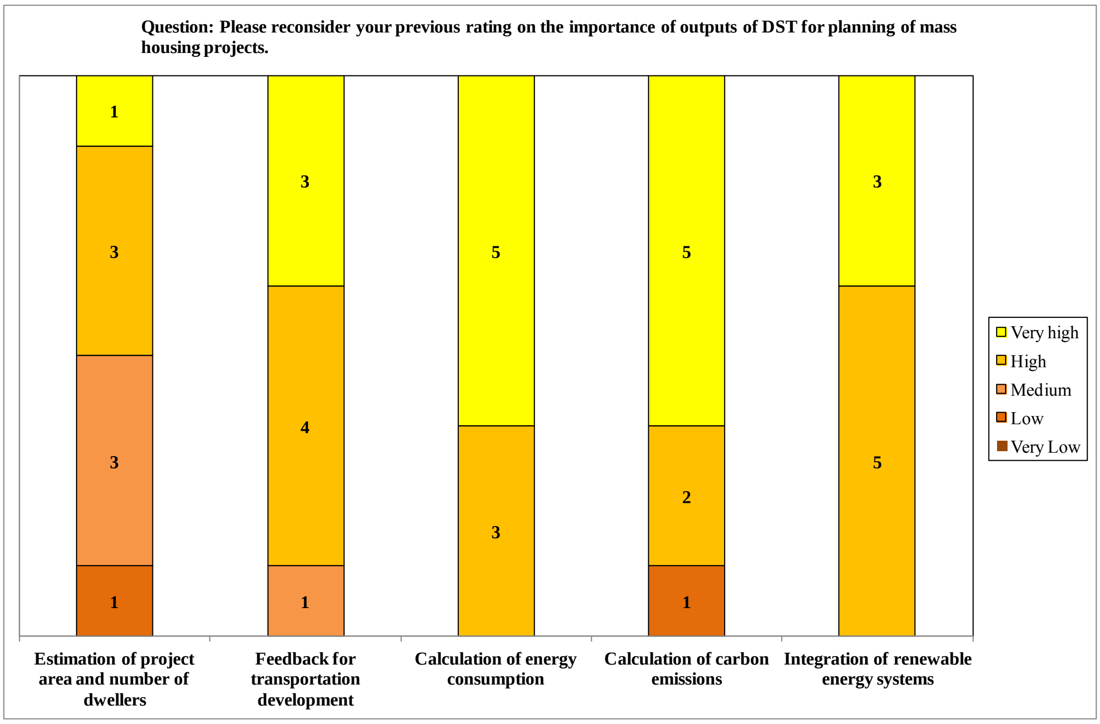

Figure 59. Results of third round of usability test - DST outputs

As a result of the validation technique, it was put forward that both architects and planners reacted to the DST tool in a positive perspective. The reason for recognizing the DST as a valuable contribution was the lack of a similar tool in the existing procedure. The average of ratings for features of DST was agreed as 3,8 and ratings for outputs of DST was agreed as 4,2. It must be noted that, except than three cases, the participants were able to reach to a consensus.

CHAPTER 5

CONCLUSION

5.1. Introduction

In this chapter, proposed LCA methodology, results of sample projects and the decision-support tool are discussed and presented with relevant recommendations. First, a summary of research is given and important findings are highlighted. Then, these findings are further discussed in the respective subheading. Findings of the research are concluded in the section “Final remarks” and future studies are suggested at the next section.

5.2. Summary of the Research

This study put forward a Life Cycle Assessment based decision-support tool for early design phase of *neighbourhood-scale built environment*. A data collection procedure was conducted with a three-clustered database, which enables flexibility on analysis of different components in urban context, building typology and sustainability solution aspects. A data validation system was introduced in order to increase the data quality and enhance accuracy of the framework. In the following sections, summary of research is given in details under respective sub-headings.

5.2.1. LCA Framework for Neighbourhood Scale

In order to evaluate the environmental impact of neighbourhood scale built environment, first an LCA framework based on ISO 14040 and EN 15978 standards was introduced. Beginning with goal and scope definition (including the function of the system and unit, boundaries, life cycle assessment method, *etc.*) and followed by life cycle inventory analysis (including necessary data, means of data collection and management), the phases of life cycle assessment were adapted for those of a neighbourhood scale mass-housing project.

Subject of the study was selected as the mass-housing projects in Ankara that are produced for middle-income group by TOKİ in last ten years. It was considered that mediocre cost per area and high rates of construction proves this group to be the most efficient mass-housing group for conducting this research. The function of the system was defined as the total of the CO_2 or equivalent greenhouse gases emitted to the atmosphere during the lifespan of mass-housing projects. A hybrid LCA methodology was utilized for impact assessment in order to enhance the accuracy of the analysis where available data was to be utilized in detail whereas missing data was to be compensated with generic data.

Environmental impacts of a mass-housing project were categorized into three such as; project typology, urban context and sustainable solutions clusters. By grouping the inputs and outputs according to these clusters, it was aimed to evaluate the mass-housing projects at various scales from different perspectives. According to this structure, a database structure was developed as the basis for environmental assessment in different levels such as; component, building and neighbourhood. Several layers of data were integrated in neighbourhood scale, such as transportation, landscape and infrastructure.

5.2.2. Three-clustered Database

The collection of environmental data on mass-housing projects was achieved by performing case study efforts which were based on well-structured data templates for different level of components. Uniformat-II structure was utilized for building components and materials. Urban context cluster was developed according to transportation preferences in Ankara. Environmental impacts in urban scale were adopted from various studies in the literature. Sustainable solution cluster was a collection of most common renewable energy systems that are being used and researched in Turkey.

Sources for the environmental data of building components were; environmental product declaration (EPD) documents, process data from manufacturers and generic data from an LCA software database. It was seen that EPD documents in Turkey regarding building components and materials increased. Hence, it was possible to have average values of EPDs or even use material's own EPD document directly.

Significance of the three-clustered database is the individual focus on each cluster while keeping the interactions between clusters valid. It also enables for more clusters to be integrated or different kind of project typologies to be studied in case the scope is changed.

At the end of the analysis, an environmental impact database with three main clusters on mass-housing projects at neighbourhood scale was achieved. Significant features are;

- The project typology cluster included different embodied carbon values for three different project typologies according to height of the buildings. Also, three different heating systems such as individual, central and district were included with respective carbon emissions per kWh.
- The urban context cluster included three different means of transportations with respective embodied and operational carbon emissions on a passenger-kilometer-travelled basis.
- The sustainable solutions cluster included different embodied and operational carbon values for three renewable energy systems such as solar panel, solar thermal and wind turbine on a per kWh basis.

5.2.3. Data Validation System

The proposed LCA model aims to increase the precision of LCA studies according to quality of data inventory. The model suggests appropriate impact assessment methods for components depending on the quality of environmental data (Kayaçetin and Tanyer, 2018). It also emphasizes the necessity to set a standard for data quality display. Without providing the data source explicitly, the level of uncertainty in LCA studies prevents comparison of LCA studies and further adoption of LCA results; decrease the credibility of outputs; and hinder the ability to build up databases.

The framework suggests a hybrid impact assessment methodology that directs users to use process-based or LCA with generic data depending on (i) the environmental impact level of component and (ii) quality of collected data. The purpose is to make best out of available data and will increase the efficiency of research efforts versus time spent. It is aimed to introduce a standardized framework for explicitly displaying data sources and evaluation.

It is also suggested to differentiate between building components with high environmental impact and low environmental impact. For this categorization, the average values in available databases are utilized. As the precision and quality of these databases increase, the definition of primary and secondary components can be enhanced. It provides practitioners with flexibility on data quality assessment. By using weighting on data quality indicators, the practitioners are capable of putting forward data quality with better precision.

Comparison of LCA studies is of crucial important to evaluate the different methods of impact assessment and system boundaries in order to develop best practices. For investigating best practices, the outputs must have high quality and credibility of results should be justified. Only when the LCA studies become standardized and credible enough to share and adopt inputs/outputs, then common databases on LCA results can be achieved.

During the impact assessment phase, the calculated environmental impact values were compared with literature and available databases at different levels, in order to validate the outputs of the study. Results on building components were compared with the ICE database (Jones and Hammond, 2011) and the results on buildings were compared with the embodied carbon database (deQo, 2017).

5.3. Discussion

In this section, significant findings are further discussed in detail. LCA results of case studies and their implication as a reference LCA study for mass-housing projects in Turkey is introduced. Then, the significance of the DST is given in detail with a focus on three-clustered database, use of renewable energy systems in mass-housing projects and validation test by the experts.

5.3.1. Reference LCA Study

The framework was conducted on three sample projects and results were displayed in a hierarchical manner based on scale. Embodied carbon assessments initiated with building components and progressed to buildings and concluded in neighbourhood level. Operational carbon assessments were conducted for each cluster for 50 years of life-time.

GWP impact category for 26 building components were calculated. These values were collected and utilized in a three-clustered database. They were used to assess the total embodied carbon of three mass-housing projects and the outputs were compared to each other and with the related studies in the literature. It was observed that both GWP values at component and building level were parallel with international examples.

According to the LCA analyses of 3 mass housing projects comprising 13 distinct building types, the average amount of carbon emissions for 50 years was 3.430 $kg_{CO_2\text{-}eq}/m^2$. In the project typology cluster, only 271 $kg_{CO_2\text{-}eq}/m^2$ (8.5%) of these emissions originate from embodied carbon of buildings. The main contributor was operational carbon of the buildings with an average amount of 2.802,5 $kg_{CO_2\text{-}eq}/m^2$ (81%). In the urban context cluster, the embodied carbon of transportation infrastructure and structural landscape added an average of 136,7 $kg_{CO_2\text{-}eq}/m^2$ (4%) where as operational emissions from transportation contributed with 218 $kg_{CO_2\text{-}eq}/m^2$ (6.5%).

The operational phase dominated the carbon emissions in a life-time of 50 years. It was also observed that there was a significant difference when urban context is included in the LCA. Altering means of transportation may have an effect of 11% decrease in total carbon emissions. The results revealed the necessity to put more focus on larger scale built environment for more precise results.

The sample projects enabled for achieving a representative LCA model for mass-housing projects which provides validated average values for embodied and operational impacts. This reference LCA model was utilized to generate a tool for decision support during early design phase of mass-housing projects.

5.3.2. Decision Support Tool

Depending on data collection on sample projects in the format of a three-clustered database, a decision-support tool (DST) was developed for mass-housing projects in neighbourhood scale. The amount of input that is required for DST to perform was adapted to a level such that it could be utilized at early-design phase. In the end, the tool was utilized for generating different scenarios of a mass-housing project and comparing them by altering several parameters. By developing a set of connections between building, urban and RE system parameters, the DST displayed interactions between main features of a mass-housing project from an environmental point of view.

The DST is capable of generating mass-housing project with varying features such as project location, building height, number of dwellings and heating system. According to the height of the buildings, specific embodied carbon values are assigned. Depending on the number of dwellings, DST can calculate the number of travels and utilizes means of transportation to estimate the environmental impact of urban context.

The most significant feature of the DST is the integration of sustainable solutions into planning of mass-housing projects in neighbourhood scale. It enables assessment of embodied and operational carbon of RE systems in mass-housing projects. It was seen that RE systems can provide savings over 10% for operational emissions and about 6% for whole life cycle emissions. The outputs of the tool may yield valuable input for designers and urban planners for decision-making processes.

According to the validation of DST with the Delphi method; it was put forward that both architects and planners reacted to the DST in a positive perspective. The features of DST was evaluated as above average with a rating of 3,8 and outputs of DST were evaluated as successful with a rating of 4,2.

5.4. Final Remarks

Environmental assessment of neighbourhood scale built-environment is an ambitious study with several layers of critical decision-making spots, such as building component, transportation and sustainability. Decisions regarding the planning of neighbourhood scale developments do have a significant effect on the environmental impact of urban areas and cities, due to large area and long lifetime they have. Residential development often constitutes the major ratio of the built-environment. Hence, it is of paramount importance to be able to have correct decisions in the early phases of designing large-scale mass-housing projects.

During this study, it was seen that there is a lack of research on environmental assessment of large-scale developments. Mass-housing projects were focused and a decision support tool was developed. With the use of the DST, the environmental impact assessment procedure for mass-housing projects in Turkey can be improved by application in early design phase and inclusion of estimation of carbon emissions. The main findings of this study can be summarized as follows:

1. Analysis of sample projects were conducted in several scales such as component, building and neighbourhood. The results of case studies were compared and validated with similar studies found in the literature. It was seen that the results were

in line with range of international studies. It also showed that the data validation system was supportive to ensure the quality of the results.

It is also shown that transparency of data sources may be a great asset and tool for strengthening the credibility of LCA studies and it can facilitate a better comparison and adoption medium for input and output data. In case of a mandatory data quality step in LCA standards, the credibility and precision of studies will at least be explicitly put forward. This will enable for other researchers to take necessary actions while making use of other sources.

2. One of the strengths of decision support systems is the guidance they provide for policy-making and change management. In order to facilitate environmental impact assessment for neighbourhood scale built-environment, it must be shown that respectable carbon savings can be achieved by;

- assessment of existing condition of mass-housing projects,
- provision of reliable and applicable sustainable solutions for carbon mitigation.

Consideration of whole life-cycle of mass-housing projects and integration of RE systems provides the DST that is suggested in this study potential for being utilized in practice by planners and decision-makers in the industry.

3. The proposed methodology was proved to be performing well within the defined scope, as it was seen from the comparative studies with the literature. It was also seen that the framework can be improved in several ways regarding the existing clusters and new clusters can also be integrated, which are currently are not in the scope of this study.

The decision support tool utilizes a reference LCA study in order to generate scenarios, hence the framework is dependent on the available data collected in the study. The amount and quality of collected data have impacts on two aspects; precision of environmental data of components and representativeness of the reference LCA study based on case studies. Sources of environmental data are third party groups such as manufacturers, researchers, etc. As the number of EPD studies on building, urban and RE system components increase and integrated into this framework, the quality of outputs can also improve. On the other, in order to refine the assessment of mass-housing projects in Turkey, number of case studies should be improved. This will enhance the representativeness of the reference LCA study statistically. Furthermore, by applying the suggested methodology on other project typologies, different development patterns such as public or commercial areas can also be included in this framework.

Moreover, number of clusters in the framework can be increased with ease due to the modular structure. This study considers the environmental aspect of sustainability. Economical and social aspects of a neighbourhood scale built-environment can provide supplementary indicators beside carbon emissions, the sole indicator in this study.

5.5. Future Work

The framework displayed potential in several aspects for future work. The use of three-clustered framework enables a flexible database that may develop on different levels. The inclusion of more data on component and building level would lead to more representative values of carbon emissions at the neighbourhood scale. More clusters can also be added on aspects such as cost optimality, user behaviour, resource management, etc.

The DST can also be adapted for different phases of a project, such as concept design or implementation phases. For achieving this, new parameters would be added and the number of parameters should also be increased.

As the relationships for parameters in and among clusters are put forward in this study, the next step is development of the software infrastructure for a more user-friendly tool for decision-making process in mass-housing planning.

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APPENDIX A

LIFE CYCLE ASSESSMENT MODELS

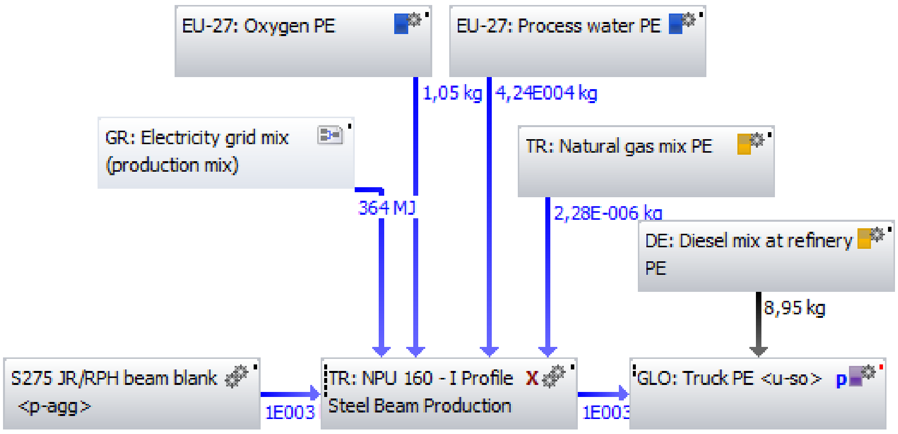

Figure A.1. LCA model for Structural Steel Beam

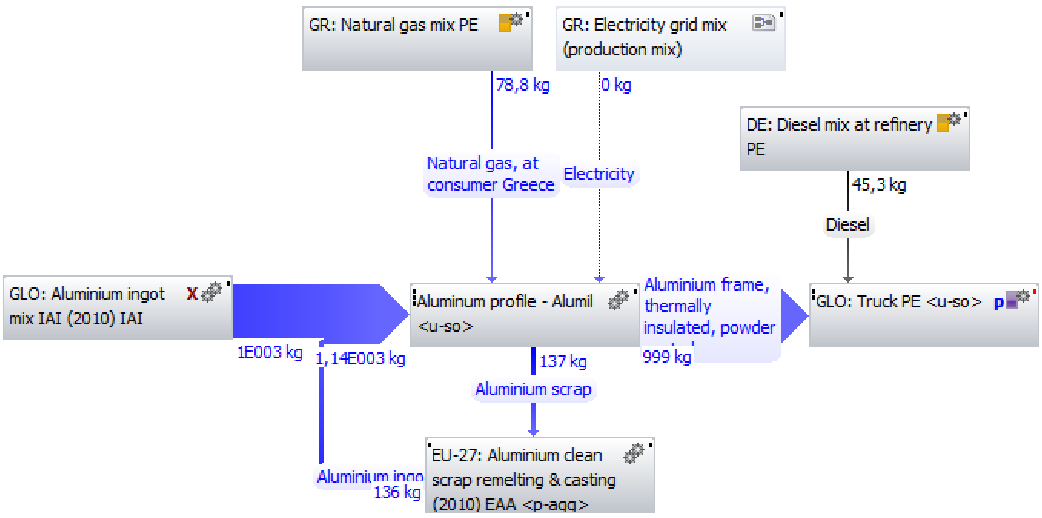

Figure A.2. LCA model for Aluminum Window Profile

APPENDIX B

QUESTIONS AND RESULTS OF THE DELPHI METHOD

Table B.1. Questionnaire for first round

No	Question	Rating (1-5)
1	How strong is the need for a decision support tool (DST) for assessing environmental impact during planning of mass housing projects?	_____
2	Please rate the importance of characteristics of a mass-housing project on environmental impact:	
	▪ Project construction area	_____
	▪ Project location	_____
	▪ Number of dwellers	_____
	▪ Transportation	_____
	▪ Energy consumption	_____
	▪ Carbon emissions	_____
	▪ Other: ____________	_____
3	Please rate the impact of components below from an environmental perspective on the planning process of mass-housing projects.	
	▪ Project typology (building geometry, project area)	_____
	▪ Urban context (location, means of transportation)	_____
	▪ Sustainable solutions (utilization of renewable energy systems)	_____
	▪ Other: ____________	_____
4	What would be the most important characteristic of a DST for assessing environmental impact of mass housing projects?	
	▪ Multi-disciplinary	_____
	▪ Flexible	_____
	▪ Comprehensive	_____
	▪ Accuracy	_____
	▪ User-friendly	_____
	▪ Web-based	_____
	▪ Other: ____________	_____
5	What would be the most important benefit of a DST for assessing environmental impact of mass housing projects?	
	▪ Estimation of project area and number of dwellers	_____
	▪ Feedback for transportation development	_____
	▪ Calculation of energy consumption	_____
	▪ Calculation of carbon emissions	_____
	▪ Integration of renewable energy systems	_____
	▪ Other: ____________	_____
6	Who would benefit the most from a DST for assessing environmental impact of mass housing projects?	_____
	▪ City planners	_____
	▪ Governmental institutions	_____
	▪ Real estate developers	_____
	▪ Residents / users	_____
	▪ Other: _____________	_____

Table B.2. Results of the first round

Q	Questions - First Round	Experts 1	2	3	4	5	6	7	8	Avg
1	How strong is the need for a decision support model (DST) for assessing environmental impact during planning of mass housing projects?	5	3	3	5	5	5	4	4	4,3
2	Please rate the importance of characteristics of a mass-housing project on environmental impact.									
	Project construction area	5	5	5	4	4	4	3	3	4,1
	Project location	5	5	4	4	5	4	4	2	4,1
	Number of dwellers	5	5	4	4	3	5	3	3	4,0
	Transportation	5	5	3	4	5	5	5	4	4,5
	Energy consumption	3	5	5	5	4	5	4	5	4,5
	Carbon emissions	2	5	5	5	5	5	5	5	4,6
3	Please rate the impact of components below from an environmental perspective on the planning process of mass-housing projects.									
	Project typology (building geometry, project area)	4	3	4	5	5	3	3	3	3,8
	Urban context (location, means of transportation)	5	5	3	4	4	5	5	4	4,4
	Sustainable solutions (utilization of renewable energy systems)	2	3	5	3	5	5	4	5	4,0
4	Please rate the importance of characteristic of a DST for assessing environmental impact of mass housing projects.									
	Multi-disciplinary	5	4	5	5	4	5	5	5	4,8
	Flexible	3	5	3	4	5	3	4	3	3,8
	Comprehensive	5	5	5	5	5	5	5	5	5,0
	Accuracy	1	4	4	4	4	3	3	3	3,3
	User-friendly	3	5	3	2	4	2	3	5	3,4
	Web-based	4	5	3	2	3	4	5	3	3,6
5	Please rate the importance of outputs of a DST for assessing environmental impact of mass housing projects.									
	Estimation of project area and number of dwellers	5	2	3	2	4	5	3	3	3,4
	Feedback for transportation development	5	2	4	3	4	5	5	4	4,0
	Calculation of energy consumption	3	5	5	5	5	5	4	5	4,6
	Calculation of carbon emissions	2	5	5	5	5	5	5	5	4,6
	Integration of renewable energy systems	2	3	5	4	5	4	4	5	4,0
6	Who would benefit the most from a DST for assessing environmental impact of mass housing projects?									
	City planners	5	3	4	5	5	5	5	5	4,6
	Governmental institutions	5	5	5	5	5	5	5	5	5,0
	Real estate developers	4	3	5	3	4	5	3	4	3,9
	Residents / users	3	4	4	2	3	3	3	2	3,0

Table B.3. Questionnaire for second round

No	Question	Rating (1st Round)	Rating (1-5)
1	Please rate the DST that was present to you according to categories identified in the first round.		
	▪ Multi-disciplinary	_____	_____
	▪ Flexible	_____	_____
	▪ Comprehensive	_____	_____
	▪ Accuracy	_____	_____
	▪ User-friendly	_____	_____
	▪ Other: ____________	_____	_____
2	Please rate the most important strength of the DST that was presented to you?		
	▪ Estimation of project area and number of dwellers	_____	_____
	▪ Feedback for transportation development	_____	_____
	▪ Calculation of energy consumption	_____	_____
	▪ Calculation of carbon emissions	_____	_____
	▪ Integration of renewable energy systems	_____	_____
	▪ Other: ____________	_____	_____

Table B.4. Results of the second round

Q	Questions - Second Round	Experts								Avg
		1	2	3	4	5	6	7	8	
1	Please rate the DST that was present to you according to categories identified in the first round.									
	Multi-disciplinary	2	5	3	4	5	5	5	4	4,1
	Flexible	4	3	4	4	3	4	3	4	3,6
	Comprehensive	3	3	3	5	5	3	5	3	3,8
	Accuracy	2	4	5	3	3	4	3	4	3,5
	User-friendly	4	3	4	4	3	5	4	5	4,0
2	Please rate the importance of outputs of the DST that was presented to you.									
	Estimation of project area and number of dwellers	4	3	5	5	4	2	3	3	3,6
	Feedback for transportation development	2	4	4	5	4	5	5	4	4,1
	Calculation of energy consumption	5	5	4	5	4	5	4	5	4,6
	Calculation of carbon emissions	2	5	5	5	4	5	4	5	4,4
	Integration of renewable energy systems	4	4	4	5	5	4	4	5	4,4

Table B.5. Questionnaire for third round

No	Question	Rating (2nd Round)	Rating (1-5)
1	Please reconsider your previous rating on DST according to the average score of second round.		
	▪ Multi-disciplinary	_____	_____
	▪ Flexible	_____	_____
	▪ Comprehensive	_____	_____
	▪ Accuracy	_____	_____
	▪ User-friendly	_____	_____
	▪ Other: _____________	_____	_____
2	Please provide your reasons if your ratings remain out of consensus for the first question.	**Average rating**	**Your rating**
	____	_____	_____
	____	_____	_____
	____	_____	_____
	____	_____	_____
	____	_____	_____
	____	_____	_____
3	Please reconsider your previous rating on the most important benefit of a DST for planning of mass housing projects.	**Rating (2nd Round)**	**Rating (1-5)**
	▪ Estimation of project area and number of dwellers	_____	_____
	▪ Feedback for transportation development	_____	_____
	▪ Calculation of energy consumption	_____	_____
	▪ Calculation of carbon emissions	_____	_____
	▪ Integration of renewable energy systems	_____	_____
	▪ Other: _____________	_____	_____
4	Please provide your reasons if your ratings remain out of consensus for the third question.	**Average rating**	**Your rating**
	____	_____	_____
	____	_____	_____
	____	_____	_____
	____	_____	_____
	____	_____	_____
	____	_____	_____

Table B.6. Results of the third round

Q	Questions - Third Round	Experts								Avg
		1	2	3	4	5	6	7	8	
1	Please reconsider your previous rating on DST according to the average score of second round.									
	Multi-disciplinary	2	5	3	4	5	5	5	4	4,1
	Flexible	4	3	4	4	3	4	3	4	3,6
	Comprehensive	3	3	3	5	5	3	5	3	3,8
	Accuracy	2	4	5	3	3	4	3	4	3,5
	User-friendly	4	3	4	4	3	5	4	5	4,0
2	Please reconsider your previous rating on the most important benefit of a DST for planning of mass housing projects.									
	Estimation of project area and number of dwellers	4	3	4	5	4	2	3	3	3,5
	Feedback for transportation development	3	4	4	5	4	5	5	4	4,3
	Calculation of energy consumption	5	5	4	5	4	5	4	5	4,6
	Calculation of carbon emissions	2	5	5	5	4	5	4	5	4,4
	Integration of renewable energy systems	4	4	4	5	5	4	4	5	4,4

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M.Sc.	Department of Building Science, METU	2009
B.S.	Department of Architecture, METU	2006
High School	Ankara Atatürk Anadolu Lisesi	2001

PROFESSIONAL PRACTICE

Year	**Place**	**Enrollment**
2017-	DE Gesellschaft für Int. Zusam. (GIZ)	Project Coodinator
2016-2017	NIRAS IC Sp. z o.o.	Building Systems Expert
2013-2016	MTK Architecture	Project Captain
2011-2014	Atölye4 Architecture	Partner
2009-2011	Directorate General of Foundations	Inspector
2006-2009	Köker, MTM, Promim Architecture	Architect

ACADEMIC PRACTICE

Year	**Place**	**Enrollment**
2018	METU / Beuth University	Instructor
2017	Çankaya University	Instructor

PUBLICATIONS

International Publications

- Kayaçetin, N. C. and Tanyer, A. M. (2018) *"Analysis of Embodied Carbon in Buildings Supported by a Data Validation System"* Embodied Carbon in Buildings, Springer.
- Kayaçetin, N. C. and Tanyer, A. M. (2009) "*Exploring Knowledge Management in the Practice of Architecture*" Journal of the Faculty of Architecture, Vol. 26 No. 2.

International Conferences

- DAAD International Seminar - Powering the energy transition, 2017
  "PhD Poster presentation, 2nd Prize"
- International Symposium on Energy Efficiency in Buildings, 2017
  "*Developing typical buildings and proposal of structure for Building inventory in Turkey*"
- SBE16 Istanbul - Smart Metropoles Congress, 2016
  "*A Life Cycle Assessment Based Decision Support Model for Architecture-Engineering-Construction (AEC) Projects*"
- International Union of Architects (UIA) İstanbul Congress, 2005

Awards and Certificates

- International Expo 2016 Antalya Concept Design Project – 1st Prize (2013)
- M.E.B Educational Campuses National Architectural Project Competition, Mardin – Honourable Mention (2013)
- T.C. Hatay Provincial Directorate of Administration Office Building National Architectural Competition – 1st Prize (2011)
- Implementing the Energy Performance of Buildings Directive, European Academy for Taxes, Economics & Law, 2017
- Life Cycle Assessment with SimaPro, Metsims, 2015