Sedat GÜLÇİMEN

A Master's Thesis

AGU 2021

A LIFE CYCLE APPROACH FOR SUSTAINABLE AND ENERGY EFFICIENT URBAN TRANSPORT

A THESIS
SUBMITTED TO THE DEPARTMENT OF SUSTAINABLE URBAN INFRASTRUCTURE ENGINEERING
AND THE GRADUATE SCHOOL OF ENGINEERING AND SCIENCE OF ABDULLAH GUL UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

By
Sedat GÜLÇİMEN
December 2021

A LIFE CYCLE APPROACH FOR SUSTAINABLE AND ENERGY EFFICIENT URBAN TRANSPORT

A THESIS
SUBMITTED TO THE DEPARTMENT OF SUSTAINABLE URBAN INFRASTRUCTURE ENGINEERING
AND THE GRADUATE SCHOOL OF ENGINEERING AND SCIENCE OF ABDULLAH GUL UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

By
Sedat GÜLÇİMEN
December 2021

SCIENTIFIC ETHICS COMPLIANCE

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

Name-Surname: Sedat GÜLÇİMEN
Signature :

REGULATORY COMPLIANCE

M.Sc. thesis titled A Life Cycle Approach for Sustainable and Energy Efficient Urban Transport has been prepared in accordance with the Thesis Writing Guidelines of the Abdullah Gül University, Graduate School of Engineering & Science.

Prepared By	Advisor	Co-Advisor
Sedat GÜLÇİMEN	Prof. Dr. Niğmet UZAL	Prof. Dr. Emel Kızılkaya Aydoğan
Signature	Signature	Signature

Head of the Sustainable Urban Infrastructure Engineering Program

Prof. Dr. Burak UZAL

Signature

ACCEPTANCE AND APPROVAL

M.Sc. thesis titled A Life Cycle Approach for Sustainable and Energy Efficient Urban Transport and prepared by Sedat GÜLÇİMEN has been accepted by the jury in the Sustainable Urban Infrastructure Engineering Graduate Program at Abdullah Gül University, Graduate School of Engineering & Science.

29 /12 / 2021

(Thesis Defense Exam Date)

JURY:

Advisor : Prof. Dr. Niğmet UZAL

Member : Prof. Dr. Ülkü YETİŞ

Member : Asst. Prof. Dr. Muhammed SÜTÇÜ

APPROVAL:

The acceptance of this M.Sc. thesis has been approved by the decision of the Abdullah Gül University, Graduate School of Engineering & Science, Executive Board dated ….. /….. / ……….. and numbered ……………..……. .

……….. /……….. / ………..

(Date)

Graduate School Dean
Prof. Dr. İrfan Alan

ABSTRACT

A LIFE CYCLE APPROACH FOR SUSTAINABLE AND ENERGY EFFICIENT URBAN TRANSPORT

Sedat GÜLÇİMEN
MSc. in Sustainable Urban Infrastructure Engineering
Advisor: Prof. Dr. Niğmet UZAL

December, 2021

The objective of this thesis study is to evaluate the sustainability of the urban transport system in Kayseri. In the first part, a life cycle sustainability assessment (LCSA) of the tramway system was performed using a cradle-to-grave approach by integrating the environmental, economic, and social aspects for the case of Kayseri, Turkey. The LCSA results revealed that the operation and maintenance phase were determined as the main contributor to the environmental load of the tramway system within its entire life cycle. For economic assessment, the main contributor to the total life cycle cost was energy cost. In the social performance evaluation, it is found that the industry performs well for society, the local community, and workers but has a weaker social performance for the consumer due to a weak feedback mechanism. In the second part, urban transport alternatives were evaluated with the integration of Hesitant Fuzzy Analytical Hierarchy Process (HF-AHP) and Multiple Attribute Utility Models (MAUT) methods. Eight sustainable transport indicators were selected and the weights of selected indicators are calculated with the utilization of HF-AHP. Based on HF-AHP results, the number of fatalities/injuries has been determined as the most significant indicator among the eight indicators with 0.158 normalized weight. Then, twelve urban transport alternatives were ranked by using the MAUT method to decide the most sustainable urban transport alternative. The results of this integrated methodology present that alternative 11, which is dominated by low-motorized vehicles, has been determined as the best sustainable alternative and alternative 1 is the worst sustainable alternative which is dominated by high-motorized vehicles with 0.69 and 0.27 of total utility values, respectively.

Keywords: urban transport, sustainability, life cycle, multi-criteria decision making

ÖZET

SÜRDÜRÜLEBİLİR VE ENERJİ VERİMLİ KENT İÇİ ULAŞIM İÇİN YAŞAM DÖNGÜSÜ YAKLAŞIMI

Sedat GÜLÇİMEN

Sürdürülebilir Kentsel Altyapı Mühendisliği Anabilim Dalı Yüksek Lisans

Tez Yöneticisi: Prof. Dr. Niğmet UZAL

Aralık-2021

Bu tez çalışmasının amacı, Kayseri'deki kent içi ulaşım sisteminin sürdürülebilirliğini değerlendirmektir. İlk bölümde, beşikten mezara yaklaşımı ile Kayseri tramway sisteminin çevresel, ekonomik ve sosyal yönleri birlikte entegre edilerek yaşam döngüsü sürdürülebilirlik değerlendirmesi (LCSA) yapılmıştır. LCSA sonuçları, işletme ve bakım aşamasının, tüm yaşam döngüsü boyunca tramvay sisteminin çevresel etkilerinin ana etmeni olarak ortaya koymuştur. Ekonomik değerlendirmeye göre, toplam yaşam döngüsü maliyetinin temel kaynağı enerji maliyeti olmuştur. Sosyal performans değerlendirmesinde, endüstrinin toplum, yerel topluluk ve işçiler için iyi performans gösterdiği, ancak zayıf bir geri bildirim mekanizması nedeniyle tüketici için daha düşük bir sosyal performansa sahip olduğu bulunmuştur. İkinci bölümde, Kararsız Bulanık Analitik Hiyerarşi Süreci (HF-AHP) ve Çoklu Nitelikli Fayda Teorisi (MAUT) yöntemleri entegre edilerek kent içi ulaşım alternatifleri değerlendirilmiştir. Sekiz sürdürülebilir ulaşım göstergesi seçilmiştir ve seçilen göstergelerin ağırlıkları HF-AHP metodu kullanılarak hesaplanmıştır. HF-AHP sonuçlarına göre, sekiz gösterge arasından 0,158 normalleştirilmiş ağırlık ile ölüm/yaralı sayısı en önemli gösterge olarak belirlenmiştir. Daha sonra, en sürdürülebilir kent içi ulaşım alternatifine karar vermek için MAUT yöntemi kullanılarak on iki kent içi ulaşım alternatifi sıralanmıştır. Bu entegre metodolojinin sonuçları, 0,69 toplam fayda değeri ile motorlu araçların az olduğu alternatif 11'in en sürdürülebilir alternatif ve 0,27 toplam fayda değeri ile motorlu araçların fazla olduğu alternatif 1'in ise en kötü sürdürülebilir alternatif olduğunu göstermektedir.

Anahtar kelimeler: kentiçi ulaşım, sürdürülebilirlik, yaşam döngüsü, çok-kriterli karar verme

Acknowledgements

First of all, I would like to express my sincere gratitude to my supervisor Prof. Dr. Niğmet UZAL for her great guidance, recommendations, trust and encouragement throughout the research. I also would like to express my gratitude to my co-supervisor Prof. Dr. Emel Kızılkaya AYDOĞAN for her valuable ideas and guidance throughout the research.

I would like to express my special thanks to Kayseri Transportation Inc. Company for their contributions to my thesis.

I would like to express my special thanks to respected committee members, Prof. Dr. Ülkü YETİŞ and Asst. Prof. Dr. Muhammed SÜTÇÜ for showing kindness in accepting to read and review this thesis.

I am especially grateful to my wife Kübra GÜLÇİMEN, who supports me in all matters in my life and has the most significant share in each success I have achieved so far.

Finally, I would like to express my deepest gratitude to my family for their endless patience, encouragement and all kind of supports in each stage of my life.

This study was supported by The Scientific and Technological Research Council of Turkey (TUBITAK) 2210/C National MSc/MA Scholarship Program in the Priority Fields in Science and Technology.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ADP	Abiotic Depletion Potential
AP	Acidification Potential
E-LCA	Environmental Life Cycle Assessment
EP	Eutrophication Potential
FWAE	Fresh Water Aquatic Ecotoxicity
GWP	Global Warming Potential
HF-AHP	Hesitant Fuzzy Analytical Hierarchy Process
HTP	Human Toxicity Potential
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LCSA	Life Cycle Sustainability Assessment
MAUT	Multiple Attribute Utility Theory
MCDM	Multi-Criteria Decision-Making
ODP	Ozone Layer Depletion Potential
OECD	Organization for Economic Co-operation and Development
PO	Photochemical Oxidation
SETAC	Society for Environmental Toxicology and Chemistry
S-LCA	Social Life Cycle Assessment
TE	Terrestrial Ecotoxicity
UNEP	United Nations Environment Program

To my wife and parents

Chapter 1

Introduction

1.1 General

Today, the majority of society gives preference to living in urban areas due to economic, technological, political, and sociological reasons. According to the UN World Urbanization Prospects 2018 report, 30% of the global population lived in cities in 1950, and this figure reached 55% in 2018. It is predicted to reach 68% by 2050 [1]. The great population increase in cities in the last decades has a close relationship with the main dimensions of sustainable development; environmental, economic, and social.

With rapid population growth and urbanization, societies' need for alternative transport services has increased gradually in the last decades. When economies develop and cities sprawl, the contribution of transport to environmental problems, illness, and death increase sharply in the world [2]. Particularly in large cities, problems related to transport reach serious levels due to high energy consumption, environmental pollution, and traffic congestion [3]. About 25% of the global energy consumption and CO_2 emissions are related to the transportation sector [4]. Thus, policymakers and researchers put significant efforts into exploring low-cost and more environmental-friendly transport alternatives in order to reduce negative environmental impacts and dependence on petroleum fuels.

As several mobility services are developing in urban areas worldwide, sustainability of the mobility services has gained more importance in the last decades. In order to assess the sustainability of these services by considering three aspects of sustainability, environmental, economic and social, life cycle-based methodologies have been developed over time [5]. Sustainable transport, one of the major elements of sustainable development [6] is defined as transport that meets the needs for access without damaging the ecosystem and human health by OECD [7]. The term covers the economic, social, and environmental aspects of transport by considering its benefit to people, planet, and profit among the triple bottom line. As urbanization gradually increases, the sustainability of transportation is affected from various perspectives [8]. To measure sustainability in transport systems with several aspects, the use of indicators has become necessary. Sustainable indicators are essential tools that convert the high volume of information to a simple, clear, and understandable form. However, a standard sustainable indicator system for transportation does not exist yet due to the disagreement about the definition of sustainability and different aims for establishing a framework [9].

For sustainable transport planning, a comprehensive decision-making process is required. Transport plans or scenarios are partially sustainable with limited environmental and economic points of view. These views should be integrated and optimized to make transport plans or scenarios more sustainable with the help of effective decision making, which is a process of choosing the best alternative from several alternatives [10]. Therefore, multi-criteria decision-making (MCDM) methods gain significant importance in choosing the best alternative.

1.2 Objectives and Scope

The objective of the study is to assess the urban transport system in Kayseri, Turkey, with a holistic approach by using LCSA and MCDM methods. The first objective of the study is to present an LCSA for tramway system by integration of environmental, economic and social aspects with implementation of environmental life cycle assessment (E-LCA), life cycle costing (LCC), and social life cycle assessment (S-LCA) methodologies for the case of Kayseri, Turkey. The second objective is to compare alternative urban transport scenarios with the integration of two MCDM methods and to decide the best transport alternative in terms of sustainability by considering the environmental, economic, and social aspects.

In the first part of the study, the sustainability performance of the tramway system was evaluated with a cradle to grave approach for assessing three aspects of sustainability. For environmental evaluations, E-LCA was applied by using SimaPro 8.4.1 PhD version based on ISO 14040 and 14044. The CML-IA baseline method, which includes nine environmental impact categories (abiotic depletion potential (ADP), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), freshwater aquatic ecotoxicity (FWAE), terrestrial ecotoxicity (TE), photochemical oxidation (PO), acidification potential (AP) and eutrophication potential (EP)), was used to assess the environmental performance of the tramway system with a functional unit of one passenger-km. For economic assessment, LCC was utilized with the functional unit of USD for one passenger-km. The S-LCA was used to assess the social performance of the tramway system based on the guideline published by the United Nations Environment Programme (UNEP) in collaboration with the Society of Environmental Toxicology and Chemistry (SETAC). For the determination of social impacts, 11 sub-categories covering health and safety for workers, fair salary, working hours, child labor, health and safety for consumers, feedback mechanism, transparency, local employment, access to immaterial resources, technology and development, public commitment to sustainability issues and 18 social indicators covering usage of personal protective equipment, presence of a formal policy concerning health and safety, presence of night work, regular payment of the salary, employees receiving less than minimum wages, legal working hours limit, child labor, organizations' efforts and measures to protect consumer health and safety, presence of management measures to assess consumer health and safety, presence of a mechanism for customers to provide feedback, management measures to improve feedback mechanisms, consumer complaints regarding transparency, publication of a sustainability report, workforce hired locally, local suppliers, presence/strength of community education initiatives, investments in technology development and presence of publicly available documents as promises or agreements on sustainability issues were selected.

In the second part of the study, twelve urban transport alternatives were evaluated with the integration of two MCDM methods for selecting the best alternative by considering the triple bottom line approach. Hesitant Fuzzy Analytical Hierarchy Process (HF-AHP) and Multiple Attribute Utility Models (MAUT) methods were integrated with this study. Eight sustainable transport indicators (CO_2 emission, energy consumption, depletion of non-renewable resources, operational costs, maintenance costs, fuel and taxes, number of fatalities/injuries, and motor vehicles for public transport per 10,000 population) were selected by considering the availability of data from the transport sector, and the weights of selected indicators are calculated with the utilization of HF-AHP. Afterward, the MAUT method was used for the selection of the best alternative among the twelve urban transport scenarios. Finally, sensitivity analysis was applied to validate the robustness of the method applied.

Chapter 2

Literature Review

In this chapter, the literature review related to the evaluation of sustainable transport with the utilization of LCSA and MCDM methods is presented. Firstly, the general structure of sustainable transport, the importance of indicators of sustainable transport, and challenges in sustainable transport systems are discussed. Then, the general framework of LCSA, implementation of LCSA in transport systems, the importance of decision-making in sustainable transport planning, and MCDM methods are discussed to understand better the significance of MCDM methods in sustainable transport planning.

2.1 Sustainable Transport

Sustainable transport, which is one of the major elements of sustainable development [6] is defined as transport that meets the needs for access without damaging the ecosystem and human health by OECD [11]. The term covers the economic, social, and environmental aspects of transport by considering its benefit to people, planet, and profit among the triple bottom line. As urbanization gradually increases, the sustainability of transportation is affected from various perspectives [8]. To measure sustainability in transport systems with several aspects, the use of indicators has become necessary. Sustainable indicators are essential tools that convert the high volume of information to a simple, clear, and understandable form. However, a standard sustainable indicator system for transportation does not exist yet due to the disagreement about the definition of sustainability and different aims for establishing a framework [9]. Besides, research on sustainable transport yields a sufficient number of indicators. In these studies, various indicator indexes are constructed to measure the sustainability of the transport system in the selected regional area.

In urban transportation planning, the share of motorized and non-motorized urban transport modes plays a significant role in terms of sustainability. Walking and biking which are the main non-motorized transport modes are cheaper, more environmental friendly and moderately fast for trips up to 3.5 km distance when compared with motorized transport modes [12]. For longer distances, motorized transport modes such as bus, tramway and light rail systems are needed for effective and comfortable urban transport. However, motorized transport modes are more expensive and less environmentally friendly. Thus, usage of the non-motorized and motorized transport modes has significant effects on the sustainability of urban transport systems. Depending on transportation demand for one-way at rush hours, urban transport modes may vary in the cities. Additionally, the length of line and number of vehicles for public transport are significant parameters for urban transport planning in terms of accessibility. Besides these parameters, environmental, economic and social indicators should be considered together for sustainable urban transport. Therefore, urban transport modes should be well optimized and integrated with each other by considering the triple bottom line approach.

2.1.1 Indicators of Sustainable Transport

In recent years, sustainable transport has become one of the essential goals of transport policy and planning. To achieve this goal, decision-makers are progressively being required to measure and monitor the sustainability performance of transport systems. Quantifying and monitoring the sustainability of transport systems is crucial as evidenced by an increasing number of studies to measure sustainability in transport systems [13]. For local governments to assess the sustainability of transport strategies, Shiau and Liu (2013) have proposed an indicator system with an evaluation of twenty-one indicators, which are divided into environment, economy, energy and society categories. They have evaluated the sustainability of transport strategies in Taipei City, the capital of Taiwan by using ten key indicators selected by a committee of government officials [14]. In addition, Shiau (2012) also studied on evaluation of sustainable transport strategies by using a hybrid approach based on AHP and Dempster–Shafer theory (DST) to deal with incomplete information for Taipei City. He also used a sustainability compound index covering 5 aspects and 10 criteria for the assessment of sustainable transport strategies [15]. Zope et al. (2019) selected the performance indicators for the comparison of the sustainability performance of existing passenger transport systems in

Indian cities. Their selected indicators were grouped into environmental, economic and social to study the use of benchmarking in performance improvement of the transport system [16]. Reisi et al. (2014) has developed a method to composite an index for assessment of sustainability for Melbourne statistical local areas. They have also selected nine sustainability indicators, environmental, economic and social, by reviewing the literature and based on available data for Melbourne [17].

Additionally, Currie et al. (2018) developed a new measure of sustainability performance for public transport in 88 world cities. They focus on regulatory structures and their impact on the sustainability performance of public transport and 15 indicators under environmental, economic, social and system effectiveness categories also adopted in the study for sustainability assessment [18]. Sdoukopoulos et. (2019) studied measuring progress toward transport sustainability through indicators. They have revealed the linkages among the sustainability pillars and selected themes. They also proposed an alternative categorization of weighting schemes concerning the index [19]. Chakhtoura and Pojani (2016) assessed the effectiveness of sustainable urban transport plans by employing indicators. They took the city of Paris as a case study for the indicator-based assessment. Their aim is to evaluate the extent to which targets of sustainable transport have been achieved and to answer the meta-question: which set of indicators is the most appropriate to assess transport sustainability achievements in a large and complex city like Paris? They suggest that to apply this flexible framework on other world cities to test its robustness further [20].

The list of sustainable transport indicators from the literature was compiled in Table 2.1. These 82 indicators are classified into three main groups: environmental, economic, and social, as shown in Table 2.1.

Table 2.1 List of sustainable transport indicators from literature

Reference	Environmental Indicators	Economic Indicators	Social Indicators
[17]	Depletion of non-renewable resources GHG emissions (CO_2-e) Other air pollutants (CO, NO_2, PM10) Land consumption for transport	Car ownership costs Vehicle and general costs of accidents	Accessibility Fatalities and injuries related to traffic accidents Mortality effects of air pollutants
[18]	Quantity of energy consumed Mass of total pollutants emitted Land area consumed by public transport facilities	Annual operating cost Cost recovery Passenger km travelled per unit GDP Average time per trip	Travel participation Average user trip distance Affordability Public transport related deaths
[15]	Emissions of air pollutants Noise perception	Transport intensity Energy intensity	Accessibility for elderly and disabled persons Transport services for remote areas
[14]	Proximity of transport infrastructure to designated ESAs Emission intensity of air pollutants Emission intensity of GHG Recycling of used tires Recycling of end-of-life vehicles	Distribution density of transport Modal split of transit Service intensity of transit Loading factor of transit The ratio of parking lots for P&R The ratio of bus exclusive lanes Modal split of non-motorized modes Loading factor of private modes Truck loading factor The effect of public depot on freight transshipment	Traffic accidents Mobility and transport for older adults and disabled persons Transport infrastructure in remote areas Transit subsidy in remote areas
[21]	Annual energy consumption and CO_2 emissions (total and per resident) Levels of CO, NOx, hydrocarbons and particles (in g/m2, total and per resident) Daily individual consumption of public space involved in traveling and parking (in m^2 h) Space taken up by transport infrastructures	Annual costs chargeable to residents for their mobility in a zone Annual average expenditures for urban mobility (per person/household) Company costs of employee parking, subsides to employees Annual public expenditures for investments and operations	Proportion of households owning 0, 1 or more cars Distance travelled Expenditures for urban mobility: amounts for private/public transport Expenditures for urban mobility: share of the average income of households
[16]	PM10, SO_2 NOx, CO (tonnes per year) CO_2 (million tonnes per year) Noise level (Db)	Population Density Motorized Vehicles per 1000 population, Peak Hour Journey Speed (kmph), Congestion Index Per capita trip rate Average Trip Length (km)	Number of fatalities Serious injuries % Trips by Walk, Cycle
[9]	Final petroleum products consumption of transport, storage and post industry Nitrogen oxides emission of motor vehicle Percentage of land for transportation facilities	Ratio of expenditure on traffic to the total cash consumption expenditure for average individual Amount of standard operating motor vehicles Investment in fixed assets of transport, storage and post industry	Amount of traffic accident Total loss of traffic accident Motor vehicles for public transport per 10,000 population, standard unit

2.1.2 Challenges in Sustainable Transport

Although the transition to sustainable transport has gradually increased in recent years, implementing the sustainable transport concept is challenging. Physical transition, public acceptance and data accessibility are the main challenges of sustainable transport. The first key problem is to physical transition from traditional to sustainable transport for reducing negative impacts such as greenhouse gas emissions, traffic congestion and detrimental air quality [22]. The physical dimension of sustainable transport includes the infrastructure and the regulatory framework that influences the use of transport systems [23]. The modifying or redesigning of the traditional transport system and their infrastructures are expensive and time-consuming. Besides, the physical transition must be preceded by changes in practices and cognitive models among the policy shapers refers to a big group of actors involved in shaping transport policies [22].

Another key issue is public acceptance, relating to the legitimacy and political support by the public for sustainable transport, such as for imposing policy measures aimed at increasing bicycle roads or electrical scooter-sharing systems in the urban areas [24-28]. Thus, the public has a significant role on the transition to sustainable transport by accepting the policies or imposing the policy-makers for sustainable transport. Data accessibility is the third key problem relating to quantifying and monitoring sustainable transport systems [29]. The indicators are significant for quantifying and monitoring the sustainability of transport systems; however, selecting a set of indicators is challenging [13]. The selection of sustainable transport indicators involves tradeoffs. While selecting a smaller set of indicators is more accessible and easier, it may lead to ignoring some significant impacts. On the contrary, selecting a larger set of indicators is more comprehensive; however, its gathering and analyses costs are expensive [17]. On the other hand, local and geographical conditions significantly affect the selection of indicators. The variety of local socio-economic and physical conditions bring about a variety of indicators in sustainability assessment. Furthermore, there is no agreement on the most appropriate methodology and framework for indicator development [30].

2.2 Life Cycle Sustainability Assessment (LCSA)

The LCSA provides an integrated sustainability evaluation of a product or process by highlighting areas of negative impact for improvements or positive impacts where opportunities can be explored. In the last decade, researchers put significant effort into performing the LCSA for sustainable material, technology or method selection in several areas such as construction, food, energy, transport and so on. For construction projects, Figueiredo et al. (2021) proposed a decision-making framework with the integration of LCSA, Multi-Criteria Decision Analysis (MCDA), and Building Information Modelling (BIM) for the selection of sustainable materials. They applied an LCSA on a residential building covering the construction, operation and end-of-life stages of the building as a case study. They have selected five criteria (global warming potential, eutrophication potential, acidification potential, life cycle cost, and fair wage potential) to compare four alternatives by considering environmental, economic and social dimensions of the sustainability concept [31]. Müller and Hiete (2021) carried out a LCSA study for choosing a sustainable packaging system for self-leveling compounds (mortar). They compared the paper bags, flexible intermediate bulk container, one-way cardboard container and a pumping truck, all used with different machinery, under several scenarios. Their results revealed that 87% of all scenarios the use of the 25 kg paper bag in combination with a mixing drum and cart resulted as a sustainable alternative [32].

Shrivastava and Unnikrishnan (2021) performed an LCSA of the crude oil process chain to evaluate its sustainability performance from well-to-tank approach in India. They reported that oil refining and transportation stages are the main contributors of emissions from environmental aspects. Their LCC results showed that the crude oil refining phase is also main contributor to the total life cycle cost due to complex operations and more raw materials are used when compared to other phases. From the social aspect, they reported that the companies need significant improvements to improve their social performance in terms of safety, health, awareness and pay [33]. Valente et al. (2021) compared the sustainability performance of renewable and conventional hydrogen which is a significant element towards a sustainable economy. They applied an LCSA by utilization of five life-cycle indicators (global warming, acidification, levelized cost, child labour and health expenditure) of three dimensions of sustainability and their results showed that renewable hydrogen was found to underperform when compared to conventional hydrogen in economic and social aspects [34]. Li et al. (2021) applied an LCSA for technology selection in hydrogen production in China. They integrated the emergy-based indicators into the LCSA to assess the hydrogen production technologies from environmental, economic, social, emergy-based and technical dimensions as a holistic approach. They found that hydrogen production from copper-chlorine thermo-chemical water-splitting is the most sustainable technology option and coal gasification is the worst sustainable option [35]. For application in electricity or vehicle fuel, Masilela and Pradhan et al. (2021) carried out an LCSA to compare the biomethane and biohydrogen produced from organic waste streams for the African context (agro-industrial, urban, and rural settings). They revealed that applying biohydrogen in vehicles shows better sustainability performance than electricity generation systems in urban settings [36].

On the other hand, Zira et al. (2021) studied on LCSA of organic and conventional pork supply chains in Sweden by considering the environmental, economic and social aspects of sustainability. They applied the LCSA by using 20 indicators for the evaluation of the sustainability performance of four main subsystems in pork supply chains. Their results indicate that the organic pork supply has better performance in 18 of the 20 indicators expressed per unit area than conventional pork supply. The organic pork supply, therefore, was a more sustainable supply chain in terms of sustainability [37].

2.2.1 Life Cycle Sustainability Assessment in Transport Systems

Today, majority of society gives preference to living in urban areas due to economic, technological, political and sociological reasons. According to UN World Urbanization Prospects 2018 report 30% of global population lived in cities in 1950, this figure reached 55% in 2018 and it is predicted to reach 68% by 2050 [1]. The great population increase in cities in the last decades has a close relationship with the main dimensions of sustainable development; environmental, economic, and social.

With rapid population growth and urbanization, the needs for alternative transport services of societies has increased gradually in the last decades. When economies develop and cities sprawl, the contribution of transport to environmental problems, illness and death increase sharply in the world [2]. Particularly in large cities, problems related to transport reach serious levels due to high energy consumption, environmental pollution and traffic congestion [3]. About 25% of the global energy consumption and CO_2 emissions are related to the transportation sector [4]. In the transportation sector, road transportation is responsible for 76% of the total oil consumption, whereas the share of rail transportation is 0.6% [38]. Thus, policymakers and researchers put significant efforts to explore low-cost and more environmental-friendly transport alternatives in order to reduce negative environmental impacts and dependence on petroleum fuels.

In recent years, cities have had more needs of railway systems particularly for urban and inter-city transportation due to population growth. Especially cities with over population 1 million have needs thousands of kilometers of railway infrastructures and hundreds of railway vehicles within the next years. Various urban railway transport modes such as metro, light railway systems are utilized in some cities due to more environmentally friendly, comfortable and economically feasible when compared with buses, minibusses and metro buses.

As several mobility services are developing in urban areas worldwide, sustainability of the mobility services has gained more importance in the last decades. In order to assess the sustainability of these services by considering three aspects of sustainability, environmental, economic and social, life cycle-based methodologies have been developed over time [5]. Although a number of researches have been done on E-LCA based on ISO 14040 and ISO 14044, a standardized approach for LCC and S-LCA has not agreed on yet. However, some examples and guidelines are used for LCC and S-LCA, and the LCC guideline by Ciroth et al. (2009) and S-LCA guideline published by UNEP and SETAC (2009, 2013) are commonly used ones in literature [39-41]. In the last decade, the number of studies on determining the environmental impacts of transport systems increases gradually, but studies on the economic and social performance of urban tramway systems are limited [42-56]. Banar and Ozdemir (2015) compared the high-speed railway (HSR) and conventional railway (CR) systems in Turkey by using LCA and LCC by considering the infrastructure and operation phases. They found that 58% of the total environmental load for high-speed railway comes from the infrastructure phase and 42% comes from the operation phase. In contrast, they revealed that the main contributor phase for environmental impacts is the operation phase with 61% share of the total and the infrastructure phase follows with 39% for the CR system [42].

Additionally, Shinde et al. (2018) analyzed the environmental impacts of the Mumbai suburban railway in India with the LCA approach. They considered the construction, maintenance and operation phases of a suburban railway system. Their results indicate that operation has the highest effect on environmental load with 87-94% share of the total due to electricity consumption, which is generated from non-renewable sources in India [43]. Bilgili et al. (2019) evaluated the various emissions of different transport scenarios from highway and railway transport which has 232 km length between two cities by utilization of LCA. They determined five different scenarios with several ratios of highway and railway transport for selected study area. It is found that rising railway transport utilization reduces greenhouse gas emissions. They also revealed that the damage ratio of ecosystem quality has decreased from 100% to 14.6% while considering all the passengers use the railway instead of the highway for transportation [44].

Although there are studies investigating the environmental (LCA) and economic (LCC) performance of railway systems, studies on S-LCA of railway systems are scarce in the literature. Agaton et al. (2020) studied on environmental and socio-economic evaluation of public transport in the Philippines. Their findings highlight the economic advantages of investment for electric vehicles in public transport with high public acceptance [57]. Kennedy (2002) compared both public and private transport systems from environmental, economic and social aspects for the case of the Greater Toronto Area (GTA). The results of the study showed that public transport was more sustainable than private transport from an environmental perspective. It is suggested that the integration of bicycles with public transit and constructing light rail systems improves the sustainability of the GTA [58]. Yang et al. (2022) proposed a framework for the large-scale transport infrastructure by integrating five social impact categories: economy, welfare, participation, safety and justice. They took the Fengtai high-speed railway station reconstruction Project in Beijing as case study to assess its social impacts with the proposed framework. The workers, users, public, value chain participants and local communities are identified as stakeholders for the case study. Their results revealed that the public and workers have the highest social benefits while the users and value chain participants receive smaller social benefits and the benefit of local communities is low and negligible [59].

The LCSA provides an integrated sustainability evaluation of a product or process by highlighting areas of negative impact for improvements or positive impacts where opportunities can be explored. In literature, few attempts can be found for LCSA application on several transport modes by excluding some dimensions of sustainability as summarized in Table 2.2. Despite the fact that several studies dealing with LCA and LCC applications for several transport modes, there is no S-LCA application on transport systems except high-speed in literature [42, 43, 47-53, 55, 56].

Table 2.2 Summary of some LCSA applications on different transport modes in literature

	Environmental (LCA)	Economic (LCC)	Social (S-LCA)	References
Tramway	✓	X	X	[47]
High Speed	✓	✓	✓	[42, 48, 49, 56, 59]
Metro	✓	✓	X	[43, 50, 51]
Bus	✓	✓	X	[52-55]

2.2.2 Multi-Criteria Decision Making Methods in LCSA of Transport Systems

For sustainable transport planning, a comprehensive decision-making process is required. Transport plans or scenarios are partially sustainable with limited environmental and economic points of view. These views should be integrated and optimized to make transport plans or scenarios more sustainable with the help of effective decision making, which is a process of choosing the best alternative from several alternatives [10]. Therefore, MCDM methods gain significant importance in choosing the best alternative.

In 1980, Thomas L. Saaty developed an MCDM method is called the Analytic Hierarchy Process (AHP) [60]. This method provides a model for complex problems with a hierarchical structure by splitting them into small and solvable problems. The hierarchy indicates the relations between goals, objectives, and alternatives. The AHP method covers pairwise comparisons, the hierarchical structure of complexity, judgments by considering aim and criteria, and an eigenvector method for getting weights [61].

Several authors propose to use the AHP method for the selection of alternatives systematically by using a fuzzy set theory and concept of hierarchical structure. Decision-makers (DMs) usually prefer this method because they find that it is more confident to provide interval judgment than fixed value judgments. Another reason for the preference of this method is that it is unable to make explicit preferences due to the fuzziness of the comparison process [61]. For the evaluation of sustainable transport strategies in Taiwan, Shiau and Liu (2013) have proposed an indicator system with an evaluation of twenty-one indicators. Based on results, the emission intensity of greenhouse gases is found as most important indicator by using AHP [14]. Besides, Erdogan and Kaya (2019) proposed a hybrid MCDM methodology, which composed of type-2 fuzzy AHP and TOPSIS method and applied it for Bus Rapid Transit (BRT) system in Istanbul [62]. With respect to five criteria, 17 alternatives are evaluated and the cost of failure has the highest score with 0.544, and repair time has the lowest score at 0.093. In addition to this study, Erdogan and Kaya (2020) also suggested a systematic approach, which covers fuzzy rule-based system (FRBS), and fuzzy MCDM to assess risks and failures in public transport systems. The proposed approach is implemented on the real case of the BRT system in Istanbul and 15 failure type based on five vehicle model are evaluated. It is observed that the proposed system based on FRBS works with 80% accuracy [63]. Besides, Chow et al. (2014) studied sustainable assessment in transport planning for recreational travel with multi-criteria aspect. In this study, a composite sustainability index (CSI) is applied to assess eight alternatives under three decision-making schemes. However, social sustainability is excluded in the study because of the lack of data [64]. Considering environmental, economic and social dimensions, Mahmoudi et al. (2019) proposed a framework based on the best worst method for evaluation of the sustainability criteria of an urban transport network and the model is applied to a case study of transportation in Isfahan, Iran. Research team has selected 17 criteria into three groups: social, economic and environmental and it is found that community cohesion, transportation cost for government and land consumption are the worst criteria in social, economic and environmental categories, respectively [65].

MAUT, another MCDM method, is an analytical tool developed by Keeney and Raiffa in 1976 [66]. It provides an evaluation of the preference of decision-makers and models it mathematically with a multiple attributes utility function. This approach is based on selecting a desirable alternative among the various alternatives. Several applications of MAUT in the transport sector are presented by authors for the selection of best alternative by calculating the best possible utility. Zietsman et al. (2006) applied MAUT for the selection of sections of freeways should be widened US 290 freeway in Houston, Texas and PWV-9 freeway in Tshwane, South Africa. They also used the Delphi process for calculating weights of criteria and specific models for scoring the several alternatives. One of their conclusions is that MAUT approach is found as most conducive to make transport decisions within the scope of sustainable transport because it covers a broad range of quantitative and qualitative sustainability issues in the decision-making process [67]. Abu-Samra et al. (2017) developed a condition-rating model involves a broad range of possible factors affecting flexible pavement performance. Eleven factors were selected for the model and they categorized into three categories: climate conditions, physical properties and operational factors. They collected data by applying survey from experts and from several pavement test to evaluate the condition by using MAUT. Their results revealed that the factor of transverse cracking amount has the highest impact with 24.52% in determining flexible pavement condition [68]. For assessing the effects of future shared mobility, Deshmukh et al. (2018) applied MAUT for quantifying the impact of ride-sharing on the growth of US vehicle fleet size. They modeled the individual's decisions process when acting five-mode alternatives (private car, ride-sharing, transit and walking) by considering multiple factors about that trip. Their results showed that improved ride-sharing with advantages of lower cost and greater availability lead to in transport mode selection away from private car [69]. Kovacevic et al. (2019) studied on the categorization of railway embankments to prioritize maintenance activities in Croatia by using MAUT. They proposed a framework for the categorization of the condition of railway embankment by utilization of multiple data sources for infrastructure manager. By considering the relevance to the problem and availability, they selected five attributes and weighted the importance of each attribute. Then, overall utility function values were calculated by MAUT to form a ranking list of the conditions for the evaluated railway embankments. Finally, the embankments were categorized into five groups, ranging from very poor to very good in accordance to the calculated overall utility function values [70].

Chapter 3

Methodology

3.1 Description of Tramway System in Kayseri

The tramway system in Kayseri, which started operation in 2008 was evaluated in the study. It spreads over 34 km route over three corridors as schematically shown in Figure 3.1. It offers service with 68 tramway vehicles, 38 of them made in Italy and 30 of them made in Turkey, and there are 55 passenger stations. The tramway system was carried over 36 M passengers in 2016 and 37 M passengers in 2017 annually [71].

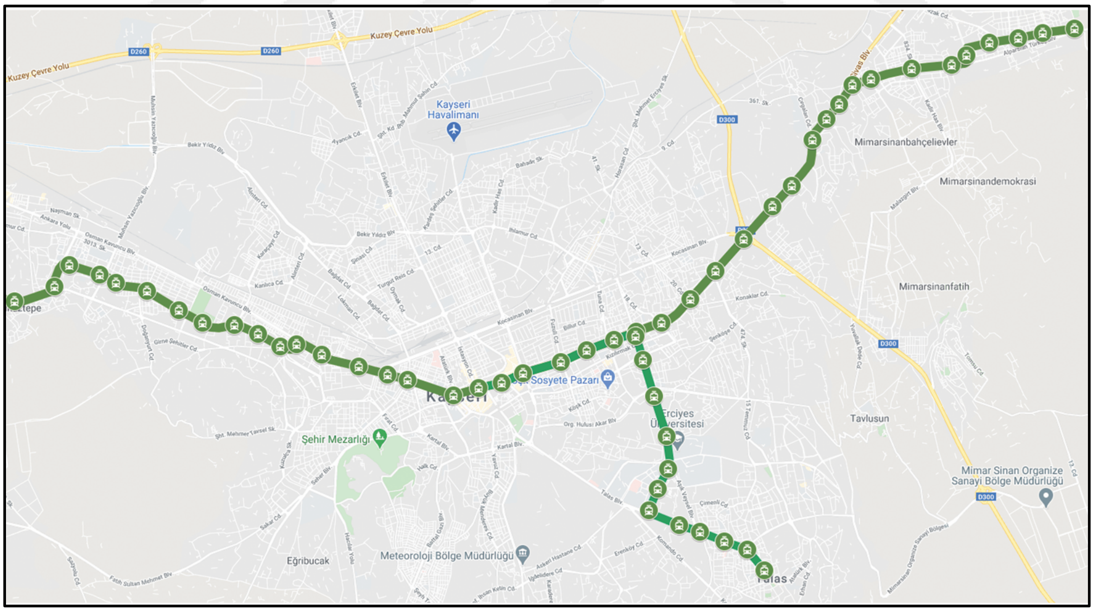

Figure 3.1 Kayseri tramway system network

3.2 Life Cycle Sustainability Assessment

In globalizing world, ‘’sustainable development’’ and ‘’sustainability’’ terms are used with increasing frequency. Sustainable development is defined as ‘’*development that meets the needs of the present without compromising the ability of future generations to meet their own needs’’* in the Brundtland Report of 1987 [72]. In 1992, the term ‘’sustainability’’ was used by UNEP in Rio de Janeiro as the main political goal for the future development of mankind [73]. It was presented to reconcile the conflict between environmental protection and economic development. This concept is usually broken down into contributions of environmental, economic and social concerns called as ‘’triple bottom line’’ or ‘’three pillar’’, which is well accepted by the industry. The term life cycle sustainability assessment (LCSA) was adopted by UNEP and SETAC to compile analyses of all aspects of sustainability, which are environmental, economic and social with the utilization of life cycle thinking [74]. The LCSA can be applied for a product, process or service based on ISO 14040 and 14044 for a holistic and comprehensive assessment [75, 76]. LCSA provides an integrated sustainability evaluation of a product or process by highlighting areas of negative impact for improvements or positive impacts where opportunities can be explored. The standard model for LCSA is formulized (Eq. 3.1) as follows [77]:

$$\text{LCSA} = \text{E-LCA} + \text{LCC} + \text{S-LCA} \quad \textbf{(3.1)}$$

where LCA is the environmental life cycle assessment, LCC stands for the life cycle costing and S-LCA refers to social life cycle assessment.

3.2.1 Environmental Life Cycle Assessment (E-LCA)

Environmental life cycle assessment (E-LCA) is a powerful tool to assess the environmental impacts of a product, process or service over its entire life cycle [78]. E-LCA is used to evaluate these impacts from the extraction of raw materials to end of the life of the product, process or service with a holistic approach. The environmental impacts can be linked to the related inputs and outputs of the product, process or service [79]. The structure and procedure of E-LCA was defined by ISO with two international standards as follows:

- ISO 14040 (2006): ‘Environmental management – Life cycle assessment - Principles and framework’ [75];
- ISO 14044 (2006): ‘Environmental management – Life cycle assessment - Requirements and guidelines’ [76].

The general methodological framework and phases of E-LCA was indicated in Figure 3.2 based on ISO 14040 [75].

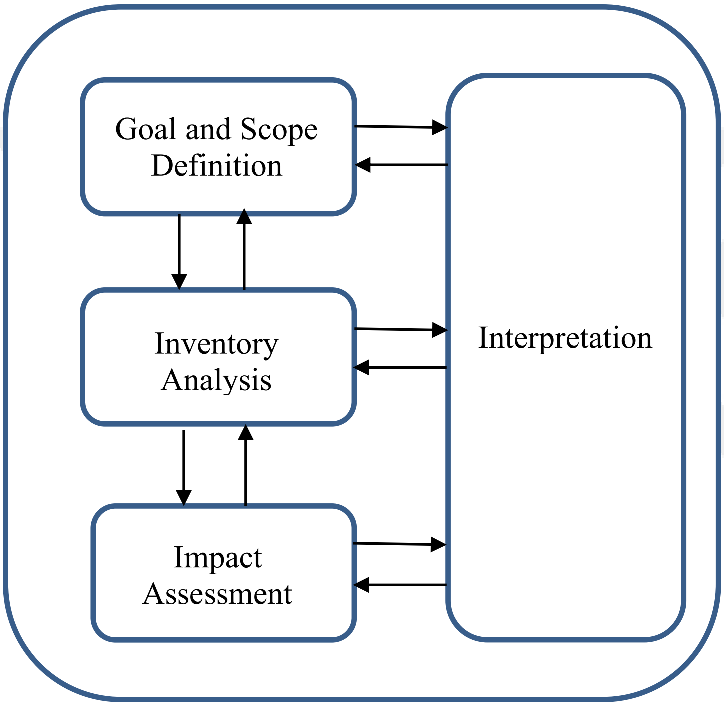

Figure 3.2 The general framework for E-LCA

3.2.1.1 Goal and Scope Definition in E-LCA

The first phase of E-LCA; the goal and scope definition is the fundamental and critical part of an E-LCA study, which include deciding the reasons for carrying out the study and its scope. Defining the goal is the most fundamental step of the E-LCA study and it guides the assessment to ensure that the most worthwhile results are obtained. The particular goals of an E-LCA study must reflect the intended use of findings and reply to the reasons for carrying out the study [79].

The defined scope of the E-LCA study includes deciding which life cycle stages are to be considered and what the system boundaries for the product, process or service with regard to the defined goal. According to ISO 14040, the following elements must be considered and clearly described [75]:

- the product system to be studied
- the functions of the product systems/s
- functional unit
- data requirements
- initial data quality requirements
- allocation procedures
- impact categories selected and methodology of impact assessment and interpretation to be used
- assumptions
- limitations
- type of critical review, if any
- type and format of report required for the study

The functional unit, one of the most important elements of an E-LCA study, is defined as quantified performance characteristics of the product, process or service being studied. It is used as a reference unit, especially to enable comparative assertions. The determination of functional unit depends on the specific function or application of the product, process or service [79].

Another significant step of this phase is defining product systems that involves many individual inputs, outputs and processes. The system boundary defines which of the unit processes, inputs and outputs are to be included in an E-LCA study. Raw materials, energy, water, and other resources from nature, ancillary materials, intermediate materials or products are the main input items. Besides, waste, emissions to air, water and land, as well as the final and any intermediate products are basic output items as illustrated in Figure 3.3 [79].

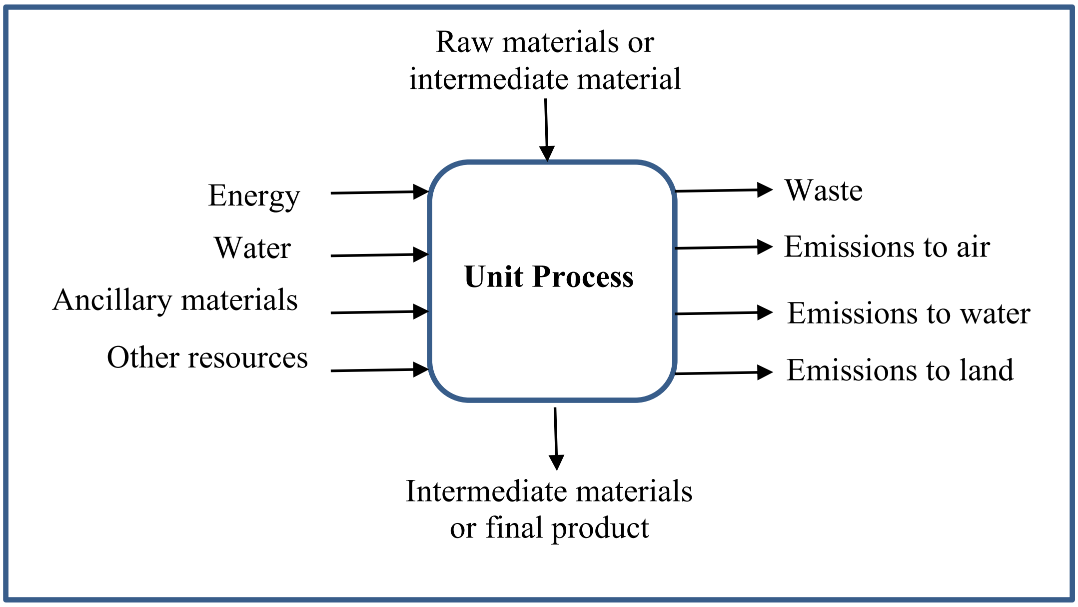

Figure 3.3 The main inputs and outputs for a unit process

The main goal of this study is to conduct an integrated study of the Kayseri tramway system regarding sustainability by implementing LCA, LCC and S-LCA, considering the environmental, economic and social impacts of the tramway system. According to this goal, the functional unit was chosen as one passenger-km rail transportation. System boundaries of the tramway system by considering the cradle to grave approach consist of extraction and production of raw materials, transportation of the raw materials to site, vehicle manufacture, transportation of the vehicles, construction of the infrastructure, operation, maintenance and waste disposal was given in Figure 3.4.

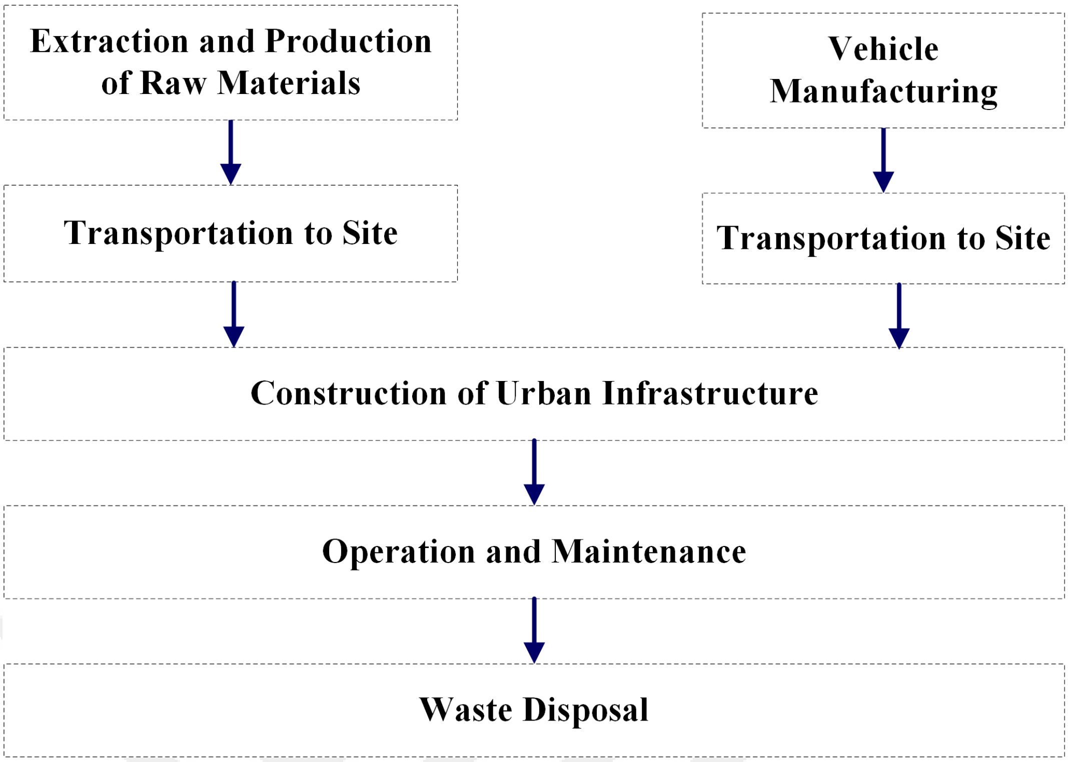

Figure 3.4 System boundary of the tramway rail system used in LCSA

3.2.1.2 Life Cycle Inventory (LCI) Analysis in E-LCA

As the second phase of E-LCA, life cycle inventory analysis covers the data collection and calculations to quantify the inputs and outputs. Although this phase is very significant to obtain reliable E-LCA results, it is one of the most cost and time-consuming phases [80]. The ISO 14040 states that the following steps should be followed for the inventory analysis [75]:

- Drawing specific process flow diagrams,
- Describing each unit process in detail,
- Developing a list that specifies a unit of measurement,
- Describing data collection techniques and calculation techniques for each data category.

The inventory data for the tramway system was collected from the company, which manages and operates the urban tramway system in Kayseri (Table 3.1 and 3.2). The service life of the system was assessed as 50 years. The transport of the raw materials to the site is assumed to be 25 km. Data for vehicle manufacturing, transportation of raw materials and vehicles were implemented into the analyses by using Ecoinvent v3. database in SimaPro 8.4 PhD version.

Table 3.1 Raw materials used during the project

Material	Amount	Unit
C12/15 Concrete	41,929.8	m^3
C20/25 Concrete	2,995.7	m^3
C25/30 Concrete	92,425	m^3
C30/37 Concrete	247,985	m^3
Wood	138,125	m^2
Steel	4,440.3	t
Steel Mesh	2,669.8	t
Cast Iron	34,086.5	kg
Aluminum	12,554	kg
Glass	881	m^2

Table 3.2 Energy consumption during the operation

Energy Consumption	Amount	Unit
Electricity	1,309,720,452	kWh
Diesel Oil	55,000	L

3.2.1.3 Life Cycle Impact Assessment (LCIA) in E-LCA

As the third phase of E-LCA, life cycle impact assessment converts the results of the life cycle inventory analysis into numerical indicators for particular categories that shows the environmental performance of a process, product or service. The main goal of the LCIA is to assess the magnitude and importance of the environmental impacts of a product, process or service depending on findings from an LCA analysis [79]. The LCIA includes some mandatory and optional elements in the E-LCA study. The ISO 14040 outlines these as [75]:

Mandatory Elements

- Selection and definition of impact categories,
- Assignment of LCI results (classification),
- Calculation of category indicator results (characterization),

Optional Elements

- Calculation of the magnitude of category indicator results relative to reference information (normalization),
- Sorting impact categories into specific areas (grouping),
- Assigning weights to different impact categories depending on their perceived significance (weighting).

In this study, the CML-IA baseline method was selected for the impact assessment of the tramway system. The impact categories of this method are as follows: abiotic depletion potential (ADP), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), fresh water aquatic ecotoxicity (FWAE), terrestrial ecotoxicity (TE), photochemical oxidation (PO), acidification potential (AP) and eutrophication potential (EP). For characterization and normalization of the environmental impacts of the tramway system, global and European database values are available in SimaPro software. Ecoinvent database that supplies broader and well-prepared data for a number of products and processes was used for this study [81].

3.2.1.4 Interpretation of E-LCA

The interpretation, the final phase of an E-LCA, includes interpreting the obtained results and findings from LCI and LCIA phases. This phase should provide evaluated results, which are consistent with the defined goal, and scope and conclusions can be drawn in an E-LCA study. Additionally, it can provide some recommendations with particular emphasis on the identification of areas for improvement. This phase involves the following steps [79]:

- Identifying important issues,
- Evaluating the obtained results,
- Drawing conclusions,
- Explaining limitations,
- Providing recommendations.

3.2.2 Life Cycle Costing (LCC)

The life cycle costing is a financial tool, which is widely used to complement LCA analyses for a better understanding of life-cycle evaluation of a product or process from an economic perspective. For the LCC method, there is no specific standard or certification system in literature, however, various examples and definitions exist as guidelines [82]. In this study, the LCC method was used in accordance with Ciroth and Franze (2009) using SimaPro 8.4.1 PhD version [39]. This LCC method was developed by following the guideline published in GreenDeltaTC Berlin for this study. Similarly, LCA, LCC analysis should consist of the following stages; goal and scope definition, cost inventory analysis, life cycle cost assessment and interpretation [83].

The inventory data for the economic assessment of the tramway system was collected from real sectoral sources and literature (Table 3.3). These costs were divided into two categories as internal and external costs by considering economic aspects. The calculations were performed considering the functional unit (USD/passenger-km) for both internal and external costs. The internal costs were divided into four categories as follows: material costs (concrete, steel, cast iron, aluminum, wood, and glass), energy costs (electricity and diesel oil), transportation costs (transport cost of raw material and vehicles) and disposal costs (landfill and incineration). External costs components cover only the environmental costs which occur as costs of the impact categories (global warming, acidification, eutrophication, ozone layer depletion, photochemical oxidation, ecotoxicity and human toxicity) in this study. The cost components of the tramway system were determined by considering the cradle-to-grave approach. The inventory data for the external cost were collected from the literature (Table 3.4).

Table 3.3 The inputs for LCC

Materials	Quantity	Unit	Price	Unit of Cost	References
C 12/15 Concrete	1	m^3	44.48	USD	[84]
C 20/25 Concrete	1	m^3	47.45	USD	[84]
C 25/30 Concrete	1	m^3	49.10	USD	[84]
C 30/37 Concrete	1	m^3	50.75	USD	[84]
Wood	1	m^2	12.01	USD	[84]
Steel	1	t	937.28	USD	[84]
Steel Mesh	1	t	932.19	USD	[84]

Cast Iron	1	kg	1.46	USD	[84]
Aluminum	1	kg	7.70	USD	[84]
Glass	1	m^2	31.96	USD	[84]
Electricity	1	kwh	0.06	USD	[85]
Diesel Oil	1	lt	0.77	USD	[86]

Table 3.4 The quantities of external costs

Environmental Costs	USD/kg emission	References
Global warming (kg CO_2 eq)	0.144	[87]
Acidification (kg SO_2 eq)	10.84	[87]
Eutrophication (kg PO_4 eq)	5.82	[87]
Ozone layer depletion (kg CFC-11 eq)	670	[88]
Photochemical oxidation (kg C_2H_4 eq)	6.63	[87]
Ecotoxicity (kg 1,4-DB eq)	421	[87]
Human toxicity (kg 1,4-DB eq)	4650	[87]

For life cycle cost assessment (LCCA), the LCC method was created by following the guideline published by Ciroth and Franze (2009) by utilization of SimaPro 8.4.1 PhD version [39]. The method mainly consists of three steps: developing an LCC method, inserting economic issues in processes and calculation of life cycle costs. Characterization, damage assessment, normalization and weighing properties were determined while creating the new LCC method. Then, each related cost was added for each process under the economic issues section per reference unit. After the life cycle with economic values was modeled, using SimaPro.

3.2.3 Social Life Cycle Assessment (S-LCA)

Social life cycle assessment is a tool to evaluate the social aspects of a product or process, their actual and potential impacts on social behavior, human welfare and cultural heritage for all of its stakeholders during its life cycle [89]. Even though there is no specific standardization for S-LCA, the guideline published by UNEP in collaboration with the SETAC was followed in the S-LCA section of the study [40, 41].

It is important to determine stakeholders affected throughout the life cycle of the tramway system that was being analyzed. The identification of the affected stakeholder categories and subcategories based on the guideline published by UNEP-SETAC [41]. In this section, four stakeholder categories, which were workers, consumers, society and local community, were identified as four social groups. For the determination of social impacts, 11 sub-categories and 18 social indicators were considered as shown in Table 3.5.

Table 3.5 Selected stakeholders, subcategories and indicators

Stakeholder	Subcategory	Indicator
Worker	Health and Safety	Usage of personal protective equipment (PPE)
		Presence of a formal policy concerning health and safety
		Presence of night work
	Fair salary	Regular payment of the salary
		Employees receiving less than minimum wages
	Working hours	Legal working hours limit
	Child labor	Child labor
Consumer	Health and Safety	Organizations' efforts and measures to protect consumer health and safety
		Presence of management measures to assess consumer health and safety
	Feedback mechanism	Presence of a mechanism for customers to provide feedback
		Management measures to improve feedback mechanisms
	Transparency	Consumer complaints regarding transparency
		Publication of a sustainability report
Local Community	Local Employment	Workforce hired locally
		Local suppliers
	Access to Immaterial Resources	Presence/strength of community education initiatives
Society	Technology and Development	Investments in technology development
	Public Commitment to Sustainability Issues	Presence of publicly available documents as promises or agreements on sustainability issues

Based on the identified categories and subcategories, inventory data gathered from industry reports, site observations and questionnaires. Online questionnaire was also conducted which consists of ‘’yes’’ or ‘’no’’ type descriptive questions for data collection given in the Table 3.6. A check list of 10 questions and 42 consumers were asked to fill the online questionnaire. The collected data was considered adequate to obtain necessary social data for implementing S-LCA. Lastly, the all gathered information by questionnaires were crosschecked to compile a reliable and consistent inventory data.

Table 3.6 Questions of online questionnaire applied on consumers for S-LCA

1) Do you use tramway system in Kayseri?
   A) Yes B) No
2) Do you think it is safe to travel by tramway system in Kayseri?
   A) Yes B) No
3) Do you find the station and vehicles sufficient in cleaning and hygiene?
   A) Yes B) No
4) Do you think Kayseri Transportation Inc. takes the necessary measures for health and safety
   A) Yes B) No
5) Have you ever had an accident while traveling by tramway system?
   A) Yes B) No
6) Have you participated in any survey conducted by Kayseri Transportation Inc.?
   A) Yes B) No
7) Can you easily report your requests and complaints to Kayseri Transportation Inc.?
   A) Yes B) No
8) Are you aware of new projects and developments of Kayseri Transportation Inc.?
   A) Yes B) No
9) Do you come across news about innovations and developments in Kayseri tramway system on
   A) Yes B) No
10) In general, are you satisfied with the tramway system in Kayseri?
    A) Yes B) No

This phase describes the social and socio-economic impacts with the calculation of sub-category indicator results, which is called characterization or scoring [40]. In this study, a methodology for aggregating the inventory results based on a scoring system was utilized to evaluate the social performance of the tramway system in accordance the selected sub-categories and indicators. Firstly, inventory results gathered from questionnaires were converted into percentages and then scores to indicators and sub-categories were assigned. The percentages obtained from the results of questionnaires were classified into five categories, namely, 0-20%, 21-40%, 41-60%, 61-80% and 81-100%. A score ranging from 0 to 4 is assigned to each sub-category as indicated in Table 3.6. The sub-categories which have more than one indicator similarly marking ranges from 0 to 4 was used for each indicator. In this case, the total marks collected to that sub-category will be the average marks of the number of indicators [90]. It is assumed that all indicators and subcategories carry equal weight and thus their weighting factors are one.

Table 3.7 The scoring system for the evaluation of social performance

Subcategory	Percentage	Marks
Cultural heritage, Access to material resources, Safe and healthy living conditions, Health and safety, Feedback mechanism, Privacy, Transparency, Equal opportunities/discrimination, Public commitment to sustainability issues, Contribution to economic development, Technology development	0-20	0
	21-40	1
	41-60	2
	61-80	3
	81-100	4
Child Labor	0-20	4
	21-40	3
	41-60	2
	61-80	1
	81-100	0

3.3 Multi-Criteria Decision-Making (MCDM)

3.3.1 Hesitant Fuzzy Analytical Hierarchy Process (HF-AHP)

A hesitant fuzzy set is a valuable tool to conduct uncertainty and hesitant situations. It provides to decide evaluations under a set for decision-makers. With the HF-AHP, evaluations of DMs for comparison matrices are demonstrated by linguistic variables. Subsequently, judgments of DMs are combined by using the hesitant fuzzy geometric operator [91].

Hesitant fuzzy sets are an extension of the fuzzy set theory first presented by Torra [92] and Torra & Narukawa [93]. Membership degrees of an element must be stated as set to use hesitant fuzzy sets. This desired element is called a hesitant fuzzy element, defined as a set of possible values. Thus, DMs can manage a hesitant situation by specifying their judgments under a set [91].

3.3.1.1 Hesitant Fuzzy Sets: Preliminaries

This section is devoted to describe some basic definition of HFSs concept and describe some operations.

Definition 1 [94]: Let X be a fixed set, then HFS defined as E on X in terms of a function $h_E(x)$ that is applied to X returns under [0,1]. Mathematical expression for HFS is as follows:

$$E=\{< x, h_E(x) > | x \in X\}; \quad \textbf{(3.2)}$$

where $h_E(x)$ describes some possible membership degrees for an element, in [0,1].

Definition 2 [92, 93]: Some basic operators are describes as follows; let h, h_1, and h_2 are HFSs:

$$h^-(x) = \min h(x); \quad \textbf{(3.3)}$$

$$h^+(x) = \max h(x); \quad \textbf{(3.4)}$$

$$h_a^+ = \{h \in h(x) \mid h \geq \alpha\}; \quad \textbf{(3.5)}$$

$$h_a^- = \{h \in h(x) \mid h \leq \alpha\}; \quad \textbf{(3.6)}$$

$$h^c(x) = \cup_{\gamma=h(x)} \{1 - \gamma\}; \quad \textbf{(3.7)}$$

$$(h_1 \cup h_2)(x) = \{h \in (h_1(x) \cup h_2(x) \mid h \geq \max(h_1^-, h_2^-)\}; \quad \textbf{(3.8)}$$

$$(h_1 \cap h_2)(x) = \{h \in (h_1(x) \cap h_2(x) \mid h \leq \min(h_1^+, h_2^+)\}; \quad \textbf{(3.9)}$$

Definition 3 [92, 93]: All intuitionistic fuzzy sets (IFSs) are HFSs. Let the IFS denoted by $\{< x, \mu_E(x), \nu_E(x) > |\}$, then the HFS can be obtained by the following operation:

$$h(x) = [\mu_E(x), 1 - \nu_E(x)] \quad \text{if } \mu_E(x) \neq 1 - \nu_E(x); \quad \textbf{(3.10)}$$

Definition 4 [94]: Assuming h, h_1, and h_2 are three HFSs, primary operations on HFSs are given as follows:

$$h^\lambda = \cup_{\gamma \in h} \{\gamma^\lambda\}; \quad \textbf{(3.11)}$$

$$\lambda h = \cup_{\gamma \in h} \{1 - (1-\gamma)^\lambda\}; \quad \textbf{(3.12)}$$

$$\widetilde{h_1} \oplus \widetilde{h_2} = \cup_{\gamma_1 \in \widetilde{h_1}, \gamma_2 \in \widetilde{h_2}} \{\gamma_1 + \gamma_1 - \gamma_1\gamma_2\}; \quad \textbf{(3.13)}$$

$$\widetilde{h_1} \otimes \widetilde{h_2} = \cup_{\gamma_1 \in \widetilde{h_1}, \gamma_2 \in \widetilde{h_2}} \{\gamma_1 + \gamma_1 - \gamma_1\gamma_2\}; \quad \textbf{(3.14)}$$

$$\widetilde{h_1} \cup \widetilde{h_2} = \cup_{\gamma_1 \in \widetilde{h_1}, \gamma_2 \in \widetilde{h_2}} max\{\gamma_1, \gamma_2\}; \quad \textbf{(3.15)}$$

$$\widetilde{h_1} \cap \widetilde{h_2} = \cup_{\gamma_1 \in \widetilde{h_1}, \gamma_2 \in \widetilde{h_2}} min\{\gamma_1, \gamma_2\}; \quad \textbf{(3.16)}$$

3.3.2 Multi-Attribute Utility Theory (MAUT)

MAUT is an analytical tool developed by Keeney and Raiffa in 1976 [66]. It provides an evaluation of the preference of decision-makers and models it mathematically with a multiple attributes utility function. This approach is based on selecting a desirable alternative among the various alternatives. It has been utilized in many fields such as energy, manufacturing, public policy, health care, and fisheries [95].

With this method, the analysis of alternatives specifies the measures, which are utilized to criticize the alternatives. Besides, it also facilitates the identifying of these alternatives that reveal excellent performance on a majority of these measurements, giving great importance to the measures which are considered more critical [96].

MAUT is a method used to identify and analyze multiple variables systematically to attain the desired decision. In this method, single utility functions and their weighing factors are the key elements to obtain multi-attribute utility functions. Although several application procedures exist in theory and application, it mainly consists of five stages as follows [97];

- Setting aim and establishing the attributes for the purpose
- Quantifying the attributes
- Deriving the utility functions of each attribute
- Calculating weights of each attribute
- Deriving multi-attribute utility function

A multi-attribute utility function is defined as [98]

U= f $[u_1(x_1), u_2(x_2), \dots, u_n(x_n)]$

where U is a multi-attribute utility function; u_i is single-attribute utility function measuring the utility of attribute i; and x_i is level of ith attribute.

In order to structure the utility functions, one needs to make assumptions regarding preferential independence (PI) and utility independence (UI). To define preferential independence, assume that the set of attributes is $\{X_1, X_2, \dots . X_n\}$. Then, if n ≥3, the pair of attributes $\{X_1, X_2\}$ is PI does not depend on the levels of the other attributes given the other attributes are held fixed. If the preference order for 'lotteries'' defined as a probability distribution over a known, finite set of outcomes over X_1 does not depend on the levels of $X_3 - X_n$ given the other attributes are held fixed, X_1 is UI of the other attributes.

Given $X_1, X_2, \ldots . X_n$, n ≥3, suppose for some X_i, both $\{X_i, X_j\}$ is PI for all j ≠ i and X_i is UI, then either

$$U(x_1, x_2 \ \ldots., x_n) = \sum_{i=1}^{n} k_i u_i(x_i) \text{ if } \sum_{i=1}^{n} k_i = 1 \quad \textbf{(3.17)}$$

or

$$1 + KU(x_1, x_2 \ \ldots., x_n) = \prod_{i=1}^{n} [1 + K k_i u_i(x_i)] \text{ if } \sum_{i=1}^{n} k_i \neq 1 \quad \textbf{(3.18)}$$

where U and u_i are utility functions scaled from 0 to 1; 0<k_i<1, i=1,2..., n, k_i denotes scaling constant; and if $\sum_{i=1}^{n} k_i \neq 1$, K>-1 is the non-zero solution to 1+K = $\prod_{i=1}^{n}(1 + K k_i)$. Equation (3.17) says that the overall utility function takes an additive from while Equation (3.18) says that the function takes a multiplicative form [98].

3.3.3 The Applied Methodology for Sustainable Transport Measurement

The applied model to measure the sustainability of alternative transport scenarios, composed of integration of HF-AHP and MAUT methods, is comprised of three critical steps: (1) selection of the indicators (2) calculation of weights with HF-AHP and (3) evaluation of alternative scenarios in terms of sustainability with MAUT and determination of final ranking. The schematic diagram of this new model for sustainable transport measurement is indicated in Figure 3.5.

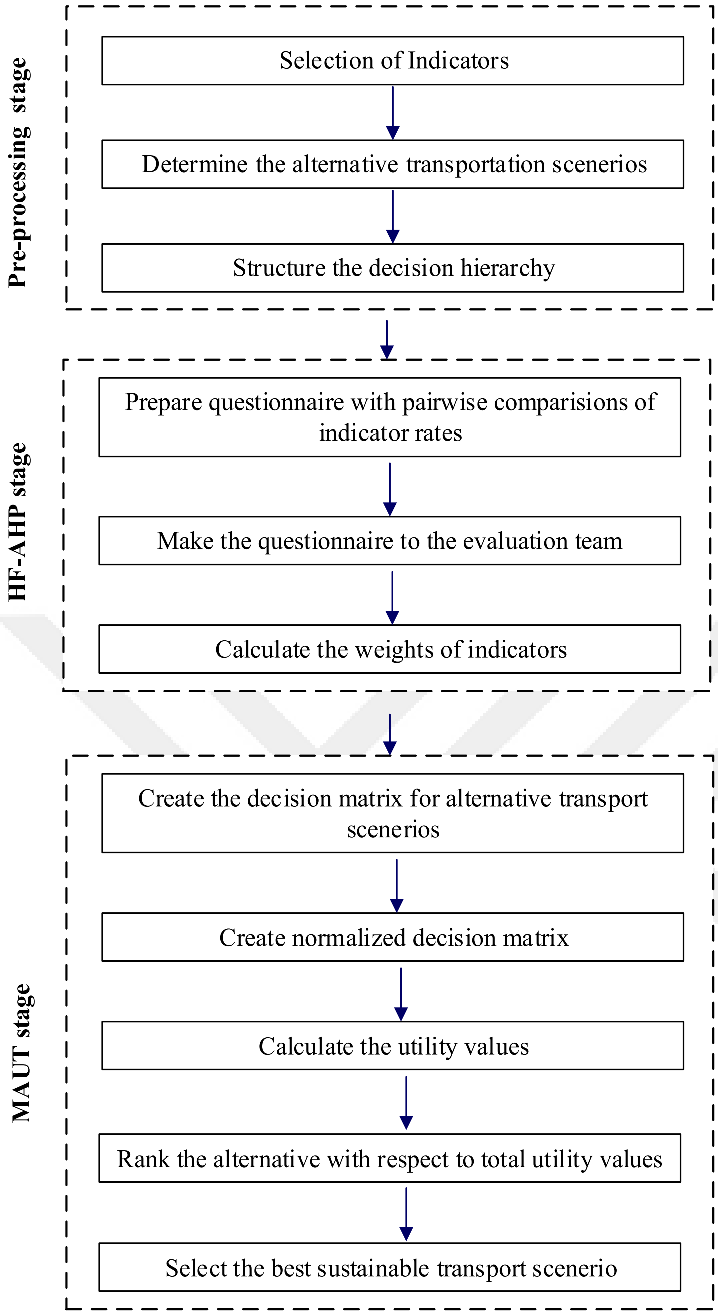

Figure 3.5 The applied model approach

Chapter 4

Results and Discussion

4.1 Life Cycle Sustainability Assessment

4.1.1 Environmental Life Cycle Assessment (E-LCA)

The environmental impacts of the tramway system for one passenger-km rail transportation by considering the cradle-grave approach were calculated with CML-IA baseline method. The results are presented in Table 4.1. LCA analysis consists of nine environmental impact categories (ADP, GWP, ODP, HTP, FWAE, TE, PO, AP and EP) to reveal the environmental performance of the tramway system. The value of ADP was calculated as 2.7E-01 MJ for the tramway system, as shown in Table 4.1. The main contributor process for ADP was operation and maintenance with a 53% share of the total (1.4E-01 MJ) and followed by waste disposal with a 16% share (4.3E-02 MJ) as illustrated in Figure 4.1. Similarly, with ADP, operation and maintenance had the highest impact in GWP with 49% (1.2E-02 kg CO_2 eq). The total value of GWP was calculated as 2.4E-02 kg CO_2 eq. In addition to ADP and GWP, the tramway system had high on impact categories of HTP and FWAE as well. The value of HTP was 8.0E-03 kg 1,4-DB eq and the value of FWAE was 8.3E-03 kg 1,4-DB eq for the tramway system per passenger-km (Table 4.1).

Table 4.1 Impact category values of tramway system per passenger-km (CML-IA baseline Method)

Impact category	Unit	Total	Extr. Pro. Raw Mat.	Vehicle Manu.	Trans. of Vehicles	Trans. of Raw Mat.	Ope. Main.	Waste Disposal
ADP	MJ	2.7E-01	4.2E-02	1.0E-03	3.0E-05	4.2E-02	1.4E-01	4.3E-02
GWP	kg CO_2 eq	2.4E-02	3.9E-03	9.3E-05	2.7E-06	3.9E-03	1.2E-02	4.0E-03
ODP	kg CFC-11 eq	1.4E-09	3.9E-10	1.5E-11	4.2E-13	3.9E-10	2.4E-10	4.0E-10
HTP	kg 1,4-DB eq	8.0E-03	1.1E-03	2.9E-04	8.3E-06	1.1E-03	4.0E-03	1.4E-03
FWAE	kg 1,4-DB eq	8.3E-03	8.1E-04	1.4E-04	4.1E-06	8.1E-04	5.6E-03	9.5E-04
TE	kg 1,4-DB eq	8.2E-05	1.9E-05	7.3E-07	2.1E-08	1.9E-05	2.5E-05	1.9E-05

PO	kg C_2H_4 eq	1.5E-05	4.1E-06	5.7E-08	1.7E-09	4.1E-06	2.6E-06	4.2E-06
AP	kg SO_2 eq	1.2E-04	1.8E-05	1.0E-06	2.9E-08	1.8E-05	6.5E-05	1.9E-05
EP	kg PO_4 eq	5.2E-05	5.3E-06	5.4E-07	1.6E-08	5.3E-06	3.5E-05	5.9E-06

In environmental performance evaluation, process-based evaluation is critical to show the effects of processes in terms of environmental impacts and to interpret the results in a systematic way. It is also important for decision-makers to decide on proper and sustainable new projects and improve the existing urban transport systems by considering the process-based sustainability assessments. The distribution of the environmental impact results based on the processes (extraction and production of raw materials, transportation of raw materials, vehicle manufacture, transportation of vehicles, operation and maintenance, and waste disposal) for the tramway system are shown in Figure 4.1.

The operation and maintenance were the main contributors within the processes considered in the life cycle of the tramway system for ADP, GWP, HTP, FWAE, acidification, and eutrophication impact categories. The operation and maintenance phase had the highest impacts for FWAE and eutrophication with 67%, followed by acidification and ADP (53%), HTP (50%), and GWP (49.0%). The main reason for this is the high amount of electricity consumption from fossil-based sources during the operation and maintenance and the long time period (50 years) for operation. In Turkey, the GWP of the electricity production from fossil-based sources (hard coal, lignite and natural gas) varies between 499-1126 g CO_2 eq./kWh while the renewable sources (hydropower, wind, solar and geothermal) have 4.1-63 g CO_2 eq./kWh. Among all alternative energy sources, hard coal has the highest GWP (1126 g CO_2 eq./kWh) impact and second-highest ADP impact with 13.5 MJ/kWh, following the lignite with 15.1 MJ/kWh [99]. Thus, the high share of fossil fuels in the Turkish national electricity mix and increasing demand due to population growth causes greenhouse gas emissions and other environmental impacts. Shinde et al. (2018) performed an LCA study for Mumbai Suburban Railway in order to assess its environmental performance. Similarly, in this study, they reported that the operation phase is the main contributor, with 87-94% of the total environmental impacts due to the production of electricity from non-renewable sources in India. In the same study, the second major contributor was the construction phase, with 24-57% of the total environmental impact due to material and energy-intensive rails usage [43]. A similar study was performed on a heavy metro train in Rome and revealed that 41-90% of the total environmental impacts (for eleven environmental impacts) were caused by the operation stage, which is the most influenced stage among the four main stages: material acquisition, manufacturing, operation and end of life [51]. Additionally, Li et al. (2018) studied on quantification of life-cycle greenhouse gas emissions of Shangai Metro. They calculated the total life-cycle greenhouse gas emissions per construction length of Shangai Metro as 109,642.81 tCO_2e with a service life of 50 years. Emissions from the operation phase account for 92.1% of the total annual greenhouse gas emissions and then materials production follows with 4.1% and the maintenance phase follows with 3.4% within its life cycle [50].

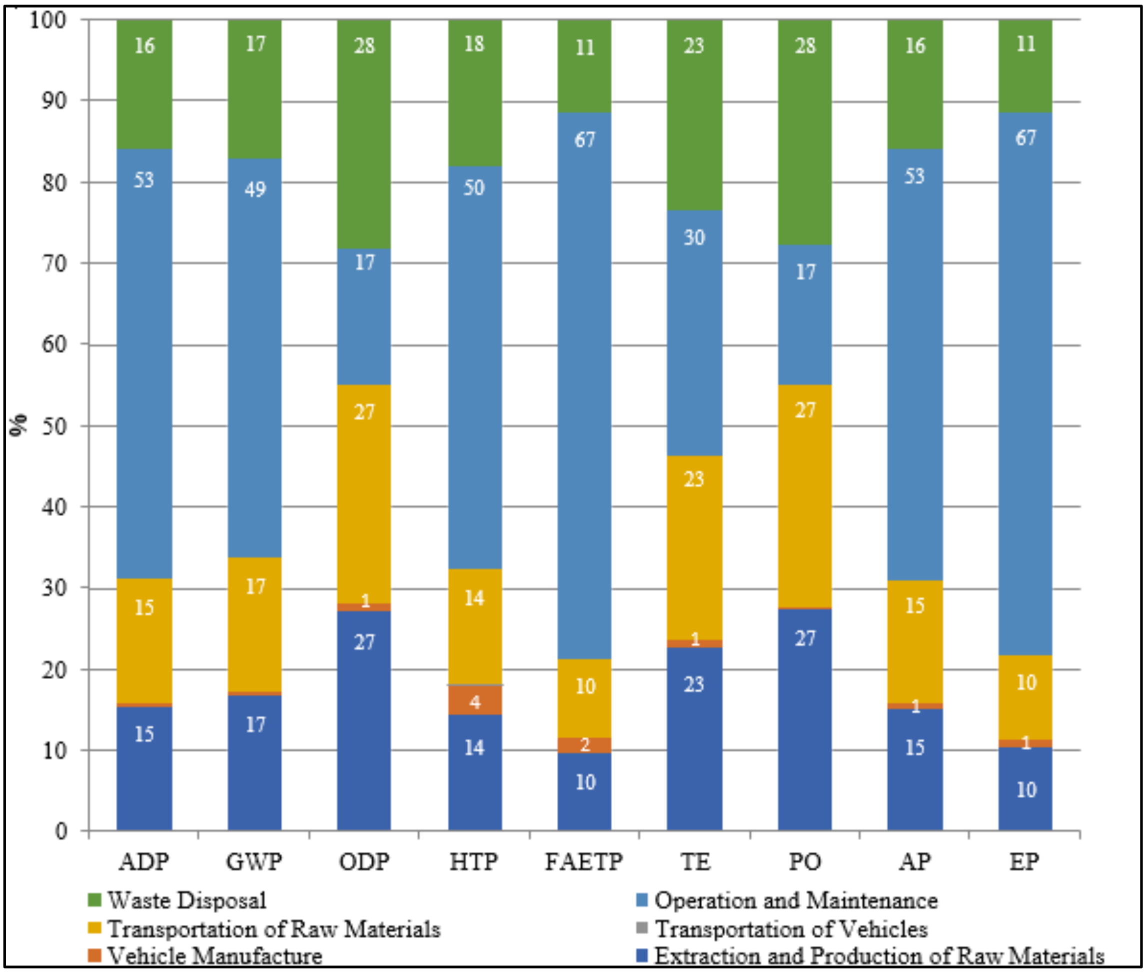

Figure 4.1 The environmental impacts of tramway system based on CML-IA baseline method: CML-IA baseline V3.04/EU25/Characterization

In the transportation sector, the GWP is one of the significant environmental parameters. In this study, the GWP of the tramway system was calculated as 2.4E-02 kg CO_2 eq (Table 4.1). The operation and maintenance process (50%) have the highest impact on GWP for the tramway system as shown in Figure 4.1. Waste disposal (16.6%), extraction and production of raw materials (16.3%), transportation of raw materials (16.3%) play also an important role for GWP due to greenhouse gas emissions generated from the production of electricity from fossil-based sources. Production of raw materials (especially concrete and steel) and transportation of the raw materials due to fossil fuel consumption contribute for GWP as well. Similarly, Banar and Ozdemir (2015) found that GWP of HSR system is 2.2E-02 kg CO_2 eq and 2.5E-02 kg CO_2 eq for the CR system per passenger-km. They also concluded that the operation of train vehicles has a higher impact on the environmental performance of HSR and CR system than the infrastructure process [42]. Moreover, Tsai (2017) implemented carbon footprinting to high-speed railways in Taiwan and carbon footprint of Taiwan high-speed rail corporation is found as 3.8E-02 kg CO_2 eq per person-km [100]. The value of HTP was 8.0E-03 kg 1,4-DB eq for the tramway system as indicated in Table 4.1. Like GWP, the main contributor phase for HTP was operation and maintenance with 50% share of the total impact and then waste disposal follows with a 17.5% contribution (1.4E-03 kg 1,4-DB eq). This impact results from materials and fuels used in the operation phase; for instance, diesel oil used in the operational phase of vehicles.

4.1.2 Life Cycle Costing (LCC)

The cost assessment for the tramway system was done using the LCC method as shown in Table 4.2. The total life cycle cost of the tramway system was calculated as 3.13E+08 USD and 0.046 USD per passenger-km. The main contributor for total life cycle cost was energy cost with 92% (2.88E+08 USD) of the total due to high consumption of electricity for the operation of the tramway system. The main reason for this is the high price of electricity in Turkey and high electricity consumption in the operational phase. Although electricity prices in Turkey (USD 0.09 per kWh) is lower than the USA price (USD 0.15 per kWh), it is expensive than in China (USD 0.08 per kWh) and Russia (EUR 0.06 per kWh) in 2020 [101]. As a developing country, the electricity market in Turkey is dominated by fossil fuel technologies. Although the renewable energy technologies for electricity production has increased in total installed capacity in the last decades, nearly 60% of the overall electricity was supplied from fossil-based plants, 22% from hydropower plants and the share of other renewables (i.e. solar, wind) was almost 11% in 2019 [102]. In the Turkish power system, natural gas has a significant share. Its supply disruptions from the import countries (i.e., Russia and Iran) resulted in some crucial problems in past winter seasons when high energy demand. Thus, foreign-source dependency, whether and system contingencies are the main major factors affecting the electricity prices in Turkey [103]. Besides, the material cost had the second-highest share with 8% (2.51E+07 USD) of the total life cycle cost as indicated in Table 4.2. The total life cycle cost of the tramway system per passenger-km was calculated as 0.046 USD.

Table 4.2 The cost values of tramway rail system (LCC Method)

Cost categories	Total Cost (USD)	Unit Cost (USD/passenger-km)
Internal		
Material Cost	2.51E+07	3.69E-03
Transportation Cost	4.36E+03	6.42E-07
Energy Cost	2.88E+08	4.23E-02
Disposal Cost	6.24E+01	9.18E-09
External		
Environmental Cost	1.02E+04	1.5E-06
Total Cost	3.13E+08	4.60E-02

This is the first time LCC of a tramway system was performed; hence it is impossible to compare these findings with previous findings. However, a study published by Banar and Ozdemir (2015) provides findings for HSR and CR systems in Turkey by using LCA and LCC methods. They compared the HSR and CR systems by considering the cradle-to-grave approach. Their results show that the total life cycle cost of the HSR per passenger-km is 0.042 €, and 72% of the total life cycle cost results from railway infrastructure components. Besides, the total life cycle cost of the CR per passenger-km is 0.037 €, and 80% of the total life cycle cost resulted from rail operation [42]. A number of studies have considered the LCC of several transport modes such as high-speed and conventional railway systems; however, LCC studies for tramway systems are scarce in the literature. Thus, this study aims to contribute the literature with the findings and paves the way for further studies.

4.1.3 Social Life Cycle Assessment (S-LCA)

The objective of the implementation of the S-LCA was to assess the social performance of the tramway system on selected four social stakeholders. The results of the S-LCA subcategories underscoring method are presented in Table 4.3. The inventory results confirmed that there was no case of child labor and forced labor and all workers enjoy social benefits. Besides, all workers receive regular payment of the salary, which is not less than minimum wages. In addition, working hours were within legal limits working hours for all workers. Thus, subcategories of fair salary, working hours, and child labor scored the highest point for stakeholders of workers (Table 4.3). However, the subcategory of health and safety for workers had a lower score than others due to the presence of night work for technicians. As indicated in Table 4.3, it adversely affects the social performance of the industry even though the workers use personal protective equipment and the presence of formal policy concerning health and safety.

Table 4.3 The score results of subcategories for each stakeholder

Stakeholder	Subcategory	Score
Worker	Health and Safety	3
	Fair Salary	4
	Working Hours	4
	Child Labor	4
Consumer	Health and Safety	3
	Feedback Mechanism	1
	Transparency	3
Local Community	Local Employment	3
	Access to Immaterial Resources	4
Society	Technology and Development	4
	Public Commitment to Sustainability Issues	4

The results of the questionnaire administered to various passenger groups who utilize the tramway system show that the feedback mechanism of the industry received the lowest score for stakeholders of consumers (Table 4.3). The main reason for this is to obtain a number of responses for weak management measures to improve the feedback mechanism of the industry. Although the industry has a mechanism for consumers to provide feedback, their responses reveal that management measures are not satisfied to present their complaints and suggestions to the industry. On the other hand, subcategories of health and safety and transparency had a better score than the feedback mechanism. The results of questionnaires for the health and safety of consumers confirmed that passengers thought that traveling with the tramway system was safe and satisfied with the hygiene of the stations and vehicles. Additionally, the transparency subcategory scored 3 out of 4 due to not enough informed about new projects and developments for passengers.

The overall results for consumers revealed that the social performance of the tramway system on consumers had the lowest score among all stakeholders. The ‘’society’’ stakeholder had the highest scores among five stakeholders under evaluation of technology and development and public commitment to sustainability issues (Table 4.3). For society, the industry had a research and development department and they share their knowledge and experiences with society. The promises or agreements on sustainability issues are published by the industry and they are publicly available. Shrivastava and Unnikrishnan (2021) studied on S-LCA crude oil process chain in India and reported that the companies need significant improvements to improve their social performance in terms of safety, health, awareness and pay [33]. Lenzo et al. (2017) performed an S-LCA study on the textile industry in Italy by using the SAM approach. They were considered only two stakeholders (workers and local community) and their results showed that only one subcategory (freedom of association and collective bargaining) was marked as ‘’Level C’’ which corresponds to the 2 [104]. Prasara and Gheewala (2018) did an S-LCA study on the Thai sugar sector revealed that fair wages, health and safety, water and land rights are needed improvements to enhance social performance [105].

The urban transport industry has an important place in society from environmental, economic and social aspects as mentioned in the introduction section. It is reported that 64% of the total global travel kilometers are done in urban areas in the world [106]. Although the urban transportation industry has a large share in the global transportation sector, there is a lack of information about its social dimension of sustainability in literature. Thus, this study presents for the first time an S-LCA point of view of the tramway systems for literature.

4.2 Multi-Criteria Decision-Making (MCDM)

4.2.1 Hesitant Fuzzy Analytical Hierarchy Process (HF-AHP)

In this part of the study, eight sustainable transport indicators (CO_2 emission, energy consumption, depletion of non-renewable resources, operational costs, maintenance costs, fuel and taxes, number of fatalities/injuries, and motor vehicles for public transport per 10,000 population) were selected by considering the availability of data from the transport sector, and the weights of selected indicators are calculated with the utilization of HF-AHP. The judgments of decision-makers, including four academicians and four professionals from the transport sector, are represented by linguistic variables and their importance is shown in Table 4.4.

Table 4.4 Hesitant linguistic terms and corresponding triangular fuzzy number

Hesitant Linguistic Variable	Triangular Fuzzy Numbers	Inverse Triangular Fuzzy Numbers
Equally Important (EI)	(1/2, 1, 3/2)	(2/3, 1, 2)
Less Important (LI)	(1, 3/2, 2)	(1/2, 2/3, 1)
More Important (MI)	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very Important (VI)	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolute Important (AI)	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

Five different linguistic variables are used in this study. The steps of HF-AHP for weight calculation are as follows:

Step 1: Defining the linguistic term cluster $S = \{S_0, S_1, \ldots, S_n\}$, as shown in Table 4.4, has been used.

Step 2: Pairwise comparison matrices for criteria and evaluations of experts by using linguistic terms are collected

Step 3: Constructing env [d_{ij}] data envelop for each i-j pairs of criteria contains linguistic terms, as shown in Table 4.5.

Step 4: Identification of linguistic terms and corresponding triangular fuzzy numbers.

Step 5: Converting env[d_{ij}] data envelops to the env[$\tilde{d}_{ij}$] data envelops contains triangular fuzzy numbers.

Step 6: Calculation of arithmetic mean of fuzzy triangular numbers within in env[$\tilde{d}_{ij}$] data envelops, as shown in Table 4.6.

Step 7: Determining the weight of the i_{th} criterion for the k_{th} level by a geometric mean operation.

Step 8: Calculation of fuzzy weights of each i_{th} criterion by using Equation (4.1).

$$\widetilde{w_i} = \tilde{r_i} \otimes (\tilde{r_i} \oplus \tilde{r_2} \oplus \ldots \oplus \tilde{r_n})^{-1} = (lw_i, mw_i, uw_i) \quad \textbf{(4.1)}$$

lw_i = lower weight of i_{th} criteria

mw_i = medium weight of i_{th} criteria

uw_i = upper weight of i_{th} criteria

Step 9: Compute final weights $\sim w_i$ by using Equation (4.2), as shown in Table 4.7.

$$M_i = \frac{lw_i + mw_i + uw_i}{3} \quad \textbf{(4.2)}$$

Step 10: Normalization of M_i fuzzy weights for each i_{th} criteria by using Equation (4.3), as shown in Table 4.7.

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \quad \textbf{(4.3)}$$

The decision-makers state their opinions for selecting a more sustainable urban transport scenario with the help of a questionnaire. With this purpose, evaluations of decision-makers have been used to establish the hesitant fuzzy linguistic comparison matrix for each i-j pair of criteria, as shown in Table 4.5. Then, the hesitant fuzzy linguistic comparison matrix is converted to the matrix with fuzzy triangular numbers for each i-j pair of criteria, and the arithmetic average is calculated for each pairwise comparison, as shown in Table 4.6.

Table 4.5 The envelope of linguistic terms for each i-j pair of criteria

	C1	C2	C3	C4	C5	C6	C7	C8
C1	[EI]	[AI,MI,VI,AI,AI]	[AI,MI,MI,MI,VI,AI]	[MI,VI,MI]	[MI,MI,LI,AI,AI]	[MI,MI,MI,VI,VI]	-	[VI,MI,VI,LI,AI,MI]
C2	[LI,AI,VI]	[EI]	[LI,VI,AI]	[VI,MI,VI]	[VI,MI,LI,MI,VI,MI,VI]	[VI,MI,LI,VI]	-	[VI,MI,MI,VI,VI,AI,VI]
C3	[VI,MI]	[VI,MI,VI,VI]	[EI]	[LI,MI,LI,LI]	[LI,MI,LI,LI,MI]	[VI,MI,MI,MI]	-	[VI,MI,MI,VI,LI,VI]
C4	[VI,MI,VI]	[MI,MI,AI,VI,VI]	[VI,AI,VI,VI]	[EI]	[VI,MI,VI,LI,AI]	[VI,MI,MI,AI,MI]	[LI,LI]	[VI,MI,MI,VI,VI,VI]
C5	[MI,LI]	[MI]	[MI,MI,VI]	[MI,VI,VI]	[EI]	[LI,MI,VI,MI,VI]	-	[VI,MI,MI,AI,VI]
C6	[LI,VI]	[LI,VI,VI,VI]	[LI,VI,AI,VI]	[MI,LI]	[VI,AI,AI]	[EI]	[VI]	[LI,MI,LI,AI]
C7	[VI,AI,VI,LI,AI,AI,AI]	[VI,AI,VI,MI,LI,MI,MI]	[VI,AI,LI,LI,LI,AI,AI,AI]	[VI,AI,MI,AI,AI,AI]	[AI,AI,MI,MI,LI,AI,AI]	[AI,LI,MI,LI,AI,AI,AI]	[EI]	[AI,MI,VI,AI,AI,AI]
C8	[LI,MI]	[LI]	[VI,LI]	[MI]	[MI]	[VI]	[AI,MI]	[EI]

Table 4.6 Arithmetic averaged fuzzy pair wise comparisons of each i-j criteria

	C1	C2	C3	C4	C5	C6	C7	C8
C1	[(0.50,1.00,1.50)]	[(2.00,2.50,3.00)]	[(1.75,2.25,2.75)]	[(1.67,2.17,2.67)]	[(1.33,1.83,2.33)]	[(1.50,2.00,2.50)]	[(0.33,0.40,0.51)]	[(1.75,2.25,2.75)]
C2	[(2.10,2.60,3.10)]	[(0.50,1.00,1.50)]	[(1.83,2.33,2.83)]	[(1.83,2.33,2.83)]	[(1.64,2.14,2.64)]	[(1.63,2.13,2.63)]	[(0.35,0.42,0.55)]	[(1.93,2.43,2.93)]
C3	[(1.88,2.38,2.88)]	[(1.88,2.38,2.88)]	[(0.50,1.00,1.50)]	[(1.40,1.90,2.40)]	[(1.20,1.70,2.20)]	[(1.63,2.13,2.63)]	[(0.37,0.47,0.64)]	[(1.67,2.17,2.67)]
C4	[(2.10,2.60,3.10)]	[(1.90,2.40,2.90)]	[(2.00,2.50,3.00)]	[(0.50,1.00,1.50)]	[(1.80,2.30,3.80)]	[(1.80,2.30,2.80)]	[(1.00,1.50,2.00)]	[(1.83,2.33,2.83)]
C5	[(1.70,2.20,3.70)]	[(1.50,2.00,2.50)]	[(1.67,2.17,2.67)]	[(1.83,2.33,2.83)]	[(0.50,1.00,1.50)]	[(1.60,2.10,2.60)]	[(0.35,0.43,0.56)]	[(1.90,2.40,2.90)]
C6	[(1.88,2.38,2.88)]	[(1.75,2.25,2.75)]	[(1.88,2.38,2.88)]	[(1.25,1.75,2.25)]	[(2.33,2.83,3.23)]	[(0.50,1.00,1.50)]	[(2.00,2.50,3.00)]	[(1.50,2.00,2.50)]
C7	[(2.14,2.64,3.14)]	[(2.00,2.50,3.00)]	[(1.88,2.38,2.88)]	[(2.25,2.75,3.25)]	[(2.00,2.50,3.00)]	[(1.93,2.43,2.93)]	[(0.50,1.00,1.50)]	[(2.25,2.75,3.25)]
C8	[(1.25,1.75,2.25)]	[(1.00,1.50,2.00)]	[(1.50,2.00,2.50)]	[(1.50,2.00,2.50)]	[(1.50,2.00,2.50)]	[(2.00,2.50,3.00)]	[(2.00,2.50,3.00)]	[(0.50,1.00,1.50)]

As the next step, geometric means of fuzzy comparisons are calculated for lower, medium, and upper values of each criterion. Then, the fuzzy weights of each criterion are calculated by using Equation (4.1). The final weights of each criterion are calculated by using Equation (4.2), and de-fuzzified weights (M_i) are shown in Table 4.7. The final step of the HF-AHP method is the normalization of weights. The normalized (N_i) relative weights of each criterion are calculated with Equation (4.3), and values are shown in Table 4.7. The results show that several fatalities and injuries (C7) have the highest weight of 0.158, and motor vehicles for public transport per 10,000 population (C8) have the lowest weight of 0.107.

Table 4.7 De-fuzzified (M_i) and normalized (N_i) relative weights of criteria

Criteria	M_i	N_i
C1	0.425	0.133
C2	0.388	0.121
C3	0.377	0.118
C4	0.410	0.128
C5	0.385	0.120
C6	0.370	0.115
C7	0.505	0.158
C8	0.344	0.107

4.2.2 Multi-Attribute Utility Theory (MAUT)

In this part of the study, considering the transport modes used in Kayseri, twelve alternative urban transport scenarios are compared in terms of selected eight indicators to decide the most sustainable transport scenario. These twelve urban transport scenarios are selected from applied transport scenarios of a city with a 1,350,000 population, and the characteristics of alternatives are given in Table 4.8.

Table 4.8 Characteristics of sustainable transport alternatives

		Number of Vehicles		
		Tramway	**Bus**	**Bicycle**
High-Motorized	**A1**	High (>40)	High (>700)	Low (<600)
	A2	High (>40)	Medium (600-700)	Low (<600)
	A3	High (>40)	High (>700)	High (>600)
	A4	High (>40)	Medium (600-700)	High (>600)
Medium-Motorized	**A5**	Low (<40)	Medium (600-700)	Low (<600)
	A6	Low (<40)	High (>700)	High (>600)
	A7	High (>40)	Low (<600)	Low (<600)
	A8	Low (<40)	High (>700)	Low (<600)
Low-Motorized	**A9**	Low (<40)	Medium (600-700)	High (>600)
	A10	High (>40)	Low (<600)	High (>600)
	A11	Low (<40)	Low (<600)	Low (<600)
	A12	Low (<40)	Low (<600)	High (>600)

The steps of the MAUT methods for evaluation of alternatives are as follow;

Step 1: Create the decision matrix and determine criteria and alternatives, as shown in Table 4.9.

Step 2: Calculate weight for each criterion. The sum of each weight w_i values must be equal to

$$\sum_{i=1}^{m} w_i = 1$$

Step 3: Create the normalized decision matrix, as shown in Table 4.10.

Step 4: Calculation of utility values

For criteria to be maximized: $ui(x_i) = \frac{x - x_i^-}{x_i^+ - x_i^-}$ **(4.4)**

For criteria to be minimized: $ui(x_i) = \frac{x_i^+ - x}{x_i^+ - x_i^-}$ **(4.5)**

where

x_i^- = the worst value of the alternatives

x_i^+ = the best value of the alternatives

Step 5: Calculation of total utility, as shown in Table 4.11.

$$U_i = \sum_{j=1}^{m} w_j U_{ij} \text{ for all i} \quad \textbf{(4.6)}$$

Step 6: Ranking the alternatives for total utility values. Higher utility value corresponds better alternatives.

Collected data for each alternative under three criteria categories are given in Table 4.9 as a decision matrix.

Table 4.9 Decision matrix of alternatives

	Environmental			Economic			Social	
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
	tCO2e	**MWh**	**litres**	**%**	**%**	**%**	**number**	**number**
A1	23,424	46,218	3,807,348	94	4	2	10	6.02
A2	22,821	24,895	3,601,906	95	3	2	9	5.53
A3	24,028	26,019	3,618,101	97	1	2	8	6.02
A4	23,424	49,877	3,807,348	96	2	2	9	6.02
A5	23,233	34,833	3,431,012	94	3	3	7	4.92
A6	23,233	38,624	3,807,668	94	4	2	10	5.96
A7	23,423	46,194	3,068,904	96	2	2	7	4.86
A8	23,233	34,846	3,807,668	96	2	2	10	5.81
A9	23,233	39,189	3,431,012	97	3	1	9	5.83
A10	23,423	49,852	3,068,904	95	3	2	7	5.75
A11	23,232	18,537	3,327,196	97	2	1	6	4.83
A12	23,232	38,600	3,327,196	95	2	3	4	4.83

The normalized utility values are calculated by using Equations (4.4) and (4.5), assigning 1 for the best value and 0 for the worst value for each criterion, as shown in Table 4.10.

Table 4.10 Normalized decision matrix

	Environmental			Economic			Social	
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
A1	0.50	0.12	0.00	1.00	0.00	0.50	0.00	0.00
A2	1.00	0.80	0.28	0.67	0.33	0.50	0.17	0.41
A3	0.00	0.76	0.26	0.00	1.00	0.50	0.33	0.00
A4	0.50	0.00	0.00	0.33	0.67	0.50	0.17	0.00
A5	0.66	0.48	0.51	1.00	0.33	0.00	0.50	0.92
A6	0.66	0.36	0.00	1.00	0.00	0.50	0.00	0.05
A7	0.50	0.12	1.00	0.33	0.67	0.50	0.50	0.97
A8	0.66	0.48	0.00	0.33	0.67	0.50	0.00	0.18
A9	0.66	0.34	0.51	0.00	0.33	1.00	0.17	0.16
A10	0.50	0.00	1.00	0.67	0.33	0.50	0.83	0.23
A11	0.66	1.00	0.65	0.00	0.67	1.00	0.67	1.00
A12	0.66	0.36	0.65	0.67	0.67	0.00	1.00	1.00

Finally, a utility matrix is obtained with the utilization of Equation 4.6, and the sum of each criteria value gives the total utility value of each alternative, as shown in Table 4.11.

Table 4.11 Utility matrix and final results

	Environmental			Economic			Social		
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**SUM**
A1	0.07	0.01	0.00	0.13	0.00	0.06	0.00	0.00	**0.27**
A2	0.13	0.10	0.03	0.09	0.04	0.06	0.03	0.04	**0.52**
A3	0.00	0.09	0.03	0.00	0.12	0.06	0.05	0.00	**0.35**
A4	0.07	0.00	0.00	0.04	0.08	0.06	0.03	0.00	**0.27**
A5	0.09	0.06	0.06	0.13	0.04	0.00	0.08	0.10	**0.55**
A6	0.09	0.04	0.00	0.13	0.00	0.06	0.00	0.01	**0.32**
A7	0.07	0.01	0.12	0.04	0.08	0.06	0.08	0.10	**0.56**
A8	0.09	0.06	0.00	0.04	0.08	0.06	0.00	0.02	**0.34**
A9	0.09	0.04	0.06	0.00	0.04	0.12	0.03	0.02	**0.39**
A10	0.07	0.00	0.12	0.09	0.04	0.06	0.13	0.02	**0.52**
A11	0.09	0.12	0.08	0.00	0.08	0.12	0.11	0.11	**0.69**
A12	0.09	0.04	0.08	0.09	0.08	0.00	0.16	0.11	**0.64**

$$U_1 = \sum_{j=1}^{8} w_j U_{ij} = 0.27 \text{ for alternative 1.}$$

The MAUT analyses were conducted by using similar calculations for the other alternatives, and the results are summarized in Table 4.11. The ranking of alternatives in descending order is 11,12,7,5,10,2,9,3,8,6,4 and 1 depending on total utility values. Additionally, Figure 4.2 indicates the results of total utility values for each alternative by a radar chart to illustrate the performance of the transport alternatives from environmental, economic and social aspects.

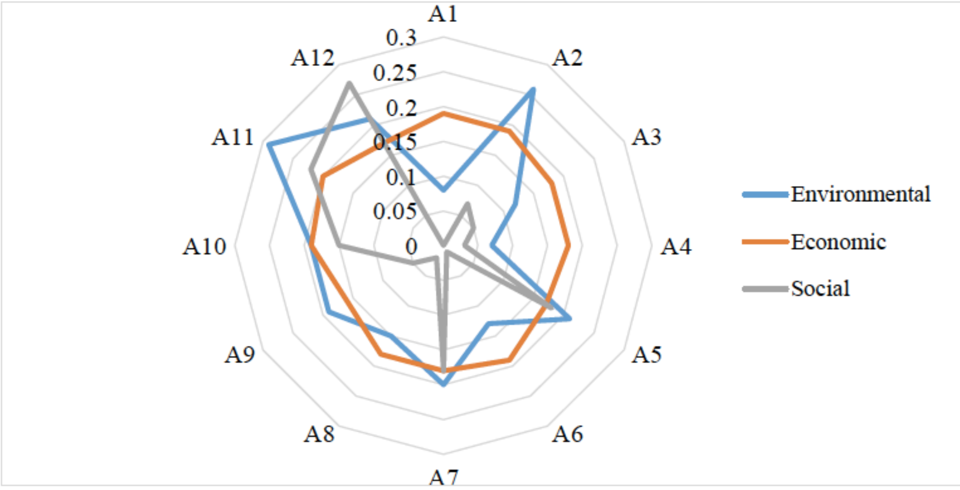

Figure 4.2 The comparison of the urban transport alternatives from environmental, economic and social aspects

From an environmental perspective, alternative A11 has the best environmental performance with 0.29 of environmental total utility value as shown in Figure 4.2 due to the lowest energy consumption and lower depletion of non-renewable resources at 18,537 MWh and 3,327,196 liters, respectively (Table 4.9). Besides, alternative A1 has the worst performance due to the highest consumption of depletion of non-renewable resources at 3,807,348 liters when compared with others (Table 4.9). As a result, high-motorized transport alternatives show low performance from an environmental aspect. Thus, a significant number of motor vehicles affect the environmental impacts of an urban transport system negatively.

From an economic perspective, alternative A11 presents the best performance (0.2 of economic total utility value) because of the lowest percentage of fuel costs and lower operational costs at 1% and 2%, respectively (Table 4.9). It also has a low number of tramway vehicles (<600), which is an environmentally friendly transport mode when compared with the bus but causes higher maintenance costs due to the requirement of periodic maintenance and repair. Besides, A9 has the worst performance from an economic view due to the highest percentage of operational cost when compared with other alternatives.

From a social perspective, alternative 12 shows the highest performance for the lowest number of motor vehicles for public transport per 10,000 population (C8) and the lowest number of fatalities/injuries (C7) with 4.83 and 4, respectively (Table 4.9). Safety is one of the main criteria to evaluate transport systems from social aspects. Thus, the lower number of fatalities and injuries indicates that the system is safer and vice versa. On the other hand, alternative A1, A6 and A8 consist of the highest number of fatalities/injuries with 10, so it is the worst case among the other alternatives from a social perspective. The results show that low motorized urban transport alternatives are more sustainable than motorized and high-motorized alternatives from social aspects.

According to overall results, alternative 11 is the first best and alternative 12 is the second-best alternative with a holistic perspective of sustainability by considering environmental, economic, and social aspects. Both A11 and A12 are low-motorized urban transport alternatives with low number of bus and tramway vehicles, which is the primary transport mode for the source of electricity consumption in an urban transport system. The results indicate that low-motorized urban transport alternatives are more sustainable than motorized and high-motorized alternatives. Intermodal, multimodal transport and mode shift approaches enhance sustainability [107]. Moreover, decision-makers should evaluate the urban transport systems with a holistic view to achieving more sustainable transport systems. This view should cover the people, planet, and profit together. If all aspects were adequately optimized, more sustainable transport systems would be achieved.

Finally, weights of criteria are calculated with the HF-AHP method which is a more sophisticated method developed from conventional AHP [108]. Fuzzy AHP is an extension of Saaty's theory which has provided a more sufficient description for most of the decision-making problems when compared with conventional AHP [109]. Then, obtained weights from F-AHP and conventional AHP are used in MAUT for selecting the most sustainable transport alternative among the twelve urban transport alternatives and compared the results of the HF-AHP and MAUT methods as shown in Table 4.12.

Table 4.12 The comparison of final results of MAUT with HF-AHP, F-AHP and AHP

	HF-AHP and MAUT		F-AHP and MAUT		AHP and MAUT	
	Total Utility Value	Rank	Total Utility Value	Rank	Total Utility Value	Rank
A1	0.27	12	0,26	11	0,23	11
A2	0.52	6	0,46	6	0,45	6
A3	0.35	8	0,36	7	0,35	7
A4	0.27	11	0,26	12	0,24	12
A5	0.55	4	0,54	4	0,53	5
A6	0.32	10	0,30	9	0,28	9
A7	0.56	3	0,53	5	0,56	4
A8	0.34	9	0,29	10	0,27	10
A9	0.39	7	0,35	8	0,33	8
A10	0.52	5	0,58	3	0,58	3
A11	0.69	1	0,66	2	0,68	2
A12	0.64	2	0,67	1	0,70	1

The ranks of alternatives are similar with three integrated method but some differences are seen due to distinctions in the calculation of weights. According to obtained results, A11 is the best alternative in HF-AHP but A12 is the best alternative in integrated F-AHP and conventional AHP integrated with MAUT method.

The Consistency Ratio (CR) is calculated CR=CI/RI (n) to assess the consistency of pairwise comparisons where Consistency Index (CI) given by CI = $((\lambda_{max} - n)/(n - 1)$, RI (n) corresponds random consistency index for matrices of order n and λ_{max} corresponds the principal eigenvalue of the judgment matrix. CR threshold value is chosen as 0.10 in this study. If the value of CR is less than 0.10, the pairwise comparison matrix has acceptable consistency, and the weights are valid for applications [110, 111]. In this study, the pair comparisons are consistent with the overall mean CR for eight criteria of <0.007.

4.2.3 Sensitivity Analysis

To determine the robustness of the results, this section presents sensitivity analyses on the weights of the criteria to reveal the influence of weights on ranking by obtaining several scenarios. Sensitivity analysis was performed to exchange each criterion weight with another so that 28 experiments were performed. The results of the experiments are given in Table 4.13. It is summarized that how many times each alternative takes place, which rank in all experiments and the average of ranks obtained from 28 experiments for the applied method in Table 4.13.

Table 4.13 Results of sensitivity analysis for applied method (HF-AHP with MAUT)

	Alternatives											
	1	2	3	4	5	6	7	8	9	10	11	12
Applied Method Rank	12	6	8	11	4	10	3	9	7	5	1	2
Sensitivity Analysis												
# of 1st rank	0	0	0	0	0	0	0	0	0	0	**28**	0
# of 2nd rank	0	0	0	0	0	0	0	0	0	0	0	**28**
# of 3rd rank	0	0	0	0	4	0	24	0	0	0	0	0
# of 4th rank	0	0	0	0	24	0	4	0	0	0	0	0
# of 5th rank	0	9	0	0	0	0	0	0	0	19	0	0
# of 6th rank	0	19	0	0	0	0	0	0	0	9	0	0
# of 7th rank	0	0	0	0	0	0	0	0	**28**	0	0	0
# of 8th rank	0	0	24	0	0	0	0	4	0	0	0	0
# of 9th rank	0	0	3	0	0	1	0	24	0	0	0	0
# of 10th rank	0	0	1	0	0	27	0	0	0	0	0	0
# of 11th rank	4	0	0	24	0	0	0	0	0	0	0	0
# of 12th rank	24	0	0	4	0	0	0	0	0	0	0	0
Avg. rank	11.86	5.68	8.18	11.14	3.86	9.96	3.14	8.86	7.00	5.32	1.00	2.00

Alternative 11, which is suggested as the most sustainable urban transport scenario in the applied method has a 28 score in 28 experiments. Besides, 1,2 and 7 ranks have exact results of average ranks in sensitivity analysis and the other ranks have similar results in the proposed method. Based on sensitivity results, it is revealed that applied methodology is robust and sensitive to the criteria weights. This study develops a novel and robust methodology for the decision of sustainable urban transport projects and renovation of current urban transport systems. The methodology provides a holistic approach in urban transport planning for decision-makers by considering environmental, economic and social aspects. Additionally, the results are discussed with urban transportation industry and it has conformed to the idea by considering sensitivity analysis.

Chapter 5

Conclusions and Future Prospects

5.1 Conclusions

The integration of three aspects of sustainability for the urban transportation sector is crucial to enhance the sustainability performance of the transportation industry. In the present study, the stages with the highest environmental impact, life cycle cost and social impact are identified by performing the LCSA. Within the scope of the LCSA implementation, the environmental, economic and social performance of the tramway system has been assessed with a holistic approach by using LCA, LCC and S-LCA.

The results showed that the majority of emissions are originated from the operation and maintenance phases of the tramway system, which corresponds the highest impact with a 50% contribution of the total. These results mainly due to electricity consumption, which is mostly dependent on fossil-based sources. In the comparison of several cost categories of the entire tramway system, it was found that energy costs are the main contributor (92%) which should be reduced to lower the overall life cycle cost. The social impact assessment showed that urban transportation industries had established a strong relationship with consumers, workers, local community and society. However, social performance on the consumer has the lowest score among the four stakeholders. Thus, an improvement in feedback mechanisms, health and safety and transparency are needed for the better social performance of the tramway system.

A number of studies have considered LCA and LCC of several transport modes such as metro, high-speed and conventional light rail systems, however integrating LCA, LCC and S-LCA studies are scarce. Even there is no study for evaluation of tramway systems by LCSA approach in the literature, this study aims to fill this gap and paves the way for further studies.

However, there are some limitations in the study include non-availability of data for environmental LCA and LCC, taking long time to collect the inventory data and a few social subcategories and stakeholders. Even though primary data mainly was used for LCA and LCC, secondary data was also used from the Ecoinvent database, sectoral reports and journal papers from literature where the primary data was not present. Another limitation was that the scope of the S-LCA was limited to the urban transportation company and there were not yet sufficient databases for an S-LCA to include all supply chains. Therefore, some stakeholders such as value chain actors and its subcategories were excluded in this study.

The proposed methodology based on HF-AHP and MAUT has been implemented for urban transport alternatives in Kayseri, Turkey to decide the most sustainable alternative among them for the first time. While the weights of sustainable indicators have been calculated with HF-AHP, the final ranking of alternatives has been obtained with the MAUT method. Twelve urban transportation alternatives have been evaluated in terms of eight sustainable transportation indicators grouped into three categories: environmental, economic, and social for comprehensive decision analysis. As a result of the analysis, ‘’Environmental’’ and ‘’Social’’ criteria have been obtained most and least significant indicators with weights of 0.372 and 0.265. Besides, the number of fatalities/injuries (C7) and motor vehicles for public transport per 10,000 Population (C8) are the most and least significant sub-criteria with weights of 0.158 and 0.107, respectively. Besides, alternative 11, which is under the low-motorized urban transportation category, has the best alternative for sustainability performance from a holistic perspective by considering environmental, economic and social aspects. Even, A11 is the most sustainable alternative from environmental and economic perspective; A12 is most sustainable one from social perspective among the twelve urban transportation alternatives. The results reveal that low-motorized urban transportation alternatives show higher sustainable performance than motorized and high-motorized alternatives.

Although AHP and MAUT are used in some areas due to their easy applicability, there is no study in the literature about integrated HF-AHP and MAUT for sustainable transportation. This study contributes to filling this research gap by providing a new integrated methodology (HF-AHP and MAUT) in sustainable transportation by considering triple bottom approach. The main advantage of using hesitant fuzzy sets is to get more reasonable decision results due to the hesitancy of the preferences of decision-makers. Besides, MAUT offers the advantage of taking uncertainty into account by assigning a utility to every possible consequence. Decision-makers, planners, professionals in the urban transportation industry can be encouraged to use this methodological framework of sustainable urban transportation to make decisions on the design and planning stage of urban transportation projects. In addition, the proposed method can be applied to different real-world problems in various areas such as industry, health and transportation sectors. In future studies, the proposed method can be applied with interval values by taking into account the interval-valued hesitant preference relations and the results can be compared.

5.2 Societal Impact and Contribution to Global Sustainability

In the last decades, people prefer to live in cities due to economic, technological, political and sociological reasons. Thus, urban transportation has gained significant importance to meet their transportation needs. However, urban transportation causes significant environmental problems such as air pollution, climate change, noise pollution, congestion and so on, economic problems like funding and investment problems, and social problems such as accidents, health and safety problems and so on. To make urban transportations in the cities more sustainable, a sustainability assessment should be performed. However, urban transportation has not been still addressed with all dimensions of sustainability yet.

In the first part of this thesis, a life cycle sustainability assessment of the tramway system was presented by the integration of environmental, economic and social aspects for the case of Kayseri, Turkey for the first time. The sustainability performance of the tramway system was evaluated from the cradle to grave approach for assessing three aspects of sustainability. We believe that this thesis will make a contribution in terms of societal impacts and global sustainability since we have applied the sustainability assessment on urban transportation in Kayseri by considering the environmental, economic and social aspects with a holistic approach.

In the second part of this thesis, a methodological framework of sustainable urban transport was proposed to make decisions on the design and planning stage of urban transport. This thesis is the first attempt to evaluate the sustainability of urban transport for Kayseri, Turkey considering the triple bottom line approach with the integration of two MCDM methods for selecting the best sustainable urban transport alternative. Thus, we believe that this thesis will make a contribution in terms of social impacts and global sustainability since we have developed a new methodological framework on sustainable urban transport to help planners and decision makers to assess the effect of their decisions and policies on urban transportation.

5.3 Future Prospects

As a suggestion for future research, more environmental indicators such as land usage and noise can be evaluated for more comprehensive sustainability assessment. Also, in further studies from the multi-objective perspective, the tradeoff between total transportation cost and environmental satisfaction objectives can be also investigated. Alternative urban transport scenarios comparing the urban transport modes can be assessed with a multi-criteria decision-making approach.

Besides all, in literature, S-LCA is a method which is limited when compared with LCA and LCC and there is no standardized approach. For this reason, while this study makes significant contributions to the virgin field of S-LCA and LCSA, it paves the need for further studies in terms of the development of alternative methods, databases and analysis.

BIBLIOGRAPHY

[1] U. Nations, ''World Urbanization Prospects: The 2018 Revision,'' (2019).

[2] L. Sagaris, and A. Arora, ''Evaluating how cycle-bus integration could contribute to "sustainable" transport,'' Research in Transportation Economics, 59, p. 218-227 (2016).

[3] J. A. Black, A. Paez, and P. A. Suthanaya, ''Sustainable urban transportation: Performance indicators and some analytical approaches,'' Journal of Urban Planning and Development, 128, p. 184-209 (2002).

[4] F. E. K. Sato, T. Furubayashi, and T. Nakata, ''Application of energy and CO2 reduction assessments for end-of-life vehicles recycling in Japan,'' Applied Energy, 237, p. 779-794 (2019).

[5] K. Gompf, M. Traverso, and J. Hetterich, ''Towards social life cycle assessment of mobility services: systematic literature review and the way forward,'' International Journal of Life Cycle Assessment, 25, p. 1883-1909 (2020).

[6] I. Batur, I. S. Bayram, and M. Koc, ''Impact assessment of supply-side and demand-side policies on energy consumption and CO2 emissions from urban passenger transportation: The case of Istanbul,'' Journal of Cleaner Production, 219, p. 391-410 (2019).

[7] Towards Sustainable Transportation, https://www.oecd.org/greengrowth/greening-transport/2396815.pdf (15 November 2021)

[8] S. Penazzi, R. Accorsi, and R. Manzini, ''Planning low carbon urban-rural ecosystems: An integrated transport land-use model,'' Journal of Cleaner Production, 235, p. 96-111 (2019).

[9] L. L. Wang, ''Framework for Evaluating Sustainability of Transport System in Megalopolis and its Application,'' International Conference on Environment Systems Science and Engineering (Esse 2014), 9, p. 110-116 (2014).

[10] L. Tupenaite, E. K. Zavadskas, A. Kaklauskas, Z. Turskis, and M. Seniut, ''Multiple Criteria Assessment of Alternatives for Built and Human Environment Renovation,'' Journal of Civil Engineering and Management, 16, p. 257-266 (2010).

[11] T. I. o. E. Australia, ''Sustainable transport : responding to the challenges : Sustainable Energy Transport Taskforce report,'', p. 1-102 (1999).

[12] P. Rietveld, ''Non-motorised modes in transport systems: a multimodal chain perspective for The Netherlands,'' Transportation Research Part D-Transport and Environment, 5, p. 31-36 (2000).

[13] H. Castillo, and D. E. Pitfield, ''ELASTIC - A methodological framework for identifying and selecting sustainable transport indicators,'' Transportation Research Part D-Transport and Environment, 15, p. 179-188 (2010).

[14] T. A. Shiau, and J. S. Liu, ''Developing an indicator system for local governments to evaluate transport sustainability strategies,'' Ecological Indicators, 34, p. 361-371 (2013).

[15] T. A. Shiau, ''Evaluating sustainable transport strategies with incomplete information for Taipei City,'' Transportation Research Part D-Transport and Environment, 17, p. 427-432 (2012).

[16] R. Zope, N. Vasudevan, S. S. Arkatkar, and G. Joshi, ''Benchmarking: A tool for evaluation and monitoring sustainability of urban transport system in metropolitan cities of India,'' Sustainable Cities and Society, 45, p. 48-58 (2019).

[17] M. Reisi, L. Aye, A. Rajabifard, and T. Ngo, ''Transport sustainability index: Melbourne case study,'' Ecological Indicators, 43, p. 288-296 (2014).

[18] G. Currie, L. Truong, and C. De Gruyter, ''Regulatory structures and their impact on the sustainability performance of public transport in world cities,'' Research in Transportation Economics, 69, p. 494-500 (2018).

[19] A. Sdoukopoulos, M. Pitsiava-Latinopoulou, S. Basbas, and P. Papaioannou, ''Measuring progress towards transport sustainability through indicators: Analysis and metrics of the main indicator initiatives,'' Transportation Research Part D-Transport and Environment, 67, p. 316-333 (2019).

[20] C. Chakhtoura, and D. Pojani, ''Indicator-based evaluation of sustainable transport plans: A framework for Paris and other large cities,'' Transport Policy, 50, p. 15-28 (2016).

[21] J. P. Nicolas, P. Pochet, and H. Poimboeuf, ''Towards Sustainable Mobility Indicators: Application to the Lyons Conurbation,'' Transportation Policy, (2003).

[22] F. Pettersson, V. Stjernborg, and C. Curtis, ''Critical challenges in implementing sustainable transport policy in Stockholm and Gothenburg,'' Cities, 113 (2021).

[23] F. W. Geels, R. Kemp, G. Dudley, and G. G. Lyons, ''Automobility in Transition? A Socio-Technical Analysis of Sustainable Transport,'' Routledge (2012).

[24] J. S. Szylowicz, ''Decision-making, intermodal transportation, and sustainable mobility: towards a new paradigm,'' International Social Science Journal, 55, p. 185-+ (2003).

[25] I. Bailey, ''Unsustainable transport: City transport in the new century,'' Journal of Transport Geography, 14, p. 472-473 (2006).

[26] D. Banister, ''The sustainable mobility paradigm,'' Transport Policy, 15, p. 73-80 (2008).

[27] M. Lindenau, and S. Bohler-Baedeker, ''Citizen and stakeholder involvement: a precondition for sustainable urban mobility,'' Sustainable Mobility in Metropolitan Regions, Mobil.Tum 2014, 4, p. 347-360 (2014).

[28] M. Wicki, L. Fesenfeld, and T. Bernauer, ''In search of politically feasible policy-packages for sustainable passenger transport: insights from choice experiments in China, Germany, and the USA,'' Environmental Research Letters, 14 (2019).

[29] D. J. Alibegovic, and Z. K. De Villa, ''he Challenge of Building Proper Urban Indicator System: A Proposal for Croatian Cities,'' 46th Congress of the European Regional Science Association: "Enlargement, Southern Europe and the Mediterranean, (2006).

[30] P. Verma, and A. S. Raghubanshi, ''Urban sustainability indicators: Challenges and opportunities,'' Ecological Indicators, 93, p. 282-291 (2018).

[31] K. Figueiredo, R. Pierott, A. W. A. Hammad, and A. Haddad, ''Sustainable material choice for construction projects: A Life Cycle Sustainability Assessment framework based on BIM and Fuzzy-AHP,'' Building and Environment, 196 (2021).

[32] D. P. Muller, and M. Hiete, ''Visualization supported corporate decision making for life cycle sustainability assessment-Illustrated using a case study for selecting a sustainable packaging system for self-leveling compounds,'' Journal of Cleaner Production, 313 (2021).

[33] S. Shrivastava, and S. Unnikrishnan, ''Life cycle sustainability assessment of crude oil in India,'' Journal of Cleaner Production, 283 (2021).
[34] A. Valente, D. Iribarren, and J. Dufour, ''Comparative life cycle sustainability assessment of renewable and conventional hydrogen,'' Science of the Total Environment, 756 (2021).
[35] H. Li, X. L. Yao, M. A. Tachega, D. Ahmed, and M. G. A. Ismaail, ''Technology selection for hydrogen production in China by integrating emergy into life cycle sustainability assessment,'' Journal of Cleaner Production, 294 (2021).
[36] P. Masilela, and A. Pradhan, ''A life cycle sustainability assessment of biomethane versus biohydrogen – For application in electricity or vehicle fuel? Case studies for African context,'' Journal of Cleaner Production, (2021).
[37] S. Zira, L. Rydhmer, E. Ivarsson, R. Hoffmann, and E. Roos, ''A life cycle sustainability assessment of organic and conventional pork supply chains in Sweden,'' Sustainable Production and Consumption, 28, p. 21-38 (2021).
[38] A European Strategy for low-emission mobility, https://ec.europa.eu/clima/policies/transport_en/ (15 August 2020)
[39] Life Cycle Costing in SimaPro https://network.simapro.com/pre/wp-content/uploads/sites/40/2017/02/LCCinSimaPro_english.pdf (July 2020)
[40] UNEP-SETAC, ''Guidelines for social life cycle assessment of products,'' United Nations Environment Programme(UNEP) and Society of Environmental and Toxicology and Chemistry (SETAC) (2009).
[41] The methodological sheats for subcategories in social life cycle assessment (S-LCA), https://www.lifecycleinitiative.org/wp-content/uploads/2013/11/S-LCA_methodological_sheets_11.11.13.pdf (December 2020)
[42] M. Banar, and A. Ozdemir, ''An evaluation of railway passenger transport in Turkey using life cycle assessment and life cycle cost methods,'' Transportation Research Part D-Transport and Environment, 41, p. 88-105 (2015).
[43] A. M. Shinde, A. K. Dikshit, R. K. Singh, and P. E. Campana, ''Life cycle analysis based comprehensive environmental performance evaluation of Mumbai Suburban Railway, India,'' Journal of Cleaner Production, 188, p. 989-1003 (2018).
[44] L. Bilgili, S. L. Kuzu, A. Y. Cetinkaya, and P. Kumar, ''Evaluation of railway versus highway emissions using LCA approach between the two cities of Middle Anatolia,'' Sustainable Cities and Society, 49 (2019).
[45] J. Akerman, ''The role of high-speed rail in mitigating climate change - The Swedish case Europabanan from a life cycle perspective,'' Transportation Research Part D-Transport and Environment, 16, p. 208-217 (2011).
[46] B. Chang, and A. Kendall, ''Life cycle greenhouse gas assessment of infrastructure construction for California's high-speed rail system,'' Transportation Research Part D-Transport and Environment, 16, p. 429-434 (2011).
[47] M. Chester, S. Pincetl, Z. Elizabeth, W. Eisenstein, and J. Matute, ''Infrastructure and automobile shifts: positioning transit to reduce life-cycle environmental impacts for urban sustainability goals,'' Environmental Research Letters, 8 (2013).
[48] H. Jones, F. Moura, and T. Domingos, ''Life cycle assessment of high-speed rail: a case study in Portugal,'' International Journal of Life Cycle Assessment, 22, p. 410-422 (2017).
[49] M. Chester, and A. Horvath, ''Life-cycle assessment of high-speed rail: the case of California,'' Environmental Research Letters, 5 (2010).

[50] Y. Li, Q. He, X. Luo, Y. R. Zhang, and L. Dong, ''Calculation of life-cycle greenhouse gas emissions of urban rail transit systems: A case study of Shanghai Metro,'' Resources Conservation and Recycling, 128, p. 451-457 (2018).

[51] F. Del Pero, M. Delogu, M. Pierini, and D. Bonaffini, ''Life Cycle Assessment of a heavy metro train,'' Journal of Cleaner Production, 87, p. 787-799 (2015).

[52] J. P. Ribau, C. M. Silva, and J. M. C. Sousa, ''Efficiency, cost and life cycle CO2 optimization of fuel cell hybrid and plug-in hybrid urban buses,'' Applied Energy, 129, p. 320-335 (2014).

[53] E. C. McKenzie, and P. L. Durango-Cohen, ''Environmental life-cycle assessment of transit buses with alternative fuel technology,'' Transportation Research Part D-Transport and Environment, 17, p. 39-47 (2012).

[54] G. Cooney, T. R. Hawkins, and J. Marriott, ''Life Cycle Assessment of Diesel and Electric Public Transportation Buses,'' Journal of Industrial Ecology, 17, p. 689-699 (2013).

[55] J. Ally, and T. Pryor, ''Life cycle costing of diesel, natural gas, hybrid and hydrogen fuel cell bus systems: An Australian case study,'' Energy Policy, 94, p. 285-294 (2016).

[56] C. von Rozycki, H. Koeser, and H. Schwarz, ''Ecology profile of the German high-speed rail passenger transport system, ICE,'' International Journal of Life Cycle Assessment, 8, p. 83-91 (2003).

[57] C. B. Agaton, A. A. Collera, and C. S. Guno, ''Socio-Economic and Environmental Analyses of Sustainable Public Transport in the Philippines,'' Sustainability, 12 (2020).

[58] C. A. Kennedy, ''A comparison of the sustainability of public and private transportation systems: Study of the Greater Toronto Area,'' Transportation, 29, p. 459-493 (2002).

[59] F. Yang, J. Yu, X. Li, and W. Qiu, ''An SLCA method based framework of large-scale transportation infrastructure in China '' Environmental Impact Assessment Review, (2022).

[60] T. L. Saaty, ''The Analytic Hierarchy Process,'' McGraw Hill (1980).

[61] B. Oztaysi, S. C. Onar, E. Bolturk, and C. Kahraman, ''Hesitant Fuzzy Analytic Hierarchy Process,'' 2015 Ieee International Conference on Fuzzy Systems (Fuzz-Ieee 2015), (2015).

[62] M. Erdogan, and I. Kaya, ''Prioritizing failures by using hybrid multi criteria decision making methodology with a real case application,'' Sustainable Cities and Society, 45, p. 117-130 (2019).

[63] M. Erdogan, and I. Kaya, ''A systematic approach to evaluate risks and failures of public transport systems with a real case study for bus rapid system in Istanbul,'' Sustainable Cities and Society, 53 (2020).

[64] J. Y. J. Chow, S. V. Hernandez, A. Bhagat, and M. G. McNally, ''Multi-Criteria Sustainability Assessment in Transport Planning for Recreational Travel,'' International Journal of Sustainable Transportation, 8, p. 151-175 (2014).

[65] R. Mahmoudi, S. N. Shetab-Boushehri, S. R. Hejazi, and A. Emrouznejad, ''Determining the relative importance of sustainability evaluation criteria of urban transportation network,'' Sustainable Cities and Society, 47 (2019).

[66] R. L. R. Keeney, H., ''Decision Analysis with Multiple Conflicting Objectives: Preferences and Value Tradeoffs,'' John Wiley and Sons (1976).

[67] J. Zietsman, L. R. Rilett, and S. Kim, ''Transportation corridor decision-making with multi-attribute utility theory,'' International Journal of Management and Decision Making, (2006).

[68] S. Abu-Samra, T. Zayed, and W. Tabra, ''Pavement Condition Rating Using Multiattribute Utility Theory,'' Journal of Transportation Engineering Part B-Pavements, 143 (2017).
[69] S. Deshmukh, M. Bustamante, and R. Roth, ''Evaluating Effects of Future Shared Mobility and Electrification Trends on Key Intermediate Indicator of Aluminum Transportation Demand: US Vehicle Fleet Size,'' Light Metals 2018, p. 627-635 (2018).
[70] M. S. Kovacevic, M. Bacic, I. Stipanovic, and K. Gavin, ''Categorization of the Condition of Railway Embankments Using a Multi-Attribute Utility Theory,'' Applied Sciences-Basel, 9 (2019).
[71] Raylı Sistem Haritası, https://www.kayseriulasim.com/tr/FaaliyetAlanlarimiz/rayli-sistem/rayli-sistem-haritasi (January 2021)
[72] N. Nations, ''Our Common Future,'' Oxford University Press (1987).
[73] W. Kloepffer, ''Life cycle Sustainability assessment of products,'' International Journal of Life Cycle Assessment, 13, p. 89-94 (2008).
[74] Towards a Life Cycle Assessment: Making Informed Choices on Products, https://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2011%20-%20Towards%20LCSA.pdf. (12 June 2020)
[75] ISO, "ISO 14040 Environmental management: LCA Principles and framework," (2006).
[76] ISO, "ISO 14044 Environmental management: LCA Requirements and guidelines," (2006).
[77] W. Klopffer, ''Life-cycle based methods for sustainable product development,'' International Journal of Life Cycle Assessment, 8, p. 157-159 (2003).
[78] J. B. Guinee, R. Heijungs, G. Huppes, A. Zamagni, P. Masoni, R. Buonamici, T. Ekvall, and T. Rydberg, ''Life Cycle Assessment: Past, Present, and Futures,'' Environmental Science & Technology, 45, p. 90-96 (2011).
[79] R. H. Crawford, ''Life Cycle Assessment in the Built Environment,'' Life Cycle Assessment in the Built Environment, p. 1-244 (2011).
[80] S. Suh, and G. Huppes, ''Missing Inventory Estimation Tool using extended Input-Output Analysis,'' International Journal of Life Cycle Assessment, 7, p. 134-140 (2002).
[81] R. Frischknecht, et al., ''The ecoinvent database: Overview and methodological framework,'' International Journal of Life Cycle Assessment, 10, p. 3-9 (2005).
[82] M. C. Reich, ''Economic assessment of municipal waste management systems - case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC),'' Journal of Cleaner Production, 13, p. 253-263 (2005).
[83] C. L. Simoes, L. M. C. Pinto, and C. A. Bernardo, ''Environmental and economic assessment of a road safety product made with virgin and recycled HDPE: A comparative study,'' Journal of Environmental Management, 114, p. 209-215 (2013).
[84] Çevre ve Şehircilik Bakanlığı-Rayiçler, https://birimfiyat.com/. (8 October 2020)
[85] Faaliyet Bazlı Elekrik Tarifeleri, https://www.tedas.gov.tr/. (8 October 2020)
[86] Akaryakıt Fiyatları, https://www.opet.com.tr/. (8 October 2020)
[87] The Concept of the Eco-costs, https://www.ecocostsvalue.com/EVR/model/theory/subject/2-eco-costs.html (8 October 2021).
[88] B. Steen, R. Carlson, F. Lyrstedt, and G. U. Y. Skantze, ''Sustainability management of businesses through eco-efficiency - an example,'' (2009).

[89] C. Benoît-Norris, ‘‘Social life cycle assessment: a technique providing a new wealth of information to informsustainability-related decisionmaking,’’ (2012).
[90] R. K. Foolmaun, and T. Ramjeeawon, ’’Comparative life cycle assessment and social life cycle assessment of used polyethylene terephthalate (PET) bottles in Mauritius,’’ International Journal of Life Cycle Assessment, 18, p. 155-171 (2013).
[91] S. M. Mousavi, H. Gitinavard, and A. Siadat, ’’A New Hesitant Fuzzy Analytical Hierarchy Process Method for Decision-Making Problems Under Uncertainty,’’ 2014 Ieee International Conference on Industrial Engineering and Engineering Management (Ieem), p. 622-626 (2014).
[92] V. Torra, ’’Hesitant Fuzzy Sets,’’ International Journal of Intelligent Systems, 25, p. 529-539 (2010).
[93] V. Torra, and Y. Narukawa, ’’On Hesitant Fuzzy Sets and Decision,’’ 2009 Ieee International Conference on Fuzzy Systems, Vols 1-3, p. 1378 (2009).
[94] M. M. Xia, and Z. S. Xu, ’’Hesitant fuzzy information aggregation in decision making,’’ International Journal of Approximate Reasoning, 52, p. 395-407 (2011).
[95] R. L. Keeney, and E. F. Wood, ’’An illustrative example of the use of multiattribute utility theory for water resource planning,’’ Water resources research, 13, p. 705-712 (1977).
[96] R. Doczy, and Y. AbdelRazig, ’’Green Buildings Case Study Analysis Using AHP and MAUT in Sustainability and Costs,’’ Journal of Architectural Engineering, 23 (2017).
[97] S. K. Kim, and O. Song, ’’A MAUT approach for selecting a dismantling scenario for the thermal column in KRR-1,’’ Annals of Nuclear Energy, 36, p. 145-150 (2009).
[98] R. Keeney, and H. Raiffa, ‘‘Decisions with Multiple Objectives: Preferences and Value Tradeoffs,’’ Cambridge University (1993).
[99] B. Atilgan, and A. Azapagic, ’’An integrated life cycle sustainability assessment of electricity generation in Turkey,’’ Energy Policy, 93, p. 168-186 (2016).
[100] W. T. Tsai, ’’Implementation status of Taiwan carbon footprint (CFP) system and a case study of the Taiwan High Speed Rail Corporation,’’ Sustainable Cities and Society, 35, p. 331-335 (2017).
[101] Electricity prices worldwide 2020, by select country, https://www.statista.com/statistics/263492/electricity-prices-in-selected-countries/ (25 January 2021)
[102] EPDK, ’’Elektrik Piyasasi Sektor Raporu,’’ (2019).
[103] G. Gayretli, A. Yucekaya, and A. H. Bilge, ’’An analysis of price spikes and deviations in the deregulated Turkish power market,’’ Energy Strategy Reviews, 26 (2019).
[104] P. Lenzo, M. Traverso, R. Salomone, and G. Ioppolo, ’’Social Life Cycle Assessment in the Textile Sector: An Italian Case Study,’’ Sustainability, 9 (2017).
[105] J. Prasara-A, and S. H. Gheewala, ’’Applying Social Life Cycle Assessment in the Thai Sugar Industry: Challenges from the field,’’ Journal of Cleaner Production, 172, p. 335-346 (2018).
[106] UITP, ’’The Future of Urban Mobility 2.0,,’’ (2014).
[107] Y. Van Fan, S. Perry, J. J. Klemes, and C. T. Lee, ’’A review on air emissions assessment: Transportation,’’ Journal of Cleaner Production, 194, p. 673-684 (2018).

[108] P. Sirisawat, and T. Kiatcharoenpol, ’’Fuzzy AHP-TOPSIS approaches to prioritizing solutions for reverse logistics barriers,’’ Computers & Industrial Engineering, 117, p. 303-318 (2018).
[109] A. Ozdoganoglu, and G. Ozdoganoglu, ’’Comparison of AHP and Fuzzy AHP for the Multi-Criteria Decision Making Processes with Linguistic Evaluations,’’ İstanbul Ticaret Üniversitesi Fen Bilimleri Dergisi, (2007).
[110] M. Kordi, and S. A. Brandt, ’’Effects of increasing fuzziness on analytic hierarchy process for spatial multicriteria decision analysis,’’ Computers Environment and Urban Systems, 36, p. 43-53 (2012).
[111] J. Ananda, and G. Herath, ’’Multi-attribute preference modelling and regional land-use planning,’’ Ecological Economics, 65, p. 325-335 (2008).

CURRICULUM VITAE

2013 – 2018	B.Sc., Civil Engineering, Abdullah Gul University, Kayseri, TURKEY
2018 – Present	M.Sc., Sustainable Urban Infrastructure Engineering, Abdullah Gul University, Kayseri, TURKEY
2019 – Present	Research Assistant, Civil Engineering, Abdullah Gül University, Kayseri, TURKEY

SELECTED PUBLICATIONS AND PRESENTATIONS

J1) Y.C. Ersan, **S. Gulcimen**, T.N. Imis, O. Saygin, N. Uzal, Life Cycle Assessment of Lightweight Concrete Containing Recycled Plastics and Fly Ash published in European Journal of Environmental and Civil Engineering (Jun. 2020).

J2) S. Gulcimen, E. Kizilkaya Aydogan, N. Uzal, Life Cycle Sustainability Assessment of a Light Rail Transit System: Integration of Environmental, Economic, and Social Impacts published in Integrated Environmental Assessment and Management Journal (Apr.2021).

J3) S. Gulcimen, T. Varisli, M.G. Khidrah, N. Uzal, Comparison of Environmental Performance of Single-Family House and Multi-Storey Apartment Building in Turkey using Life Cycle Assessment (Under Review in Environmental Science and Pollution Research Journal).

J4) S. Qadri, **S. Gulcimen,** R.O. Donmez, N. Uzal, A Holistic Sustainability Assessment of a University Campus Using Life Cycle Approach (Under Review in International Journal of Environmental Science and Technology Journal).

J5) S. Gulcimen, E. Kizilkaya Aydogan, N. Uzal, Robust Multi-Criteria Sustainability Assessment in Urban Transportation (under preparation).

C1) S. Gulcimen, T. Varisli, M.G. Khidrah, N. Uzal A Comparative Life Cycle Assessment of Single-Family House and Multi-Storey Apartment Building in Turkey in 8th International Conference on Sustainable Solid Waste Management (3-6 Jun. 2021). Thesselanoki, Greece (online oral presentation)