EMBODIED CARBON ASSESSMENT OF URBAN RAILWAY SYSTEMS IN TURKEY BASED ON MATERIAL QUANTIFICATION

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

BY

MÜGE YÜKSEL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
BUILDING SCIENCE IN ARCHITECTURE

DECEMBER 2021

Approval of the thesis:

EMBODIED CARBON ASSESSMENT OF URBAN RAILWAY SYSTEMS IN TURKEY BASED ON MATERIAL QUANTIFICATION

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ABSTRACT

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Master of Science, Building Science in Architecture
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December 2021, 90 pages

Due to global sustainability movements, environmental impact assessments are steadily accelerating in the Architecture – Engineering – Construction (AEC) sector. In order to achieve the 2030 and 2050 carbon targets, laws and regulations are published by governments and decision makers to reduce carbon emissions. Nowadays, transportation is the second-largest contributor to anthropogenic greenhouse gas emissions in the European Union, including Turkey.

As a developing country, Turkey strives to catch not only the level of wellbeing level of the EU but also to follow up the targeted carbon levels, so for this reason, advancements in infrastructure systems are accelerating in Turkey. Another significant point to take into consideration is that each project brings its own carbon footprint which requires to be controlled to be able to generate a healthy carbon circle of the whole picture. In other words, the benefits of infrastructure projects are indisputable, but the exponential increase in the number of projects causes the increase of the value of the carbon burden so their assessments become more and more important.

The aim of this study is to create a reference study for carbon footprint assessments of infrastructure systems in Turkey. Accordingly, the embodied carbon of urban railway systems (metro lines) were calculated based on material quantifications. Specifically, four urban railway lines, including 18 metro stations in Istanbul, Turkey were examined. With these assessments, a reference carbon footprint value of the urban railway systems was provided.

The findings indicate that the total carbon footprint (CFP) of the subterranean railway metro stations ranged between 36,734.47 tCO_2-eq and 89,551.80 tCO_2-eq with the average of 58,557.58 tCO_2-eq. The CFP per m^2 of the stations ranged between 2,39 tCO_2-eq/m^2 and 11,04 tCO_2-eq/m^2 with the average of 6,8 tCO_2-eq/m^2. At the line level, the total CFP of all the lines ranged between 336,897.58 tCO_2-eq and 1,630,278.09 tCO_2-eq with the average of 705,261 tCO_2-eq. The CFP per construction length (km) of the lines ranged between 52,152 tCO_2-eq/km and 88,634 tCO_2-eq/km with the average of 75,991 tCO_2-eq/km.

Keywords: Embodied Carbon, Urban Railway Systems, Low-carbon Infrastructure.

ÖZ

TÜRKİYE'DE KENT İÇİ RAYLI SİSTEM PROJELERİNDE MALZEME MİKTARLARI ÜZERİNDEN YAPILAN GÖMÜLÜ KARBON DEĞERLENDİRMELERİ

Yüksel, Müge
Yüksek Lisans, Yapı Bilimleri, Mimarlık
Tez Yöneticisi: Prof. Dr. Ali Murat Tanyer

Aralık 2021, 90 sayfa

Küresel sürdürülebilirlik hareketleri nedeniyle, Mimarlık – Mühendislik – İnşaat (AEC) sektöründe çevresel etki değerlendirmeleri istikrarlı bir şekilde hızlanmaktadır. 2030 ve 2050 karbon hedeflerine ulaşmak için hükümetler ve karar vericiler tarafından karbon emisyonlarını azaltmaya yönelik kanun ve yönetmelikler yayınlanmaktadır. Günümüzde ulaşım, Türkiye de dahil olmak üzere Avrupa Birliği'nde antropojenik sera gazı emisyonlarına en çok katkıda bulunan ikinci sektördür.

Gelişmekte olan bir ülke olarak Türkiye, sadece AB'nin refah seviyesini yakalamakla kalmayıp, hedeflenen karbon seviyelerini de takip etmeye çalışmakta, bu nedenle Türkiye'de altyapı sistemlerindeki gelişmeler hızlanmaktadır. Dikkate alınması gereken bir diğer önemli nokta da her projenin, tüm resmin sağlıklı bir karbon çemberini oluşturabilmek için kontrol edilmesi gereken kendi karbon ayak izini getirmesidir. Diğer bir deyişle, altyapı projelerinin faydaları tartışılmaz, ancak proje sayısındaki katlanarak artan artış karbon yükünün değerinin artmasına neden olmakta ve değerlendirmeleri giderek daha önemli hale gelmektedir.

Bu çalışmanın amacı Türkiye'deki altyapı sistemlerinin karbon ayakizi değerlendirmeleri için bir referans çalışması oluşturulmasıdır. Buna göre kentsel raylı sistem metro istasyonlarında kullanılan malzeme başına cisimleşmiş karbon birim malzeme değeri üzerinden hesaplanmıştır. Spesifik olarak, İstanbul, Türkiye'deki 18 metro istasyonu dahil olmak üzere 4 kentsel demiryolu hattı incelenmiştir. Bu değerlendirmeler ile kentsel raylı sistemlerin karbon ayak izi ölçütüne, dolayısıyla Türkiye'deki düşük karbonlu altyapı projelerine referansta bulunulmaktadır. Değerlendirmeler doğrultusunda, Türkiye'deki altyapı projelerinin yaşam döngüsündeki somutlaştırılmış karbon değerlendirmelerine ilişkin bir kıyaslama düzeyi sunulmaktadır.

Hesaplamaları özetlemek gerekirse, istasyon düzeyinde tüm tren istasyonlarının toplam karbon ayakizi 36.734,47 tCO_2-eq ile 89.551,80 tCO_2-eq arasında değiştiğini ve ortalama 58.557,58 tCO_2-eq olduğunu göstermektedir. İstasyonların m^2 başına karbon ayakizi 2.39 tCO_2-eq/m^2 ile 11.04 tCO_2-eq/m^2 arasında değişmekte olup, ortalama 6.79 tCO_2-eq/m^2'dir. Hat düzeyinde, tüm hatların toplam karbon ayakizi 336.897.58 tCO_2-eq ile 1.630.278.09 tCO_2-eq arasında değişmekte olup, ortalama 705.261 tCO_2-eq. Hatların inşaat uzunluğu (km) başına karbon ayakizi 52.152 tCO_2-eq/km ile 88.634 tCO_2-eq/km arasında değişmekte olup, ortalama 75.991 tCO_2-eq/km'dir.

Anahtar Kelimeler: Gömülü Karbon, Kent İçi Raylı Sistemler, Düşük Karbonlu Altyapı.

to Emine Çölgeçen and

my beloved family,

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my advisor Prof. Dr. Ali Murat Tanyer for his guidance, encouragement, and motivation throughout the thesis. He supported me with continuous advice and patience to complete my dissertation.

I would like to express my deepest gratitude to my parents Hülya and Metin, my sister Melike. I am also grateful to my grandmother Emine Çölgeçen, for all her wisdom, love and support. Words cannot describe how I feel lucky to have such a precious family. Finally, I want to thank all my extant family, especially Derya Şahin, and also to Muharrem Çölgeçen, Fatma Özdemir and Hatice Çölgeçen for their endless support and belief in me.

I would like to express my sincere thanks to the Yüksel Proje family, who shared their valuable experiences and provided continuous input to this research. Finally, I would like to thank Ebru Yılmaz, Ali Okan Toksöz, Kürşad Elmalı, and Cihan Kayhan, who played the most important roles in the research process, for their support and wisdom.

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LIST OF ABBREVIATIONS

AEC	Architecture-Engineering-Construction
AIA	The American Institute of Architects
BIM	Building Information Modelling
BoQ	Bill of Quantities
BREEAM	the Building Research Establishment's Environmental Assessment Method
BS EN	British Standard European Norm
BSI	The British Standards Institution
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
CFP	Carbon Footprint
CMB	Capital Market Bond
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
COP	Conference of Parties
DLH	(Railways, Ports, Airlines) Demiryolları, Limanlar, Hava Yolları
EC	Embodied Carbon
ECC	Embodied Carbon Coefficient
EN	European Norm
EPC	Engineering Procurement Construction
EPD	Environmental Product Declarations

ESG	Environmental Social Governance
ETS	Emission Trading Market
EU	European Union
EUR	European Union Currency
CEN	European Committee for Standardization
g	gram
ICE	Inventory of Carbon and Energy
IPCC	International Panel on Climate Change
ISO	International Organization for Standardization
KAIs	Key Assessment Indicators
Kg	kilogram
LCA	Life Cycle Assessment
LCI	Low Carbon Infrastructure
LEED	Leadership in Energy and Environmental Design
MW	Megawatt
NATM	New Austrian Tunneling Method
OC	Operational Carbon
GBA	Gross Built Area
GHG	Greenhouse gases
GWP	Global Warming Potential
PAS	Publicly Available Specifications
PCR	Product Category Rules

RICS	Royal Institute of Chartered Surveyors
SMQ	Structural Material Quantities
t	tone
TBM	Tunnel Boring Machine
UIC	Union Internationale des Chemins de fer
UK	United Kingdom
USA	United States of America
USD	United States Dollar
UKGBC	United Kingdom Green Building Council
WGBC	World Green Building Council

CHAPTER 1

INTRODUCTION

This thesis consists of five chapters. This chapter includes the origins of the problem and the significant motivators of the research. Also, the main objectives that drive the purpose of the dissertation were introduced. The chapter concludes with the disposition section.

1.1 Background and Motivation

In a state-of-the-art, where global warming is at a very excessive stage, sustainability issues have become a necessary investigation area, particularly in the construction industry. For clustering sustainability, there are three key pillars, namely; economic, social, and environmental. Concordantly, the sustainable approach for the architecture, engineering, and construction (AEC) industry comprises the integration of several disciplines both for the macro and micro circumstances, which is the major responsibility.

By 2050, the population of cities is estimated to be more than double, which directly affects the infrastructure requirement. Infrastructures constitute the backbone of the cities, providing essential services and welfare. Climate change, urbanization, and economic growth are driving forces to form a basis for sustainable infrastructure (Adshead et al., 2019). The ‘big five’ infrastructure system sectors, energy, transport, water, waste, and digital communication directly or indirectly influence 72% of the sustainable development goals, and it also includes hospitals, schools, and community centers (Thacker et al., 2019). Moreover, investments in infrastructure are promising, and they have a massive potential to apply sustainability perception.

Succeeding the Paris Agreement (2017), many countries have published climate change and carbon reduction policies. The increasing number of nations in different levels of development take severe steps for this movement. Leading countries such as the United States, Japan, and the United Kingdom have defined standards and set some rules. Some examples to these are; Leadership in Energy and Environmental Design (LEED), Comprehensive Assessment System for Built Environment Efficiency (CASBEE) and Building Research Establishment Environmental Assessment Method (BREEAM). Nevertheless, authorities generally stand for the operational energy efficiency, which neglects the embodied carbon, the fundamental component of the subject. Energy-efficiency may decrease carbon emissions in the short-term, yet at the same time, evaluation of embodied carbon and focusing on its reduction may provide long-term rescuing.

In the literature, there is a gap in sustainable implementations from the infrastructure perspective. Contrary, the infrastructure system is a public good that has a significant role in both economic development and social requirement. The infrastructure term covers a wide range of services such as public utilities, public works, railways, urban transport, ports, waterways, and airports. Further, for developing countries, infrastructure projects have more than 30% investments, and it is on the rise (Shen et al., 2011). In addition to its economic and social contribution, infrastructure plays a vital role in the mitigation of climate change through sustainable practices, especially in developing countries. Embodied carbon is responsible for 11% of all global carbon emissions and encompasses half of the carbon footprint of new structures until 2050. Hence, EC refers to no small part of the carbon budget, which requires rapid efforts to tackle while reducing the OC (WGBC, 2019).

The construction sector is responsible for a considerable amount of materials and embodied energy worldwide; thus, it is one of the most critical factors for social and economic developments. In academia and profession, there exist several studies for sustainable development, mostly about building level. For better improvement, a broader perspective, such as the built environment level and even urban level, is obliged. Among these, infrastructure systems may assess as an interface of the built environment and the city. The fact remains that infrastructure projects incline significant investments and have a leading role in the construction industry's environmental impacts. Among infrastructure facilities, transportation projects constitute a vital share of carbon emissions, thus railway systems. Remarkably, the greenhouse gas (GHG) emissions associated with the construction of railway systems need to be exposed. In this dissertation, railway systems, an extension of the infrastructure projects was identified as a vital improvement potential for sustainable advancements.

Infrastructure has a notable impact on sustainability contribution, and low emissions from this effort can provide higher resilience on Climate Change (UNCTAD, 2014). To compass both present and future needs adequately, providing sustainable vision for infrastructure services throughout the life-cycle of the project is essential. For universal recognition, it is significant to set a national framework. For this competence, quantification and comparison of databases, policy options across the market, and interdisciplinary cooperation are required.

The energy demand usually supplied from fossil fuels increases perpetually based on human activities that accelerate global warming due to population growth and technological improvements. Current studies indicate the need for a comprehensive understanding of philosophy beyond the clusters of an environmentally friendly approach. Accordingly, literature proves that several operational and embodied energy parameters affect sustainability so that the integrative approach may provide a clear picture of the problem and better results. On the other hand, the Intergovernmental Panel on Climate Change (IPCC, 2018) declared that carbon reductions are urgently required, not by 2050. Accordingly, lowering carbon become the urgent topic for the AEC industry.

Considering the complexity of the AEC projects and different parameters that cause environmental impacts creates a picture that requires a holistic approach. Concerning that, Life Cycle Assessment (LCA) is a well-defined and accurate method; therefore, it may provide better outcomes for thinking about a sustainable built environment. LCA includes the whole process of the project: raw material, production, extraction, energy consumption, manufacture, transportation, use, recycling, and disposal. Via LCA, measuring sustainability at the material, product, and construction levels, give flexibility on efforts to the architects and engineers. On this opportunity, it is possible to assess alternatives from the early phase of the projects, which may require a lot of time before. LCA methodology is based on a set of standards: ISO 14040 and ISO 14044, EN 15978, EN 15804, and The European CEN and TC 350 standards emphasized. Furthermore, various software applications are used in LCA; however, the database is region-oriented. Moreover, carbon emissions include all the life cycle stages, even the operational life of the construction.

In recent researches, carbon emissions are the first address of the cause of Global Warming Potential (GWP). To control GWP, efforts on reducing carbon dioxide emissions are continuing both in the academy and profession. The process of sustainable design is complicated due to inadequate data (De Wolf et al., 2017). There are direct and indirect emissions that are classified as Operational and Embodied Carbon emissions. While there are plenty of studies and solutions on Operational Carbon (OC), there are fewer efforts to evaluate the Embodied Carbon (EC) in the literature. However, compared to the OC, EC has more effects on overall outcomes. Additionally, a decrease of EC provides cost reduction of resources and also gives a clear picture of longer-term risks about resources (UKGBC, 2015). Embodied carbon is responsible for 11% of all global carbon emissions and encompasses half of the carbon footprint of new structures until 2050. Hence, EC refers to no small part of the carbon budget, which requires rapid efforts to tackle while reducing OC (WGBC, 2019). Considering studies about mostly focusing on a building level and OC, there is an urgent need for the EC researches and studies.

Turkey is increasing its investments in infrastructure projects in order to achieve the welfare level of the European Union. Railway systems and Metro projects have received the most investment since the 1990s, and a serious network (approximately 600 km) has been built, especially in the city of Istanbul.

Furthermore, there is great effort of Turkey to reach EU's carbon targets for 2030 and 2050. Infrastructure projects serve the cities' development purposes yet, in this uncontrolled growth and development should also be evaluated in terms of carbon such as reviewing projects from low-carbon perspective.

The main aim of the thesis is to assess the embodied carbon of urban railway systems, specifically metro lines and metro stations. The main objective of this study is to put forward a reference study for a due diligence assessment in a developing country like Turkey which invests heavily in infrastructure projects.

In light of these, it is aimed that these evaluations will serve the low-carbon infrastructure target as a reference by focusing on the area that brings the most carbon burden, such as material (the carbon footprint from the material has been determined to be quite high and changeable in the literature) on real cases in the city of Istanbul.

In this research, case studies; urban railway systems were evaluated by considering their size in the denominator, and Istanbul, which is the densest city, was preferred. All materials, including tunnels and station structures in 4 lines and 18 stations, were calculated within the scope of 'cradle-to-gate' in the A1-A3 scope range. Construction, operation and end of life phases were not taken into consideration because some of the projects have not been implemented yet, some of them are quite old and reliable data cannot be found.

This research appraises the ongoing AEC industry practice, including a review of both academic and professional literature. Moreover, existing databases, tools, certifications, and methodologies are also analyzed to understand what is incentivized by the authorities. A life cycle assessment (LCA) method might provide a broader perspective for sustainability implementations since there are plenty of parameters that directly affect environmental impacts. Furthermore, carbon footprint (CFP) calculations may give a clear picture of embodied CO_2. Correspondingly, the ultimate approach of GWP, the Carbon Footprint (CFP) of the urban railway systems in Turkey, is evaluated. In addition to this, the benchmark of the material data was collected and aggregated.

The study is based on the International Standardization Organization (ISO), related LCA standards, and it refers to Environmental Product Declarations (EPD) and Product Category (PC) rules. Also, European standard, EN 15978, was adopted for the classification of life cycle stages and modules. In addition to looking at these issues in general, this research is the first concern of embodied carbon evaluations at the infrastructure level, which may accelerate Turkey's efforts on sustainable improvements. Further thought, in this research, LCA methodology is followed within the scope of 'cradle to gate with options EC' to meet on the standard denominator.

Turkey, as a developing country, urbanizes; therefore, efforts increase on railway systems, which is a crucial constituent of transportation. Since there is no tool or certification system for Turkey's sustainable infrastructure, a transparent region-based framework is an urgent need. Following this, CFP perspective within the LCA methodology is chosen to catalyze the investigation. In light of this condition, this dissertation assists to thinking for low-carbon approach of urban railway systems in Turkey with the assessment of embodied carbon.

The purpose of this study is to estimate the embodied carbon dioxide of materials in railway systems. The main motivator of this study is answering the following questions:

- What is the amount of overall carbon footprint that railway systems have in Turkey?
- How can architects and engineers reduce carbon footprint within the railway system project process?

1.2 Aim and Objectives

This thesis aims to provide a benchmark of the embodied carbon of urban railway systems in Turkey. In the light of these goals and objectives, this research aimed to contribute maximum effect through the cases in line with the data and scope limits of the projects. To frame the main focus it should be noted that mentioned aims and objectives require extensive interdisciplinary study. In this research, 4 different railway systems projects were focused on the construction material part and were handled only in the architectural and structural disciplinary manner. On the other hand, LCA scope is studied with a "cradle-to-gate" scope, that is, from A1 to A3 which is explained in detail in Chapter 3.

Following objectives have been identified in order to satisfy this stated aim:

- Developing a methodology for the calculation of CFP and the environmental impacts of urban railway systems in Turkey,
- Collecting and identifying the data for the resolution of the CFP of urban railway systems in Turkey comparative with EU countries,
- Constituting a national database for the calculation of CFP and environmental impacts of metro stations and related products in Turkey,
- Comparing Turkey with the case studies around the world, and ultimately lowering embodied carbon of infrastructure projects.

The big picture that this study aims to contribute both practitioners and researchers might have an idea about the mitigation of carbon dioxide in the early phase of the projects. Besides, policymakers and organizations might address regulations or guides for national carbon reduction in Turkey.

1.3 Disposition

This research is composed of five chapters. The first chapter covers background information with motivation, problem statement, aim and objectives, and disposition. The second chapter comprises a literature review of preceding investigations on sustainability assessments of railway systems. The third chapter describes the method and material of the research. It constitutes case studies of urban railway systems with a breakdown of lines and stations. The fourth chapter concludes the assessment surveys and associates collected results. Case studies are evaluated through the LCA methodology. The fifth chapter concludes the research with discussion and highlights remarks for future works.

CHAPTER 2

LITERATURE REVIEW

''Even before a building is occupied, between 30% - 70% of its lifetime carbon emissions have already been accounted for.''

RICS, 2014

2.1 Introduction

This literature review section introduces the subjects attributed to sustainable infrastructure, embodied carbon, low-carbon infrastructure, and railway systems. General legislation and standards about sustainability are mentioned based on climate change mitigation. The state-of-the-art of low-carbon infrastructure and its applications are scrutinized. Afterward, recent approaches and prevailing methodologies are presented briefly. Finally, a critical review is given to emphasize the significance of this dissertation. Reducing embodied carbon emission is crucial feedback to global targets for carbon mitigation (De Wolf et al., 2016).

2.2 Sustainable Infrastructure

The construction industry is a crucial part of the economy, especially in developing countries. While significant investment made in infrastructure projects, growing demand for carbon emission mitigation needs to be projected. Net-zero carbon goals were set in the Paris Agreement which requires an 80% reduction of carbon emissions all over the world from 1990 to 2050 (IPCC, 2014). Besides, an important share of carbon emission belongs to infrastructure projects.

There is growing interest in climate change, the trend towards low-carbon urban transport development as global demand. In literature, the environmental impact assessments have already proven that a significant reduction of embodied carbon

(EC) emissions is only possible with country-specific evaluation. Following the European (EU) Countries, Turkey must ensure low-carbon infrastructure to tackle the climate change challenge. Furthermore, regulators and the government have key roles to generate country-based data and provide a framework accordingly.

It is explicit that transportation frameworks are vital to the density of any country or local economy, as well as the versatility of its inhabitants. On the other hand, it is noted that the transport sector has an important share in the European economy and society. However, while providing great benefits to society, there are also generous expenditures. For example, the current development of highways is far from reasonable. It is the main area in Europe with constant and continuous energy use and CO_2 discharges and is currently responsible for about 25% of all substances that cause ozone damage in the EU. By 2030, greenhouse gas emissions show that European railways are projected to reduce specific final energy consumption from train operation, measured per passenger-km (passenger service) and ton-km (freight service), by 30% compared to the 1990 base year. It is also estimated that European railways will attempt to halve the specific final energy consumption from train operation by 2050 compared to the 1990 base year, measured per passenger-km (passenger service) and ton-km (freight service) (UIC, 2012).

2.3 Embodied Carbon

The total life cycle carbon is composed of embodied and operational carbon (RICS, 2017). While Embodied Carbon (EC) includes material extraction, transportation, construction, and demolition whereas Operational Carbon (OC) includes only the use phase that comprises heating, cooling, powering, and supplying water (De Wolf et al., 2017). It is stated that embodied carbon dioxide cannot be reversed while operational carbon dioxide can be reduced over time (Circular Ecology, 2019). Recent regulations and standards about sustainable design, have directed practitioners to mitigate OC.

In order to minimize environmental impacts, certification programs such as the latest versions of the Building Research Establishment's Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED) encourage the reduction of EC (RICS, 2017).

Embodied carbon causes the impact of greenhouse gases (GHG) in the life cycle of the infrastructure project. Essentially, the requirement of raw material for construction constitutes 40% of all material flows. Each GHG is converted to CO_2-eq (i.e., CO_2 equivalent) to have the same measurement unit of Global Warming Potential (GWP) (RICS, 2017). Embodied carbon requires to comprehend building codes and incentives voluntarily researched for further enhancement (Bionova, 2018). As it is frequently mentioned in the literature, the EC in construction materials comes from two sources: fossil fuel inputs (directly related to the embodied energy) and that released, for example, from converting limestone to cement (Hammond and Jones, 2011).

According to Greenhouse Gas Protocol (2011), there are some equations to monitor the carbon assessment process, in this thesis following equations are used:

- When process activity data is collected, the basic equation to calculate CO_2-eq for input, output, or process is as below:

  Kg CO_2-eq = Activity Data x Emission Factor x GWP (unit) [kg GHG/unit] [kg CO_2-eq/kg GHG]

- When direct emissions data has been collected, an emission factor is not needed and the basic equation to calculate inventory results for input, output, or process is:

  Kg CO_2-eq = Direct Emissions Data x GWP (kg GHG) [kg CO_2-eq/kg GHG]

The Carbon Leadership Forum used the deQo[1] database and other industry-collected databases and case studies to create the first benchmarks for embodied carbon in buildings (De Wolf, 2019).

The ECCs (expressed in $kgCO_2$-eq/kg) of the considered materials are then used to calculate the total embodied carbon. This is presented in the following equation:

$$\textbf{Embodied Carbon}_{\textbf{building}} = \sum_{m=1}^{M} \sum_{l=1}^{L} \textbf{SMQ}_i \textbf{ x } \textbf{ECC}_i \text{ (2)}$$

where:

- m is a particular material or component in the building m = 1, 2, 3, M;
- l is the number of replacements within the life cycle of the building for each material
- l = 1, 2, 3..., L.
- SMQ is Structural Material Quantities (kg);
- ECC are the corresponding Embodied Carbon Coefficients ($kgCO_2$-eq/kg).

In the absence of strict carbon-based regulations, there is an increasing urgency for carbon calculation tools. With this motivation, like many academics, Galli et al. (2020) evaluated individual carbon calculators available to the public. This tool was designed for Brazil with a combination of 15 calculators and showed a large difference between emission factors and carbon stock values. Inconsistencies found can adversely affect the reliability of calculators, their potential to increase environmental awareness, and their impact on decision-making. Therefore, the spread of carbon calculators should be accompanied by more specific guidelines to minimize uncertainties associated with estimates.

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[1] The database of embodied Quantity outputs (deQo) is a service provided by the MIT Building Technology Program and the Circular Engineering for Architecture (CEA) lab at ETH Zurich. Prof. Dr. Catherine De Wolf is the project head. Prof. Dr. John Ochsendorf is the research advisor.

[2] Embodied Carbon Calculation Formula

2.4 Low-Carbon Infrastructure

In recent years, significant investment and effort are spent on infrastructure projects, these issues are also included in Turkey's development goals. From the Kyoto Protocol to the Paris Agreement, it is inevitable to consider the Greenhouse Gas (GHG) reduction included in the construction sector as a perspective on infrastructure projects. The transportation sector, which is an important shareholder in carbon emissions, takes steps in the environmentally friendly design and is of great importance for modern society. Finally, as stressed firmly in the European Green Deal, given the current era and circumstances, for the sake of a globally sustainable economy a paradigm shift is an obligation to tackle environmental and climate-related challenges. However, this is not only the responsibility of academics, practitioners, and authorities but also a matter that can be achieved through the conscious behavior of each and every individual (European Green Deal, 2019).

It seems that the United Kingdom (UK) is the pioneer country to initiate climate change mitigation around the world and mostly gives inspiration to both the United States and European countries. According to Infrastructure Carbon Review Technical Report (2013), the total contribution of the transport sector to greenhouse gas emissions in the UK is 21%. While providing a competitive and diverse transport sector necessary for economic growth, it needs to be aligned with the incentives and policies that cause reductions in the overall sector. Three key solutions to reduce carbon in the UK solutions are supporting the transition to new technologies and cleaner fuels, using market mechanisms to promote lower carbon preferences, and lower carbon transition alongside industry-leading organizations which impulse towards the low-carbon transport industry (The UK Low Carbon Transition Plan, 2009). Additionally, those solutions would shape the leadership, innovation, and procurement values with a variety of aspects.

With a focus on the construction industry, the largest consumer of materials worldwide, and one-third of the GHG involved, the effects of change can be seriously observed (Ibn-Mohammed et al., 2013). Despite such a serious sectoral share, the construction industry fell far behind other sectors in terms of sustainability. The main reason for this is the construction industry has a difficult atmosphere for change since it has multiplayer, and it is also a multifunctional industry which strongly requires interoperability. The slightest positive change in the fight against climate change in the form of any stakeholder or way of doing business can be effective for the entire system, on the other hand, it is necessary to develop in parallel in order to observe the positive effects of the related efforts. Therefore, all possible tools such as innovation and technology to aid this change should be used rationally, and alternative perspectives should also be developed.

In line with the foregoing ideal, to be able to describe environmental problems and find innovative ways to solve them, a holistic life cycle approach is needed (Stripple and Uppenberg, 2010). Infrastructure represents the level of welfare of the country so there exists an urgent need for the evaluation of sustainability assessment to attain the Climate Change Act target: reducing 80% of carbon emission by 2050 (Business, Innovation and Skills 2010). As mentioned in the Paris Agreement, the net-zero carbon vision requires a significant amount of reduction by 2050. Furthermore, it is underlined in the European Green Deal that the EU purposes to be climate neutral in 2050. A road map and actions to be taken to achieve this goal have been declared.

It is known that the development and implementation of sustainable strategies go far beyond infrastructure projects in building projects. Wei and Chen (2020) asserted that in order to catch up with the pace of technological advances at the building level in the planned new infrastructure projects, the carbon footprint must be continuously reduced, thereby improving the average urban economy. Complementarily they designed a dynamic life cycle tool to evaluate an approach and long-term regulatory policies towards a more sustainable transport infrastructure system for cities.

In most cases, in the process of implementing infrastructure projects, effective assessment indicators are unavailable. These indicators present a barrier to the effective assessment of infrastructure project sustainability. There is a study as shown in Figure 1, introduces key assessment indicators (KAIs) for assessing the sustainability performance of an infrastructure project (Shen et. al. 2011). As can be deduced from their study, there are several parameters and possible cause and effect scenarios related to sustainable infrastructure.

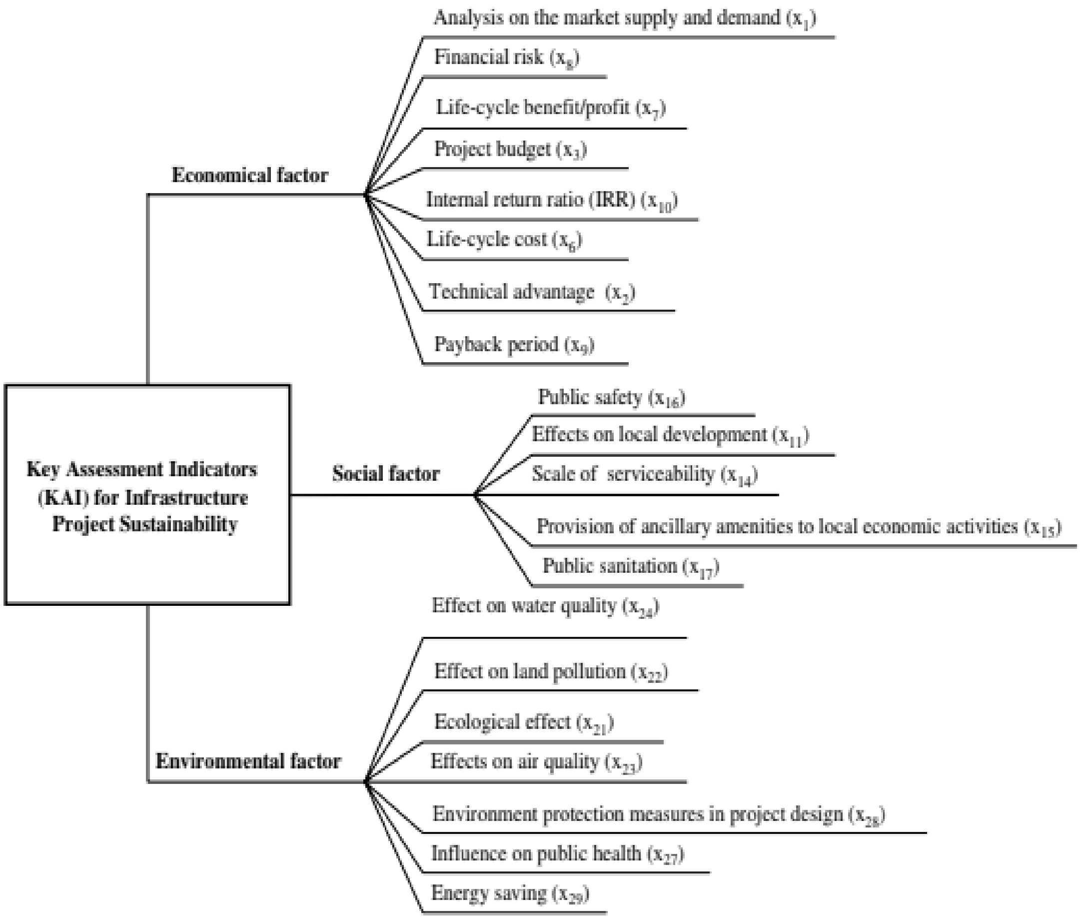

Figure 1. KAIs for infrastructure project sustainability (Shen et. al. 2011).

According to the literature, there are various methods for practicing sustainable development principles through LCA. However, there is no specific methodology developed for the performance of the construction site, its geometry, specifications, prominence on the entire life cycle, legal constraints, socio-economic factors, or the physical and environmental conditions of the construction site. Obviously, further research is needed to generate standardized embodied GHG assessment which is also confirmed by related authorities.

UK Green Building Council (UKGBC) prepared a report to investigate the decarbonization of infrastructure. It includes the current carbon target, beyond that the reasons and consequences of these targets. It is found out that there are no specific targets, no single method, and regulations have a great influence on carbon emission mitigation. However, tackling the low-carbon challenge in infrastructure will ensure a low-carbon future. For this, the government and regulators have key roles to encourage excellence.

Developing a carbon strategy for infrastructure requires a deeper understanding of the current carbon level, provision of negative emissions, developing a cross-industry dialogue, and subdividing targets between organizations. Since the scope of infrastructure projects shows the variety, there are challenges such as project output diversity, lack of relation with global pathways, long life span projects, and meeting 2050 goals as net-zero carbon.

There are many different activities in infrastructure projects where carbon should be considered and measures for reducing carbon emissions taken, both during planning and design and during construction. According to PAS 2080 (BSI, 2016), an 80% EC reduction is targeted to accelerate the process by 2050. The following carbon emissions reduction hierarchy should be followed by all value chain members when identifying opportunities to reduce carbon (HM Treasury, 2013):

1. *Build nothing:* evaluate the basic need for an asset and/or program of works and explore alternative approaches.

2. *Build less:* evaluate the potential for re-using and/or refurbishing existing assets to reduce the extent of new construction required.

3. *Build clever:* consider the use of low carbon solutions (including technologies, materials, and products) to minimize resource consumption during construction, operation, and use.

4. *Build efficiently:* use techniques (e.g., construction, operational) that reduce resource consumption during construction and operation.

Further to that, a wide variety of challenges can be identified at first glance for low-carbon infrastructure targets. However, basically, the evaluation for low-carbon infrastructure can be divided into three main categories as structural, cultural, and practical. The value to which this thesis is more relevant can be considered from the structural perspective. The Figure 2 below shows the relationships between the broad spectrum of stakeholders involved in the management and creation of infrastructure assets that can be referred to as the value chain. All parts of the value chain are partially dependent on others to enable low-carbon solutions, but there are currently some bottlenecks in the network. Customers play a crucial role in removing these blockers and continue to get the most out of them. Still, each of the key stakeholder groups has a role to play.

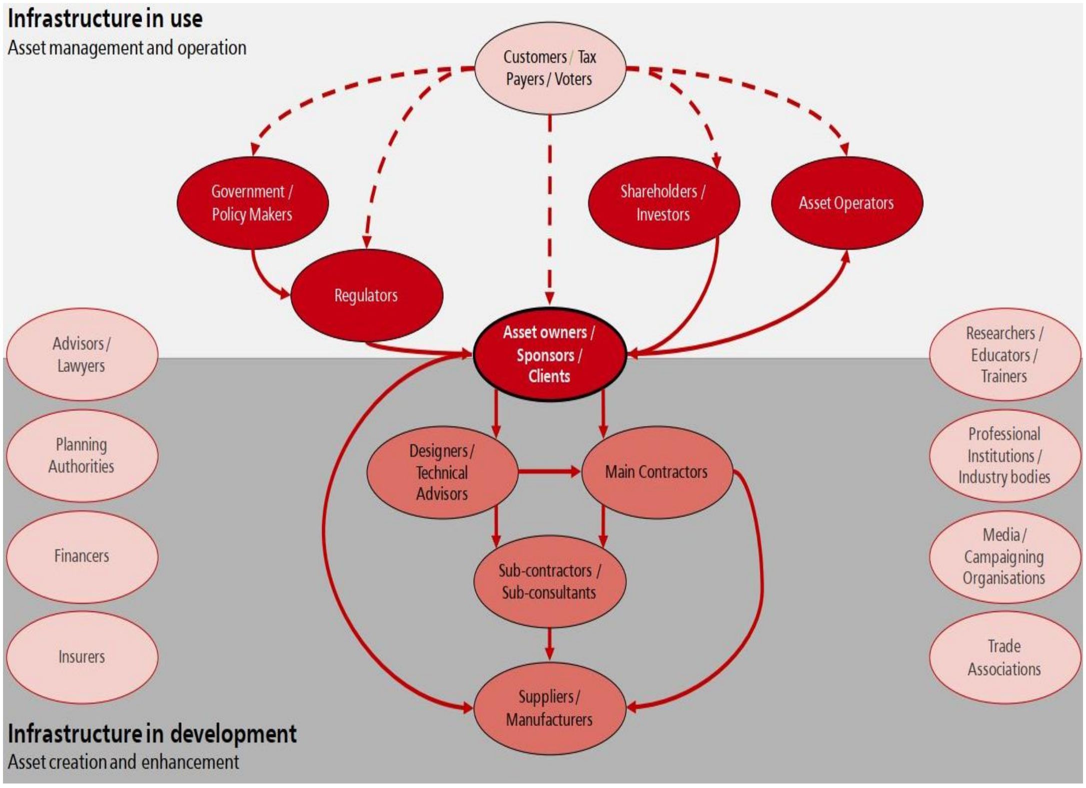

Figure 2. Infrastructure sector stakeholder network and value chain (Green Construction Board, 2013).

Managing structural barriers is key to recognizing the value of low carbon solutions across the infrastructure. A simplified value chain expression is presented in the Figure 3 below. Each stakeholder group has some possibilities to gain some value by reducing capital autonomously and operating carbon. However, the maximum value can only be reached by participating in the value chain.

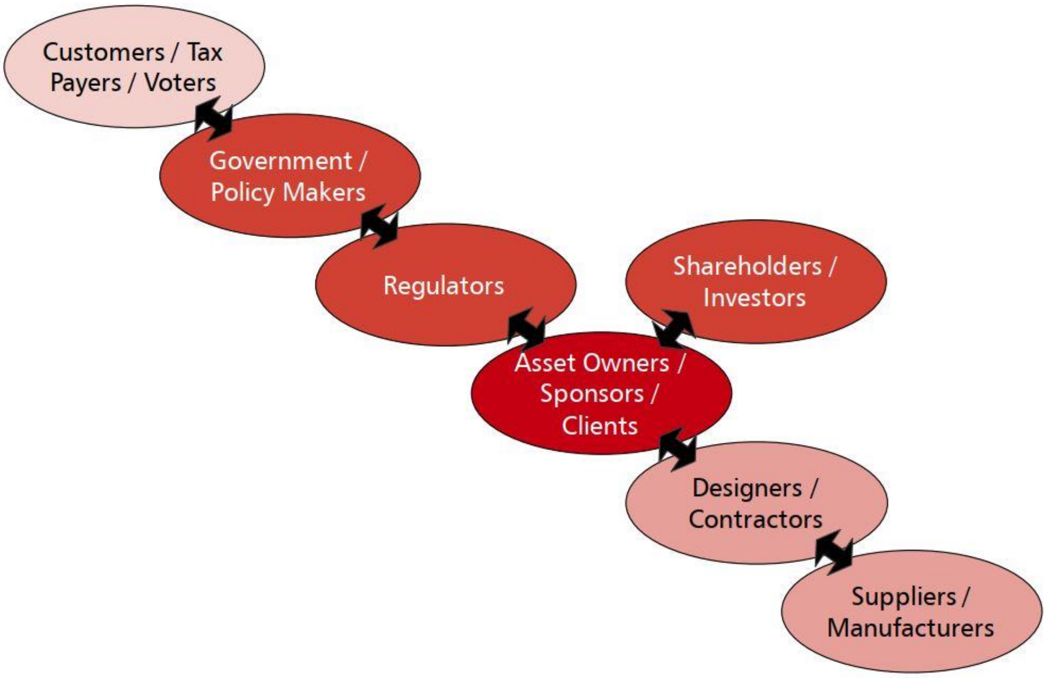

Figure 3. Simplified value chain (Green Construction Board, 2013).

A stable and measured lifetime carbon balance is required to effectively incorporate the sustainability framework of infrastructure projects. This goal should be pursued to ensure that an 80% reduction target is met by 2050 and that the longer-term target for net-zero carbon, as currently set out in the Paris Agreement, is achieved. In order to tackle climate change, the carbon footprint methodology has become the preferred tool for a sustainable decision-making framework (Wright et al., 2011).

2.5 Related Studies

There is limited understanding of the net GHG impact of the urban railway systems on urban emissions. In the literature, there are many studies examining the GHG emission of Infrastructure Systems in different scopes. In this section, several similar railway system studies are reviewed with the intention of inspiring the thesis.

Andrade et al. (2016) proved that it is possible to reduce carbon emissions in the city transport system in Rio de Janeiro with a holistic study throughout the life cycle of the Rio de Janeiro Metro Line. This promising research contributes to the higher goals of this thesis because due to Istanbul's being a crowded and carbon-intensive city. Reducing embodied carbon in urban railway systems of Turkey in Istanbul has the potential to seriously reduce to capture the carbon load which will lead the country in carbon mitigation target. The main recommendations of the Rio de Janerio case study highlighted the need to focus on the share of renewable energy in electricity generation and steel and concrete production with high use of railway systems. These results should be compared with the cases examined for the thesis and it should be evaluated whether similar results have been obtained.

A state of the art expressed that most of the carbon emissions in infrastructure systems origins from the material manufacture and use phases. Cement, concrete, and steel are the leading roles of the materials responsible for most of the carbon emissions (Andrade et al., 2016). On account of the large variety of manufacturers and types of these materials, it is recommended to use the benchmark of each material to acquire upstream mission values. However, it is an advantage to have been used Environmental Product Declaration (EPD) certified materials and make calculations with real values. According to a study qualified by Chang and Kendall (2011), the significance of the production of materials used in infrastructure construction of railway systems is responsible for 80% of the emissions from the construction of a high-speed rail system in California.

Li et al. (2019) evaluated the Shanghai Metro Line with the LCA methodology, which provides a comparative study of GHG from different urban transport systems around the world. The results display that the total life cycle GHG emissions per construction length of the entire Shanghai Metro is found 109,642.81 tCO_2-eq throughout 50-year service life. The rate distribution of emissions is as follows; material production 4.1%, material transportation 0.1%, on-site construction 0.4%, operation 92.1% and maintenance 3.4%. Shanghai Metro Line study addresses two crucial questions as purposed to be replied also in this thesis for Istanbul Metro Lines. First, how much greenhouse gas does the Shanghai Metro embodied during its entire life cycle? Second, what is the emission level of the Shanghai Metro compared to other case studies worldwide? As a result, carbon emissions from above-ground construction activities 4,909.3 tCO_2-eq/km; for the underground part, this value is 5,041.2 tCO_2-eq/km. Also, the footprint per passenger is 23.4 grCO_2-eq/pkt.

Saxe et al. (2017) studied on Sheppard Subway Line in Toronto, Canada. In this article, greenhouse gas is considered more globally. In other words, GHG has included all processes as life cycle modeling and integrated it into the current real situation. The GHG emissions associated with construction, operation, ridership, and changes in residential density associated with the provision of the new metro rail infrastructure is assessed. An evaluation was made at the neighborhood level. It is examined that how many years after starting the business the GHG would make up for itself. After nine years of operation, the Sheppard Subway Line is found to have nearly paid back its initial GHG investment in the optimistic case. The GHG payback of the Sheppard Subway line is dependent on PKT shifted from automobile travel and savings in energy use associated with increased density. This study was evaluated together with vehicle use and public transportation use. It is underlined that the limited understanding of the net impact of new metro rail infrastructure on urban emissions.

Tiwari et al. (2017) analyzed a comparison of the urban bus system and metro line in Delhi in terms of environmental impact. The total impact of the Delhi metro is calculated as 1.46 times more than the bus transportation system despite the metro has been promoted as the cleanest public transport system having the least adverse effect on local air pollution. According to the research of Banar and Özdemir (2015), the highest contribution of GHG of the railway systems in Turkey occurs from the operation of train vehicles, infrastructure materials, and infrastructure work. In this study as well, it is considered that to reduce the environmental effects resulting from materials comprised mainly of steel and concrete. Finnegan et al. (2018) have asserted an idea from a technology perspective for associated embodied carbon. They have also emphasized the necessity of further studies on the embodied carbon or CO_2 equivalent (CO_2-eq) impact of sustainable energy technologies and the contribution to the total CO_2-eq budget of a project.

Yu et al. (2020) designed a detailed carbon emission assessment mechanism for Chinese citizens, a special method called the Carbon Generalized Preferences System. A carbon emission measurement using a sophisticated method for individual excursions in the Nanjing Metro has been proposed, resulting in the recommendation of accurate individual monitoring of carbon emissions. This study shows that the government has the opportunity to set up a comprehensive monitoring system to establish a carbon tax and carbon supplement mechanism for citizens.

Baron et al. (2011) worked on HSR projects focusing on the contribution of the tunnels to the overall energy consumption and carbon emissions of the project. The contribution of tunnels has an enormous impact. There is also a commercial electricity consumption in the operation phase, but it can be calculated by taking advantage of having a different value in that region. It has been found that tunnels add significantly to both the embodied and operational energy consumption and GHG emissions of railway infrastructure. With this research, the importance of including tunnels in the calculations is emphasized.

Landgraf and Horvath (2021) assessed the life cycle GHG emissions associated with the railway network of Austria with a top-down approach. The first case for the country, the railway infrastructure emits 235,000 tons of CO_2-eq per year, 0.3% of the Austrian total. Within railway infrastructure, rails (including rails, fasteners, sleepers and ballast) are the largest contributor to GHG emissions with 55% of the total. This can be noted as an important part that is not mentioned much in the literature. Furthermore, it is investigated that the GHG emissions associated with concrete tunnels are 16 times higher per kilometer per year than rail, but only account for 22% of total emissions. Within the holistic picture railway infrastructure contributes 141% additional GHG emissions compared to emissions from passenger traffic, which are much higher than estimated.

Stripple and Uppenberg (2010) analyzed the LCA of the railway systems through the Bothnia Line in Sweden which is projected by the help of EPD certifications. It is found that construction phase dominates the GHG over the other phases of LC. With an energy efficient solutions as green electric power and hydropower operation phase stand as the smallest portion of the GHG emissions which inspirational when the other cases taken into the consideration. As a result, the main contributions came from materials such as steel and concrete.

Monaco and Ryan (2016) reported the Green House Gas Impact Assessment of Melbourne Metro Rail Project. All dimensions of the life cycle and possible scenarios are a well-studied project for thinkers. The greenhouse gas emissions from the activities are summarized as follows in Figure 4. The fact that most of the embodied carbon source is construction material supports the focus of this thesis.

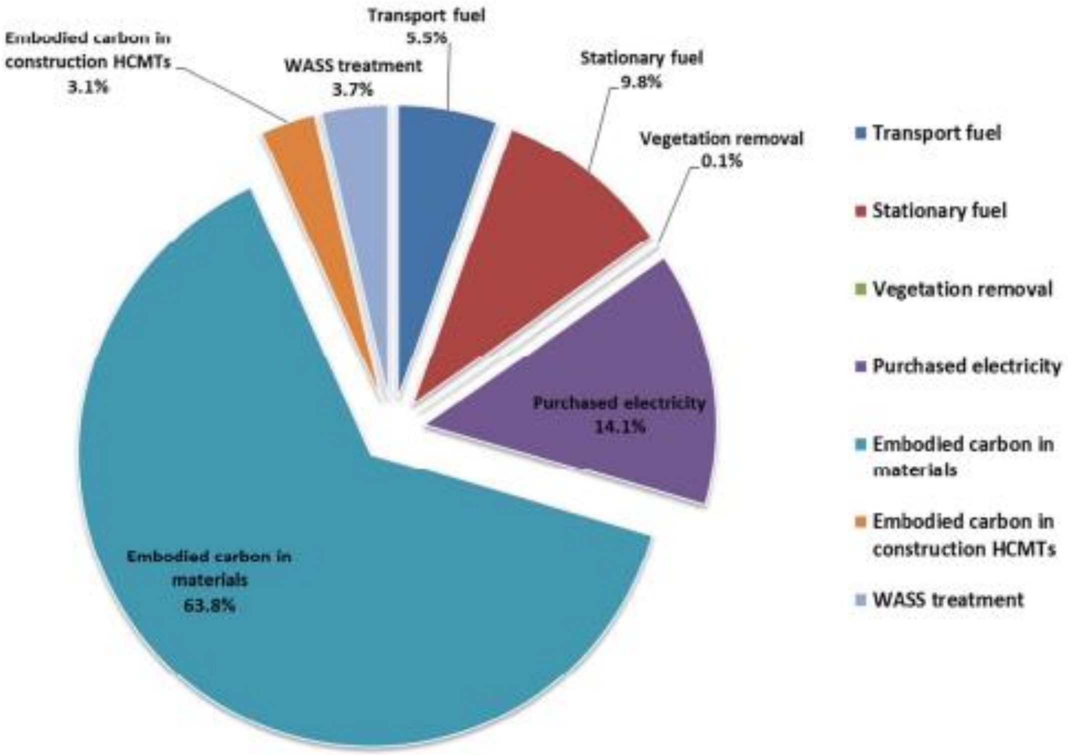

Figure 4. Summary of construction GHG emissions by activity type (Monaco and Ryan, 2016).

Olugbenga et al. (2019) studied the EC of railway systems and mentioned the following challenges: differences in system boundaries, and study objectives, and inventory methods adopted in publications. In these studies, the concrete emissions range from 0.5 to 12.700 t CO_2 km. The main reason for the inconsistencies derived from types; slope tunneling, elevated tunnel, or covered one. The authors severely endorsed the requisite for standardization of GHG for rail infrastructure to better facilitate hotspot detection, engineering design, and GHG policy decision making. Their statistical model proved that overall, 941 (±168) tCO_2-eq is embodied per kilometer of the railway on slope and tunneling has 27 (±5) times more concrete GHG per kilometer than level construction. It is also noted that the statistical model was based on the findings of published literature and does not explicitly take into account function, geometry, specifications, emphasis on the whole life cycle, legal constraints, socio-economic factors, or physical and environmental conditions of the construction site. This study reveals how much care should be taken in the selection of tunnels and cut-and-cover structures. As a matter of fact, this situation should be taken into account in the case studies in this thesis. In the same research it is also mentioned that as in general, metro rail had the largest embodied GHG emissions, followed by intercity rail, high-speed rail, and light rail as indicated Figure 5. However, this must be evaluated in the context of the varying number of case studies.

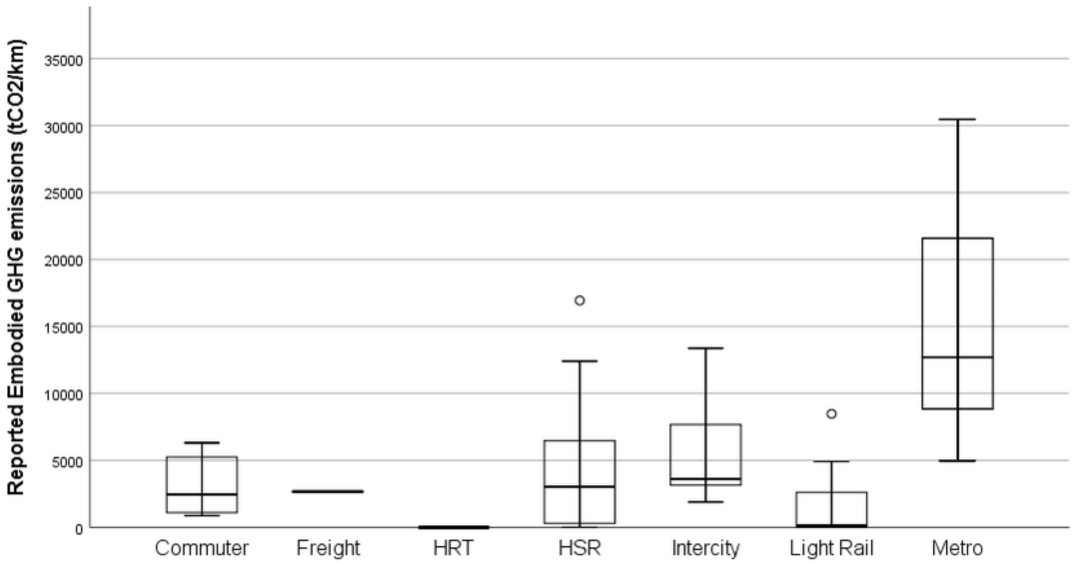

Figure 5. Embodied GHG Emissions reported for the different rail infrastructure (Olugbenga et al., 2019).

Saxe et al. (2016) emphasized the provision of rail transport is widely recommended to reduce transport GHG emissions, but the provision of new infrastructure itself is GHG-intensive. Understanding of the GHG emissions impact of railway projects is limited and few longitudinal studies have been done. The study examined railway infrastructure projects and their associated greenhouse gas emissions. The provision of railway infrastructure is greenhouse gas intensive in terms of materials used and energy expended, and the net greenhouse gas impacts of such projects are not well understood. A holistic assessment of greenhouse gas emissions should inform project design in an integrative/iterative process to ensure the long-term environmental success of these major engineering projects. The study stressed the importance of making a complete assessment of greenhouse gas impacts. To the works of the future, which we would recommend being considered in all its dimensions and with reality, to be considered in our work. It proposes the key factors to be considered in a holistic assessment of the GHG impact of railway infrastructure projects, as shown in the Figure 6 below.

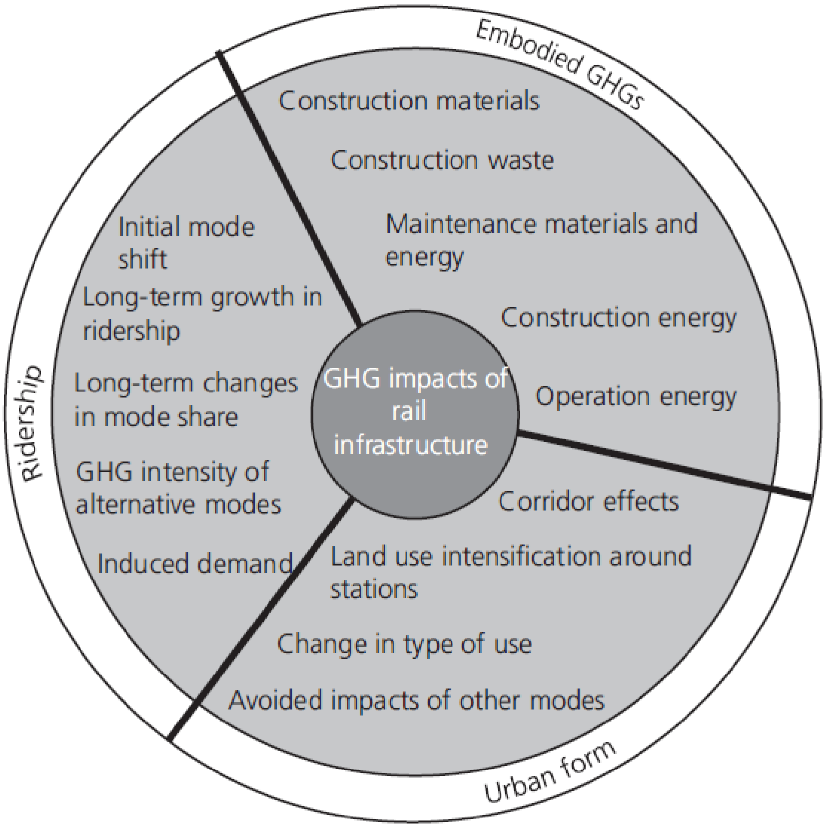

Figure 6. Key Elements of the net GHG impact of rail infrastructure projects (Saxe et al., 2016).

Based on these dissertations, it is necessary to address the issue with an innovative perspective. As the key to improvement, innovation in both infrastructure and carbon mitigation trends proceed gradually in the literature. Critical and rapid development within the low-carbon infrastructure (LCI) framework has occurred recently. This development needs to move forward to strengthen low-carbon progress, but this must be done reliably. It is essential that the LCI is planned for toughness and lifespan, plus low-impact recovery, direct reuse, and, where important, reuse, and regeneration. Achieving a low carbon infrastructure and applying new methods for it will also trigger innovation.

2.6 Critical Review

In this section of the report, the literature is reviewed, and deductions are summarized and criticized. As can be deduced from the literature review, this thesis relates directly and indirectly with a number of issues in the Kyoto Protocol, the Paris Agreement, and the European Green Deal. These topics can be listed as follows: construction industry, infrastructure projects, railway systems, transportation sector, materials industry, and sustainable cities, smart cities. Europe supports the steps taken to achieve climate-neutral by 2050 targets. It is essential for also Turkey to fight against climate change with sensitivity to be able to catch European countries and initiate sustainable development.

When working on sustainable transport, it has a great importance of scrutiny of infrastructure components and the amount of capacity utilization assumed among other transport systems. Hence, it is explicitly emphasized in the literature that this issue varies from project to project from country to country. Several studies bring the idea that once again underlines the necessity of designing projects and region-based sustainable transportation framework. A well-formed policy can only be designed with proper attribution of energy consumption and emissions.

At a first glance in the literature, it is quite clear that institutions responsible for infrastructure should demand lower carbon. The primary task is that Government and industry customers should work collaboratively to implement carbon reduction targets in infrastructure projects. Achieving this leadership will provide flexible solutions on reducing carbon in supply chains, catching net-zero carbon targets, and contributing to low-carbon infrastructure innovation.

There is plenty of research about the assessment of the environmental impacts of the construction sector up to date, which are mostly on building level. On the contrary, there is a lack of carbon assessment on the level of infrastructure. Often the beneficial efforts for certification programs are not sufficient to achieve the ultimate goal of low-carbon infrastructure. Therefore, there is an urgent need for specialized methodologies such as LCA and CFP and derivatives to achieve the main purpose. These methodologies require clarifications in terms of system boundaries to process the data and produce a transparent output. On the other hand, existing methodologies and tools required to be validated to settle specific methodology for each project and to be able to establish a framework for low-carbon infrastructure.

State of the art emphasizes that the embodied carbon corresponds to a crucial volume of annual global carbon emission. However, correlating system boundaries, study goals, and inventory methods to the embodied emissions are difficult because of the variety of data. State of the art stimulates the need for standardization across the reporting of embodied GHG for the infrastructure and GHG decision-making policy. Future research should comprehend all-embracing real case infrastructure projects to demonstrate heterogeneity as, for instance; ground conditions, construction approaches, design, materials, and fuel use vary across projects. In this respect, authorities have a vital data-sharing role in collecting data as a driver for using a subset of data and linear assumptions.

In the literature it is mentioned that lack of data about LCA on the following three subjects causes the major problems: reliable data, characterization factors, and LCA modeling methods. Retrieving these qualification factors is beyond the breadth of the existing literature. Nonetheless, as seen in certain studies it is possible to develop a hybrid LCA modeling method by using the existing data. Guinée et al. (2002) defend that this advancement is challenging as LCA itself because it requires a multi-model multi-paradigm situation with the necessary assumptions. As a matter of example, the GHG intensity of materials, the accuracy of construction documents as predictive of material-use are compelling to verify.

It is proved that metro rail had the largest embodied GHG emissions, followed by intercity rail, high-speed rail, and light rail (Olugbenga et al., 2019). However, this must be aforethought in the terms of the various case studies per rail type and infrastructure type (e.g., tunneled, or elevated) to embodied GHG across rail types. Further research is needed to generate framework for generalized embodied GHG assessment of rail projects. As the field moves forward, clear communication of boundaries and data will be necessary to advance beyond the limitations.

Besides, identification and selection of materials provide convenience for embodied carbon mitigation over design processes. For example, high-impact materials such as concrete, steel and iron produce nearly 9% of annual global GHG (AIA, 2030). While operational carbon emissions can be restricted over time with building energy efficiency and renewable energy principles, embodied carbon emissions are irremediable just as the construction phase is finished. As a matter of fact, it is assumed that embodied carbon will be in charge of 72% of the carbon emissions related to global new construction till 2030 (AIA, 2030). In light of this information, for the mitigation of embodied carbon of infrastructures, a project-specific approach and its related methodology is required including LCA and CFP. The summary table of the related literature review is as given Table 1.

Table 1. Summary of the related Literature Review.

Authors	**Publication Title**	**Country/ Region**	**Type of Rail**	**Results**
Chester, M. and Horvath, A. (2010)	Life cycle assessment of high-speed rail: the case of California	USA/ California	3*HSR	Total life-cycle energy inputs and greenhouse gas emissions contribute an additional 63% for on road, 155% for rail, and 31% for air systems
Yue, Y. et al. (2015)	Life Cycle Assessment of High-Speed Rail in China	China/ Beijing	6*HSR	Vehicle operation dominates most impact categories
Del Pero et al. (2015)	Life Cycle Assessment of a heavy metro train	Rome/ Italy	Heavy Metro Train	Use is largely the most influential stage for the majority of the considered impact categories
Li, Y. et al. (2016)	Calculation of life-cycle greenhouse gas emissions of urban rail transit systems: A case study of Shanghai Metro	China/ Shanghai	Metro	carbon emissions from above-ground construction activities 4,909.3 tCO_2-eq/km; for the underground part, this value is 5,041.2 tCO_2-eq/km. In addition, the footprint per passenger is 23.4 $grCO_2$-eq/pkt.
Andrade et al. (2016)	Energy use and carbon dioxide emissions assessment in the lifecycle of passenger rail systems: the case of the Rio de Janeiro Metro	Rio de Janeiro/ Brazil	passenger rail systems	Construction & Operation 6.93 & 0.77 $grCO_2$-eq/pkt.
Saxe, S., Miller, E. J. and Guthrie, P. (2017)	The net greenhouse gas impact of the Sheppard Subway Line	Canada/ Toronto	Metro	17,54 tCO_2-eq/km or the concrete and rebar use alone
Shinde et al. (2018)	Life cycle analysis based comprehensive environmental performance evaluation of Mumbai Suburban Railway, India	India/ Mumbai	Suburban Railway	The results show that operation phase is the main contributor (87-94%) to the total environmental impact
Stripple and Uppenberg (2010)	Life cycle assessment of railways and rail transports	Sweden	Urban Railway	operation dominates most impact categories
Landgraf and Horvath (2021)	Embodied greenhouse gas assessment of railway infrastructure: the case of Austria	Austria	Railway Network	The railway infrastructure causes 235.000 tons of CO_2-eq emissions per year
Monaco 2016	Melbourne Metro Rail Project	Melbourne/ Australia	Metro Rail Project	63.8% embodied carbon from construction materials

To conclude, this so-called multi-model multi-paradigm approach needs validation with sufficient data and several case studies. Furtherance of this research it would be possible to generate a concrete framework for low-carbon infrastructure according to each project. Further research is needed to generate robust formulas for generalized embodied carbon assessment of railway systems. As more academic steps will be taken, the data would be summarized, and the graduated conversion approach can be used to update the benchmark. In pursuit of these efforts, the boundaries and data will need to be intelligibly communicated to go further through the related boundaries.

CHAPTER 3

MATERIAL & METHOD

"You cannot manage what you do not measure."

- Peter Drucker

This chapter comprises the research material and method. In the material section, sample projects are demonstrated and briefed with details. Overview of railway systems in Turkey, characteristics of the selected metro lines are also introduced in this section. In the method section, the life cycle assessment methodology is explained, also the low-carbon infrastructure perspective is detailed. As a result of this approach, the scope of the embodied carbon calculation is interpreted as well. Additionally, information about case studies is presented. This effort would aid the AEC industry to mitigate EC and achieve a low-carbon infrastructure target.

3.1 Research Material

The study displays the benchmark of the embodied carbon with a case study on 4 metro rail lines, including the stations and tunnels, in Istanbul, Turkey. An assessment of the embodied carbon of these projects was conducted to generate a reference embodied carbon model that may represent urban railway systems in Turkey. Case Studies were evaluated through the main components of stations and tunnels.

3.1.1 Urban Railway Systems in Turkey

Rapid urbanization causes the expansion and diversification of the infrastructure network. Urban railway systems are the preferred systems concerning speed, capacity, and flexibility. Istanbul is the most crowded city of Turkey. Therefore, there is an urgent requirement to solve the transportation problem. In development plans, railway systems are the pioneer efforts and projects are implemented rapidly. In Istanbul, the subway network is highly developed including 18 different itineraries with 170 kilometers length. On top of that, it is envisaged that until 2023, metro lines are strived to reach 600 kilometers.

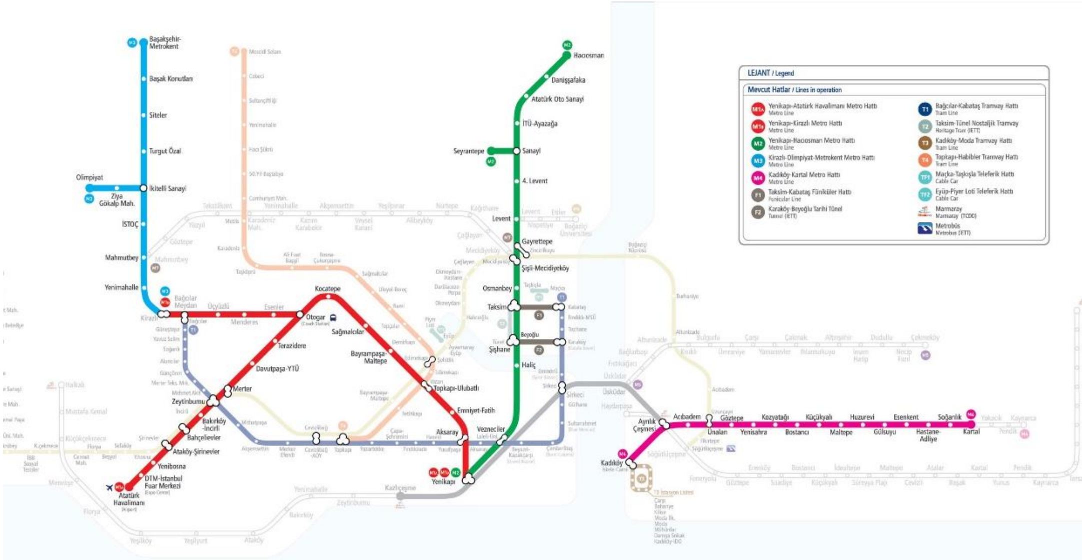

Figure 7. Istanbul Metro Map (Metro Istanbul, accessed 2020).

3.1.2 Case Studies: Lines and Stations

As is mentioned in the introduction part, the sample projects consist of 4 different metro lines including 18 stations in total, which are in Istanbul. With this research, it is targeted to generate a benchmark will be the output of this study. Therefore, the selection was conducted according to the different types of metro lines in terms of operation year, construction methodology, and characteristics of the line. This research is conducted with real case data which are confidential, so lines and stations are abbreviated as 'L' and 'S' iterations. Detailed information about lines and stations are given in the following explanations and summarized in Table 2;

Specification of the Lines and Table 3; Construction Typologies of the Metro Stations.

Table 2. Specification of the Lines

SPECIFICATION OF THE LINES							
Lines	**Number of Stations**	**Gross Built Area of the Stations (m2)**	**Length of the Stations (m)**	**Length of the Lines (km)**	**Construction Method of the Lines**	**Tunnel Types of the Lines**	**Start Year of the Operation**
Line 1 (L1)	4	30,200	180	4.5	Cut and Cover & Tunnel	A & B1	2017
Line 2 (L2)	7	103,858	180	21	Cut and Cover & Tunnel	A & B1	2022
Line 3 (L3)	3	24,930	180	7.4	Cut and Cover	A & B1	2021
Line 4 (L4)	4	20,800	90	4.2	Cut and Cover & Tunnel	A & B1	2015

Line - 1 is one of the oldest metro lines of Istanbul which started operation in 2017. The line length is around 5 kilometers and 4 metro stations have been designed on the line. The total gross built area (GBA) of 4 stations is around 30,000 m^2. Each of the metro stations on this line, which was built with cut-and-cover and tunnel construction methods, has a platform length of 180 meters, and a train with 8 wagons was used according to the relevant passenger load calculations. Additionally, line-length tunnels were designed with A and B1 tunnel types, the details of which are explained in the literature review chapter.

Line - 2 is one of the most significant and the longest metro lines of Istanbul which will start operation in 2022. This line was projected on the European Side of the Istanbul, and it was integrated with the current network to ease rapid access. The line length is around 21 kilometers and 7 metro stations have been designed on the line. The total GBA of 7 stations is around 105,000 m^2. Each of the metro stations on this line, which was built with cut-and-cover and tunnel construction methods, has a platform length of 180 meters, and a train with 8 wagons was used according to the relevant passenger load calculations. Also, line-length tunnels were designed with A and B1 tunnel types.

Line - 3 is a pilot project, either from the Government or professional point of view. Engineering, Procurement and Construction (EPC) Contractor was encouraged to apply the latest technologies not only during the design process but also throughout the life cycle of the project. Thereupon, all innovative applications and technological developments have been tried to be applied to this project by pushing the boundaries. Another importance of this project is that it will connect an already functioning line with one of the existing airports in Istanbul. This urban railway system is of great strategic importance and consists of 3 stations and the total length of the line is 7 km. It was designed and managed using the Building Information Modelling (BIM) concept. Furthermore, it was the first time to evaluate the project in terms of sustainability efforts in the history of Istanbul urban railway systems. In other words, this crucial project, which is innovative in many respects and contains many firsts, is expected to be put into operation in 2021. The total GBA of 3 stations is around 30,000 m^2. Each of the metro stations on this line, which was built with only cut-and-cover construction methods, has a platform length of 180 meters, and a train with 8 wagons was used according to the relevant passenger load calculations. Also, line-length tunnels were designed with A and B1 tunnel types.

Line - 4 was extended to the existing network to ease rapid access and this line is also one of the oldest metro lines of Istanbul which was started to operate in 2015. The line length is around 5 kilometers and 4 metro stations have been designed in this scope of urban railway systems. The number of wagons is 4 due to the connection to the previously implemented line, hence the platform length is 90 meters. Accordingly, since the platform length is 90 meters the construction area is less than other projects but not half due to technical requirements. The total GBA of 4 stations is around 23.000 m^2. Each of the metro stations on this line was built with cut-and-cover and tunnel construction methods. Furthermore, line-length tunnels were designed with A and B1 tunnel types. The lines of the case evaluations are as abovementioned, and the station-based evaluations as Construction Typologies of the Metro Stations are summarized in Table 3.

Table 3. Construction Typologies of the Metro Stations.

CONSTRUCTION TYPOLOGIES OF THE METRO STATIONS										
Line Code	**Station Code**	**Platform**	**Mezzanine**	**Technical Floor**	**Ticket Hall**	**GBA (m²)**	**Length (m)**	**Staircase**	**Escalator**	**Lift**
L1	**S1**	2400	300	2400	2400	7500	180	interior: 6 outdoor: 4 emergency: 1	16	5
	S2	2400	300	2400	2400	7500	180	interior: 6 outdoor: 3 personnel: 2 emergency: 1	20	5
	S3	2400	400	2400	2400	7600	180	interior: 6 outdoor: 4 emergency: 1	18	5
	S4	2400	400	2400	2400	7600	180	interior: 9 outdoor: 4	16	5
L2	**S1**	6765	1760	2840	3404	14769	180	interior: 6 outdoor: 3 service: 2	18	6
	S2	6766	1998	2899	3404	15067	180	interior: 6 outdoor: 3 service: 2	16	5
	S3	6765	1827	3374	3404	15370	180	interior: 7 outdoor: 3 service: 2	16	5
	S4	6765	1827	3374	3404	15370	180	interior: 6 outdoor: 3 service: 2	18	6
	S5	6759	1761	2561	3404	14485	180	interior: 6 outdoor: 3 service: 2	16	5
	S6	6759	1696	2561	3404	14420	180	interior: 6 outdoor: 3 service: 2	18	6
	S7	6769	1693	2511	3404	14377	180	interior: 6 outdoor: 3 service: 2	18	6
L3	**S1**	2120	N/A	3790	2283,2	8110	180	interior: 2 outdoor: 2 emergency: 2	4	3
	S2	2120	N/A	3790	4898,6	8110	180	interior: 2 outdoor: 2 emergency: 2	8	5
	S3	2120	N/A	3790	4470	8710	180	interior: 2 outdoor: 2 emergency: 2	8	6
L4	**S1**	2200	N/A	1800	1200	5200	90	interior: 7	8	3
	S2	2200	N/A	1800	1200	5200	90	interior: 4 emergency: 1	3	3
	S3	2200	N/A	1800	1200	5200	90	interior: 2 outdoor: 1 emergency: 2	1	6
	S4	2200	N/A	1800	1200	5200	90	interior: 4 outdoor: 1 emergency: 1	7	5

In this research to be able to make a proper comparison, it was aimed to have the related cases in the same province. In addition, the variety of cases has been increased by choosing Istanbul, which has the largest urban rail system network in

Turkey and is continuing and planning related projects in this context. In summary, 4 metro lines and a total of 18 metro stations on these urban railway systems located in Istanbul Turkey are evaluated as cases for this thesis. By comparing these cases based on separate strategic development plans with the different design, management, construction, and operation & maintenance methods, it is aimed to generate a reliable benchmark for the EC of the urban railway systems for both Istanbul and Turkey. Moreover, secondary motivation is to be able to complete the related gaps in the literature.

3.1.3 Material Distribution

The materials focused on in this study were determined in line with the mostly used components used in Urban Railway Systems of Turkey. Mostly used materials were primarily analyzed and categorized in the scope of the Uniformat Class Level. The aggregation logic of the components is classified as the Uniformat Level as shown in Figure 8.

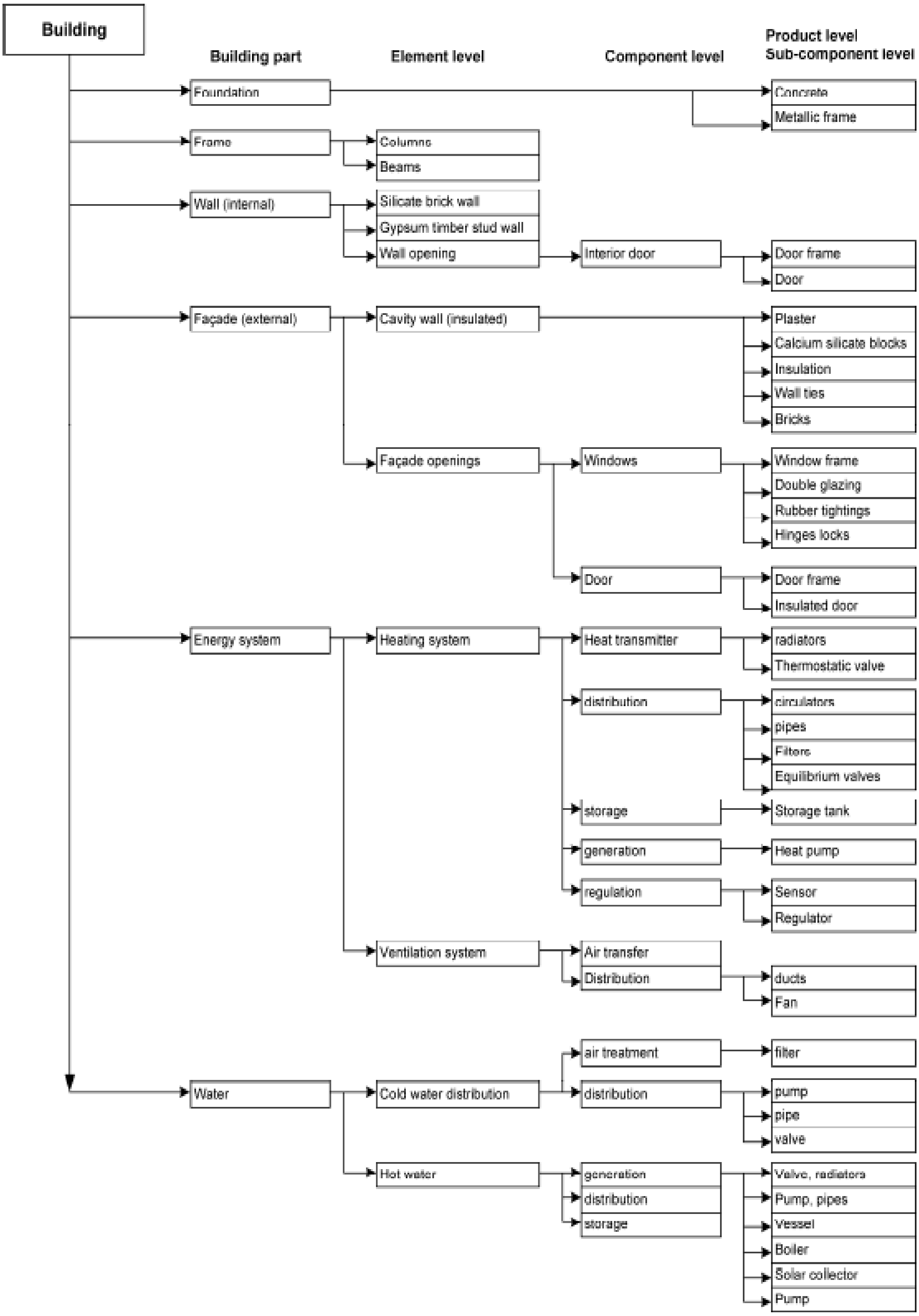

Figure 8. Aggregation Logic of the Components.

In this study, materials were categorized for evaluation and comparisons in order to make homogeneous comparisons due to the complexity of urban railway systems. Accordingly, the most used and high-impact materials given below were selected for the calculations. Related components are given below. Each material category was analyzed according to its performance, location, and specifications such as the manufacturer's name and product description. The Environmental Product Declaration (EPD) of the materials has been checked for carbon footprint calculations and if there is no EPD the value is collected from similar products. For these calculations, the quantity list is calculated and classified using the Uniformat system. This classification system is presented in detail in the Table 3.

- Reinforced Concrete,
- Concrete,
- Steel,
- Wood,
- Granite,
- Terrazzo,
- Brick,
- Glass Fiber Reinforced Concrete,
- Plaster,
- Paint,
- Glass,
- Laminated Glass,
- Aluminum,
- Galvanized Steel,
- Insulation,
- Gypsum,
- Carpet,
- Ceramic Tiles and Ceiling Tiles,
- Epoxy,
- PVC,

To achieve a common understanding in calculations, working limits were determined by referring to local and internationally approved standards, and it was aimed to simplify the work and make the same calculation by meeting with experts in this process. With the guidance of practitioners, applicable data, and methods regarding the use of materials applied in National and International Standards were processed and the same detail was brought together. At the same time, in calculations, the Uniformat II classification as shown in the Table 4 was used to make a presentation to be made in the world language while it is being processed.

Table 4. ASTM Uniformat II Classification for Building Elements (E1557-97).

Level 1 Major Group Elements	Level 2 Group Elements	Level 3 Individual Elements
A SUBSTRUCTURE	A10 Foundations	A1010 Standard Foundations A1020 Special Foundations A1030 Slab on Grade
	A20 Basement Construction	A2010 Basement Excavation A2020 Basement Walls
B SHELL	B10 Superstructure	B1010 Floor Construction B1020 Roof Construction
	B20 Exterior Enclosure	B2010 Exterior Walls B2020 Exterior Windows B2030 Exterior Doors
	B30 Roofing	B3010 Roof Coverings B3020 Roof Openings
C INTERIORS	C10 Interior Construction	C1010 Partitions C1020 Interior Doors C1030 Fittings
	C20 Stairs	C2010 Stair Construction C2020 Stair Finishes
	C30 Interior Finishes	C3010 Wall Finishes C3020 Floor Finishes C3030 Ceiling Finishes
D SERVICES	D10 Conveying	D1010 Elevators & Lifts D1020 Escalators & Moving Walks D1090 Other Conveying Systems
	D20 Plumbing	D2010 Plumbing Fixtures D2020 Domestic Water Distribution D2030 Sanitary Waste D2040 Rainwater Drainage D2090 Other Plumbing Systems
	D30 HVAC	D3010 Energy Supply D3020 Heat Generating Systems D3030 Cooling Generating Systems D3040 Distribution Systems D3050 Terminal & Package Units D3060 Controls & Instrumentation D3070 Systems Testing & Balancing D3090 Other HVAC Systems & Equipment
	D40 Fire Protection	D4010 Sprinklers D4020 Standpipes D4030 Fire Protection Specialties D4090 Other Fire Protection Systems
	D50 Electrical	D5010 Electrical Service & Distribution D5020 Lighting and Branch Wiring D5030 Communications & Security D5090 Other Electrical Systems
E EQUIPMENT & FURNISHINGS	E10 Equipment	E1010 Commercial Equipment E1020 Institutional Equipment E1030 Vehicular Equipment E1090 Other Equipment
	E20 Furnishings	E2010 Fixed Furnishings E2020 Movable Furnishings
F SPECIAL CONSTRUCTION & DEMOLITION	F10 Special Construction	F1010 Special Structures F1020 Integrated Construction F1030 Special Construction Systems F1040 Special Facilities F1050 Special Controls and Instrumentation
	F20 Selective Building Demolition	F2010 Building Elements Demolition F2020 Hazardous Components Abatement

3.2 Research Methodology

Efforts to reduce carbon dioxide emissions are crucial to controlling global warming potential (GWP). Achieving the reduction of EC is a complex process that requires a comprehensive method such as LCA. With the LCA method, ISO 14040 and EN 15978 standards are followed for this research. The study assumed a lifespan of 100 years for the facilities of railway systems. Basically, EC of each station and line was analyzed.

3.2.1 Stages of Work

The research is carried out under the following sections:

- **Analysis of the Lines:** The lines to be worked on were discussed with the experts of the subject and selected to obtain a broad perspective.
- **Decision of the Methodology:** Drawing boundaries for through LCA methodology. Determination of the LCA scope A1 – A3.
- **Creating the Bill of Quantities for the Selected Lines:** Drawings and solutions of line and station projects were studied. Project details were confirmed by meeting with relevant experts.
- **Organization of the BoQ Tables:** Project related data (e.g., bill of quantities of each line) were organized using a common computing environment called MS Excel®. Spreadsheet templates were prepared because of discussions with experts. The material codes of Uniformat Class and the Ministry of Environment and Urbanization were grouped. Prepared calculations were tabulated using the Uniformat Classification system.
- **Analyzing the BoQ Tables to Identify the GWP of Metro Lines:** After sorting, calculating, and grouping, special quantity studies were carried out on each line and station. The effect values of the materials used were investigated and EPD documents were obtained. The EPD documents of the relevant materials were accessed. Calculations were finalized by verification

and evaluation. LCA method was used through the A1-A3 scope (product stage). Detailed methodology was discussed under Section 3.2.5. Excel was used for calculations.

- **Identification of the Embodied Carbon for Projects based on Material Quantifications:** Calculations were verified and validated. Detailed methodology was discussed under Section 3.2.5. The documents were confirmed and the impact value coefficient and the material quantity from the relevant unit were multiplied to arrive at the GWP in accordance with the calculation method described in the methodology. The resulting values were verified and checked with experts.13. GWP results were achieved based on stations and lines. The results obtained were compared both within the lines and between each other. Since there is no one-to-one scope and focus on the literature, a comparison could not be made, but a range of values was found.

3.2.2 Life Cycle Assessment

The International Organization for Standardization (ISO 14040, 2006) described life cycle assessment (LCA) as “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle”. LCA contains the whole life cycle of a product/material from extraction to its demolition. It is a scientific method to measure the environmental footprint of materials, products, and services during the life span of the project (Athena SMI, 2016). LCA comprises four stages that are; goal and scope, inventory analysis, impact assessment, and interpretation, following ISO 14040 and ISO 14044 (Y. Dong et al., 2018).

LCA has the potential to transform the progress of the project design phases and initial decisions. Moreover, providing quantified data is wieldier by using the system boundary of LCA. The data includes environmental impacts such as global warming, ozone depletion, land/water acidification, eutrophication, tropospheric ozone, and nonrenewable energy use (US Green Building Council 2011).

An LCA process typically involves four different phases: definition of goals and scope, inventory creation, impact assessment, and results from interpretation. A systematic approach as can be seen in Figure 9, is built for LCA as a part of the Environmental Management by virtue of Environmental Product Declarations (EPD) and Product Category Rules (PCR). While performing ISO assumptions are included in the LCA method, it also deals with Product Category Rules (PCR) developed by the International Environmental Product Declarations (EPD) System. An EPD declares the environmental impacts of a product over its expected life, and it should be third-party verified and made public upon completion. An EPD and the respective PCR should be compliant with ISO 14025 in their entirety. Product Category Rules (PCRs) are guidelines that define industry-specific measurements for the purpose of producing an EPD. PCRs provide the structure needed to report the results of EPDs and are typically developed with the input of the industry trade organizations which the PCR covers (Carbon Leadership Forum, 2021).

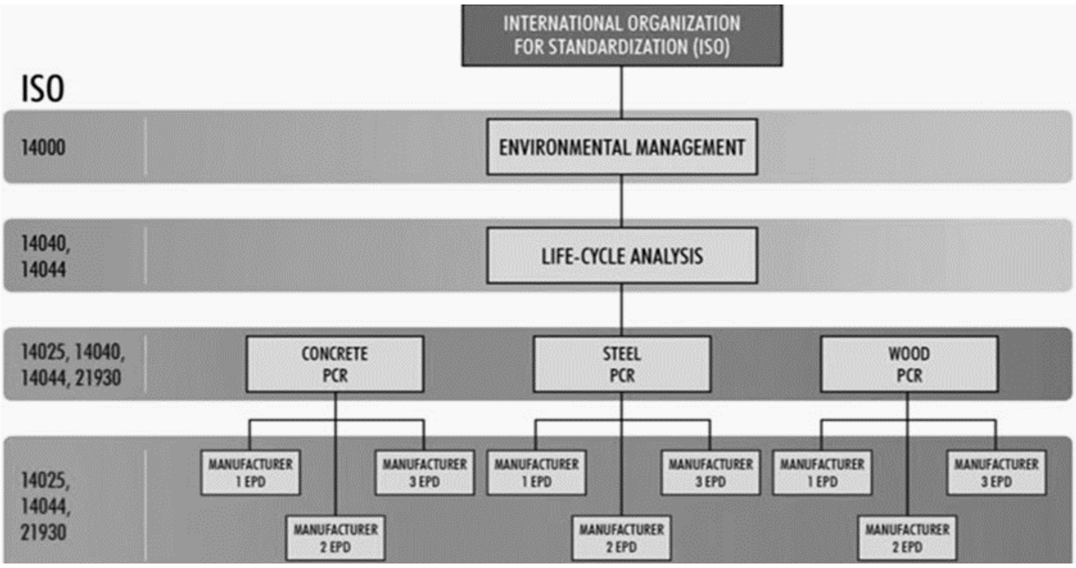

Figure 9. Relationships between ISO Standards, LCA, PCRs, and EPDs (Embodied Carbon in Buildings, 2018).

While performing ISO assumptions are included in the LCA method, it also deals with PCR developed by the EPD System. To tackle climate change, the carbon footprint methodology became the preferred tool for sustainable decision-making framework (Wright et al., 2011).

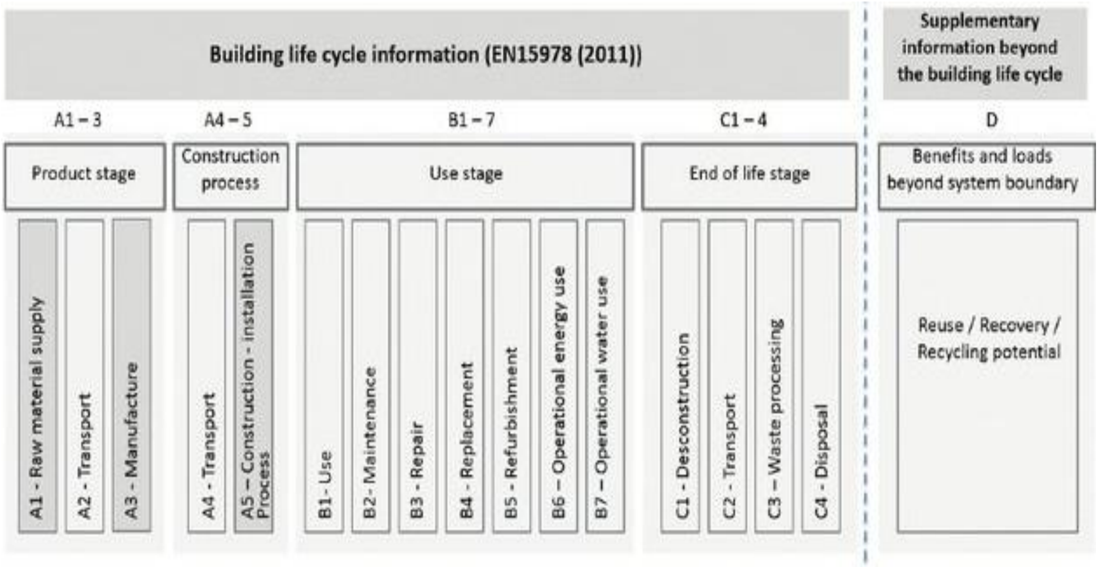

Figure 10. Building Life Cycle stages (BS EN 15978, 2011).

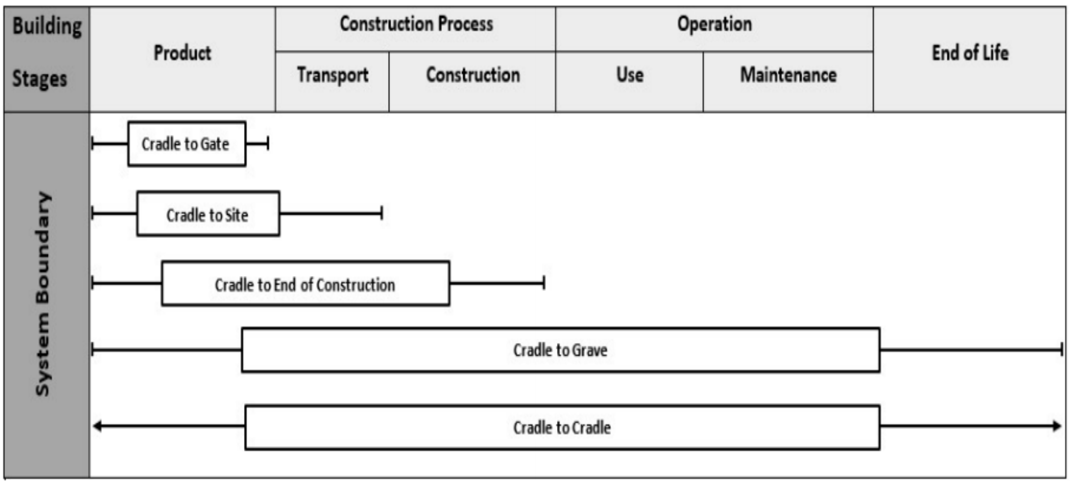

Figure 11. Summary of the process of establishing cradle-to-gate embodied carbon factor (RICS, 2012).

Cradle-to-gate (A1 - A3)

Materials or merchandise manufacture cradle-to-gate emissions are those associated with the production of building products/materials. The emissions arise from the power used in extracting materials, refining them (i.e., primary manufacture), transporting and processing them to produce a completed product (i.e., secondary manufacture). The CO_2 emissions resulting from these processes are often referred to as embodied carbon (RICS, 2012).

Included in cradle-to-site and cradle-to-end of construction (A1-A3, A4-A5)

Emissions from the building phase encompass energy and fuel consumption during transportation of material to the website online (cradle-to-site), as properly as enabling works, remediation, clearance, removal/ demolition of existing structures, ground improvements, earthworks, assembly (cradle-to-end of construction). The use of carbon emissions from the construction includes operations emissions resulting from energy fed on for heating, lighting, ventilation, air conditioning, etc. These are typically accountable for around 75 percent of the lifestyles cycle of carbon emissions (RICS, 2012). The actual parent will be closely influenced by using occupier behavior as properly as with the aid of the building type. Emissions related with this segment are normally estimated via mechanical engineers who use software applications designed to calculate operational impacts. There will also be extra embodied carbon bobbing up from maintenance, repair, replacements, and refurbishments of building elements (e.g., fabric or services). Life cycle experts will be capable of suggesting predictions of lifespans of buildings elements.

Included in cradle-to-grave (A1-A3, A4-A5, B1-B7, C1-C4)

End of existence emissions is those associated with power fed on at some stage in building demolition and waste disposal processes. However, unless a planned deconstruction is scheduled it is cautioned that these influences are no longer assessed as a section of the project’s emissions. Demolition emissions are greatly assessed at the beginning of the life cycle as a section of the emissions related to the new building (RICS, 2012).

Included in cradle-to-cradle

Module D quantifies the carbon influences beyond the constructing life cycle emissions. It acknowledges the ‘design for reuse and recycling’ concept as it approves to display the benefits resulting from reuse, recycling, and energy recovery.

In the light of this research, the architecture engineering and construction (AEC) industry mostly working with infrastructure projects may have the opportunity to identify embodied carbon and relatively environmental impacts even in the early phase of the design. To have an average of embodied carbon dioxide, 4 metro lines including 18 stations were surveyed. Since there is no reliable study or database for this study, a project-based assessment approach is used (De Wolf, 2017). Accordingly, the analysis includes two primary variables: Bill of quantities (BoQ: expressed in $kg_{material}/m^2$) and embodied carbon dioxide coefficient (ECC: expressed in $kg_{CO_2}/kg_{material}$). The embodied carbon dioxide of the stations is attained by multiplying both variables which indicates the global warming potential (GWP, measured in $kg_{CO_2\text{-eq}} / m^2$) of the station.

- $$\mathbf{GWP_{station} = \sum N_{material_{i=1}} (BoQ_{material_i} \times ECC_{material_i})}$$ (2)

This approach provides a GWP result directly. While efforts and discussions are continuing ECCs, the results of this study may base the embodied carbon dioxide of stations.

In this research, first, station information is collected and the BoQs are prepared. Then, cradle-to-gate ECCs are obtained to calculate the result of GWP for the projects. With this approach, it is aimed to have more accurate and transparent GWP consequences to have comparison opportunities. Moreover, normalizing the quantities and results provide a clearer picture even for further assessments.

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[2] GWP Calculation Formula

For this thesis, the assessments required data were provided by both industry and the academy. From professional side, EPC Contractor shared the information about those metro lines. The updated literature raises the embodied carbon consciousness yet also pointed that there is not just one simple solution for it. At the beginning of this study, after comparing 4 metro lines in Istanbul, clear results were expected. In progress, it turned out that the data collected was more complex than that and simplification was necessary.

Even being able to compare lines, stations, and designs were challenging due to the type of data that had to be processed. Since these projects were carried out with several different stakeholders, these projects could not be completely compared in terms of management.

3.2.3 Embodied Carbon Assessment

For a reliable study, the embodied carbon emissions need to be considered from the national and regional carbon perspective. Assessment of whole life carbon should meet best practice targets for embodied carbon of materials. The embodied carbon refers to the upfront emissions correlated with the construction, including the extraction and processing of materials and energy and water consumption in the production, assembly, and construction of the project. Besides, it includes the 'in-use' stage (the maintenance, replacement, and emissions associated with refrigerant leakage) and the 'end of life' stage (demolition, disassembly, and disposal of any parts of product or structure) and any transportation relating to the aforementioned.

There is a lack of knowledge in the infrastructure industry surrounding embodied carbon reduction strategies and calculations, and the carbon verification of the materials. Therefore, there is an urgent need for a region-based framework in the form of a benchmark of EC of the materials. When the database is insufficient at the regional level for calculating the embodied carbon of material, a whole life cycle assessment might be required for the sensitivity. In this study, a consistent methodology is embraced and a dataset for embodied and whole life carbon analysis was chosen Life Cycle Stages of EN 15978. For calculation of the phase of the life cycle of materials, the mandatory requirement of EPDs were referenced from the Turkish Construction Material Database (TurComDat[3]) that is region oriented.

[3] TurComDat is an LCA database for Turkish construction materials. The data sets follow the international standards and norms and formatted to be used in building environmental performance assessments. It is developed to address the need for measurability of the environmental performance of buildings. Every data set includes 24 environmental impacts from carbon to energy at each life cycle stage of the product. Most of the data sets are independently third-party verified by international experts and the rest is by the Academic Committee of The Turkish Centre for Sustainable Production, Research and Design called SÜRATAM.

CHAPTER 4

RESULTS

4.1 Introduction

In this chapter, results of embodied carbon assessment of case studies are presented in three levels as component, station and line. Also, stations in case projects were evaluated. The environmental impacts of the components were analyzed as embodied carbon of stations and lines during the products' life cycle. Concluding the chapter, the results are interpreted, and the obtained benchmark is given.

4.1.1 Background of the Case Studies

The embodied carbon analysis was taken as a reference in 4 urban railway projects according to the EPD certificate of each product.

Results were prepared in three levels:

- component,
- station,
- line,

GWP values were calculated in terms of total and kgCO_2-eq/m^2 at the three levels determined above. Statistical analyzes were made at the project and component levels. The results were compared with the relevant database and studies in the literature to measure validity.

Categorization of the railway system components has been assembled by adopting the Uniformat-II classification system. Listing of components for detailed analyses was prepared in line with the bill of quantities of each project. A little amount of the components of the station that had low embodied carbon per unit and low quantity in the project were eliminated as their impact on the overall outcome was considered insignificant. The list of components for the embodied carbon analyses includes 31 different components. The methodology and data sources utilized for the analyses for station components were given in Chapter 3. The embodied carbon of each component was calculated on a per kilogram basis (kgCO_2-eq/kg). Results can be seen in Table 5.

Table 5. List of building components chosen for CFP calculations.

Construction Cluster	Construction Component	Material	Component ID	Unit	Environmental Impact – GWP ($kgCO_2$-eq/kg)			
					L1	L2	L3	L4
Structure	**Tunnel & Station**	Reinforced Concrete	Y.16.050/16	ton	0.92	1.13	1.13	0.92
		Reinforcement Steel	Y.23.101	ton	1.25	1.49	1.49	1.25
		Water Insulation	Y.18.461/006	m2	1.73	1.73	1.73	1.73
Basement	**Tunnel & Station**	Foundation Concrete	Y.16.050/15	ton	0.92	1.13	1.13	0.92
		Foundation Reinforcement Steel	Y.23.101	ton	1.25	1.49	1.49	1.25
		Basement Water Proofing	Y.18.461/005	m2	1.73	1.73	1.73	1.73
		Levelling Concrete	Y.27.581/A	ton	0.92	1.13	1.13	0.92
Walls	**Station & Rooms**	Brick Wall 10 cm	Y.18.001/C12	kg	15.64	15.64	15.64	15.64
		Brick Wall 20 cm	Y.18.001/C16	kg	15.64	15.64	15.64	15.64
		Plaster	Y.27.501/02	kg	0.48	0.10	0.10	0.48
		Paint	Y.25.004/04	kg	2.00	1.80	1.80	2.00
		Ceramic Wall Tile 30x30 cm	Y.26.008/304B	m2	20.54	13.72	25.04	13.51
		Ceramic Wall Tile 30x60 cm	Y.26.008/310B	m2	20.54	13.72	25.04	13.51
		Granite Ceramic Wall	1.1.2.1.3	m2	18.92	not used	25.04	13.51
		GFRC Wall Panels	N/A	m2	3.08	not used	3.08	3.08
		Laminated Glass Wall	06.645/21B	kg	13.85	9.36	9.36	13.85
Floors	**Station & Rooms**	Granite	Y.26.020/311A-A	m2	18.92	18.92	18.92	18.92
		PVC Floor	Y.25.116/A03	kg	1.35	1.35	1.35	1.35
		Granite Terrazo	Y.26.015/013	m2	18.92	18.92	18.92	18.92
		Ceramic Floor	Y.26.008/305A	m2	14.40	8.20	26.10	10.17
		Epoxy Floor	Y.19.090/003-A	kg	2.60	2.60	2.60	2.60
		Cement Based Waterproof	Y.19.085/025	kg	0.12	2.49	2.49	0.12
		Surface Hardened Concrete	Y.19.090/001A	kg	0.12	2.49	2.49	0.12
		Granite Ceramic Floor	1.1.2.2.9	m2	18.92	not used	not used	18.92
Ceilings	**Station & Rooms**	Galvanized Steel	23.243/27	ton	2.30	1.43	1.43	2.30
		Skylight Glass	04.645/24D	m2	not used	not used	33.64	not used
		Aluminum Ceiling	23.243/3	m2	20.30	21.00	21.00	20.30
		Ceiling Paint	Y.27.503/14	kg	0.10	0.10	2.20	0.10
Doors	**Rooms**	Fire Proof Door	N/A	p	36.50	36.50	36.50	36.50
		Galvanized Door	N/A	p	11.80	11.80	11.80	11.80
		Laminated Door	Y.22.009/03	p	23.00	23.00	23.00	23.00

4.1.2 Station Level

Following the analysis of the components, the total environmental impacts of 18 stations in 4 case projects were evaluated. The GWP per kg or m2 were calculated in the previous section was multiplied by each component of the cases' detailed BoQs in order to identify the total environmental impact at the station level.

Results can be seen in Figure 12 below.

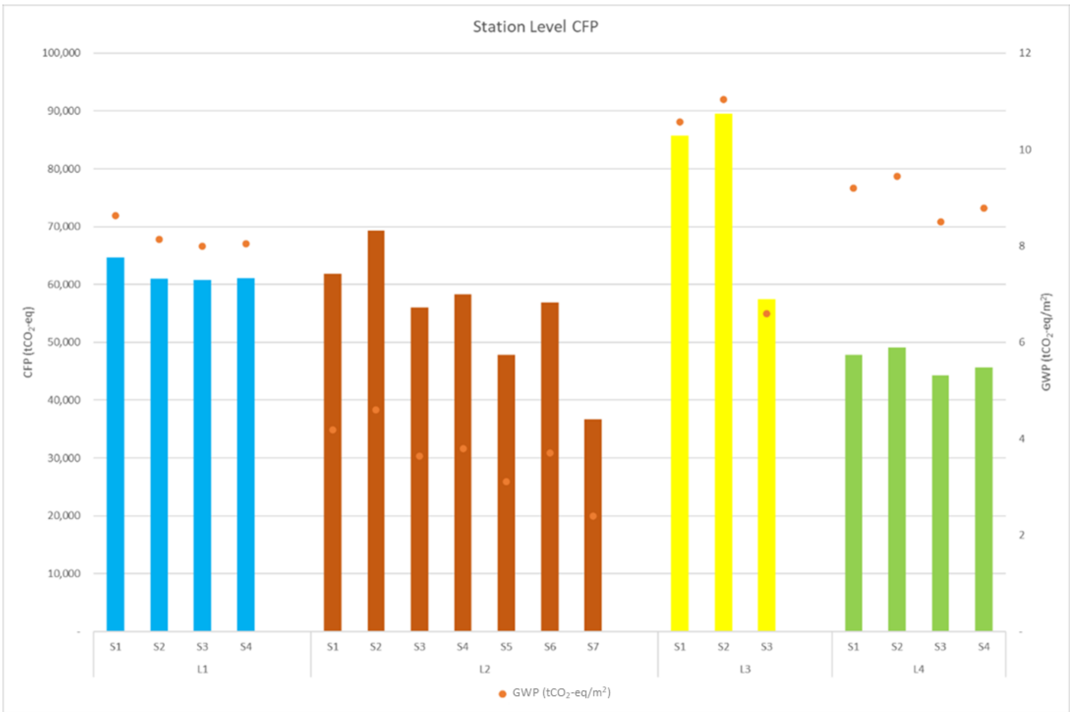

Figure 12. Figure. Station Level CFP & GWP Calculations.

Total CFP of all the railway stations is ranged between 36,734.47 tCO_2-eq and 89,551.80 tCO_2-eq with the average of 58,557.58 tCO_2-eq. The GWPs of the stations is ranged between 2,4 tCO_2-eq/m^2 and 11,04 tCO_2-eq/m^2 with the average of 6,8 tCO_2-eq/m^2.

4.1.3 Line Level

Following the analysis of the stations, the total environmental impacts of 4 case lines including 18 metro projects were evaluated. The GWP per kg or m^2 were calculated in the previous section was reflected as total of the cases' detailed BoQs in order to identify the total environmental impact at the line level.

Results can be seen in Figure 13 below.

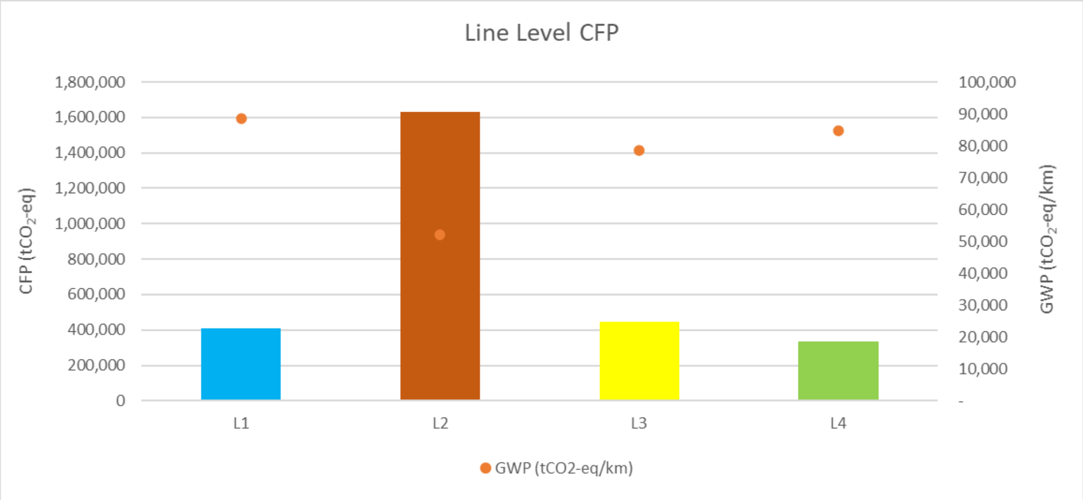

Figure 13. Line Level CFP & GWP Calculations.

Total CFP of all the lines is ranged between 336,897.58 tCO_2-eq and 1,630,278.09 tCO_2-eq with the average of 705,261 tCO_2-eq. The GWPs of the lines is ranged between 52,152 tCO_2-eq/km and 88,634 tCO_2-eq/km with the average of 75,991 tCO_2-eq/km.

4.2 Evaluation of Case Projects

Abovementioned ranges compromise the first steps for benchmarking the environmental impact of railway systems. The survey of metro stations reveals the concrete steel and PVC materials have higher material usage and environmental impacts, whereas ceramic and terrazzo materials have lower weights.

These results prove that the best way to lower the EC of railway projects is a case-by-case analysis. Conducive, architects, and engineers have more responsibility to achieve sustainable design goals.

4.3 Findings

Based on the material in the lines, the capital carbon was calculated by the embodied carbon of the component level. However, it has been discovered that making an assessment by only looking at the capital carbon will not give an adequate result, especially in terms of tunneling. Because the main issue in tunnels is the construction method and its adaptation to the project, as it is frequently emphasized in the literature. Since each line is evaluated within itself, it would be misleading to look only at the concrete quantity and impact assessment. In order to obtain a healthier result in later studies, the construction phase must be taken into account.

There are many reasons why stations are so different within themselves. The reasons for this were discussed with engineers and architects who are experts in rail systems. Case Studies are mostly typical projects. Among the typical solutions, different solutions were preferred. Since such infrastructure projects require interdisciplinary effort, a framework should be drawn in line with the impact parameters. The parameters in the processes to be considered can be summarized as follows throughout the project life cycle:

- **Planning Phase:**
    - Program Requirements,
    - Function expectation,
    - Purpose of usage,
    - Project area analysis,
    - Project scope Assessment,
    - Public Permissions,
    - Standards and regulations,

    - Expectations of the project owner administration (i.e., for example, the special design condition can be asked especially in terms of energy efficiency and innovation).
    - Expectations from the project as part of program management,
    - Expectations in terms of innovation and technological contributions of the project,
    - The project firm and the contractor companies that handled the project,
- **Design Phase:**
    - Construction Method,
    - Date and Timeline of the construction,
    - Time Schedule of the Project,
    - Budget of the Project,
    - Quality of Experts,
    - Criteria for material selection,
    - Expectations of the project owner administration (i.e., for example, the special design condition can be asked especially in terms of energy efficiency and innovation)
- **Construction and Operation Phase:**
    - The suitability of the construction site during the construction and operation process,
    - Material selection and supply,
    - Authorities in the design and construction phase of the project,
    - Monitoring and Reporting the Process.

The situation shows that all stakeholders and experts of the relevant project have a share in the carbon footprint with different effects. Especially in infrastructure projects, as the project becomes more complex and is handled in different ways with the main decision mechanisms such as the vision of the city and the view of the management, the parameter increases, and the range of influence expands. In this case, it is not enough for designers and engineers to be conscious. This awareness needs to be internalized by all participants from A to Z in the project life cycle from the beginning of the project. Since such a solution will not be possible in a short time and the diversity of the participants will make it difficult to deal with the issue, at this point, the control mechanisms need to deal with the issue in a more controlled and more systematic way.

4.4 Discussion

As stated in many studies in the literature, many different disciplines need to work in detail on various parameters in order to reduce carbon emissions in infrastructure projects. In this thesis, the effect of this scope and multiplicity of parameters on the study was clearly observed. Cradle-to-gate examination of the materials, which is emphasized to have the highest carbon load in the literature, was carried out to narrow the scope. The remarkable thing in the calculations is the low carbon footprint of the Line 2. According to the study focused only on the materials of architectural and static disciplines. Because there is a serious difference between tunnel and cut-and-cover methods. It is also mentioned in the literature that the amount of carbon consumed for the tunnel is 27 times more than the cut-and-cover method.

The aim of this thesis is to contribute to a national database and to be a roadmap for further studies. It is not possible to take a project-based reference of the carried out work because the scope is limited to verifiable and accessible information and documents. However, the points to be studied are given in the Chapter 5 of the thesis and further issues are mentioned to be discussed.

As a result, it has been reached that an urban rail system project in Turkey can be compared on station basis and in architectural and static scope, construction materials can be compared within the scope of A1-A3. Based on these further studies, it has become a reference that can be studied within the same scope. A discussion on how and what factors should be evaluated for further studies is also discussed in the last section.

CHAPTER 5

CONCLUSION

5.1 Introduction

In this chapter, LCA methodology applied for the case studies and key findings and main conclusions are presented. First, a discussion is provided with the key findings obtained from the research results. Second, strategies that would be implemented to lower embodied carbon are represented according to key findings. Then, final remarks are emphasized and it is concluded with the recommendations for future works.

Results reached in line with the objectives of this study are presented as follows:

- ***Developing a methodology for the calculation of CFP and the environmental impacts of urban railway systems in Turkey;***
  - A hybrid calculation method is proposed in the study, thus providing a benefit to assist the development of a calculation methodology for the environmental impacts of urban rail systems in Turkey.
- ***Collecting and identifying the data for the resolution of the CFP of urban railway systems in Turkey comparative with EU countries and constituting a national database for the calculation of CFP and environmental impacts of metro stations and related products in Turkey,***
  - Most of the materials have an EPD document, but it is clear that the database should not be strengthened for materials outside the scope and classification. Although there is no contribution to the creation of a national database for the calculation of CFP and environmental impacts of metro stations and related products in Turkey, this study has proven how important this is.

- ***Comparing Turkey with the case studies around the world and ultimately lowering embodied carbon of infrastructure projects,***
    - Determining the CFP of urban rail systems in Turkey for comparison with EU countries is a serious step on the subject, as it is a study that has never been done in Turkey before. At the very least, the value levels to which the next projects can be compared have emerged.

5.2 Discussion

The applied methodology provided GWP results that were comparable calculations at all levels of component, station, and line. The outputs at the relevant levels were compared both within themselves and with the studies in the literature. It was observed that both GWP values at component and building level were parallel with international examples.

According to 4 lines and 18 stations case study results there is no meaningful correlation found between carbon footprint and construction method. However, it should be noted that just like the predictive factors, it is really problematic to comment on the predicted materials here as well. The main contribution of this thesis is to draw a unified method for defining accurate EC benchmarking and calculating the GWP of stations. Comparing to the literature and tools, this study generates the basis for a more unified, basic and transparent method. This thesis is to first experiment to give ranges and specific weights of materials EC assessment of railway systems in Turkey.

This research could also arouse sustainable design developers and policymakers. According to these preliminary benchmarks and rating schemes, the low-carbon infrastructure goals can be monitored. The collective target of the study is to reach achieving a low-carbon infrastructure project. Accordingly, EC reduction strategies are indicated as follows:

- Modifying concrete properties,
- Using alternative low-carbon materials,
- Using recycling and reuse potential of materials,
- Embodied Carbon as an evaluation criteria for energy efficiency,
- Eco-labelling for construction materials.

5.3 Final Remarks

Awareness of climate change is increasing day by day among all actors in business and social life. This increasing awareness has become a kind of green transformation race, especially among commercial actors. Regardless of the sector, companies aim to be more green, clean and responsible than their competitors. At the same time, they aim to gain certain advantages over their competitors by creating a circular economy model. With these goals, companies aim to fulfill their responsibilities towards society and the world, to differentiate from their competitors, to be prepared for the future and change by maintaining their competitive power, and to have a higher brand image.

In today's commercial life, where climate change and its related effects gain great importance at the global level, a green and sustainable reputation to be gained by existing and potential customers has turned into a very important competitive tool. Climate change, which is a global crisis, concerns Turkey and the commercial actors in our country very closely. With the concrete steps it has taken recently, the European Union has compelled countries and companies to take action to adapt to climate change on green and sustainability.

EU Green Deal

The European Green Consensus, which was implemented by the European Commission in 2019 to make the EU economy environmentally sustainable, is among the developments that closely concern our country. The EU Green Deal is an inseparable whole of the Paris Agreement and the United Nations Framework

Convention, which were previously published within the scope of combating climate change. The publication of the EU Green Deal right after the COP25 was held in October 2019, in which criticism and reservations were voiced, and that the Paris Agreement did not contain adequate sanctions and did not sufficiently direct the parties to the fight against climate change, reveals this. The Constitutional Court was established to embody the aims determined by the previous regulations and to pave the way for the realization of these aims.

EU Green Deal aims to make the European continent the world's first carbon-neutral continent with zero carbon emissions by 2050 while protecting the EU's industry and employment. Although the EU Green Deal is based in Europe, it emphasizes that global change is needed to cope with climate change. Considering that the whole world is responsible for the climate change crisis, and acting with the awareness that the fight against this crisis can only be achieved with a global contribution, the EU aims to prevent "carbon leaks" and a framework compatible with climate change.

The concept of carbon leakage means that economic activities in countries with a carbon cap or tax are only repositioned, not directed towards countries without such a limit and therefore not reducing emissions. The main purpose of these regulations, which the European Union put forward to prevent this transfer, is to prevent commercial actors residing in countries like Turkey that do not impose any restrictions on their exporters and producers or that do not apply strict practices like the EU, from getting ahead of the EU.

Another critical point for our country is that the Green Deal includes provisions that require the implementation of the Paris Climate Agreement. Turkey signed the Paris Climate Agreement in 2016; however, it is the only G20 country that has not ratified the agreement due to its status as a developed country, being subject to the responsibilities imposed on these countries and not being able to receive financial aid. Although only 22 percent of the world's emissions are regulated by the carbon pricing method under the name of ETS or carbon tax mechanisms, the revenue generated by these mechanisms is estimated to be around USD 45 billion. While even a quarter of the world's emissions are not subject to these mechanisms, the fact that such a high income is obtained with the additional financial obligations envisaged raises questions such as where and for what purpose this income will be spent. In principle, the income obtained here is planned to be collected in a fund and allocated to green financing resources that will support green investments.

Green Deal Action Plan in Turkey

Since Turkey has ratified the Paris Climate Agreement recently on November, 2021; will be able to benefit from the financial support provided in this framework. COP26 is also very important as it will be the first summit to evaluate developments, improvements and failures after the signing of the Paris Climate Agreement. At this point, Turkey needs to act pragmatically and be among the leaders of this change by ratifying the Paris Climate Agreement and setting sustainable climate targets. In fact, Turkey is expected to be one of the facilitators of the process and gradually shift the use of coal-based energy sources to renewable energy.

Furthermore, the Green Deal Action Plan was published by the Turkish Ministry of Commerce on July 13th, 2021. The Plan includes Border Carbon Regulations, Green and Circular Economy, Green Finance, Clean, Economic and Safe Energy Supply, Sustainable Agriculture, Sustainable Smart Transport, Combating Climate Change, Diplomacy, European Green Consensus Information and Awareness Activities. As the next steps, the Ministry announced that the Sustainability Bond Framework, Green Bond Guide and Green Sukuk Guide will be prepared.

Innovative actions of companies on sustainability and climate change also directly affect the investment decisions of investors. Estimates and reports on companies' approaches to ESG (Environment - Social - Governance) sustainability play a very important role, especially when making long-term investment decisions. The gains to be gained by the actions that companies will take to stand out in the competition are not limited to the positive commercial reputation they will create in the eyes of consumers and investors and the positive effect of purchasing decisions. In addition to these, it should not be forgotten that companies gain very serious costs in their production processes and most importantly, they make significant contributions to the prevention of the negative effects of climate change. Making the right cost analysis in determining in which areas and through which channels carbon emissions can be reduced by companies (energy saving, transition to hydrogen, green energy tariff, the establishment of green energy production facilities, carbon capture technologies, tree planting, etc.) are very important advantages in the coming periods. provides. will provide. In addition, while planning new investments and equipment purchases, conformity assessments for green financing, focusing on ESG/ESG projects within the company, and starting reporting are other examples that we think should be consulted with financial institutions in this direction. included in the action plans.

As a result, in order to implement all these action plans, monitoring studies should be carried out on certain indicators and the current situation of companies in terms of adaptation and adaptation to climate change should be determined. The data to be obtained as a result of these monitoring activities should be evaluated in terms of companies' adaptation to climate change, setting sustainable production and economy targets, planning strategies for these targets, and managing existing and potential risks within their bodies. Integration of the capitalist order with academic studies is critical for them to implement their action plans.

To summarize, in this case, the most important part to be emphasized by the academy is that a strong cooperation should be established between the market and the academy so that the various action plans put forward by the decision mechanisms and which the market is trying to implement or are forced to implement, can be properly planned and implemented and work properly.

Green Agenda of the World

Moreover, The UK set a new target in law in April 2021 to reduce emissions by 78% by 2035. The UK's sixth Carbon Budget will, for the first time, pool the UK's share of international aviation and shipping emissions to bring the UK more than three-quarters of the way to net-zero by 2050. Government analysis reveals that the costs of action on climate change outweigh the significant benefits – reduction of pollutant emissions, as well as fuel savings, improved air quality, and increased biodiversity. The government expects the net-zero cost to continue to fall as green technology advances, industries decarbonize and private sector investment grows. Reaching net-zero will also be essential for sustainable long-term growth and therefore the health of public finances, while also creating new opportunities for the UK economy, employment, and trade, and the government's ambitious proposals are essential to seizing these opportunities. At the end of 2021, HM Treasury will publish the Net Zero Review, which plans to see how the government plans to maximize economic growth opportunities from the net-zero transition and ensure that contributions are fair among consumers, businesses, and the UK taxpayers.

Returning to Turkey again, the Capital Markets Board (CMB) now examines compliance with sustainability principles in its annual reports. In case of incompatibility; it awaits a detailed explanation of the impacts on environmental and social risk management. Reporting requirements have been disclosed to the public by the CMB through a press release. In order to ensure that the basic principles (Sustainability Principles Compliance Framework) that are expected to be disclosed while conducting Environmental, Social and Corporate Governance activities of publicly held partnerships in the Corporate Governance Communiqué numbered II-17.1 and entered into force by being published in the Official Gazette dated 3 January 2014 and numbered 28871, Corporate Governance The Communiqué on the Amendment of the Corporate Governance Communiqué, in which the necessary additions were made to the 1st and 8th articles of the Communiqué (II-17.1.a), was published in the Official Gazette and entered into force.

Position of the Thesis

Taken globally, the sustainable development goals refer to various perspectives and critical points and can be summarized under the following themes; Net Zero Energy Projects, Energy Efficiency, Low Carbon Strategies, Life Cycle Assessment, Carbon Footprint Analysis, and Circular Economy. The carbon issue, which is the common point of these issues, should be well defined and followed in production, construction, market, and commercial dimensions.

Achieving low-carbon infrusructure goals requires embodied carbon reduction of the primary materials within the scope of the project related to the project-specific baseline scenario. Researchers and practitioners should classify and assess mitigations from intentional actions concurrently with a design and construction phase to lower the total EC of the project. Indeed, selection of materials has a great importance to lower the industry baseline of EC emissions. Rules might be set at the early phase of the project for mitigation of carbon emission, an adopted principles are given below (AIA, Carbon Smart Materials Palette).

Low-Carbon Design Thinking

- Reuse existing structure,
- Recycle materials,
- Construct with lean philosophy,
- Designate materials which naturally sequester carbon,
- Mention renewable energy manufactured materials,
- Approach project with life cycle thinking,
- Analyze climate for appropriate design and materials,
- Think about carbon involvement of transportation,
- Use regional sources as much as possible,
- Set up both operational and embodied carbon performance purposes to achieve targets.

There is an urgent need for a national standard which is specified for Turkey as EN 15978 to accelerate sustainable design progress and to form a basis for comparison of the baseline assessments.

Turkey needs a legal obligation for reducing carbon emission. For a long term achievement, a developed lowering carbon strategy should be implemented for the construction industry. It is known that, since 2005, Turkey has been hosting projects that develop certificates traded in Voluntary Carbon Markets. Also, Acquis Harmonization Program (2007 - 2013) had taken to make “Regulation for Emissions Trading” in order to determine the procedures and principles for emissions trading and to harmonize the Emissions Trading Directive 2003/87/EC. One subsidiary of The Istanbul Metropolitan Municipality started to sell carbon credits for the first time. 10 thousand tons of carbon credits were sold to the British company.

One of the important ongoing projects in Turkey is the MidSEFF Carbon Market Development Support Programme. The aim of this program is to develop and encourage the participation of Turkish banks and companies in the carbon markets in Turkey and abroad. This project helps further strengthen Turkey's interest in carbon pricing and carbon markets by building capacity at three levels:

1. Support at the national level: capacity building and policy dialogue,

2. Support at the bank level: Improving the carbon market services of Turkish banks,

3. Project level support: Supporting the carbon asset development process.

To date, with the MidSEFF program 71 projects have financed worth 1.1 billion EUR and supported the installation of 1350 MW of renewable energy power. With the clean energy produced, the consumption of 1.76 million residences is met every year, and CO_2 emissions equivalent to air pollution caused by 870 thousand cars are prevented.

Another worthwhile project is the Partnership For Market Readiness Turkey Program “Shaping the Next Generation of Carbon Markets". This technical assistance program aiming at supporting developing countries which have significant importance in the global fight against climate change in their efforts to reduce greenhouse gas emission, through effective use of market-based instruments. To summarize main aims below:

- Encouraging market-based approaches in reducing greenhouse gas emissions,
- Encouraging innovative carbon pricing instruments,
- Serving as a platform for technical discussions,
- Providing innovative and collective approaches for market instruments,
- Sharing its experiences with the international community including the parties of the United Nations Framework Convention on Climate Change.

5.4 Future Work

Nowadays the role of carbon footprint becomes more and more crucial since it is widely applied in several sectors which are both governmental and nongovernmental based. In other words, to be able to achieve global sustainable development goals, it is vital to consider carbon emission values. Considering the developments in the market, carbon emissions have now become niche solutions independent of sustainability certificates in projects and have taken their place in environmental social governance reports. This progress, which takes itself one step further, naturally finds a tangible equivalent in terms of cost.

With the emergence of the carbon exchange, carbon taxes have also started to come into effect, and with these situations pointing to legal requirements, carbon emissions have become visible and recognized from all perspectives also in the market. By way of explanation, recognizing and measuring carbon and valuing it is not only limited to the environmental aspect, but it is also attractive for the market and has become an added value with the realization of the cost reduction in the advanced stages. It is promising that the developments in the market are gaining such speed.

The reduction targets in carbon emissions, which developed countries quickly put on their agenda and put into practice, are very instructive. Researches show that Turkey, unfortunately, lags behind the world in this regard as well. The main purpose of this study was to see the results of academic research on real projects and to inspire the steps that Turkey should take regarding carbon emissions.

To illustrate the ideal picture for Turkey, in order to evolve the future works on lowering carbon there are steps to be taken that can be summarized as follows:

1. Understanding the seriousness of the situation,

2. Taking a picture of Turkey’s position,

3. Generating benchmark to grasp where Turkey stands in the world,

4. Targeting exemplary countries and developing an action plan,

5. Setting short, medium, and long-term visions,

6. Checking the progress periodically,

7. Targeting even better with the developments within the progress,

8. Defining clear boundaries of complex projects through the life cycle to lower carbon,

9. Collaborating representatives from academic, industrial, and governmental authorities for a proper evaluation,

10. Learning from failures and incentivizing practitioners and users.

5.5 Further Inquiries

This research triggered many ideas and questions. Some of them can be listed as follows:

- Are infrastructure projects in Turkey, which are among the development goals and have significant investment shares in the planning of cities, integrated with a low-carbon design approach? How are the railway systems positioned between the Smart Cities and Sustainable Cities targets? Does this big picture consider which transportation system is required and how much is needed?
- How long does it take to compensate for the emission load of the projects and is this taken into account in the project planning? How is the carbon burden of

infrastructure projects evaluated? These projects also have social and economic dimensions, how is this load distribution weighted? What kind of a picture emerges when the situation before the infrastructure project is made and the situation after it is done? Simulation of real data is important in this comparison.

- Is it possible to suggest any other mixed-use of structures such as tunnels that have a very serious carbon load and cost, beyond just serving for transportation?
- Can alternatives be produced to materials that bring a serious carbon load such as concrete and steel? Or can the carbon emissions of these materials be reduced? What can be done to reduce the carbon effect in the material focus?
- How can the short, medium, and long-term targets overlap with the macro-carbon evaluations for the whole world, and then for Turkey in particular, in terms of environmental, social and economic aspects?
- What is required to establish a national database with sufficient maturity to make a sound assessment for Turkey? What kind of mechanisms are needed to work on real data, plan it and monitor it in the process? How can it be checked whether these mechanisms work? How to train experts on this subject?

Due to the nature of infrastructure projects, this study triggers many topics and disciplines to think about important points. These and similar questions can be reproduced and their derivatives can come. In fact, these questions indicate the necessity of addressing the issue from a broader perspective. It is seen that there is a need for a separate study and a serious awareness both on project basis and on the people involved in the project.

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APPENDICES

A. Urban Railway Systems

The productivity of the infrastructure projects determines the welfare level of the city at an urban scale. Therewithal, the transportation sector is the lead of infrastructure systems for the rapid improvement in metropolitan cities. As a part of the transportation network, railway systems include several areas of expertise such as metro, light rail, heavy rail, and high-speed rail. Dalkic et al. (2017) asserted that railway systems become the crucial option for intercity transportation and one of the most major carbon emitters of GHG. Farran and Zayed (2009) emphasize that metro systems are one of the most promising designs for metropolitan cities. Besides, designing metro stations is one of the most challenging and rewarding fields of practise. Andersson and Carlson (2012) emphasized that, metro is a multidisciplinary project where cooperation is needed between researchers from different disciplines with practitioners.

Toksöz and Yüksel (2019) indicated that the life cycle of a railway system is assumed to be 100 years in Turkey including the construction of infrastructure, manufacture of the train, maintenance, operation of infrastructure, and operation of the train. On the other hand, Andrade et al. (2016) considered the life cycle of the metro line as 60 years and this proves differentiation possibilities related to the country. Another point similar to this, the carbon emission weights in the different phases of the infrastructure life cycle may also differ according to jurisdiction. This situation once again emphasizes the importance of regional and project-based examinations and studies.

Railway systems, if evaluated technically can be constructed either underground or above-ground on the authority of environmental conditions railway facilities. According to the parameters several configurations are possible such as cut and cover (10 to 25m), mined (25 to 35m) and deep mined (35 to 50m), as shown in Figure 14.

It is also possible to construct mixed types in terms of requirements and restrictions of the project.

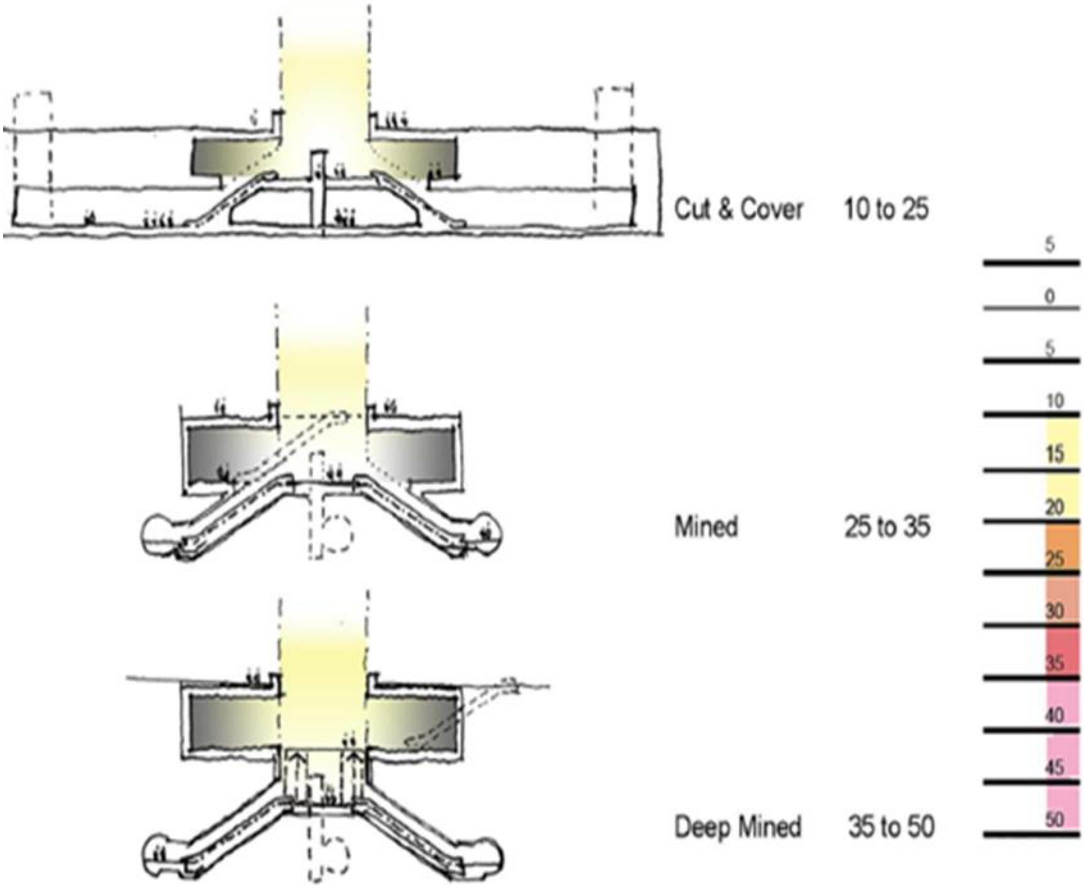

Figure 14. Railway Facility Types (Yüksel Proje - Arup, 2016).

Underground Urban Railway Systems

Underground railway systems can be classified into two variation as cut and cover type and tunnel type in terms of construction methods. There are specific parameters as land availability, depth, soil conditions and the cost estimation which defines the construction methods.

Cut and Cover Type Railway Sytems

Stripple and Uppenberg (2010) claimed that cut and cover types of structural systems can be preferred in terms of land availability and soil type. The 'cut and cover' technique is a simple construction method widely applied in railway systems that consist of excavating an open cut by applying, practically. Mostly used and typical cut and cover metro stations can be seen in Figure 15.

Figure 15. Cut and Cover Type Metro Station (Yüksel Proje, 2016).

Tunnel Type Railway Sytems

The tunnel method is preferred when the cut-and-cover method cannot be applied due to the unavailability of the soil and traffic conditions. If the depth is more than 25 meters, it is preferable to open and close the road and make the platform a deep mined tunnel. A schematic picture of the main railway tunnel is shown in Figure 16.

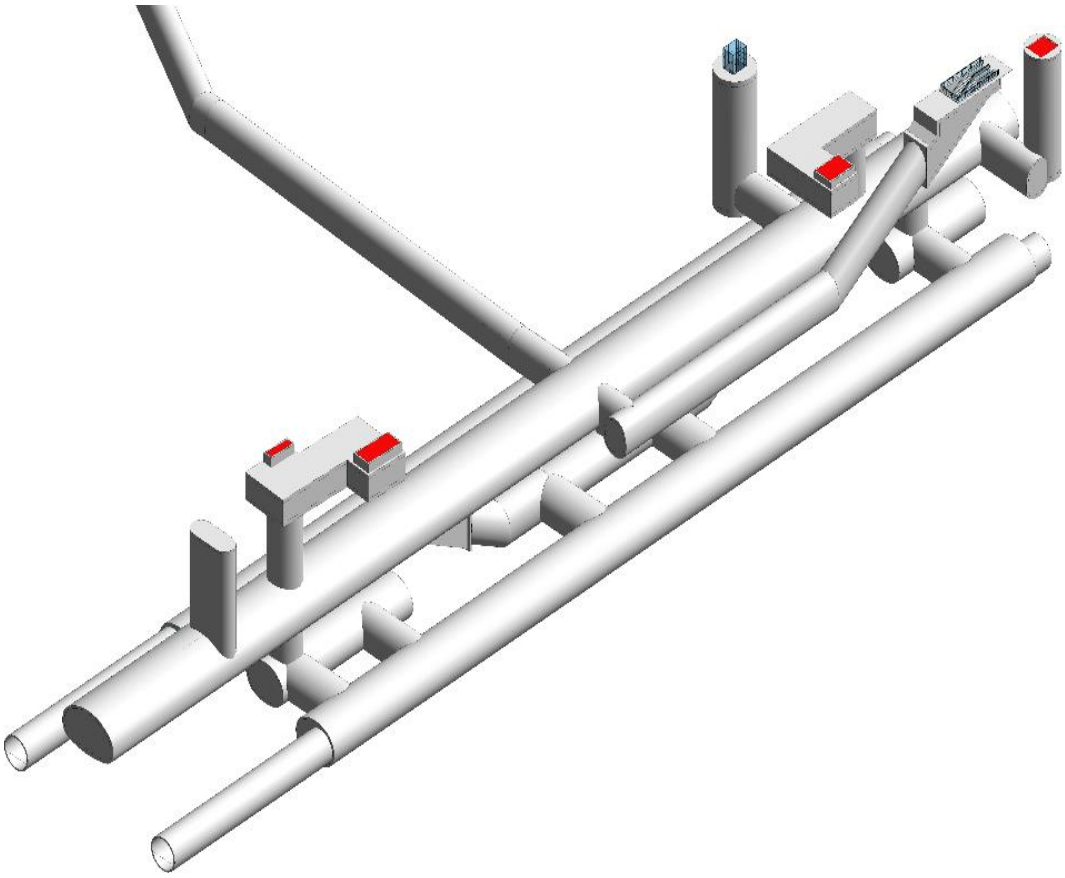

Figure 16. Tunnel Type Metro Station (Yüksel Proje, 2019).

Mixed Type Railway Sytems

When the feasibility of the project parameters and cost estimations do not meet with the same typical type of the stations, mixed type railway systems are preferred for the optimum solution. A schematic picture of the mixed type metro station is shown in Figure 17.

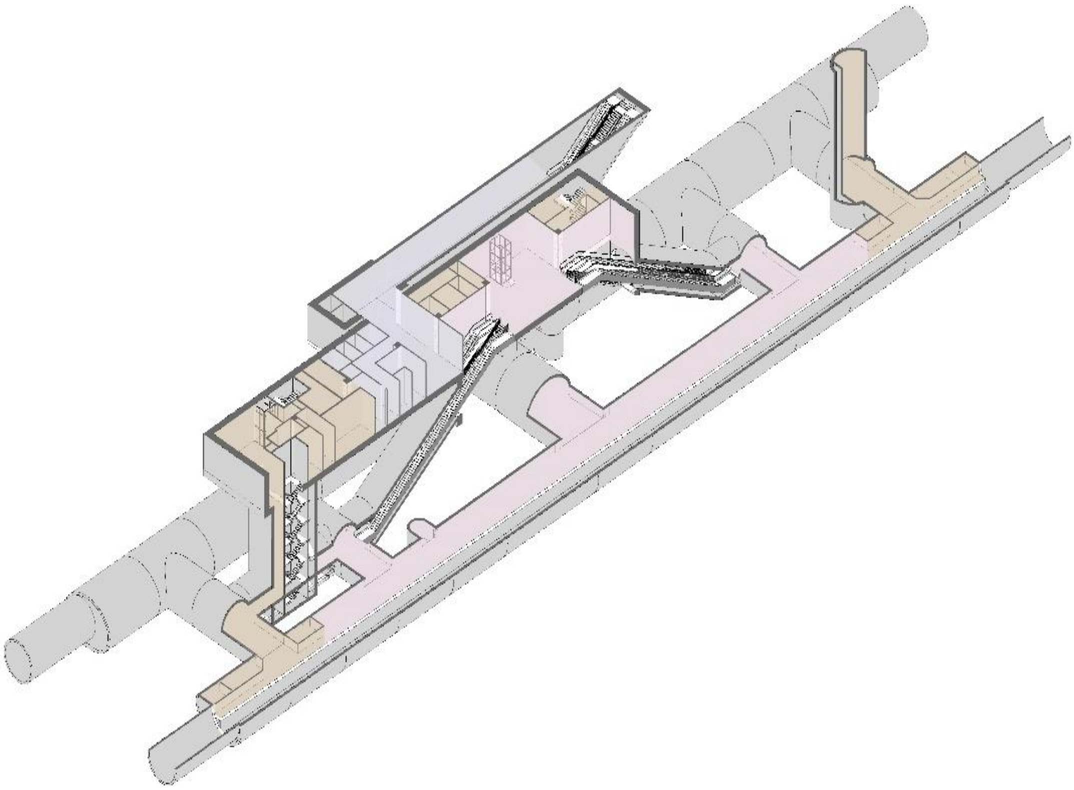

Figure 17. Mixed Type Metro Station (Yüksel Proje, 2016).

Above-Ground Urban Railway Systems

According to DLH (2011), above-ground railway facilities can be both on the same level or elevated type. Above-Ground railway facilities must include a complete drainage system, pedestrian tracking, uninterrupted cable line, traverses and ballasts, security barriers, and safety lines. Two kinds of above-ground railway facilities are shown in Figures 18 and 19, below.

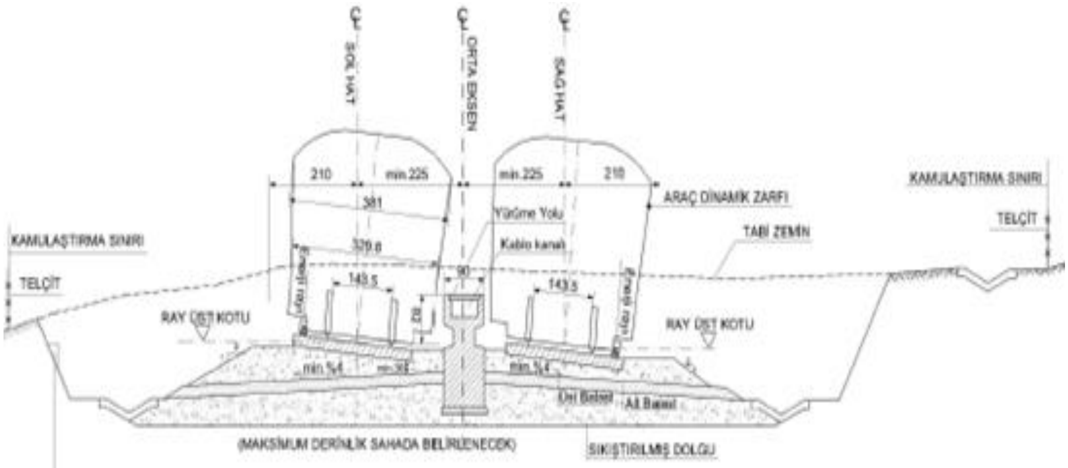

Figure 18. On the same level above-ground railway system (DLH, 2011).

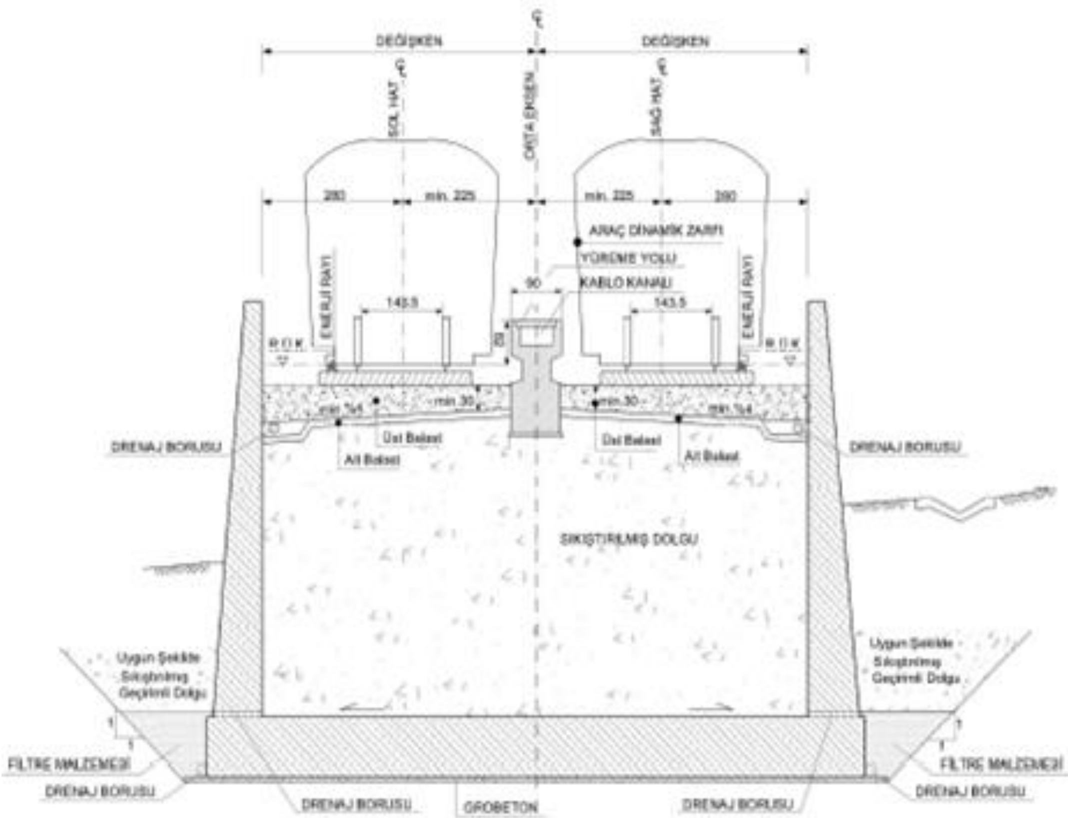

Figure 19. Elevated above-ground railway system.

Design of Metro Station

Spatial organization is crucial for metro stations because it is aimed to provide serviceable circulation even for a foreigner person. For a clear scenario it is necessary to meet the technical requirements of the station. Besides public service there are technical requirements for subway stations as well as for their own functioning structures. Main areas of station can be classified as Platform, Ticket Hole and Technical Spaces as can be seen in the Figures 20, 21, 22 below. These figures show how a generic station separated in terms of their function. There is also another classification as 'controlled' and 'uncontrolled' space that depend on use permittance of passengers.

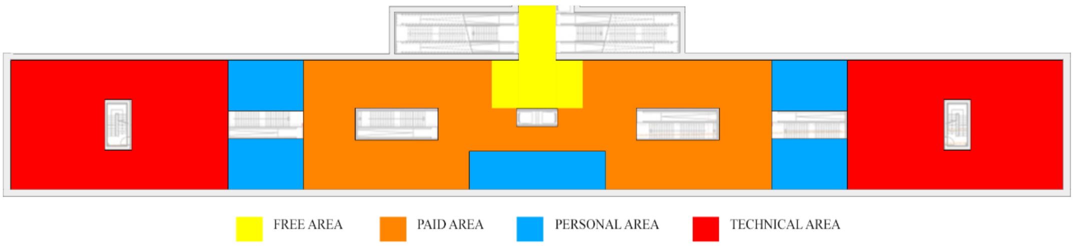

Figure 20. Ticket Hall Plan Organization (Toksöz and Yüksel, 2019).

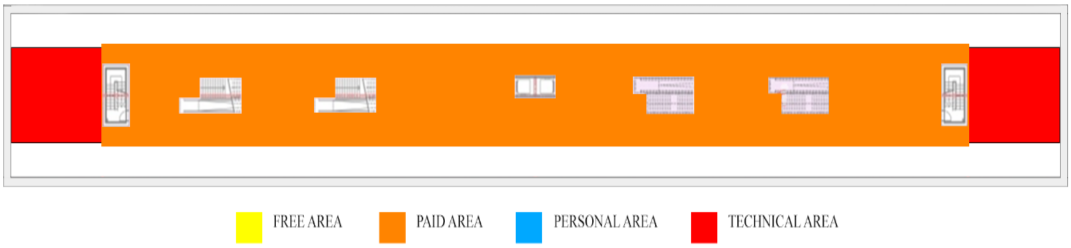

Figure 21. Platform Plan Organization.

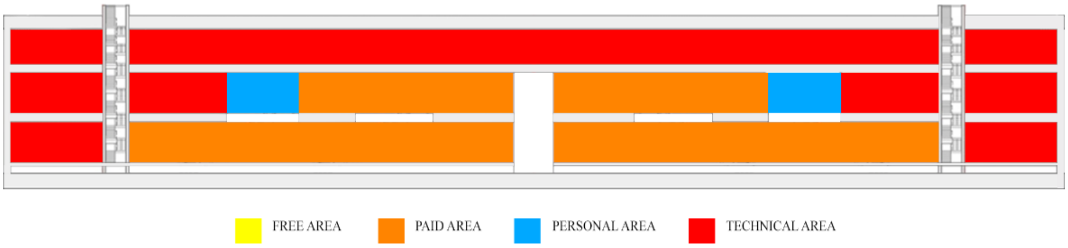

Figure 22. Section Organization.

There are certain rules and requirements for the system to use its function correctly and safely, as well as for the service of passengers. To meet these requirements, some technical spaces other than the areas used by the passengers in the stations and the places to be used by the personnel related to these places are also included in the stations. Technical spaces are evaluated under three main headings as mechanical, electrical, and electronic.

Furthermore, the significant issue is that functional integrity between stations is very important for transported passengers. The basis of the principles is the understanding of pedestrian movements. The general principle of functional design; entrance hall, ticket hall, forming the main functional parts and these functional requirements shape the organization, vertical circulation and landing emphasizes the proper arrangement can be listed as:

- Entrance,
- Ticket Pass,
- Going to platform,
- Waiting,
- Landing from Vehicle,
- Exit.

To provide technical requirements design decisions should be taken, equipment and technical offices must be provided. For a generic metro station technical rooms can be listed as:

- HV Panel Room,
- LV Panel Room,
- Transformer Room,
- Electric Panel Room,
- Escalator Panel Room,
- Tunnel Ventilation Fan Room,
- Traction Transformer Room,
- Signaling Room,
- Drainage Pump Room
- Water Tank,
- Fire Equipment Room,
- Station Ventilation Room,
- Battery Room,
- Communication Room.

In the stations which are the most important elements of the subway, the priority passengers and passengers' rooms are somehow to use the system. However, there are certain rules and requirements to ensure that passengers work in a correct and safe manner, as well as serving passengers. To meet these requirements, some technical spaces outside the areas used by the passengers at the stations and the locations to be used by the personnel related to these places are also in the stations. Following Figures 23, 24, 25 shows the functional separation of the generic metro station.

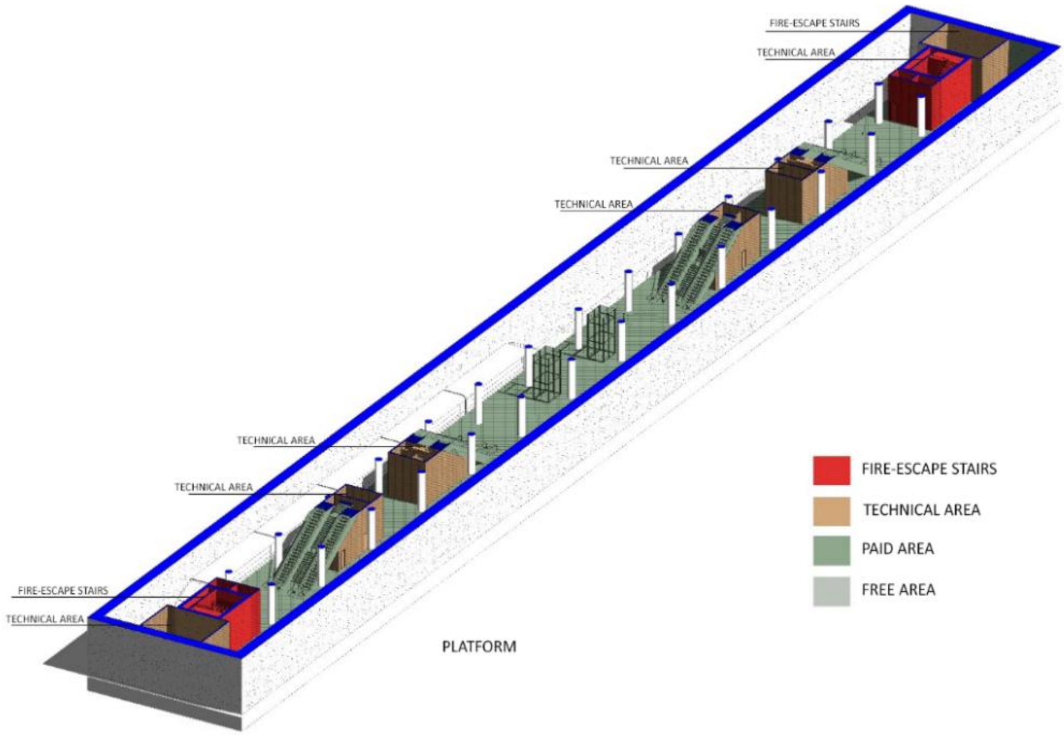

Figure 23. Functional Organization of Platform (Toksöz and Yüksel, 2019).

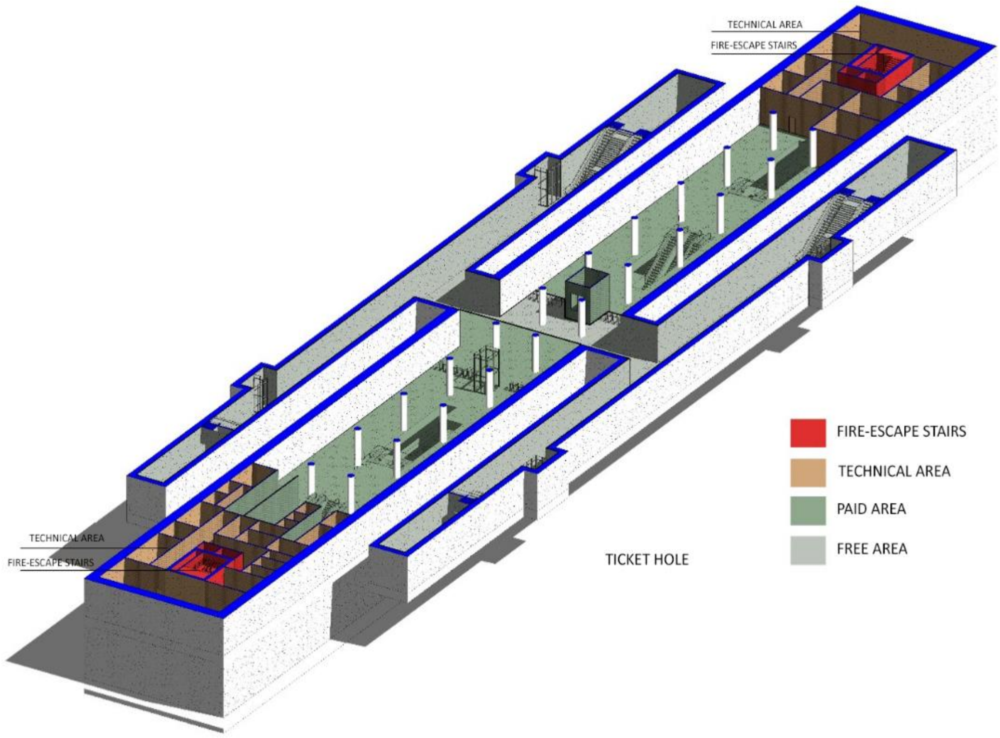

Figure 24. Functional Organization of Ticket Hole.

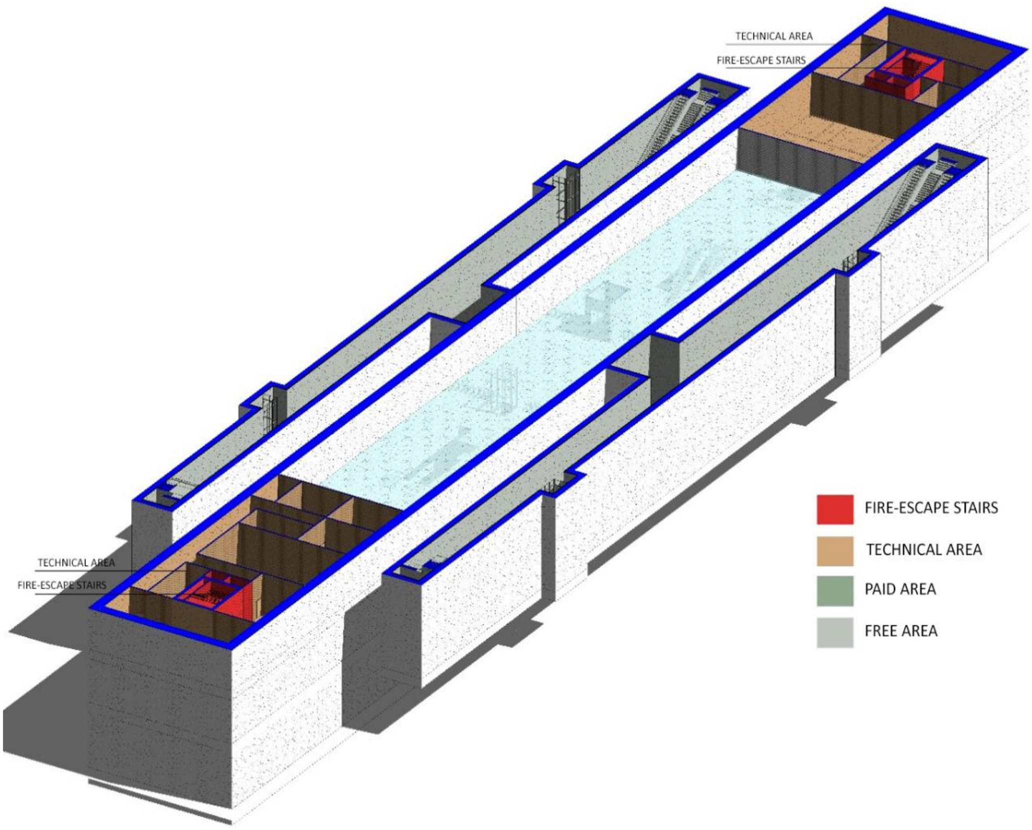

Figure 25. Functional Organization of Technical Floor.

Design of Tunnels

The state-of-the-art construction technologies will be used in the construction of the mentioned rail system line. Tunnels will be made with NATM (New Austrian Tunneling Method) and TBM (Tunnel boring machine) methods according to the requirements. Station structures, on the other hand, will be constructed with the cut-cover and top-down methods. Hence, the station and tunnel constructions are independent of each other during the construction project life cycle. All the lines included 2 methods that are TBM and NATM as shown in previous Figures 26 and 27.

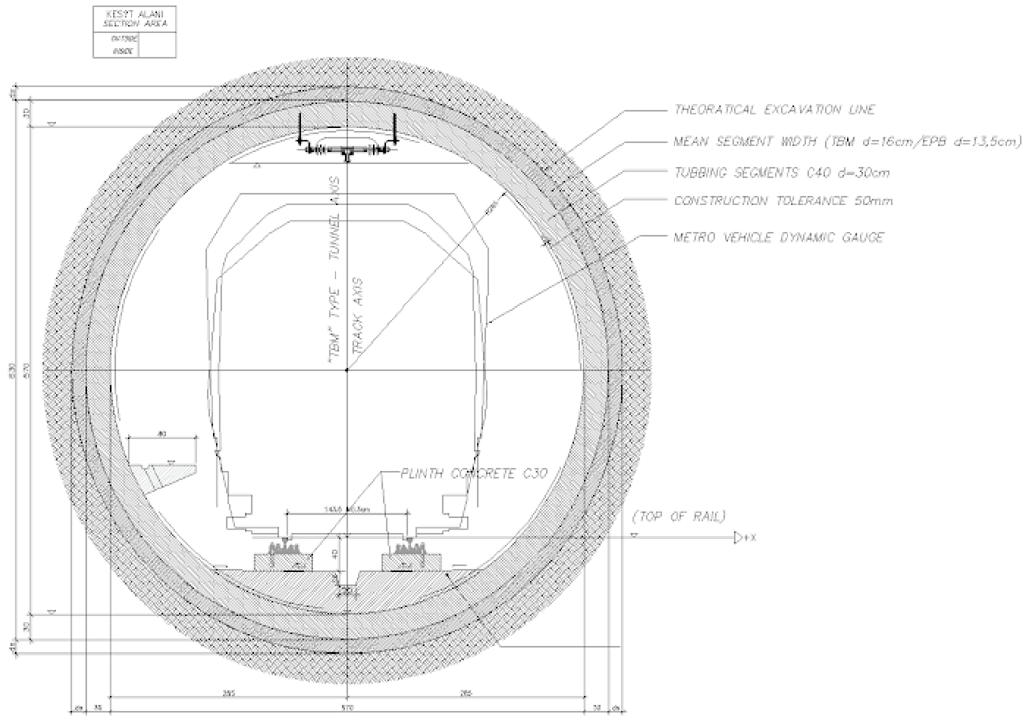

Figure 26. TBM Type Tunnel (B1 Type).

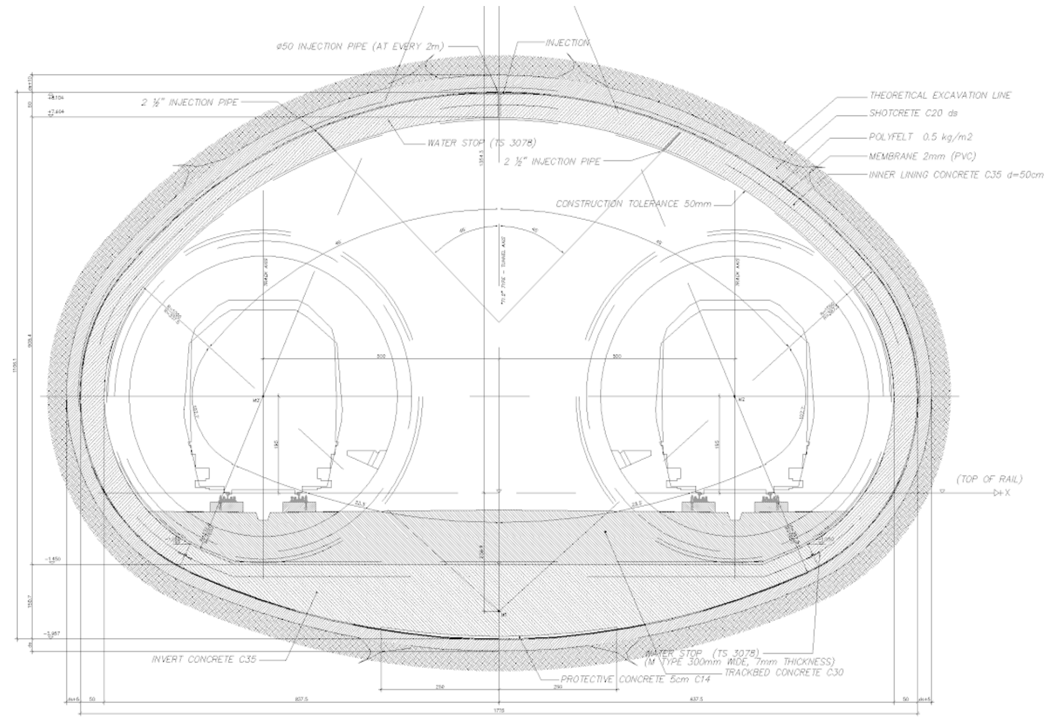

Figure 27. NATM Type Tunnel (A type).

B. Bill of Quantities of the Lines

Table 6. Bill of quantities of Line - 1.

Constructional Cluster	Constructional Component	Material	Component ID	Unit	L1 - S1	L1 - S2	L1 - S3	L1 - S4	L1 Total Amount
Structure	Tunnel & Station	Reinforced Concrete	Y.16.050/16	m³	21215	21320	21320	21320	85175
		Reinforcement Steel	Y.23.101	t	9780	7780	6960	3650	28170
		Water Insulation	Y.18.461/006	m²	19674	17320	16263	13882	67139
Basement	Tunnel & Station	Foundation Concrete	Y.16.050/15	m³	5837	5660	5631,7	5941,7	23070,4
		Foundation Reinforcement Steel	Y.23.101	t	1934	1886	1920	1968	7708
		Basement Water Proofing	Y.18.461/005	m²	3425	3425	3425	3425	13700
		Levelling Concrete	Y.27.581/A	m³	11320	10980	11360	12980	46640
Walls	Station & Rooms	Brick Wall 10 cm	Y.18.001/C12	m²	25	25	25	25	100
		Brick Wall 20 cm	Y.18.001/C16	m²	3300	3300	3400	3420	13420
		Plaster	Y.27.501/02	m²	20145	20145	20145	20145	80580
		Paint	Y.25.004/04	m²	31210	33460	32520	31130	128320
		Ceramic Wall Tile 30x30 cm	Y.26.008/304B	m²	120	120	120	120	480
		Ceramic Wall Tile 30x60 cm	Y.26.008/310B	m²	180	200	180	190	750
		Granite Ceramic Wall	1.1.2.1.3	m²	6720	7340	6980	7130	28170
		GFRC Wall Panels	n/a	m²	820	940	780	890	3430
		Laminated Glass Wall	06.645/21B	m²	50	40	60	50	200
Floors	Station & Rooms	Granite	Y.26.020/311A-A	m²	3250	3460	3310	3890	13910
		PVC Floor	Y.25.116/A03	m²	480	580	510	540	2110
		Granite Terrazzo	Y.26.015/013	m²	1455	1455	1550	1550	6010
		Ceramic Floor	Y.26.008/305A	m²	170	170	170	170	680
		Epoxy Floor	Y.19.090/003-A	m²	420	420	420	420	1680
		Cement Based Waterproof	Y.19.085/025	m²	650	650	680	680	2660
		Surface Hardened Concrete	Y.19.090/001A	m²	6300	6300	6450	6450	25500
		Granite Ceramic Floor	1.1.2.2.9	m²	9890	10950	9980	9960	40780
Ceilings	Station & Rooms	Galvanized Steel	23.243/27	m²	6890	7260	7130	6920	28200
		Skylight Glass	04.645/24D	m²	n/a	n/a	n/a	n/a	n/a
		Aluminum Ceiling	23.243/3	m²	620	740	720	680	2760
		Ceiling Paint	Y.27.503/14	m²	2470	3160	2485	3260	11375
Doors	Rooms	YK	n/a	pcs	60	60	61	61	242
		SK	n/a	pcs	15	12	13	14	54
		LK	Y.22.009/03	pcs	8	8	8	8	32

Table 7. Bill of quantities of Line – 2.

Constructional Component	Material	Component ID	Unit	L2 - S1	L2 - S2	L2 - S3	L2 - S4	L2 - S5	L2 - S6	L2 - S7	L2 Total Amount
Tunnel & Station	Reinforced Concrete	Y.16.050/16	m³	111600	111600	111600	111600	111600	111600	111600	781200
	Reinforcement Steel	Y.23.101	t	17628	22680	13711	15910	8840	14920	1386	95075
	Water Insulation	Y.18.461/006	m²	5900	6850	4590	5320	3000	5000	500	31160
Tunnel & Station	Foundation Concrete	Y.16.050/15	m³	4320	4320	4320	4210	4210	4210	4210	29800
	Foundation Reinforcement Steel	Y.23.101	t	1120	1120	1120	1080	1080	1080	1080	7680
	Basement Water Proofing	Y.18.461/005	m²	1800	1900	1165	1720	800	800	750	8935
	Levelling Concrete	Y.27.581/A	m³	4000	4000	4000	3800	3800	3800	3800	27200
Station & Rooms	Brick Wall 10 cm	Y.18.001/C12	m²	90	90	90	90	90	90	90	630
	Brick Wall 20 cm	Y.18.001/C16	m²	5800	5800	5800	5800	5800	5800	5800	40600
	Plaster	Y.27.501/02	m²	14306	14306	14306	14306	14306	14306	14306	100142
	Paint	Y.25.004/04	m²	36038	36038	36038	34012	35150	36012	35120	248408
	Ceramic Wall Tile 30x30 cm	Y.26.008/304B	m²	600	600	600	500	500	500	500	3800
	Ceramic Wall Tile 30x60 cm	Y.26.008/310B	m²	3086	3086	3086	2800	2800	2800	2800	20458
	Granite Ceramic Wall	1.1.2.1.3	m²	1249	1249	1249	1320	1320	1300	1300	8987
	GFRC Wall Panels	n/a	m²	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Laminated Glass Wall	06.645/21B	m²	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Station & Rooms	Granite	Y.26.020/311A-A	m²	7745	7745	7745	7260	7260	7260	7260	52275
	PVC Floor	Y.25.116/A03	m²	400	400	400	200	200	200	200	2000
	Granite Terrazzo	Y.26.015/013	m²	6668	5882	6155	6155	6155	6155	6155	43325
	Ceramic Floor	Y.26.008/305A	m²	95	95	95	95	95	95	95	665
	Epoxy Floor	Y.19.090/003-A	m²	702	760	748	748	748	748	748	5202
	Cement Based Waterproof	Y.19.085/025	m²	751	751	751	751	751	751	751	5257
	Surface Hardened Concrete	Y.19.090/001A	m²	692	692	692	692	692	692	692	4844
	Granite Ceramic Floor	1.1.2.2.9	m²	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Station & Rooms	Galvanized Steel	23.243/27	m²	1892	1892	1892	1640	1640	1640	1640	12236
	Skylight Glass	04.645/24D	m²	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Aluminum Ceiling	23.243/3	m²	1238	1238	1238	1120	1120	1120	1120	8194
	Ceiling Paint	Y.27.503/14	m²	5552	5552	5552	4862	4862	4862	4862	36104
Rooms	YK	n/a	pcs	105	109	99	99	99	99	99	709
	SK	n/a	pcs	20	23	23	18	18	18	18	138
	LK	Y.22.009/03	pcs	8	8	8	8	8	8	8	56

Table 8. Bill of quantities of Line – 3.

Constructional Cluster	Constructional Component	Material	Component ID	Unit	L3 - S1	L3 - S2	L3 - S3	L3 Total Amount
Structure	Tunnel & Station	Reinforced Concrete	Y.16.050/16	m³	42300	42300	42300	126900
		Reinforcement Steel	Y.23.101	t	22420	23540	3230	49190
		Water Insulation	Y.18.461/006	m²	31500	32340	5000	68840
Basement	Tunnel & Station	Foundation Concrete	Y.16.050/15	m³	6883	6883	7883	21649
		Foundation Reinforcement Steel	Y.23.101	t	2336	2336	2428	7100
		Basement Water Proofing	Y.18.461/005	m²	16000	16000	17000	49000
		Levelling Concrete	Y.27.581/A	m³	6745,7	7513,7	5798,8	20058.14
Walls	Station & Rooms	Brick Wall 10 cm	Y.18.001/C12	m²	140	140	148	428
		Brick Wall 20 cm	Y.18.001/C16	m²	4400	4400	4400	13200
		Plaster	Y.27.501/02	m²	17688	17688	17688	53064
		Paint	Y.25.004/04	m²	14453	15237	14129	43817,74
		Ceramic Wall Tile 30x30 cm	Y.26.008/304B	m²	447,13	447,13	420,18	1314,44
		Ceramic Wall Tile 30x60 cm	Y.26.008/310B	m²	235,07	235,07	278,72	748,86
		Granite Ceramic Wall	1.1.2.1.3	m²	164,23	164,23	160,28	488,74
		GFRC Wall Panels	N/A	m²	6945,3	6427,7	6276,1	19649,1
		Laminated Glass Wall	06.645/21B	m²	1281,5	2344,9	459,4	4085,77
Floors	Station & Rooms	Granite	Y.26.020/311A-A	m²	2136,4	2124	2086,8	6347,2
		PVC Floor	Y.25.116/A03	m²	520,36	520,36	523,6	1564,32
		Granite Terrazzo	Y.26.015/013	m²	4200	4200	4350	12750
		Ceramic Floor	Y.26.008/305A	m²	250	250	250	750
		Epoxy Floor	Y.19.090/003-A	m²	865	865	865	2595
		Cement Based Waterproof	Y.19.085/025	m²	2030	2030	2030	6090
		Surface Hardened Concrete	Y.19.090/001A	m²	165	165	171	501
		Granite Ceramic Floor	1.1.2.2.9	m²	N/A	N/A	N/A	N/A
Ceilings	Station & Rooms	Galvanized Steel	23.243/27	m²	N/A	N/A	N/A	N/A
		Skylight Glass	04.645/24D	m²	N/A	N/A	N/A	N/A
		Aluminum Ceiling	23.243/3	m²	3306,6	3871,2	2624	9801,8
		Ceiling Paint	Y.27.503/14	m²	2822,3	3036,1	2741,7	8600,1
Doors	Rooms	YK	N/A	pcs	77	77	77	231
		SK	N/A	pcs	19	21	17	57
		LK	Y.22.009/03	pcs	8	8	8	24

Table 9. Bill of Quantities of Line – 4.

Constructional Cluster	Constructional Component	Material	Component ID	Unit	L4 - S1	L4 - S2	L4 - S3	L4 - S4	L4 Total Amount
Structure	Tunnel & Station	Reinforced Concrete	Y.16.050/16	m³	24200	24200	24200	24200	96800
		Reinforcement Steel	Y.23.101	t	7280	8860	4380	2680	23200
		Water Insulation	Y.18.461/006	m²	6520	6760	3620	1640	18540
Basement	Tunnel & Station	Foundation Concrete	Y.16.050/15	m³	4860	4860	4860	5120	19700
		Foundation Reinforcement Steel	Y.23.101	t	1640	1640	1640	1710	6630
		Basement Water Proofing	Y.18.461/005	m²	3390	3390	3390	3390	13560
		Levelling Concrete	Y.27.581/A	m³	8720	8440	8730	9980	35870
Walls	Station & Rooms	Brick Wall 10 cm	Y.18.001/C12	m²	20	20	20	20	80
		Brick Wall 20 cm	Y.18.001/C16	m²	3000	3000	3100	3100	12200
		Plaster	Y.27.501/02	m²	17680	17680	17680	17680	70720
		Paint	Y.25.004/04	m²	24260	26340	25630	25980	102210
		Ceramic Wall Tile 30x30 cm	Y.26.008/304B	m²	100	100	100	100	400
		Ceramic Wall Tile 30x60 cm	Y.26.008/310B	m²	120	120	140	160	540
		Granite Ceramic Wall	1.1.2.1.3	m²	5220	5680	5460	5570	21930
		GFRC Wall Panels	n/a	m²	580	580	620	800	2580
		Laminated Glass Wall	06.645/21B	m²	40	40	60	80	220
Floors	Station & Rooms	Granite	Y.26.020/311A-A	m²	2820	2820	2960	3120	11720
		PVC Floor	Y.25.116/A03	m²	380	380	390	390	1540
		Granite Terrazzo	Y.26.015/013	m²	1370	1370	1370	1390	5500
		Ceramic Floor	Y.26.008/305A	m²	170	170	170	170	680
		Epoxy Floor	Y.19.090/003-A	m²	400	400	400	400	1600
		Cement Based Waterproof	Y.19.085/025	m²	600	600	600	600	2400
		Surface Hardened Concrete	Y.19.090/001A	m²	5800	5800	5900	5900	23400
		Granite Ceramic Floor	1.1.2.2.9	m²	7600	7600	7720	7840	30760
Ceilings	Station & Rooms	Galvanized Steel	23.243/27	m²	4260	4280	4390	4510	17440
		Skylight Glass	04.645/24D	m²	N/A	N/A	N/A	N/A	N/A
		Aluminum Ceiling	23.243/3	m²	540	540	560	580	2220
		Ceiling Paint	Y.27.503/14	m²	1860	1860	1920	2160	7800
Doors	Rooms	YK	N/A	pcs	54	54	54	54	216
		SK	N/A	pcs	13	13	16	18	60
		LK	Y.22.009/03	pcs	8	8	8	8	32