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SUSTAINABLE CONSTRUCTION PRACTICES AND LIFE CYCLE ASSESSMENT: A COMPARATIVE ANALYSIS OF PRIMARY SCHOOL TYPOLOGIES IN TURKIYE

M.Sc. Thesis by

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SUSTAINABLE CONSTRUCTION PRACTICES AND LIFE CYCLE ASSESSMENT: A COMPARATIVE ANALYSIS OF PRIMARY SCHOOL TYPOLOGIES IN TURKIYE

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M.Sc. THESIS EXAMINATION RESULT FORM

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2025, 05 February **Gülsüm TAÇ**

SUSTAINABLE CONSTRUCTION PRACTICES AND LIFE CYCLE ASSESSMENT: A COMPARATIVE ANALYSIS OF PRIMARY SCHOOL TYPOLOGIES IN TURKIYE

ABSTRACT

The construction industry is one of the largest contributors to global environmental challenges, emphasizing the need for sustainable practices in building design and construction. Educational buildings, as essential public facilities, offer a unique opportunity to address these challenges while promoting sustainability. This thesis analyzes the environmental impacts of primary school building typologies (8, 12, 24, and 32 classrooms) employed by the Ministry of National Education of Türkiye (MEB) using the Life Cycle Assessment (LCA) methodology. By examining all life cycle stages—from material extraction to recycling—the study provides a comprehensive evaluation of the environmental performance of these typologies. Conducted in accordance with international standards and utilizing BIM-integrated Tally software, the research evaluates key environmental impact categories, focusing on resource use, emissions, and material efficiency. The findings underscore the critical role of material selection, resource-efficient design, and recycling processes in minimizing environmental burdens. By offering actionable insights, this study aims to guide architects, engineers, and policymakers toward more sustainable and environmentally responsible school building practices.

Keywords: Life cycle assessment (LCA), school buildings, sustainability, environmental impacts, building information modeling (BIM)

SÜRDÜRÜLEBİLİR İNŞAAT UYGULAMALARI VE YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ: TÜRKİYE'DEKİ İLKOKUL TİPOLOJİLERİNİN KARŞILAŞTIRMALI ANALİZİ

ÖZ

İnşaat sektörü, küresel çevresel sorunlara en büyük katkıyı sağlayan alanlardan biri olarak, bina tasarımı ve inşaatında sürdürülebilir uygulamalara duyulan ihtiyacı vurgulamaktadır. Kamuya ait temel tesisler olan eğitim binaları, bu sorunlara çözüm getirmek ve sürdürülebilirliği teşvik etmek için benzersiz bir fırsat sunar. Bu tez, Türkiye Cumhuriyeti Millî Eğitim Bakanlığı (MEB) tarafından kullanılan ilkokul bina tipolojilerinin (8, 12, 24 ve 32 derslik) çevresel etkilerini, Yaşam Döngüsü Değerlendirmesi (LCA) yöntemiyle analiz etmektedir. Malzeme temininden geri dönüşüme kadar tüm yaşam döngüsü aşamalarını inceleyerek, söz konusu tipolojilerin çevresel performansını kapsamlı biçimde değerlendirmeyi amaçlamaktadır. Uluslararası standartlara uygun olarak ve BIM entegrasyonlu Tally yazılımı kullanılarak yürütülen bu araştırma, kaynak kullanımı, emisyonlar ve malzeme verimliliği gibi temel çevresel etki kategorilerine odaklanmaktadır. Elde edilen bulgular, malzeme seçimi, kaynak açısından verimli tasarım ve geri dönüşüm süreçlerinin çevresel yükleri azaltmadaki kritik rolünü öne çıkarmaktadır. Çalışma, mimarlar, mühendisler ve politika yapıcılara somut öneriler sunarak, daha sürdürülebilir ve çevreye duyarlı okul binaları uygulamalarının geliştirilmesine rehberlik etmeyi hedeflemektedir.

Anahtar Kelimeler: Yaşam döngüsü değerlendirmesi (LCA), okul binaları, sürdürülebilirlik, çevresel etkiler, bina bilgi modellemesi (BIM)

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NOMENCLATURE

Subscripts

CO_2eq	Carbon dioxide equivalent (global warming potential)
SO_2eq	Sulfur dioxide equivalent (acidification)
Neq	Nitrogen equivalent (eutrophication)
O_3eq	Ozone equivalent (smog formation)
CFC-11eq	Chlorofluorocarbon – 11 equivalent (ozone depletion)
MJ	Megajoule (energy unit)
m^2	Square meter

Acronyms

LCA	Life Cycle Assessment
ISO	International Organization for Standardization
EN	European Standard
BIM	Building Information Modeling
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

Environmental Impact Categories

Global Warming	$kgCO_2eq$
Acidification	$kgSO_2eq$
Eutrophication	kgNeq
Smog Formation	kgO_3eq
Ozone Depletion	kgCFC-11eq
Primary Energy	MJ
Non-Renewable Energy	MJ
Renewable Energy	MJ

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CHAPTER 1

INTRODUCTION

The construction sector is a major contributor to global environmental challenges, including resource depletion, energy consumption, and greenhouse gas emissions. Educational buildings, such as schools, represent a significant segment of this sector, highlighting the importance of evaluating their environmental impacts to guide sustainable design and construction practices. This thesis focuses on the environmental performance of four primary school typologies (8, 12, 24, and 32 classrooms) defined by the Ministry of National Education (MEB), using the Life Cycle Assessment (LCA) methodology to provide a comprehensive analysis of their environmental impacts. The thesis adopts a holistic approach by evaluating the entire life cycle of school buildings, from raw material extraction to recycling and reuse, ensuring that all stages contributing to environmental burdens are considered. The key life cycle stages examined include the product stage, transportation stage, use and maintenance stage, end-of-life stage, and recycling/reuse stage. Each stage is assessed in detail to identify the critical sources of environmental impacts and to propose strategies for mitigation. The methodological framework of the study is designed in alignment with internationally recognized standards such as ISO 14040, ISO 14044, EN 15804, and EN 15978, ensuring the robustness and comparability of the findings. The analysis leverages building information modeling (BIM)-based software, Tally, integrated with Autodesk Revit. Tally enables the assessment of material properties, quantities, and environmental impacts with high precision, utilizing the GaBi LCI 2018 database for reliable life cycle inventory data. To address data gaps, appropriate proxy datasets have been incorporated, ensuring consistency with geographic, technological, and temporal alignment criteria. Key environmental impact categories, including Global Warming Potential (GWP), Primary Energy Demand (PED), and Acidification Potential (AP), are the primary focus of this research. These categories provide a comprehensive perspective on both global impacts, such as carbon emissions, and regional issues, such as acid rain and energy use. By comparing the environmental performance of each typology, the

study identifies the stages and materials that contribute the most to environmental burdens, with particular emphasis on energy-intensive materials like concrete and steel. In addition to analyzing environmental impacts, the research highlights the potential of recycling and reuse processes in mitigating these effects. For instance, the findings demonstrate that recycling can significantly reduce carbon emissions and material extraction demands. This thesis not only contributes to the growing body of knowledge on sustainable architecture but also provides practical guidance for integrating life cycle thinking into the design and construction of educational buildings. By offering a detailed assessment of environmental impacts and proposing targeted strategies for improvement, this thesis aims to support the development of more sustainable school projects that align with global sustainability goals. Educational buildings, such as schools, represent a significant segment of this sector, highlighting the importance of evaluating their environmental impacts to guide sustainable design and construction practices. This thesis focuses on the environmental performance of four primary school typologies (8, 12, 24, and 32 classrooms) defined by the Ministry of National Education (MEB), using the Life Cycle Assessment (LCA) methodology to provide a comprehensive analysis of their environmental impacts.

It is important to note that while energy consumption is a critical factor in the life cycle environmental impact of buildings, this study specifically focuses on material-based environmental impacts rather than operational energy use. Unlike studies that integrate energy consumption and emissions from heating, cooling, and lighting into their analysis, this thesis prioritizes the embodied environmental burdens associated with building materials and construction processes. As a result, operational energy consumption was not modeled in this LCA study, leading to a relatively lower representation of energy-related impacts in the findings. This approach enables a detailed comparison of school typologies based on material usage and construction-related impacts while recognizing the importance of future research integrating energy consumption into similar assessments.

Consequently, the exclusion of operational energy in this analysis does not imply that energy use is negligible but rather that the primary focus of the study is on the

material life cycle impacts. While this study does not model operational energy consumption, its findings provide valuable insights into the material-driven environmental footprint of school buildings. Future research can expand upon this approach by incorporating energy modeling and usage scenarios to develop a more holistic understanding of sustainability in school design. Future studies could build upon this research by incorporating energy performance simulations to gain a more comprehensive understanding of the total environmental impact of school buildings.

1.1 Background of the Study

The construction industry is a significant driver of environmental challenges, contributing substantially to resource depletion, energy consumption, and greenhouse gas emissions. In response to these challenges, sustainability has emerged as a critical focus in building design and construction practices. Among various building types, educational facilities, such as schools, hold a unique position due to their widespread use and long-term impact on communities. School buildings, as essential public infrastructures, consume significant resources during their construction and operational phases. With the increasing demand for sustainable practices, understanding the environmental performance of these facilities is crucial for reducing their ecological footprint. While numerous studies have examined the sustainability of buildings in general, research specifically focusing on school typologies remains limited, particularly in the context of different design and size variations.

Life Cycle Assessment (LCA) has become a widely accepted methodology for evaluating the environmental impacts of buildings throughout their life cycles. By analyzing all stages—from material extraction and manufacturing to usage, maintenance, and recycling—LCA provides a comprehensive framework for assessing the environmental burdens associated with construction projects. Moreover, the integration of Building Information Modeling (BIM) with LCA tools has enabled more precise and efficient analyses, making it possible to evaluate the environmental performance of building components in detail. In the context of this study, the Ministry of National Education in Türkiye has standardized school designs into

various typologies based on classroom numbers (8, 12, 24, and 32 classrooms). These designs offer a unique opportunity to analyze the environmental impacts of educational facilities across different scales and to identify strategies for minimizing these impacts. By focusing on these typologies, this study aims to address the need for sustainable design practices in educational buildings, contributing to the broader goals of reducing environmental burdens and promoting sustainable construction.

1.2 Research Design And Scope

This section aims to define the objectives, scope, and fundamental framework of the thesis, clarifying research design and scope. First, the primary research questions guiding this study will be discussed, highlighting the potential for both quantitative and qualitative outcomes. Next, the objectives and goals of the study will be introduced, outlining how it intends to address existing gaps in the literature concerning the environmental impacts of school buildings.

1.2.1 Statement of the Research Problem

The construction industry is one of the primary contributors to global environmental challenges, including resource depletion, energy consumption, and greenhouse gas emissions. In response, sustainable design and construction practices have gained significant importance. Among various building types, school buildings play a critical role due to their widespread use and societal impact. This study focuses on analyzing the environmental performance of standardized school typologies in Türkiye, aiming to address gaps in sustainability research and provide strategies for reducing their ecological footprint. To comprehensively explore the environmental impacts of school buildings from both quantitative and qualitative perspectives, the following research questions have been formulated:

i. How does the total carbon footprint vary across MEB standardized school typologies with different classroom capacities?

Addressing this question reveals the relationship between building scale and carbon emissions, highlighting critical phases that demand closer scrutiny.

ii. Which typologies exhibits greater resource utilization (e.g., concrete, steel, insulation material) according to material density and construction volume?

Exploring how different typologies prioritize or consume specific materials facilitates better understanding of cost and environmental load variations linked to construction phases.

iii. Which life cycle stages contribute the most to the environmental impacts of different school typologies?

Identifying which stages (e.g., raw material extraction, transportation, construction, end-of-life) contribute the most to environmental impacts helps in targeting effective sustainability interventions.

iv. In light of LCA results, what sustainability-driven improvements can be made in school buildings?

By integrating quantitative LCA data with sustainable design principles, this study develops recommendations focusing on material selection, resource efficiency, recycling potential, and waste reduction strategies. By addressing these research questions, the study aims to generate both measurable findings (e.g., CO_2 emissions, material consumption, waste generation) and interpretative insights (design considerations, policy recommendations, and sustainable construction strategies). Consequently, this thesis contributes to the academic discourse on environmental impact assessment for school buildings while also offering practical guidance for architects, engineers, and policymakers in the implementation of sustainable material practices.

1.2.2 Research Aim and Objectives

The primary aim of this thesis is to systematically identify the environmental impacts that arise in the construction and demolition phases of school buildings, and to interpret the findings within a sustainability framework in order to propose concrete avenues for improvement. Specifically, by focusing on MEB standardized school typologies, this research endeavors to quantitatively assess how effective these

commonly used educational building standards are with respect to environmental considerations.

i. Life Cycle Assessment (LCA): This study employs LCA as a widely recognized method for quantifying the environmental impacts within the construction sector. The LCA approach enables comprehensive evaluation of resource consumption, emissions, and waste generation spanning from raw material extraction to post-demolition waste management.

ii. Sustainability Context: By interpreting these findings in light of sustainable material selection, resource efficiency, and waste minimization principles, the study intends to put forward practical recommendations. Hence, it aims to produce insights that address both academic (bridging gaps in the literature) and practical (informing policymakers, design offices, and construction professionals) needs.

iii. Gap in the Literature and Contribution: Although numerous LCA studies exist on the construction industry's environmental impacts, MEB standardized school typologies have seldom been the focus of comprehensive, multi-scale research. By conducting comparative LCA across various classroom capacities, this thesis offers a broader framework than prior work, which often examines only a single prototype or scale. Moreover, as educational buildings affect a wide segment of society, the study also provides insights into public awareness and the social dimensions of sustainable design.

iv. Practical Contribution and Expectations: Considering environmental impacts in the design and management of school buildings serves the goal of creating healthy and eco-conscious spaces for future generations. This research aims to determine which design alterations or innovative materials and technologies can most effectively reduce the carbon footprint of MEB standardized school typologies by optimizing material selection and construction methods. Thus, it aspires to function as a guiding resource for decision-makers (the Ministry of National Education, local authorities), architectural offices, and on-site professionals (architects, engineers).

CHAPTER 2

MATERIALS AND METHODS

In this section, the overall research design and methodology adopted to analyze the environmental impacts occurring throughout the life cycle of school buildings constructed according to MEB standardized typologies—widely employed in Türkiye—are outlined. First, attention is directed to the rationale behind selecting the typologies included in the study (e.g., those with 8, 12, 24, or 32 classrooms), as well as the reasons why these are commonly utilized in educational settings. The primary research question involves determining which stages and components in school buildings, differing in the number of classrooms, contribute to environmental impacts from the construction phase to the end of their service life. Subsequently, a BIM (Building Information Modeling)-based approach was employed to digitally model these projects. The dataset, originally in AutoCAD format, was imported into Revit and reorganized to include material properties and quantity data for each building element. Moreover, by leveraging standards such as IFC, the model can be processed by various software tools. This BIM-based model facilitates consistent and systematic management of the material and quantity inventory for the selected projects. For a quantitative assessment of the environmental impacts throughout the life cycle of these school buildings, the Life Cycle Assessment (LCA) method was adopted. Designed in accordance with ISO 14040 and 14044 standards, this evaluation focuses on all phases from raw material extraction to demolition and waste management. Using a software add-in such as Tally, which runs on Revit, key indicators—such as carbon footprint, material resource use, and waste quantities—were calculated. Consequently, the environmental performances of the chosen prototype projects could be compared, providing concrete data to develop improvement suggestions aligned with sustainable architecture principles. This approach enables both a comparative analysis of MEB typologies with differing classroom capacities and an evaluation of the benefits arising from the combined use of BIM and LCA. The outcomes not only introduce an environmental perspective into the design and construction processes of educational buildings, but also aim to

offer guiding recommendations for both the academic community and decision-makers.

2.1 Selected Typologies and Rationale

Widely employed throughout Türkiye, MEB standard school typologies are standardized in accordance with the basic requirements of educational facilities and are implemented in diverse regions with varying climatic and topographical conditions. In particular, the present study examines:

I. 8-Classroom Typologies

II. 12-Classroom Typologies

III. 24-Classroom Typologies

IV. 32-Classroom Typologies

Investigating these typologies makes it possible to compare material usage, resource consumption, and other environmental factors as the number of classrooms expands. Examining different building scales and capacities reveals how economies of scale and resource efficiency might manifest in educational structures. Key considerations for selecting these typologies include:

Standardization and Geographic Coverage: As these typologies are commonly built nationwide, results obtained from their analysis can be generalized to a national context, transcending local conditions.

Comparative Analysis: Varying classroom capacities significantly affect both construction volume and material typologies, allowing for direct comparison of environmental impacts as building scale increases.

Policy and Societal Relevance: School buildings are public-service entities, playing a critical role in shaping the environmental awareness of future generations. Enhancing the sustainability of MEB standardized school typologies could have implications not

only for educational quality but also for societal consciousness about environmental issues.

Information regarding plans, sections, elevations, and quantity take-offs for the selected typologies has been collected, then modeled within a Building Information Modeling (BIM) environment. Subsequently, Life Cycle Assessment (LCA) was conducted to quantify parameters such as carbon emissions and material resource use. By comparing results across different classroom capacities, the study elucidates which elements or phases pose higher environmental burdens and how they might be mitigated.

2.2 Bim-Based Modeling Process

This section provides a comprehensive explanation of the steps taken to model the MEB school building typologies in a digital environment. The goal is to generate accurate and integrated data for Life Cycle Assessment (LCA), enabling a systematic evaluation of each component's environmental impact. Accordingly, the discussion covers critical stages such as migrating from AutoCAD drawings to Revit, defining materials, achieving an appropriate LOD (Level of Detail), and ensuring IFC compatibility.

2.2.1 Data Collection

The 2D AutoCAD drawings for the selected projects were obtained from institutional archives or MEB project documentation. These documents typically include:

Basic Drawings (plans, sections, elevations),

Material Lists (types and properties of components such as walls, floors),

Quantity Data (dimensions, volumes, and stratification details),

Technical Specifications (wall thickness, insulation layers, window glazing, etc.).

Additional requirements for certain building elements (e.g., thermal conductivity values) were digitized and integrated into the modeling process. Key considerations at this stage include:

Data Accuracy: Any discrepancies across multiple drawing sets were resolved, referencing MEB standards to maintain consistency.

Consolidated Inventory: Material and quantity lists were converted into a digital database format (e.g., Excel) to facilitate BIM modeling.

Traceability: All revisions and updates made to the project documents were recorded to ensure methodological transparency.

2.2.2 Creating the Model in Revit

a) Importing AutoCAD Data into Revit

Existing 2D CAD files were imported or linked into Revit. Layer adjustments and organization were performed so that walls, columns, and other elements could be accurately reconstructed in a 3D environment. This step is essential for maintaining geometric consistency.

b) Material Definitions

Walls, floors, roofs, columns, beams, windows, and doors in Revit were assigned material types (e.g., C30 concrete, B500 rebar, mineral wool insulation). For each material:

Density (kg/m^3),

Thermal Conductivity (W/mK),

Service Life and maintenance parameters were registered in the Revit database. This level of detail is critical for producing a reliable material inventory during LCA analysis.

c) Level of Detail (LOD) — LOD 300

To ensure sufficient accuracy for LCA, the model aimed for LOD 300, providing:

Geometric Consistency: Precise dimensions and positions for structural elements.

Layered Information: Separate definitions for each layer (e.g., insulation, structural material), enabling detailed environmental evaluations of each component.

2.3 Life Cycle Assessment Analysis Process

2.3.1 Implementation and Phases of LCA

In this study, Life Cycle Assessment (LCA) was conducted in accordance with ISO 14040 and ISO 14044 standards, comprising four fundamental phases:

a) Goal and Scope Definition

The primary objective of this thesis is to compare the life cycle impacts of different MEB standardized school typologies identify stages with high environmental impacts, and develop recommendations contributing to sustainable architecture. Within this framework, the LCA method is employed to conduct a detailed environmental performance analysis of the typologies. The analysis encompasses all stages from raw material extraction to demolition and waste management, defined comprehensively to include raw material extraction, production, transportation, construction, use, maintenance/repair, demolition/waste management. The functional unit is defined as “1 m² of net floor area.” This unit allows for comparative evaluation of environmental impacts across different project scales. Additionally, the environmental load of the total construction area is assessed as an additional analysis. The functional unit ensures consistency and comparability of LCA results.

b) Life Cycle Inventory (LCI)

Material information (density, volume, etc.), transportation distances to the site, and resource consumption during construction within the BIM model are collected and transferred to the LCI database. This process includes:

Material Information: Detailed identification of material types and quantities for each building component.

Default Database: Standard databases such as GaBi utilized by the Tally add-in, form the basis for LCI data. Where suitable data is unavailable, local LCI studies or literature examples are referenced to ensure data integrity.

Data Quality and Accuracy: Ensuring the accuracy and reliability of data is paramount in the LCI process. Therefore:

Data Source: Reliable and valid sources are meticulously selected.

Data Consistency: Verification of consistency across different data sources.

Traceability: Clear documentation of data sources and acquisition methods to enable replication.

c) Life Cycle Impact Assessment (LCIA)

Impact Categories: The environmental impact categories assessed in this study include: carbon footprint (global warming potential - GWP), resource depletion, acidification, eutrophication.

Data Interpretation and Comparison: Environmental impact distributions across different projects are compared to identify which typologies exhibit higher environmental burdens in specific categories. This comparative analysis highlights the varying environmental performances based on classroom capacities and associated factors.

d) Interpretation

Analysis of Results: The environmental impact concentrations in each project type are identified, particularly focusing on stages and materials with significant impacts.

2.3.2 Use of Tally Add-in

Tally Add-in operates within Revit and automates or semi-automates the environmental impact calculations by matching each building component with material identities. The process proceeds through the following steps:

a) Material Matching

Integration with Tally Library: Materials defined in the Revit model are matched with the Tally add-in's material library. This ensures that each material type is accurately reflected in the LCA analysis. Accurate material matching is crucial for precise environmental impact calculations.

b) Running the Analysis

Impact Category Calculations: For each project phase (construction, use), potential impact categories are calculated. The results are then presented in tabular and graphical formats, facilitating a clear comparison of environmental impacts across different projects.

Visualization of Results: Data visualization tools (graphs, charts, infographics) are utilized to effectively present the environmental performance of each project. These visual aids simplify the understanding of complex data and highlight key areas of concern.

c) Compilation of Results

Comparative Analysis: The same methodology is applied to all projects (8, 12, 24, 32 classrooms), resulting in comparative findings. This allows for the identification of which typologies have higher environmental burdens in specific impact categories.

2.3.3 Functional Unit and Compliance with ISO Standards

In this study, the functional unit is defined as "1 m² of net floor area." This unit serves as the basis for all environmental impact calculations, ensuring that comparisons between different project scales are fair and standardized. Additionally, the environmental load of the total construction area is evaluated as an auxiliary analysis, providing a comprehensive understanding of the overall environmental

impacts. This research strictly adheres to ISO 14040 and ISO 14044 standards, which outline the principles and framework for conducting LCA studies. Key aspects of compliance include:

System Boundaries: Comprehensive inclusion of all life cycle stages from raw material extraction to end-of-life waste management.

Data Quality: Ensuring that data used in the LCA is accurate, reliable, and sourced from credible references.

Traceability: Maintaining clear records of data sources and methodologies used to facilitate transparency and reproducibility.

Adhering to these standards ensures that the LCA analysis is methodologically sound and the results are credible and comparable with other studies.

2.3.4 Conclusion and Future Steps

In this section, the Life Cycle Assessment (LCA) process has been thoroughly detailed, covering the phases from Goal and Scope Definition to Interpretation. By adhering to ISO 14040 and ISO 14044 standards and employing a robust methodological framework, this study ensures the reliability and validity of its environmental impact assessments. The integration of the Tally add-in within the Revit environment facilitates accurate and efficient data analysis, while the defined functional unit enables fair comparisons across different project scales.

Future Steps: Building upon the LCA findings, the next phase of the thesis will involve developing sustainable architectural recommendations tailored to the identified high-impact life cycle stages and material choices. These recommendations aim to enhance the sustainability of MEB standardized school typologies through optimized material selection and waste reduction strategies, contributing to the broader goal of sustainable education infrastructure development in Türkiye.

CHAPTER 3

LITERATURE REVIEW

Environmental sustainability, being one of today's most paramount issues, presents ever-increasing challenges in the construction industry. The impact of the design, construction, and operation of buildings, especially school buildings, on sustainability goals is apparent. Meanwhile, Life Cycle Assessment (LCA), a well-known measurement and optimization tool for construction processes in terms of the environmental impacts they generate, has gained increasing importance in recent years. LCA helps assess environmental impacts throughout the entire life cycle of buildings, thus contributing to the development of sustainable construction practices. The purpose of this study is to provide an in-depth literature review of the factors affecting the role of LCA in sustainable construction, utilizing theoretical frameworks, practical strategies, and innovative approaches. The study begins with an examination of the literature related to LCA and sustainable construction. Within this context, the relationship between theoretical understandings and practical applications will also be explored. On this basis, extensive applications in the construction industry will be discussed, along with the impacts on different types of buildings and the feasibility of implementing LCA. Hence, in these sections, various approaches and methodologies for better management of environmental impacts in construction processes will be suggested through the application of LCA. Building on all this, this section will develop a baseline understanding of the role of LCA in developing sustainable construction practices while providing important methodological insights into evaluating environmental impacts during construction processes. Moreover, the analysis conducted herein will contribute to deepening the understanding of LCA applications in various construction projects in the subsequent chapters of this thesis.

3.1 Life Cycle Assessment and Sustainable Construction: A Comprehensive Review from Theoretical Foundations to Practical Strategies and Innovative Methods

The 1970s primarily focused on assessing and contrasting various consumer products; however, these studies made minimal contributions to the utilization phase [1]. During the early 1980s, the construction sector began adopting life-cycle thinking, prioritizing utilizing renewable resources [2]. In the 1990s, the Society for Environmental Toxicology and Chemistry (SETAC) spearheaded efforts to unite LCA practitioners and establish standards for the field's framework, method, and terminology. This ultimately improved the SETAC "Code of Practice" [3]. During this time, SETAC's program significantly contributed to LCA's methodological and scientific advancement, strengthening its reputation as a responsible method for environmental impact estimations. The International Organization for Standardization (ISO)'s involvement in 1994 created the ISO 14040 series, published in 1997, to provide guidelines and general principles for conducting an LCA. Several years later, the ISO 14044, published in 2006, contains requirements and guidelines for carrying out LCA studies. In 2013, ISO 14025 was published, which provided guidelines for developing Type III environmental declarations, a type of LCA-based product environmental labeling. Since the beginning of the twenty-first century, LCA has been increasingly emphasized. In the last decade, in addition to the standards ISO 14040, specific developments have been aimed at the construction industry [4]. In addition, many academic papers have significantly supported the development of LCA. [5], for example, introduced the LCA methodology, data collection, interpretation, and impact assessment. According to [6], the report included practical tips on how to do a life cycle assessment study, like the quality and uncertainty of data analysis. On the other hand, [7] offered his most recent version of a thorough manual on LCA studies, the review of existing standards and tools, and applications. Life Cycle Assessment is a widely used method to determine the environmental impact of products and systems. It has advanced through many influential academic and commercial contributions that enable LCA to be recognized as an essential tool for sustainable development due to the holistic appraisal of any kind of product or service. Studies from LCA are classified according to studies that cover building sustainability. These sections of the building life cycle assessment help to provide valuable information about the various concepts and publishing goals on life cycle assessment in the construction sector. There exist classification systems, including

the division of LCA studies based on the type of environmental impact assessment, energy analysis, and building material assessment. Environmental impact assessment is focused on the environmental impacts of a product or service, while energy analysis is assessing an entire system that uses all inputs and outputs as directly consumed. Several studies in the literature explore the integration of LCA and other approaches to support sustainable building practices caused by multiple construction materials and techniques. In addition, various studies in the literature explore the integration of LCA and other integrated approaches to support sustainable building practices.

3.1.1 In terms of Environmental Impact Assessment

Many studies have been carried out on the environmental impacts of building designs and construction projects in the context of environmental impact assessment. [8] stated that an integrated study of building performance is required throughout the design phase to avoid creating buildings with unacceptable performance characteristics. Computer-aided simulation is the most efficient way to achieve this goal. This study provides a viable technique for assessing building performance, encompassing elements like comfort (including lighting, ventilation, and heating), room acoustics, and environmental impacts that can be implemented in the ESP-r design. In their comprehensive environmental LCA, [9] strove to establish the causal relationship between the potential environmental impacts of the various environmental life cycle components. This research assesses the main environmental impacts of a brand-new and upscale office building over 50 years. As the results show, electricity consumption and building material production have considerable environmental impacts, while construction and demolition have relatively small effects. [10] aimed to determine and contrast the probable environmental impacts of an office building throughout its existence. The study's findings confirmed that a typical contemporary office building has many of the same environmentally critical life cycle phases and components, regardless of the design groups, contractors, or occupants. The emphasis by [11] highlights the necessity of prioritizing environmental performance in the design procedure to mitigate the environmental impacts of buildings. The multi- criteria optimization method

presented in this study could help designers create green buildings. The LCA methodology is utilized to evaluate design options on both ecological and economic bases. Using data from the German "Centre for Construction Costs" [12] performed an extensive LCA on several buildings. This analysis mainly aimed to assign significant phases or components of the construction process that needed a high-level assessment and effort from an environmental point of view. LCA model designed by [13] for building cooling and heating source systems. In addition to evaluating energy consumption, this model incorporates resource use and pollutant emissions, delivering a complete index for assessing the total environmental impact throughout the structure's lifespan. Moreover, [14] categorized the construction of a wide variety of schools by analyzing their construction processes. They technically and sustainably analyzed the building technologies in way that identified how they improved quality while reducing the environmental burden of buildings. As a result of their research, [15] proposed a new method to calculate the environmental impacts of residential building refurbishment in Türkiye. The current study estimated the various environmental impacts of renovation techniques, and it helps people to approach the sustainable building topic within the Turkish housing typology. Moreover, several architectural parameters, such as window-to-wall ratio (WWR), building age, and face orientation, are analyzed. Finally, it is understood from the results that WWR is the most dominant factor that affects the percentages of the environmental performance achieved due to renovation. Furthermore, [16] proposed a hybrid LCA example to perform a more exhaustive study of the embodied environmental impacts of constructions. [17] aim was to look at the differences in the environmental impacts that a single module of a building is experiencing through a series of stages, which are supposed to be seen as the layers of a life cycle shearing. The research showed how individual steps in a building's cycle impact the environment and, therefore, gave more insights into the overall building design and construction methods being sustainable.[18] carried out the Life Cycle Assessment, an analytical technique, to measure and evaluate the environmental impacts of common residential construction works in Egypt. Using life cycle assessment, [19] studied the environmental impacts of 23 primary schools in South Korea. A parametric LCA technique has been suggested, according to [20], that will allow

architects to effectively design buildings where the environmental impacts are reduced. Also, [21] conducted a comprehensive life cycle analysis of the environmental impacts of modular prefabricated houses in Italy. They have contributed a favorable opinion on sustainability in Italy through this study by giving an in- depth analysis of the positive and negative influence of such building practices on the environment. Lastly, [22] estimated the environmental implications of a residential structure in a significant Indian metropolis throughout the construction period.

3.1.2 In terms of Energy Efficiency

Several studies have been conducted to evaluate various energy efficiencies and consumption in the design and construction of buildings from an energy analysis point of view. [23] utilized life cycle energy assessment to investigate the energy efficiency of various design concepts for a residential dwelling in Australia. [24] conducted an energy analysis on a bioclimatic dwelling for low-income families to determine potential areas for advancement in future large- scale residential initiatives in developing nations. [25] examined the fundamental requirements for regulatory and certification programs for buildings to regulate and limit energy consumption in the construction sector beneficially. [26] proposed a systematic approach to evaluating the life cycle energy efficiency of smart buildings. This approach solves a multi- criteria decision-making problem and provides useful information in assessing these buildings. [27] presents results of energy value comparison between different materials in order to determine what conclusions can be drawn by urbanists and architects for a longer-lasting building with a greater advantage towards the environment. [28] have studied the potential for energy savings that could be attained by adopting bioclimatic building design in desert regions. The aim of the study was to evaluate bioclimatic strategies for sustainability practices in building construction while restraining energy consumption under local environmental criteria investigated. Furthermore, [29] investigated five distinct residential structures to determine the amount of embodied energy linked with the principal materials used in each construction project. [30] laid the groundwork for a construction LCA program concentrating on energy usage and carbon dioxide emissions. The phrase net energy

is introduced and employed in the study by [31] for the built environment. This uses a technique that considers both the building elements' embodied energy and energy consumption during operation. The study suggested incorporating the net energy ratio (NER) into building design as a metric that considers the entire lifespan of the structure. The primary objective of the research conducted by [32] is to determine which operation phase most influences the life cycle of a tourism facility. An analysis was conducted on a subset of hotels' energy consumption, refuse generation, and carbon dioxide emissions over fifty years. Based on the findings, it was determined that the operational phase, which considers between 70 and 80 percent of the overall energy usage, had the most significant influence. When it comes to the process of how a building can be energy efficient, [33] argues that enhanced environmental performance allows all aspects that are responsible for increasing the efficiency of energy in a building to be incorporated through effective strategies. Even so, this work shows how to combine different data aspects like legal and voluntary regulations, rating systems for recognizing energy efficiency, and life cycle evaluations and simulations as part of the assembly/disassembly phase processes and materials selection. In an investigation executed in Lisbon, [34] did a study in Lisbon about energy efficiency and greenhouse gases from three typical urban buildings. They focused on homes and wanted to check the overall energy use during the buildings' life cycle. Their analysis helps them define what an "eco-friendly" building is—a home that produces minimal emissions throughout its life. [35] conducted research in order to find the environmental impacts of building two museums in China with one of the lowest energy-saving. Among other things, the life LCA was done to find out the energy usage and greenhouse gas emissions connected to the museums. [36] performed a thorough LCA to measure the energy and carbon emissions an industrial building produces throughout its development. The LCA, presented by [37], is related to a low-energy industrial building in Thailand seeking green building certification from the German Sustainable Building Council (DGNB). Also, [38], in their investigation, performed an in-depth LCA for the energy efficiency of an Italian prefabricated home module and showed the energy efficiency of prefabricated housing as a key part of a sustainable energy system. [39] created the China Building Development Model, in which the authors analyzed

the amount of carbon pollution and energy consumption due to the development of buildings in China. The researchers utilized the CBCM to investigate the trends in environmental impacts resulting from Chinese building construction between 2000 and 2016. [40] accomplished the first comprehensive evaluation of a campus in the Asia Pacific region at Nanyang Technological University (NTU). Twenty-two academic buildings were subjected to a life cycle energy assessment. [41] investigated sustainable design principles and assessed the energy efficiency of a residential unit structure employing a life cycle energy analysis. [42] thoroughly reviewed measures related to embodied energy and greenhouse gas emissions in construction processes between the United Kingdom, Canada, Australia, and the United States. Their analysis aimed at recognizing differences among these regions from the perspective of methodologies and their longer-lasting implications for future industry developments.

3.1.3 In terms of Building Material Assessment

As for building material assessment, much research has been done in the field to find out the eco-profiles, characteristics and impacts of different construction materials. [43] conducted an LCA to compare ceramic tiling against marble tiles as a floor covering material to identify one with more environmentally preferable characteristics than another. Compared to marble tiles, ceramic tiles have a life cycle score of almost twice as low. In [27] study, building materials with extensive use, including cement, steel, and aluminum, are examined for their embodied energy and determined in the parts of the building that use the most energy over its whole life. A study conducted by [29] examined the embodied energy of five residential structures that used concrete, brick, glass, and steel. According to the result, the building sector would significantly decrease its environmental impacts and embodied energy by using recyclable and reusable materials. [44] offered a life cycle assessment of an insulating board made from kenaf fiber using international standards. In the conducted study, several types of insulation were compared. Using simulations, In their study, [45] analyzed the impact of construction materials on the energy usage and global warming potential of four comparable office building designs throughout their life cycle: timber, steel, concrete, and timber plus. In their analysis, [46]

evaluated the climatic impacts of reinforced concrete structures versus timber structures across four buildings, seeking to estimate the effect of each construction material on environmental sustainability. The analysis utilized LCA to gather relevant data. Furthermore, [47] evaluated the environmental impacts of twenty masonry residential buildings concerning their installation materials. It has been determined that foundation materials are responsible for the most adverse environmental impacts. [48] examined, with the LCA approach, the carbon footprint of precast concrete pile products during their whole life cycle. [49] used an LCA-based carbon emission model to calculate the greenhouse gas emissions of residential construction materials in multiple regions.

3.1.4 In Terms of Integrated Integrated Approaches to LCA: Emphasis on Sustainability, Circular Economy and Building Information Modelling

Several integrated studies and research attempts combined several methodologies to demonstrate comprehensive evaluations and perceptions in regard to sustainable construction activities. [50] study focused on the environmental impact of the consumption of natural resources and disruption in pollutant emissions between areas during the construction sector, aiming at finding new ideas to promote sustainable development. The analysis offers a unique LCA method, "region-type life cycle impact assessment (R-LCIA)," to comprehensively examine building environmental impacts. This can provide both the regional and overall environmental burden at different scales. In another study, [51] developed the Life Cycle Green Cost Assessment (LCGCA) due to a demand for comprehensive evaluation systems that highlight sustainability in construction activities. An innovative method that combines LCA with a study of life cycle costs (LCC) makes it possible to assess the environmental and economic aspects of the buildings throughout their whole lives. This integrated approach redefines the frontiers of traditional LCA by combining concepts of LCC within a framework that allows the assessment of holistic sustainability performances. Furthermore, [52] carried out a full LCA study in order to investigate the potential for combining Building Information Modeling (BIM) to accomplish a detailed life- cycle assessment of whole buildings. BIM tools and Ecotect can aid LCA by providing important base data and calculation means for an

LCA. The life cycle carbon emissions model, abbreviated as the LCCE model, was conceptualized by [53]. The newly suggested model facilitates the estimation of the collective carbon footprint generated by all buildings within a city throughout the entire duration of their operational life. Review studies by [54] of a commercial building in Singapore revealed life-cycle assessment data with waste generation over the operating time frame. The research has also seen the compatibility between techniques of minimization, sorting, collection, and recycling for the building level. This analysis was informally reviewed against a policy framework of full solution provision. A conceptual structure was introduced by [55] to integrate the interior environmental quality (IEQ) impacts of an entire building into a life cycle analysis. The findings demonstrated that incorporating IEQ factors in the entire building LCA revealed internal effects in several life cycle impact assessment (LCIA) classifications equivalent to external effects. To ensure that all Canadian schools' exterior and structural systems undergo extensive sustainability evaluations, a paradigm combining the LCA and the Leadership in Energy and Environmental Design (LEED) program was proposed by [56]. This model incorporates LCA into LEED and provides suitable LEED ratings. This helps the individual to make informed decisions and aids in creating building design and construction that is environmentally appropriate. Incorporating the LCA within BIM, [57] give a decision-making methodology within the context of the building that is very useful in sustainable development and environmental protection. An integrative LCA concept was proposed by [58]. This model integrates all life cycle assessment data related to building materials, structural components, and the complete building into a unified framework. [59] proposed that integrating machine learning (ML) and LCA can significantly decrease environmental impacts. [60] suggest that integrating BIM with LCA and LCC analysis offers a feasible technique for evaluating and optimizing buildings' economic and environmental impacts.

3.1.5 Other Methodological Approach

Other than discussing the different methods listed, supporting models and frameworks have been presented to ensure the life cycle assessment of buildings and indicate sustainable construction measures. A hybrid method for building life cycle

evaluation was proposed by [61] that utilizes national input-output data to complement the gaps in standard LCA data. The primary objective of [62] paper is to provide a novel semi-quantitative technique for calculating the embodied and carbon building's environmental impacts and compare several LCA tools for the building industry. [63] demonstrate the implications of applying an LCA methodology to buildings during the initial stages of the design process. In another research, [64] described a method for incorporating LCA data into early-stage design decisions for commercial structures, making a comparison to the existing LCA tools and databases, and outlining the "next stages" in creating an extensive LCA standard. [65] proposed a dynamic LCA framework that considers the temporal perspective and value preference of users. The methodology was then illustrated in an elementary school case study, showing the importance and insights of dynamic LCA as compared with conventional static LCA. Using life-cycle analyses, [66] sought to choose an earthquake-resistant design that is ecologically friendly.

3.2 Life Cycle Assessment (LCA) in Educational Buildings: Examples from the Literature

Presently, the construction sector is a key contributor to the intensive consumption of natural resources and environmental impacts. In particular, school buildings continue to hold utmost importance environmentally and socially for the sustainable continuation of educational activities. Therefore, their proper evaluation of potential environmental impacts throughout the life cycle is considered paramount for sustainable construction practices. Life Cycle Assessment (LCA) is a systematic evaluation of the environmental impacts of a product or building at every stage of the life cycle, from raw material extraction and production, via use and maintenance, to waste management. This criterion is widely adopted to evaluate and provide analysis on buildings as environmentally friendly and also further identify possible solutions for more sustainable design. Especially in structures like school buildings that provide societal benefits, LCA assumes distinctive significance in design because such buildings see an extended lifespan and hence high energy consumption. This section reviews existing studies on life cycle assessment in school buildings. It contributes the findings of studies focusing on LCA analyses of school buildings

with different typologies in various regions, including methods and evaluation criteria. Additionally, it identifies the importance of sustainable design and materials selection. It, thus, highlights the contribution and position of methods and findings found in this study in the existing literature. Through the literature on construction and retrofitting of sustainable schools, the importance of including environmental, economic, and social aspects into decision-making frameworks is evident. Various studies describe methodologies, tools, and strategies for achieving sustainability in educational buildings. [67] developed the Integrated Value Model for Sustainable Assessment (MIVES), a multi-criteria decision-making framework designed to evaluate the sustainability of architectural technologies used in school construction in Catalonia, Spain. The model assesses sustainability based on environmental, economic, and social parameters, highlighting emissions from materials, energy consumption across different life cycle stages, and the adaptability of construction techniques. Additionally, their comparative analysis of onsite concrete, precast concrete, steel, and timber technologies demonstrated that prefabricated systems can significantly enhance sustainability without compromising functionality. [68] investigated the role of Life Cycle Assessment (LCA) in enhancing energy efficiency and environmental performance in building construction. The consideration of both operational and embodied energy throughout a building's life cycle necessitates holistic applications of LCA. Their incorporation of international LCA standards demonstrated how life cycle thinking can drive sustainable innovations aimed at reducing the consumption of materials and energy. A case study by [69] emphasizes the relationship of energy-saving features with cost-effectiveness through thermal modernization of school buildings in Poland. They demonstrated the potential benefits of using the LCA approach integrated with energy audits to identify the optimal retrofit strategy that reduces heating loads and emissions. Their findings show that policy support and financial instruments play a vital role in achieving sustainable retrofitting of educational institutions. In an assessment of campus buildings, [70] applied LCA methods, narrowing in on impacts regarding operational energy. They presented new parameters for energy performance certification, recognizing not only the direct energy use of buildings (including heating and cooling), but also energy impacts of a more indirect nature, notably through material

production. This holistic approach indicated that more informed decision-making processes could be put into place when considering sustainability at operational phases in educational buildings. [71] explored educational patterns related to improvement, emphasizing the key role of contextual factors, leadership dynamics, and collaborative practices. This study focuses predominantly on academic performance, in which the corresponding methodological frameworks and longitudinal analysis reveal some valuable insights into the integration of environmental sustainability into wider school improvement strategies. [72], within the framework of the GAIA project, developed a methodology that uses Internet of Things (IoT) infrastructures to create conscious energy-saving behaviors in school facilities. The findings demonstrated the significant energy reduction that could occur as a result of the use of real-time sensor data and gamified approaches, all while enhancing sustainability awareness among students and teachers. [73] concluded a Life Cycle Energy Assessment (LCEA) on a nearly Zero Energy Building (nZEB) school in Spain. They emphasized the pre-use phase energy consumption occasionally equals or exceeds operational energy, thereby establishing the need for adopting an overall life cycle perspective in building design. [74] carried out a case study investigating envelope improvements and energy-efficient building materials in the context of an existing school building in Istanbul, Türkiye. Energy and Environmental benefits of passive design strategies are quantified through computer simulations with Energy Plus, showing considerable reductions in operational as well as embodied energy. A comparative analysis was conducted between the demolished historic and current school structures in Greece [75]. The analysis manifested substantial differences in embodied energy and Global Warming Potential owing to the differences in structural materials and the period of service of the buildings. LCA conducted by [76] on a building for a school in Iceland, focused particularly on materials used and their transportation. It found that local production plays a significant role in reducing embodied emissions and a smaller environmental footprint in areas depending on imported materials for construction. In their work, [77] assessed the whole life carbon footprint of a Finnish educational building using two commercial LCA software tools, GaBi and One Click LCA. The study revealed that embodied carbon contributed most to total carbon footprint, with concrete and

steel identified as the principal contributors to negative environmental impacts. The authors emphasized the need for harmonization in software methodologies to improve comparability and accuracy in LCA studies. The integrated model of Life Cycle Assessment (LCA) and Leadership in Energy and Environmental Design (LEED) was introduced by [78] to assess the sustainability of structural and envelope systems of school buildings in Canada. This study within LEED criteria integrated LCA to provide insight into the trade-offs in operational energy and embodied energy of materials, such as concrete, steel, and wood, supporting claims for sustainability. [79] addressed the thermal rehabilitation of schools in Portugal, comparing traditional and cork-based mortars. Their LCA showed that the use of cork-based mortars significantly reduced embodied energy and CO2 emissions compared to EPS (Expanded Polystyrene)-based alternatives. This further indicates the viability of sustainable materials in addressing energy efficiency issues coupled with environmental sustainability. The paper provides early guidance on the trade-offs between locally produced and imported materials and offers preliminary guidance to the entire region dependent on external sources.

3.3 Findings and Conclusion

After a comprehensive review of the existing literature, it became evident that a substantial amount of research has been dedicated to LCA in the building sector, indicating a notable emphasis on promoting sustainable building methods.

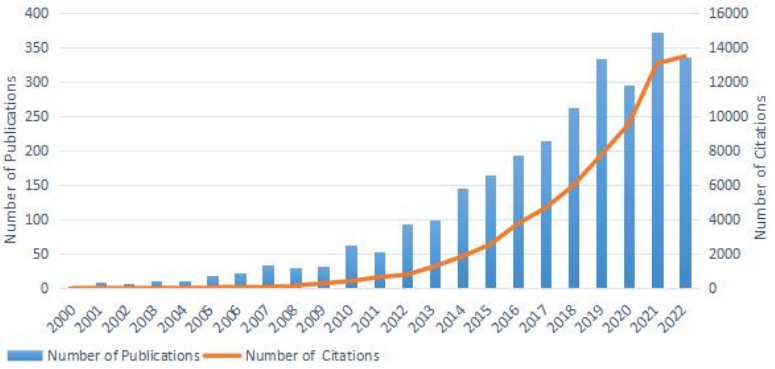


Figure 3.1 Number of publications, citations from 2000 to 2022 (created using data from the web of science)

The number of papers about building Life Cycle Assessment (LCA) has increased noticeably, as shown in the presentations in Figure 3.1. This movement underscores the research community's growing interest in and attention to sustainable building practices. The number of publications reached its height in 2021 with 373 publications. The quantity of citations has continuously increased throughout the years (Figure 3.1). The increasing number of studies being conducted in this field suggests that LCA is being acknowledged as an effective tool for estimating the sustainability of structures during each phase of their existence. Based on the various studies mentioned, building performance's effect on the environment is a big consideration in the building sector. LCA provides a basis for thoroughly evaluating the environmental impacts of each phase in the life cycle of a building, from construction to operational energy use and eventual demolition. Additionally, the studies conclude that architectural issues such as building ages, orientation, and window-wall ratio could affect the performance of buildings towards their environmental aspect. Overall, the studies demonstrate how critical it is to prioritize environmental implementation throughout the layout and installation of buildings and use LCA to evaluate the environmental impacts throughout a structure’s lifetime. The energy analysis investigations specifically emphasize LCA and embodied energy and demonstrate various energy examination methodologies in the built environment. These studies emphasize the necessity of considering buildings' embodied energy and operational phase. It also emphasizes the capacity to implement energy-saving strategies and sustainable design standards that reduce energy consumption and, consequently, lessen greenhouse gas emissions. Several of these studies also demonstrate the international scope of research in this area, including countries such as Australia, China, Italy, Portugal, Thailand, and the United States. These conclusions are of great guiding significance to the development and building of energy conservation and environmental protection buildings, and the evaluation may be mainly oriented to building materials when the research is deepened. LCA’s of various building materials have been conducted, such as ceramic and marble tiles, cement, steel, aluminum, concrete, glass, bricks, and insulating boards made from kenaf fiber and timber. The results of all these studies suggest that, indeed, the integration of recyclability and reusability in the materials employed may lead to a

significant reduction in the environmental impacts as well as embodied energy. The findings prove helpful in material selection for use in new modern constructions and highlight the environmental requirements. When replacement, in the case of older buildings, is required, the replacement now matches the modern-day environmental needs. In conclusion, building material assessment should be one the priorities in sustainable construction, and LCA can provide significant data that act as useful tools for you to make decisions to wisely select the best materials. The approach employs the complete set of indicators effectively and efficiently with an entire overview of the sustainability of the building that may guide future activities or assist in accountability and complying with targets linked with environmental management and sustainable development. Several integrated approaches and models are mentioned, such as LCGCA, the combined consideration of the LCAeLEED model, R-LCIA, and LCCE. Machine learning (ML) has also been identified as having the potential to significantly contribute to reducing impacts. The study presents the significance of the native point about developing sustainability assessment in terms of numerous aspects across life cycle stages for buildings. The results of this study are a strong indication that LCA is very important for the establishment and implementation of sustainable construction methods. Life cycle assessment is a necessary tool for proper decision-making of sustainability in construction sectors, which in turn is achieved through the full life cycle of the building. The findings demonstrate that using LCA is a method for the identification of the best choices for the selection of construction materials, design, and the operation of surfaces and buildings.

The construction industry, which is an essential participant in environmental degradation, has therefore been experiencing an increase in eco-friendly methods in response to environmental issues. Sustainable practice becomes vital today, as this is one of the ways for the industry to solve environmental issues with the help of energy efficiency, resource conservation, and the reduction of harmful emissions. The most vital element of the sustainable building approach is the use of a holistic method that integrates the entire life cycle of a component or system. Life cycle assessment is a multi-perspective evaluation of building construction, operation, and maintenance life cycles to determine their respective environmental impacts. This

presents developers, designers, and policymakers with valuable information that helps in identifying improvements to make the decision process more sustainable. LCA allows the comparison of different architectural and construction choices with regard to their environmental impact. This approach is aimed at selecting the most sustainable alternatives while setting the stage for the development of environmentally friendly practices. An extensive literature review was carried out to provide a full overview of the use of LCA in the property construction sectors. It provided synthesized information on the progress of knowledge regarding the application and feasibility of these methods, specifically within property-building areas, including research studies conducted so far. In conclusion, LCA is the technique that helps get a detailed view of all the environmental impacts associated with industrial processes and products. Therefore, sustainability is considered an essential part of efforts.

CHAPTER 4

THEORETICAL BACKGROUND: ENVIRONMENTAL IMPACTS, SUSTAINABILITY, AND LIFE CYCLE ASSESSMENT IN THE CONSTRUCTION INDUSTRY

In the modern world, with rapidly increasing population and urbanization, the construction sector accounts for a significant share of global energy consumption and carbon emissions. This situation necessitates evaluating the sector's activities not only in economic terms but also in terms of their environmental and societal impacts. In particular, various approaches are being developed to reduce the ecological footprint that arises at all stages of a building's life cycle—design, construction, use, and post-demolition waste management. In this context, the concepts of sustainable architecture and Life Cycle Assessment (LCA) offer the potential to analyze and address the environmental impacts of the construction sector from a more holistic perspective. Sustainable architecture shapes the design and implementation processes of buildings by considering their ecological, economic, and social dimensions together. The goal is to minimize environmental impacts throughout the building's life cycle by efficiently using energy, water, and material resources, while also ensuring a high level of health and comfort for occupants. When applied broadly in the construction sector, this approach not only reduces the environmental footprint of individual projects but also contributes to the creation of a more environmentally conscious future at the societal level. In particular, educational buildings constitute one of the most critical examples of this transformation, as they serve a large user base and play a crucial role in cultivating environmental awareness among future generations. Strengthening such awareness—both among students and the broader community—is closely related to designing school buildings in accordance with sustainability principles. Life Cycle Assessment (LCA), which allows for an objective and quantitative evaluation of the construction sector's environmental impacts, conducts a comprehensive analysis of the environmental indicators at every stage of a building—from raw material acquisition to waste management. Under

LCA, various data are collected, ranging from the production of building components and on-site processes to the energy and water consumption during operation and the recycling or disposal processes at the end of a building's service life. Consequently, it becomes possible to measure how decisions made during the design phase or improvements made throughout the project affect the building's environmental performance. This, in turn, simplifies the integration of sustainability goals into architectural practice by backing them up with concrete outcomes.

Examining these concepts—sustainable architecture, environmental impacts in the construction sector, and LCA—in an integrated manner makes it feasible, within the scope of this thesis, to understand how these approaches can be applied to educational buildings, especially certain typologies or standardized projects. Accordingly, this thesis aims to establish a guiding theoretical framework by jointly evaluating the construction sector's environmental impacts, the fundamental principles of sustainable architecture, and LCA methodology for the development of eco-friendly strategies in the design and construction of school buildings.

4.1 Introduction: Focusing on Environmental Problems

Through historical processes, humanity's relationship with natural resources has undergone significant transformations driven by technological and societal changes. This dynamic relationship, shaped by humanity's pursuit of knowledge, utility, and the influence of a changing environment, has significantly impacted natural systems. During earlier periods of human history, societies heavily relied on the resources provided by nature to satisfy their fundamental needs. These practices relied primarily on water for crop irrigation and community sustenance. Similarly, wood became the principal material for construction and fuel. Although these activities may have locally disrupted forest cover or soil quality, their limited scale and gradual pace of development minimized their environmental impact [80]. However, key moments like the Industrial Revolution represented a pivotal moment in this longstanding and proven pattern. The Industrial Revolution—marking the transition of societies from agrarian to industrial economies in the late 18th century—represents a pivotal moment in history. Mechanization, steam power, and

the use of fossil fuels accelerated production processes, propelling many societies toward unprecedented economic growth. However, it led to the gradual and uncontrolled over exploitation of natural resources and extensive environmental damage caused by industrial activities. Industrial emissions and waste became major contributors to environmental degradation, with air and water pollution emerging as critical issues [81]. Since the mid-20th century, these problems have intensified and transformed into global crises. Notable among them are global warming and climate change, propelled by elevated greenhouse gas concentrations in the atmosphere. These changes have led to notable increases in global temperatures, melting glaciers, rising sea levels, and more frequent extreme weather events. Concurrently, biodiversity loss has accelerated significantly. Habitat destruction, pollution, overfishing, and climate change collectively threaten numerous species with extinction. Studies around the globe illustrate the increasing extinction rates, underscoring the profound consequences of human activities [82,83]. Currently, humanity is grappling with profound challenges in mitigating the environmental and resource-related impacts of human activities. This section critically examines these core environmental crises, emphasizing the urgent need for evidence-based, globally coordinated solutions. This research investigates the multifaceted dimensions of critical environmental issues, including climate change, biodiversity loss, pollution, and urbanization, all of which threaten the stability of natural ecosystems. By delving deeply into these pivotal challenges, the subsequent sections aim to elucidate their root causes and far-reaching implications.

4.1.1 Climate Change and Its Global Consequences: An In-depth Analysis

Climate change is a significant issue affecting natural, economic, and social balances worldwide, particularly due to accelerated global warming during the last century. The phenomenon originates from increasing concentrations of greenhouse gases in the atmosphere due to human-related activities such as industrial processes, transportation, and energy production. The processes contributing to increased greenhouse gas emissions since the Industrial Revolution—fossil fuel use, deforestation, agricultural practices, and industrial production—have collectively contributed to the rise in global temperatures [82]. These long-term patterns

underscore the cumulative impacts of industrialization on the environment, highlighting the strong need for sustainable solutions. An increase in temperature on the planet has influenced various ecosystems across the globe, especially in the polar regions. One of the major ways through which rising sea levels are brought about is melting polar ice caps and retreating land glaciers. Satellite and ground measurements show that global sea level is rising at an average rate of approximately 3.3 millimeters a year since the middle of the twentieth century [84]. Sea level rise poses significant threats to coastal communities, including flooding, eroded shorelines, saltwater intrusion, and damage to infrastructure [82]. Global sea levels are expected to rise approximately 0.3 to 1 meter by 2100—thereby increasing the vulnerability of many coastal areas to such risks [84]. Such projections draw out the importance of strategic planning to respond to the challenges faced by coastal communities. Additionally, temperature rises influence not only the rise of sea levels but also terrestrial ecosystems and agricultural productivity. Agriculture is negatively impacted by climate change because water becomes scarcer, and in high-temperature regions, plant growth cycles do not function optimally, lowering harvests. Occasional droughts and erratic rainfall cause serious damage to water-dependent agricultural enterprises. For example, rising temperatures and diminishing water resources are resulting in notable yield reductions for agricultural lands in the Sahel region of Africa and the Middle East [85]. This, in turn, exerts notable pressure on global food security and exacerbates problems of hunger and malnutrition across the planet [85]. The pressures on global food security are not solely due to declines in agricultural production but also due to increasing populations of pests. Conditions of warmer and more humid climates promote the dispersal of insects, thereby increasing agricultural product losses. For example, many countries in Asia, Africa, and South America are experiencing considerable agricultural losses due to the spread of pest infestations exacerbated by climate change. These interlinked challenges demand coordinated global efforts to enhance food security and resilience in agricultural systems. Developing nations are most affected by this phenomenon, where human livelihoods are compromised. Climate change significantly threatens biodiversity. Many species of plants and animals are unable to accommodate changes in temperature, lose habitat, or change migration routes. This type of ecosystem degradation interrupts

natural cycles, thereby threatening the biological balance of our planet. Alterations in ecological systems will affect not only flora and fauna but also human communities, resulting in long-term negative impacts on health and quality of life [86]. Addressing these interconnected issues requires both immediate local action and long-term international strategies to sustain biodiversity and ecosystem health.

Thus, climate change has significant implications across a broad spectrum of fields, from environmental systems to agricultural production, food security, and biodiversity. Addressing climate change impacts requires direct international actions—transitioning to renewable energy sources, adopting sustainable practices in agriculture and water management, and protecting natural ecosystems. This global challenge keeps raising a strong need for immediate resolution and a multidisciplinary approach toward ensuring sustainability for future generations.

4.1.2 The Decline in Biodiversity: Exploring the Environmental and Societal Consequences

Biodiversity loss, together with climate change, stands at the forefront of contemporary environmental challenges, endangering the resilience, functionality, and health of ecosystems. Essential to the sustainability and development of ecosystems, the rapid extinction of many species, such as pollinators like bees, keystone predators like wolves, and marine species like coral and fish, compromises ecosystem functionality and results in ecosystem degradation. Contributors to biodiversity loss include human-initiated habitat destruction, among which are deforestation, pollution, overfishing, agricultural expansion into forests, and global warming. Deforestation, rising sea temperatures, pollution, and overfishing are among the foremost threats to marine ecosystems and significantly accelerate extinction rates beyond natural baselines [86]. Tropical forests, including the Amazon Rainforest, harbor much of the world's biodiversity. The Amazon Rainforest is not only a habitat for millions of species but also an important regulator of the global climate. However, deforestation in the region has been high in recent years due to land clearing for agriculture and livestock, forest fires, and illegal logging—the main culprits of biodiversity loss [87]. Biodiversity loss extends beyond deforestation; the oceans, which play a critical role in sustaining these

ecosystems by regulating climate, supporting marine food chains, and facilitating carbon sequestration, are under significant threat. The destruction of biodiversity-rich areas such as coral reefs is due to the combined impacts of overfishing, pollution, and ocean temperature increases driven by climate change [88]. Coral bleaching, occurring as a result of extreme increases in sea surface temperatures, is rapidly degrading marine ecosystems [89]. Ocean acidification and overfishing have been cited as the major contributors to marine biodiversity depletion due to dwindling populations of marine life [90]. This decline has notable impacts on human society, wherein risks to food security arise from declines in agricultural production, economic depressions due to fisheries and tourism disruptions, and increased vulnerability to natural disasters as a result of the depletion of ecosystem services. The reduction of ecosystem services endangers the socio-economic stability and cultural heritage of indigenous peoples and local communities dependent on these ecosystems. Ecosystem degradation has been linked to decreased agricultural productivity, polluted aquatic systems, and an increased frequency of natural disasters [91]. Consequently, the preservation of biodiversity is essential not just for the viability of ecosystems but also for economic stability. Global policies aimed at conservation, including the expansion of protected areas and sustainable management supported by adequate financial resources, are strongly needed. Restoring the principles of ecological resilience will, then, ensure the sustainability of ecosystems by balancing the needs of present and future generations.

4.1.3 From Pollution to Preservation: Effective Management of Resources and Waste

The growing air and water pollution during the industrial revolution has evolved into a significant environmental challenge of the modern era. The fast pace of urbanization, expansion of industrial activities, use of fossil fuels, and ineffective waste disposal have exacerbated air and water pollution worldwide. This pollution hinders the sustainable management of these resources and leads to adverse effects on ecosystems as well as human health in the long term [92]. Air pollution is a major health concern for urban residents. The list of air pollutants includes fine particulate matter (PM2.5), ozone (O3), nitrogen dioxide (NO2), and sulfur dioxide (SO2),

which cause a range of diseases in the respiratory and cardiovascular systems, leading to millions of premature deaths each year [93]. According to the WHO (World Health Organization), almost 7 million people die every year because of air pollution [93]. Air pollution can affect general health, with a more pronounced impact on vulnerable groups such as children, elderly people, and those with chronic diseases. Research suggests a direct association between air pollution exposure and serious health impairments such as asthma and bronchitis, as well as lung growth retardation in children [94]. In addition to air pollution, water pollution poses equally significant challenges, further exacerbating the strain on ecosystems and human health. Water pollution threatens drinking water sources, industries, farmers, and natural ecosystems throughout the globe. Currently, urban and industrial waste is released into rivers, lakes, and oceans without treatment, and pesticides and chemical fertilizers from agricultural land contaminate groundwater and rivers. Indeed, poor water quality has significantly restricted access to potable water. Water pollution is a significant environmental issue involving pollutants such as heavy metals, pesticides, and industrial chemicals, which severely impact human health and biodiversity. The accumulation of garbage in freshwater ecosystems is rapidly diminishing the rich habitat of numerous aquatic species [95]. Plastic waste poses a notable concern for aquatic ecosystems. Ingestion of plastic by marine animals, mistaking the particles for food, or entanglement in debris leads to the death of these creatures. Research shows that plastic pollution has resulted in extensive degradation of marine ecosystems worldwide and rendered many marine species endangered. [96] found that 9% of the total plastic ever made in the world is recycled, while the rest either goes into landfills or is immediately discarded into the environment. Over time, these plastics disintegrate into microplastics, which cause long-lasting harm to aquatic ecosystems. These concerning trends underscore the strong need for innovative strategies to address pollution at its source. Addressing pollution challenges necessitates pollution reduction and the sustainable management of natural resources. Particularly in the context of climate change and the increasing demand for water, water management must be sustainable. Poor water management can increase vulnerability to water scarcity in many parts of the world. Similarly, reducing fossil fuel demand, transitioning to renewable energy, and promoting the diffusion of clean

energy technologies are crucial for mitigating air pollution [95]. Sustainable natural resource management will be one of the major strategies for pollution control and ecosystem management. Comprehensive global efforts focusing on pollution control and sustainable resource management are essential to safeguarding both environmental and human health.

4.1.4 The Rise of Urbanization: Shaping Ecosystems and Society

Urbanization is one of the different aspects of modernization that constitute its direct and visible characteristics, affecting large portions of the entire population. This process has led to environmental impacts on infrastructure demand, energy consumption, and the use of natural resources. Urban areas are centers of economic development, fostering advancements in industries such as finance, commerce, and information technology. In addition, they provide a background of technological innovations such as smart city infrastructure, renewable energy technologies, and advanced transportation systems. While urban areas concentrate resources, they also contribute significantly to pollution and environmental degradation [97]. This increasing urbanization not only drives resource consumption but also exacerbates challenges related to energy efficiency and climate change. Urbanization increases energy demand, thereby driving fossil fuel consumption and amplifying the carbon footprint. The accelerated rate of urbanization has caused an unsustainable escalation in energy use, as cities have become a notable strain on our climate system. Energy systems reliant on fossil fuels such as coal, oil, and natural gas drive greenhouse gas emissions, including carbon dioxide (CO2) and methane (CH4), contributing to the progression of climate change. Globally, cities are accountable for around 75% of global energy consumption and 70% of greenhouse gas emissions [98]. Thus, on this issue, supplementing renewable energy sources and using technological advancements to potentially improve energy efficiency would be essential in addressing the challenges of urbanization. According to UN data, 55% of the global population currently lives in cities, and it's estimated that this number will rise to 68% by 2050 [97]. Urbanization will lead to further degradation of the environment, with additional pressure on infrastructure and energy consumption. In the year 2030, the World Bank estimates the cost of climate change will be about 2.5 trillion USD a

year [99]. Economic burdens emerge from the direct and indirect consequences of climate change. These include natural disasters such as hurricanes, floods, and wildfires, as well as losses in agricultural productivity due to changing weather patterns. The increasing spread of climate-sensitive diseases and heat-related ailments invariably results in higher health care expenditures. Urbanization also contributes to biodiversity loss and excessive exploitation of natural resources. Furthermore, urban expansion depletes forest cover, agricultural land, and natural habitats, significantly threatening biodiversity. Land degradation poses notable challenges to the sustainable management of ecosystems and biodiversity conservation. At the same time, city population growth exerts increasing pressure on essential resources such as water and energy. Safeguarding and managing natural resources in a sustainable manner is a critical step to reducing the future environmental footprint of cities [99]. These adverse effects can be mitigated using sustainable development strategies and smart city technologies. These strategies include the adoption of circular economy principles, efficient public transportation systems, and green building designs. For cities to reduce their environmental footprint, integrating renewable energy technologies, enhancing urban planning, and implementing biodiversity conservation measures are vital steps.

4.1.5 Results and Environmental Implications

In recent years, the relationship between humanity and nature, along with its consequences, has received increasing attention. Climate change has significant effects on agriculture, water resources, and human health worldwide. According to most global climate models, higher temperatures and changing rainfall patterns are likely to increase the frequency and intensity of droughts, extreme rainfall, and other meteorological phenomena. The reduction in water resources caused by drought diminishes agricultural productivity, thereby compromising food security. Arid regions, in particular, should reevaluate their water management strategies and implement effective policies. Water scarcity due to drought reduces irrigation capacity, thereby impairing farmers' ability to produce. Farmland degradation results from excessive rainfall and flooding. Flooded agricultural land can result in soil erosion and nutrient leaching, ultimately reducing soil fertility. This, in turn, can

result in economic instability characterized by fluctuations in food prices. Another notable challenge is biodiversity loss. Human activities such as habitat destruction, pollution, and climate change have pushed many species to the brink of extinction. Additionally, plastic pollution poses a notable threat to marine biodiversity through ingestion, entanglement, and habitat degradation. Environmental challenges pose considerable threats on a global scale, necessitating coordinated action to ensure a sustainable future. Addressing climate change, biodiversity loss, pollution, and urbanization requires comprehensive policy frameworks that integrate technological advancements and community engagement. However, achieving sustainable outcomes ultimately depends on the actions taken by individuals, communities, organizations, and governments. Strengthening grassroots movements through education and awareness campaigns can encourage organizations to adopt environmentally sustainable practices, enhancing the resilience of both ecosystems and human communities in the long run. In conclusion, the adverse effects of climate change on agriculture, water resources, and human health rank among the most significant global challenges. Addressing these challenges requires collective action and the implementation of sustainable practices.

4.2 Construction Industry's Contribution to Environmental Challenges: Pathways to a Sustainable Future

The construction industry today plays a crucial role not only in economic development but also in promoting environmental sustainability. However, this sector has also led to significant environmental challenges, including climate change, biodiversity loss, and depletion of natural resources. Globally, the construction sector is one of the largest industries in terms of environmental impact. Throughout the entire life cycle of buildings—from material production to eventual demolition—the construction process consumes substantial natural resources and contributes to environmental pollution. The sector accounts for approximately 40% of total global carbon emissions, with the majority originating from energy consumption (Figure 4.1 [100]).

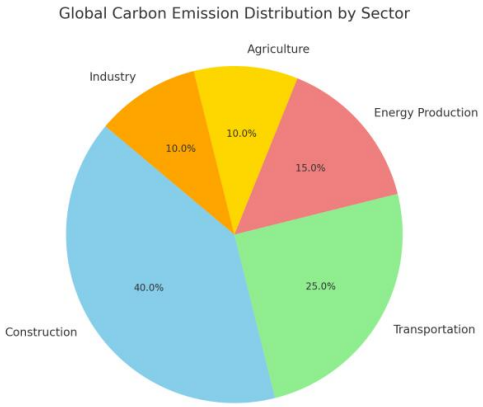


Figure 4.1 Global carbon emission distribution by sector [100]

As shown in Figure 4.1, this notable proportion results from a series of energy-intensive processes, including the manufacture and transportation of materials, on-site construction activities, and building operation. The construction sector ranks among the highest emitters of carbon emissions, alongside sectors such as transportation, energy production, and agriculture. According to the International Energy Agency, transportation accounts for approximately 25% of global CO2 emissions, while energy production contributes around 15% [90]. Agriculture and industry collectively account for roughly 10% each, driven primarily by land-use changes, deforestation, and industrial processes [90,101]. These comparisons highlight the importance of implementing further decarbonization strategies within the construction sector to reduce its environmental impact, thereby fostering sustainable building practices. In addition to its high energy consumption, the construction sector also uses vast amounts of water and raw materials. Significant greenhouse gas emissions are generated during the production of essential building materials such as cement and steel. For example, cement production alone represents 8% of global carbon emissions, constituting an important environmental concern [102]. Moreover, construction and demolition activities generate approximately 30% of global waste, making them considerable contributors to global waste generation [103]. The low energy efficiency of many buildings further exacerbates environmental challenges by increasing energy consumption throughout their life cycle, thereby intensifying reliance on fossil fuels and worsening air pollution. These

issues are compounded by the limited implementation of reuse and recycling practices, further straining natural resources. The construction sector presents both opportunities and challenges for advancing sustainability. This section examines the industry's contributions to climate change, natural resource depletion, and environmental pollution through the evaluation of its environmental impacts from material extraction and manufacturing to the operational phase of buildings.

4.2.1 The Role of the Construction Industry in Climate Change: Impact and Mitigation

Buildings are responsible for a notable portion of global greenhouse gas emissions. They represented nearly 39%–40% of total emissions in 2019, and this percentage has increased in recent years [100]. Concrete is a major contributor to these emissions. Substantial amounts of carbon dioxide are released during cement production, one of concrete's key components. Cement is produced at high temperatures and requires significant energy consumption, resulting in notable greenhouse gas emissions and contributing to climate change [90]. While cement production considerably contributes to carbon emissions, the adoption of alternative materials and processes presents opportunities for mitigation. The climate crisis poses both environmental and socioeconomic challenges for the construction industry. The phenomena of rising temperatures, extreme weather events, and sea-level rise—key indicators of climate change—present considerable risks to construction projects. In particular, coastal areas are under threat from sea-level rise, jeopardizing infrastructure investments and raising concerns about the durability of existing structures. Addressing these risks requires a transformative approach that integrates sustainability into every stage of construction.

In this context, promoting sustainability in the construction industry through the use of energy-efficient materials is essential. Materials that are more environmentally sustainable and less energy-intensive can significantly reduce the environmental consequences of construction activities. Recycled materials reduce cement consumption, thereby lowering carbon emissions and mitigating environmental impacts. Therefore, to lower emissions from the construction sector, sustainability-focused strategies should be implemented. In the future, industry

reforms guided by environmentally responsible strategies will support both the aims of preserving ecosystems and strengthening social resilience to climate change. To achieve these dual goals, industry stakeholders must prioritize innovation in sustainable practices and foster a culture of environmental responsibility.

4.2.2 The Impact of Construction on Biodiversity: Understanding Nature's Loss

The construction sector contributes to the ongoing decline of biodiversity, modifying ecosystems and threatening the survival of many species. Activities like deforestation, draining of wetlands, and urban expansion change ecosystems, pushing various species further down the path of extinction. Approximately 10 million hectares of forest are lost each year globally [101]. These changes destabilize ecosystems, reducing their resilience and the essential services they provide, including carbon sequestration, water purification, and soil fertility. Ecological concerns extend to the cumulative impacts of biodiversity loss driven by climate change. For example, forest destruction reduces the carbon sequestration capacity of forests, while the depletion of wetlands weakens natural flood regulation systems. Such impacts intensify climate-related pressures through vegetation alteration, as ecosystems exhibit varying capacities to adapt to environmental changes [91]. These detrimental effects highlight the urgent need for integrating conservation strategies into construction practices to balance development with ecological preservation. To mitigate these effects, construction projects necessitate enhanced planning and execution practices. Environmental Impact Assessments (EIAs) should become an integral part of all construction activities, identifying potential risks and recommending strategies to minimize environmental harm. Protecting natural areas and incorporating conservation strategies into urban planning should be prioritized to safeguard biodiversity [104]. Sustainable construction practices present practical options for balancing development and the environment. Renewable materials, the creation of environmental infrastructure, and the adoption of eco-friendly technologies can vastly mitigate the impact of construction on nature. Restoration of the damaged landscape by sustainable construction could pave the way for preserving biodiversity. By emphasizing biodiversity protection, the construction sector can play a crucial role in creating a healthy coexistence between development

and nature. Understanding and minimizing construction's direct impact on biodiversity would ultimately ensure sustainable development. Accordingly, the construction industry can contribute significantly to developing a green and sustainable world.

4.2.3 Excessive Consumption of Natural Resources in the Construction Sector: Limited Resources, Endless Needs

The construction industry relies heavily on natural resources, creating significant challenges for environmental sustainability. This dependency illustrates the industry's reliance on essential resources that significantly influence its environmental footprint. Cement, steel, and timber, among others, have a significant impact on the environment due to their substantial direct and indirect environmental footprints. For instance, cement production accounts for approximately 8% of global carbon dioxide emissions, significantly impacting climate change [82]. Cement, which is a fundamental constituent of concrete, is produced at high temperatures and depends on fossil fuels, a highly energy-intensive process [104]. This increases greenhouse gas emissions, aggravating climate change. Many construction projects waste water resources. Although water management is an important consideration in construction processes, it is often overlooked. The consequences of this neglect are lower groundwater levels and the depletion of other vital resources such as agriculture, energy, and drinking water [105]. In urbanizing cities, the generation of excessive water consumption on one side and water discharging on the other contributes to the shortage of many other important areas such as agriculture, energy generation, and safe drinking water. These practices not only degrade natural resources but also disrupt local ecosystems, highlighting the interconnected nature of these challenges. Natural resource overharvesting has caused serious disturbances in ecosystem dynamics and hastened the loss of biodiversity. Habitat destruction by construction activities disrupts these local ecosystems, upsets natural equilibrium, and poses a significant threat to biodiversity. For instance, deforestation not only contributes to environmental degradation through increased carbon emissions but also threatens to destroy the habitats of local communities. Addressing these pressing issues requires the integration of sustainable practices and innovative approaches

within the construction sector. Overconsumption of natural resources exacerbates social and economic inequalities, contradicting the objectives of sustainable development. The conservation and sustainable management of natural resources have gained impetus from the United Nations Sustainable Development Goals. The current strategies are insufficient to achieve these objectives. Therefore, the construction industry must redirect its energies toward sustainable materials, integrate processes of recycling, reduce resource consumption, and increase energy efficiency. Lastly, by mitigating its contribution to resource over-exploitation, the construction sector can align with global sustainability goals, fostering a balance between development and environmental preservation.

4.2.4 Waste Management in Construction: Life Cycle Challenges and Waste Issues

While the construction industry is one of the most important forces driving the global economy, its expansion and high demand generate a substantial volume of waste during construction and demolition processes. Waste from these activities constitutes a critical environmental hazard, accounting for about 30% of total solid waste in 2018 [106]. These challenges underscore the urgent need for sustainable waste management practices in the construction sector. Various types of waste are generated during construction and demolition processes, including valuable materials such as cement, bricks, metal, wood, and plastics. Worldwide, construction waste generated each year is estimated to be around 1.3 billion tons [103]. If this waste is not recycled or reused, it accumulates in the environment, causing significant pollution. Insufficient waste management not only exacerbates environmental pollution but also contributes to resource depletion. Improper construction waste management results in intensifying environmental consequences that eventually threaten ecosystem health. For instance, construction waste can disrupt ecosystems by contaminating soil and water sources, causing long-term ecological damage [107]. As a result, waste management in the construction industry will be a critical aspect of sustainability and concerns regarding the environment. To address these challenges, throughout a building's life cycle, applying effective waste management methods that promote recyclability and reusability can significantly reduce waste. Recycling not

only conserves natural resources but also helps cut costs for builders. Reevaluating the environmental footprint of the construction sector is a critical first step toward a more sustainable future. By integrating innovative waste management practices, the construction sector can significantly reduce its environmental footprint and contribute to a more sustainable global economy.

4.2.5 Escalating Air and Water Pollution: The Construction Sector's Environmental Impact

The construction industry has significant environmental impacts. As a key driver of economic development, it has been a major contributor to air quality degradation and water pollution. These environmental concerns constitute significant threats to both public health and natural ecosystems. These environmental impacts are most evident in the construction sector's contributions to air and water pollution, which require immediate attention. The construction sector is a major source of air pollution and greenhouse gas emissions, further exacerbating climate change. These emissions directly affect local air quality, causing respiratory health issues among nearby populations and amplifying global warming through the accumulation of greenhouse gases in the atmosphere. As indicated by the World Health Organization [108], air pollution is linked to millions of premature deaths annually, posing serious health risks—especially to children. Dust and particulate matter emitted by heavy equipment at construction sites deteriorate air quality, contributing to respiratory health problems among workers and nearby residents [109]. Construction processes also pose significant threats to water resources. Soil erosion and insufficient drainage systems at construction sites enable harmful chemicals to infiltrate water bodies, resulting in the contamination of both groundwater and surface water ecosystems. Chemicals used in construction processes induce toxic effects on water systems. Contaminated water sources represent both a critical environmental issue and a major public health concern. Such contamination can pollute drinking water supplies and agricultural lands, creating further public health risks. Environmental and health consequences underlying air and water pollution caused by construction activities reveal the need for integrated environmental impact assessments and sustainable construction practices. Addressing these issues through sustainable practices and

comprehensive assessments is imperative for mitigating the construction sector's environmental footprint.

4.2.6 Carbon Footprint in Construction: The Lasting Shadow on Tomorrow

While the construction sector drives societal development, it is also a major environmental polluter, significantly contributing to the carbon footprint. This is because the construction sector alone accounts for a significant part of the carbon footprint of any nation and is exacerbated by the extensive use of energy-intensive materials. Fossil fuels dominate the energy consumption for heating, cooling, and lighting in buildings, highlighting the dependency on non-renewable energy sources [110]. [111] estimates that the economic impact of climate change may be as large as $2.5 trillion by 2030. This highlights the inefficiencies in the building sector's energy use and the insufficiency of current carbon dioxide emission reduction efforts. Since the need for energy is a fundamental driver of environmental change—it generates diverse economic and social complexities—reliable energy resource availability reduces construction costs. The increasing deficiency of energy resources leads to high costs for power generation, which includes the construction cost. Reducing carbon footprints in the construction sector is critical, not only in the fight against climate change but also for the sustainability agenda. Measures should include increased energy efficiency and the incorporation of renewable energy sources in this industry. The construction industry significantly contributes to the global carbon footprint. This issue is possible to address by taking up more sustainable and environmentally friendly construction practices in the future. New solutions and sustainable methods are to be developed to mitigate environmental impacts threatening future sustainability. Taking decisive measures to mitigate the environmental impacts of the construction sector is imperative within this context.

4.2.7 Final Thoughts: Addressing Environmental Challenges in the Construction Sector

The construction sector accounts for large-scale environmental issues, such as climate change, loss of biodiversity, demands on natural resources, solid waste management, and air and water pollution. For this reason, the implementation of

sustainability principles is imperative in reducing these environmental impacts. Damage to natural resources as well as the health of ecosystems caused by construction processes presents a critical challenge not only environmentally but also economically and socially. The construction sector must adapt by integrating advanced materials and incorporating sustainable building practices if the environmental footprint of this industry is ever going to decrease. The use of innovative materials has a measurable impact on the environment and provides cost savings in energy, durability, and maintenance throughout the life cycle. Active design strategies constitute essential components of a comprehensive approach to addressing environmental concerns within architecture, alongside green infrastructure and waste recycling processes. Additionally, collaborating with policymakers will be crucial in establishing effective partnerships between industry professionals and experts who aim to build a sustainable future. It is necessary to educate and raise awareness while fostering innovative solutions so the sector itself can reduce the environmental impact of construction and meet sustainable development goals. From a global perspective, the construction sector is a powerful economic force but must be effectively managed. Embracing sustainable methods will contribute to building an environmentally friendly future while generating employment and fostering economic development in many sectors. Thus, building may integrate into a more sustainable economic and ecological balance, considerably benefiting future generations and maintaining a habitable planet.

4.3 Sustainable Architecture: Building the Future through Principles, Practices, and Perspectives

Sustainable architecture is a perspective aimed at shaping architectural design through three fundamental dimensions: environmental, economic, and sociocultural. In this context, the increasing environmental challenges and limited resources have underscored the importance of sustainable architecture more than ever before. This section defines the concept of sustainability, reviews its historical development and basic principles, and explores its applications across various domains.

4.3.1 The Evolution of Sustainability: Tracing Its Origins

Sustainability refers to the act of using present resources to fulfill the needs of every individual, the communities they interact with, and the ecosystem without compromising the resources available for the future [112]. In the Brundtland Report, sustainability is described as "the ability to fulfill the needs of the present without compromising the capability of future generations in meeting their own needs" [113]. Such a definition implies a balanced approach where the three principles are mutually supporting: environment, economy, and society. The terminology of sustainability is founded upon the understanding of sustainability itself. The term "sustainability" is derived from the verb "sustain" in English. This verb comes from the Latin roots "sub" (under) and "tenere" (to hold), meaning "to support or maintain something" [114]. The concept has its origin in late 18th-century Germany, where the term nachhaltigkeit was used to describe sustainable forest resource management. Although it first appeared in German, the evolution and spread of the term sustainability is much broader and has become globally recognized in various contexts [115]. With the advent of the 20th century, sustainability began to expand its scope to include how natural resources could be provided across future generations without diminishing. It established legitimacy in environmental protection circles along with spheres of economics and social well-being [116]. Sustainability is a concept that originated in the mid-20th century. This era, particularly with the advent of the post-industrial revolution, fast-paced environmental degradation, and ecological troubles, emphasized environmental consciousness. Emerging environmental movements in the 1960s, along with worries that natural resources were being depleted, resulted in greater awareness. Silent Spring (1962), by Rachel Carson, is a classic book that laid down the general problem of pesticides damaging the environment. Carson’s work not only highlighted the environmental damage caused by pesticides but also emphasized the disruption of ecosystems and the effects on public health [117]. The concept of sustainable development started to gain attention at the international level with the publication by the Brundtland Commission, set up by the United Nations in 1987, of its report Our Common Future. This report significantly strengthened the global understanding of sustainable development and laid out an approach that combines ecological, social, and economic aspects. It was noted in the report that "sustainable

development" is defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [112]. This definition included a sustainable development approach incorporating environmental, social, and economic aspects. The United Nations Conference on Environment and Development, or Earth Summit, held in Rio de Janeiro in 1992, placed sustainability on the global agenda and presented larger environmental principles. The conference emphasized that all countries should develop their technical environmental protection and development planning strategies based on the principle of sustainability. Some of the most important documents arising from this summit include Agenda 21 and the Declaration on Environment and Development. Sustainability is at the heart of tackling challenging issues of the 21st century, such as climate change, resource depletion, loss of biodiversity, social inequality, and poverty. During this time, sustainability has been discussed not just as an environmental issue but as equally related to economic and social inequality. The United Nations proposed the Sustainable Development Goals (SDGs) in 2015, opening a way for governments and organizations worldwide to set precise targets associated with sustainable development. Sustainability, therefore, is no longer a single-issue approach as it integrates environmental protection and economic growth with social equality and justice, human rights, and policies providing for individual welfare. [118] , in Limits to Growth, emphasized the necessity of aligning economic growth with planetary boundaries, highlighting the fundamental role of integrating sustainability into economic systems to achieve sustainable development. Although the focus of the work was primarily on environmental limits, it has had a significant impact on contemporary sustainability thinking, emphasizing the necessity of harmonizing environmental protection with social and economic considerations in the context of climate change. Sustainability, owing to these developments, has become an intertwined integration a policy domain attempting to address environmental, economic, and social dimensions. The combined perils of global environmental dangers and social inequities have made sustainable development a significant agenda across the globe.

4.3.2 Sustainable Practices in Architectural Design: Origins and Evolution

Sustainable architecture focuses on the use of natural resources, energy savings, and minimizing environmental impact in all phases of a building's life cycle. The philosophy of sustainable architecture identifies sustainability as creating buildings with the goal of minimizing environmental impact from planning and construction to operation to deconstruction [119]. Sustainable architecture is designed on the principles of the health of the occupants, comfort for the occupants, and well-being of the occupants, with approaches of renewable resources, efficient water use, waste management, and selecting low-carbon materials [120]. These guidelines include reducing the negative effects on the environment, enhancing energy efficiency, and creating environments that enhance the well-being of their occupants. Therefore, sustainable architecture aligns with future-oriented design principles by respecting nature cycles and the needs of present generations without compromising those of the future ones. It incorporates modern technologies to enhance energy savings while supporting green material and process choices. As a result, sustainable architecture that follows this approach integrates the artificial environment and natural ecosystems, promoting a lifestyle in which it can fulfill human requirements as humanity currently understands them without imposing depletion on the resources required by future generations. Sustainable architecture was formed in the mid-20th century as responses to ecological degradation and resource depletion arose [121]. Early pioneers in sustainable architecture demonstrated the relevance of building practices being carved by natural processes to equal ecological design principles with less environmental harm. It featured the conservation of natural resources as well as the design of buildings that would be in a symbiotic relationship with their environments. Over the following decades, sustainable architecture developed in parallel with green building science and renewable energy technologies. This enables the integration of energy systems, green construction materials, and advanced waste management technologies into the design of buildings, creating a paradigm shift in architecture itself [122]. As the green building movement gained increasing recognition and widespread adoption, and more countries committed to international climate agreements such as the Kyoto Protocol and the Paris Agreement, complementary architectural solutions were needed to do their part in minimizing carbon emissions on a global scale. Contemporary sustainable architecture extends

beyond energy efficiency to include material sourcing, water conservation, and spaces that enhance the health and well-being of those living and working in it. It has also evolved to meet contemporary challenges in environmental performance, including mitigation of urban heat islands, pollution, and biodiversity loss. It moves from the original concepts of ecodesign to an overall architectural concept with social, economic, and environmental aspects. Sustainable architecture has progressed from the margins of building design to central in how responsibly we build for the future, constantly influenced by new technological discoveries and our ever-changing environment. The following sections present the chronological development of sustainable architecture. Significant milestones, environmental movements, and technological innovations are described in order to follow the path of sustainable architecture. The earliest societies often constructed buildings in alignment with environmental conditions and resource availability using limited and local natural resources. Traditional structures, particularly those made with natural materials, constituted another important model from the viewpoint of environmental sustainability [123]. The yurt tents from central Asia, the traditional homes of the Arabian desert, and stone or adobe structures in Anatolia are examples showing that building climate-compatible Using locally available resources provides the historical basis of sustainable architecture[124]. The emergence of sustainability concepts in the 20th century was driven by increasing environmental challenges such as pollution, fossil fuel dependence, and rapid urbanization that became evident by the mid-20th century. This period marked the rise of an environmental movement that laid the foundation for sustainable architecture. The oil crisis of the 1970s highlighted the critical need for energy conservation and resource efficiency, prompting efforts to improve buildings' energy performance [125]. Sustainability gained international prominence with the publication of the Brundtland Report in 1987, which defined sustainability as meeting current needs without compromising the ability of future generations to meet theirs [112]. These principles resonated strongly within architecture and urban planning, emphasizing the reduction of environmental impacts. In the 1990s, the green building movement—a vital piece of the larger sustainable architecture—advanced. During this time, the American LEED (Leadership in Energy and Environmental Design) certification system helped towards becoming

established in sustainable architecture by forming standards that encouraged energy-efficient, water-saving, and environmentally friendly buildings [126]. Further, certification systems like BREEAM have also made inroads towards giving credibility to sustainable design [127]. In the 2000s, the technologies in digital design and building information modeling (BIM) started to be used in sustainable architecture. These breakthroughs involved calculating and being able to see in advance what the building's environmental impacts, including energy consumption and water use, are to be able to realize objectives for sustainability [128]. Later on, with the advancement of renewable energy technologies, intelligent building systems, and energy efficiency-enhancing applications, sustainable architecture became within reach and more efficient [129]. Thus far, global climate protocols have driven the expansion of sustainable architecture practices. Initiatives like the Kyoto Protocol, the Paris Agreement, and the European Green Deal set different targets for the construction sector to minimize its carbon footprint [130,131]. Sustainable architecture plays a crucial role in the development of cities and buildings, which provide energy independence by minimizing environmental impacts [132].

4.3.3 The Essential Principles of Sustainable Architecture: Balancing Functionality, Efficiency, and Ecology

The major principles of sustainable architecture involve designing parameters concerning environmental and social responsibility during the life cycle of a building. Energy Efficiency: One key principle of energy efficiency states that the energy needs for a building are to be minimized. These are obtained through passive design, natural ventilation, and solar energy strategies [133]. Material selection, another key decision while construction relates to the use of materials that are not hazardous to the environment. Recyclable and locally sourced materials are to be preferred so that natural resources are preserved and the carbon footprint is checked [134]. Water conservation is an important principle that ensures that sustainable architecture works towards preserving freshwater resources. In architecture, rainwater harvesting, graywater recycling, and low-flow fixtures have been incorporated as water-saving methods [135]. Sustainable architecture protects the preceding health of indoor space by following design methodologies that include natural ventilation, low-VOC

materials, and biophilic design elements to create healthier living environments [136]. A key objective of sustainable architecture is ensuring harmony with the natural environment while minimizing disturbance to the local ecosystem. The preservation of biodiversity is targeted through features such as green roofs, vertical gardens, and natural landscaping [137]. Sustainable architecture includes some primary principles and strategies to minimize buildings' environmental impacts while improving the occupants' quality of life. These aspects combine to create efficient energy utilization, minimize waste, and prioritize a built environment that supports health and well-being. Examples of these include green roofs and facade systems, which are the main components that improve the use of insulation while uplifting the energy efficiency of some existing buildings. In this way, indoor comfort can be sustained at optimal levels with less dependence on the systems used for artificial heating and cooling; also, these systems contribute to rainwater retention, stormwater runoff control, and mitigation of the urban heat island effect, which is particularly an issue in more densely populated cities [138]. Passive design strategies have paramount significance for energy consumption. Several techniques in promoting the use of natural resources like sunlight and wind in passive design aspects include orientation of the building, natural ventilation, and daylight [139]. The addition of some renewable energy technologies—solar panels, wind turbines, and geothermal systems—constitutes another major addition to the sustainability of a building. They have helped to reduce the building sector's reliance on nonrenewable energy resources, improve energy economics, and reduce to a large extent the carbon footprint of use [140]. An equally important component in the construction process is the use of recyclable and sustainable materials. The selection of materials that are recyclable, reusable, or sustainably sourced significantly helps the reduction of waste, preserves natural resources, and reduces the carbon footprint of both construction and the long-term use of the building [141]. Finally, smart building systems use sophisticated technology to optimize the utilization of energy and water resources. The systems automatically monitor and adjust their energy consumption to save utility costs by increasing efficiency while adding a benefit to environmental sustainability [142]. Together, these components contribute to a more sustainable

built environment by enhancing energy efficiency alongside enhancements in the living quality of its occupiers.

4.3.4 Türkiye's Sustainable Architecture Path: A Brief Look from Policy to Practice

The growing recognition of environmental issues and global sustainability standards has significantly advanced sustainable architecture practices in Türkiye. Some of these advances became further motivated by the recent visibility of environmental concerns, over-exploitation of energy resources, and growing significance being given to global challenges, particularly those posed by climate change. Sustainable building design, the expansion of green spaces, energy conservation technologies, and environmentally conscious material choices have become increasingly significant, especially in metropolitan areas. Significant progress has been made in achieving these sustainability objectives within Türkiye through international agreements and domestic policy initiatives. Türkiye signed the Paris Climate Agreement in 2015 and formalized its commitment by ratifying the agreement in 2021, marking a pivotal step in promoting sustainable architectural practices [143,144]. In addition, Türkiye has voluntarily aligned several of its policies with the European Green Deal framework, demonstrating its proactive approach to promoting eco-friendly development and reducing carbon emissions, despite not being an official signatory. These international and national certification systems largely play the indispensable role of expediting the acceptance of sustainable building standards, thereby providing legal frameworks suitable for gauging environmental performance. Among the most widely adopted international certification systems in Türkiye are LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) [145]. At the national level, Türkiye's Green Building Certification, led by CEDBİK (Cevre Dostu Yesil Binalar Dernegi), has gained prominence. CEDBİK, a non-profit organization, proactively promotes sustainable methods in designing, constructing, and operating projects throughout Türkiye. Its certification system aims to align with global standards while also considering Türkiye's unique climate, culture, and regulatory environment. This dual approach demonstrates the commitment to environmentally

friendly practices in Türkiye's building industry, combining marketplace value with community support for green buildings, thereby contributing to global sustainability efforts and reducing environmental damage [145]. The application of sustainable architectural principles has expanded generally in public and private sector projects over recent years. In the public sector, the Ministry of National Education and other organizations mainly sprang to energy-efficient school buildings supported by renewable energy designs while conserving water, contributing to sustainability. For instance, designs for new school projects maximize water-saving systems with features such as solar panel designs and enhanced insulation materials for energy efficiency [146]. This has radically expanded the use of the private sector in developing sustainable office buildings such as the established alternative-use mix in cities like İstanbul, Ankara, and İzmir. These projects address environmental degradation while producing economic value. Renewable energy sources such as solar, wind, and geothermal energy take to mind easier building integration into architecture. Solar panels are presently mounted on rooftops in countless residential as well as commercial establishments, whereas others even distribute surplus energy back to the grid [147]. The employ of recycled and local natural building materials is also a frequent practice in sustainable architecture projects. These materials also promote environmental sustainability while offering opportunities for economic growth. Sustainable principles can also be recognized in urbanism and urbanization projects, wherein urban designs in big metropolitan areas are adopting bigger green patches, low-carbon transport alternatives, and smart city technologies. Within the country itself, urban proposals for places like İstanbul have relatively recently emphasized basic concepts like integrating cycling corridors, public transport systems, and pedestrian-priority zones in an effort to create sustainable mobility. Similar efforts are noted for houses on urban developments in Ankara and İzmir, which increasingly include designs for managing stormwater and greening [143]. Nonetheless, sustainable architecture in Türkiye is confronted with a number of other hurdles. High economic costs, lack of understanding on the topic of sustainable design theories, and under development in the regulatory structures are some of the most significant hurdles. Fortunately, increasing environmental awareness, converging sustainability agenda of local authorities, and Türkiye's commitment

toward global climate agreements will facilitate long-term enhancements in the area. Türkiye's objective of achieving its revised objectives under the Paris Climate Agreement further attests to its pledge to promote sustainable construction practices.

4.3.5 From Kyoto to Paris: International Agreements Guiding Sustainable Architecture

The growing urgency of climate change and environmental degradation has made sustainable architecture even more crucial, as it plays a central role in all facets of global environmental strategy. International protocols and frameworks provide structured guidance for sustainable and environmental development, laying a foundation for transforming nations by minimizing their environmental impacts, particularly in the construction and urban planning sectors. Environmental conventions on the global scale, such as the Kyoto Protocol, the Copenhagen Accord, the Paris Agreement, and the European Green Deal, have gained major significance in defining a process of sustainable architecture. Extending beyond greenhouse gas emissions, these agreements also cover energy conservation, sustainable design and construction practices, as well as large-scale green technologies in the built environment. The Kyoto Protocol, an international treaty signed in 1997 and entering into force in 2005, was one of the first binding international agreements aimed at combating climate change [148]. Significant measures were proposed to realize targets and mechanisms to reduce greenhouse gas emissions, particularly in industrialized nations. The protocol implemented measurable objectives and pathways toward achieving these reductions, particularly for sectors with significant ecological impacts, such as building and construction. Since the building sector is one of the largest contributors to carbon emissions, it was a focal point of many strategies included in the protocol. The Kyoto Protocol directly contributed to the growth of sustainable architecture by promoting energy efficiency upgrades in buildings, encouraging the integration of renewable energy technologies, and advocating for the use of sustainable materials for buildings. These initiatives focused on reducing the carbon footprint of buildings, which are responsible for a substantial portion of global energy consumption and greenhouse gas emissions [149]. Thus, the protocol stimulated a shift toward greener construction practices and

established a global appreciation for the importance of integrating sustainability into architectural design and urban planning. The protocol's first commitment period covered 2008-2012, while the second extended from 2013-2020. Although its formal period has concluded, the policy foundations established under the protocol continue to influence sustainable construction practices globally. In the fight against climate change, the 2009 UN Climate Summit in Copenhagen represented another key milestone after the Kyoto Protocol. It led to the Copenhagen Accord [150], which, although non-legally binding, encouraged countries to make voluntary commitments to reduce carbon emissions and recognized the importance of sustainable architecture in addressing climate change. Copenhagen deliberations covered energy-efficient construction practices, the promotion of low-carbon buildings, and, importantly, achieving an increasingly efficient use of resources. As energy efficiency remains a fundamental objective, the summit reiterated the importance of sustainable structures, whether residential, commercial, or institutional, in meeting long-term climate goals [151]. The Paris Agreement, signed in 2015, is one of the most significant global environmental agreements, targeting a limitation of global warming to well below 2°C compared to pre-industrial levels while striving to limit the increase to 1.5°C [152]. This treaty, signed by 196 countries, binds countries to a long-term strategy to reduce carbon emissions. The countries have been encouraged to intensify efforts on energy efficiency, the dissemination of renewables in the building sector, and facilitating the use of sustainable building materials to meet this objective. It has also supported the development of green building standards and the proliferation of such buildings, framing sustainable architecture and construction practices. The treaty is aimed at prompting worldwide construction practices that prioritize energy efficiency, environmental sustainability, and low carbon emissions [153]. The European Union has taken decisive steps with the European Green Deal, aiming to reduce carbon emissions to zero by 2050, establishing a comprehensive pathway for energy efficiency, promoting green building construction, and improving energy performance in existing buildings [154]. Establishing incentives guided by policy for sustainable buildings, creating benchmarks for energy-efficient designs, and offering assistance for the development of green structures will enhance the proliferation of

sustainable architecture across Europe and serve as a model for other regions and countries[155].

4.3.6 Global Commitments: Türkiye and the World's Journey Toward Environmental Protocol Compliance

In the fight against climate change, countries may benefit from consulting various international protocols in their efforts to mitigate the existing environmental problems. Agreements presently being used include the Paris Agreement and the European Green Deal, with each of these agreements placing commitments and obligations upon each of the states that become part of those agreements while also promoting sustainable construction and urbanization. Türkiye, too, attempts to attain its environmental sustainability objectives while observing those protocols. Türkiye has registered significant advancement in its environmental sustainability with the recent adoption of the Istanbul Environment and Climate Action Plan by the Istanbul Metropolitan Municipality. It has specific, local-level responses to help meet the sustainability targets of the country. This plan is oriented towards sustainable urbanization and climate resilience, with targets on energy reduction, increasing public green areas, and climate-friendly urban habitats [156]. Istanbul is undertaking a variety of projects towards improving the city's infrastructure into energy-efficient and environmentally sustainable options. They are mainly concentrated on public buildings and include the refurbishment of old structures to ensure improved energy performance, the use of sustainable building materials, and the incorporation of renewable energy systems into new constructions. Green building practices and eco-friendly construction are at the forefront of demonstrating how a city can minimize its environmental impact while preparing to meet the challenges posed by climate change in Istanbul. This integrated approach also advances national climate action goals and provides a strong model for other cities across Türkiye. Such sustainable architecture and urban planning in Istanbul highlight the role of the city as a pioneering force to propel environmental change locally. It could stimulate other cities throughout the country to introduce these strategies by promoting successful projects and demonstrating strength through green construction. Apart from the apparent positive impact of such practices on the environment, they will also allow

Türkiye to fulfill its obligations as part of the international climate agreements to which it is a party, like the Paris Agreement. Focusing on climate resilience, energy efficiency, and carbon neutrality at the city scale is a local solution addressing both the environmental challenges facing Istanbul as well as international challenges to sustainability. This agenda reinforces the concepts of sustainability and prosperity and encourages other metro areas to follow comparable climate action policies and practices. Türkiye approved the Paris Agreement on October 7, 2021, pledging to achieve carbon neutrality by 2053 [157]. Additionally, the country announced its net zero emission target for 2053 [157]. Notably, Türkiye requested to be recognized as a developing country under the agreement, which offers flexibility in defining its national contributions. The Energy Performance Certificate (EPC) system has been in place in Türkiye since 2011, becoming mandatory for new buildings from January 1, 2020, and for existing buildings from January 1, 2021 [159]. Though not an EU member, Türkiye aims to align with the European Green Deal to maintain trade relations with the EU. This is a strategic adjustment rather than a legal obligation, aiming at reducing carbon emissions and promoting green transformation in the country's industrial and export sectors [160]. The Zero Waste Project was initiated in 2017 in Türkiye, targeting waste separation at the source, increasing recycling rates, and creating a comprehensive waste management system [158]. As of 2021, its implementation expanded beyond public institutions to include the private sector as well, reinforcing Türkiye's environmental sustainability goals. This provides an update on Türkiye's active commitment toward environmental sustainability and climate change under major international protocols. The extensive approach demonstrates that Türkiye is committed to addressing environmental degradation issues through local and national strategies.

4.4 Life Cycle Assessment

Today, environmental sustainability is much broader than protecting the environment: It also embraces social and economic dimensions. The environmental impacts of these sectors and their possible accompanying intrusion into the realm of diminishing resources and possible damages toward ecosystems have become all the more pressing with the rise of the industrial and construction sectors. Systematic

assessment of the environmental impacts of a product from production through use up until its final disposal has become a crucial implement in the selection and attainment of sustainable development goals. LCA is a technique that can methodically and systematically apportion the appropriate environmental impacts of a product or service through all stages—from extraction of natural resources through production and use to disposal. It demonstrates both the environmental impacts of a project—insofar as it has proposed mitigation measures to lessen those impacts and ensure efficient use of resources. Such methodology would significantly contribute to sustainable design and production processes. The basic definition and aim of LCA will be discussed in this section, with specific attention to the analysis of environmental impacts and how analysis supports the attainment of sustainability goals. In addition, the procedure of LCA will be thoroughly discussed concerning the stages it goes through and how it operates. The development of LCA will also be discussed with regard to how it has developed and fused inside global environmental policies and standards. Finally, the areas of application of LCA, its advantages, and its participation in environmental decision-making will be comprehensively discussed.

4.4.1 Life Cycle Assessment: Tracing Impacts Every Step of the Way

Life Cycle Assessment examines certain environmental impacts of a product or service. The assessment covers raw material extraction, production, distribution, consumption, and disposal stages involved during the product or service life cycle [161]. The primary objective of the Life Cycle Assessment is to scientifically utilize an array of data and analyses to identify a product's or service's total impact on ecosystems, assess it, and evaluate its environmental effects. LCA, in general, aims for improving environmental sustainability and optimizing resource use efficiency. Thus, this methodenables both producers and consumers to assess and enhance their environmental performances. Importantly, LCA is a vital tool for carrying out environmental impact studies and is considerable in decision-making processes. Generally, an LCA will involve the following four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation of results. These processes form the foundation of LCA and indicate the crucial steps for methodical assessment

[162]. The LCA process begins with the goal and scope definition stage. This stage determines the scope of the product or service to be assessed as well as identifies which categories of environmental impact will be taken into account. Inventory analysis is the collection and organization of data and information recorded along the life cycle. At this stage, different environmental indicators are assessed—from the use of raw materials to energy consumption. At the impact assessment stage, environmental impacts are evaluated based on this data. Finally, in the results interpretation stage, there is analysis of findings against the objectives and recommendations for decision-makers. However, LCA represents an integrated tool both for evaluating the environmental impacts of products and services throughout their life cycle according to ISO standards and for sustainability objectives. It helps in understanding and managing impacts on the environment, which gives valuable insights to both producers and consumers.

4.4.2 The History of LCA: From Its Beginnings to Today

Life Cycle Assessment (LCA), since the late 1960s, has developed side by side with growing concern for environmental sustainability and resource management. It was during this phase that, mitigating the environmental consequences of the Industrial Revolution, the overconsumption of the earth's natural resources, and greater visibility of environmental concerns highlighted the necessity for systematic approaches aimed at environmental impact assessments. The LCA, fulfilling this very purpose, lays the foundation for identifying the environmental impacts that any product or service underwent throughout its life cycle and also offers a comprehensive understanding of sustainability. Environmental concerns in the 1970s continued to speed up the development of environmental impact assessment methods. The rise of environmental movements and wider public discussions centered on environmental issues prompted the development of environmental management systems. In 1975, the first proposals for environmental impact assessments were published by the United States Environmental Protection Agency; some of these guidelines exemplified the significance of LCA in this endeavor [163]. Various methodologies for systematically analyzing environmental impacts emerged during this period, on which LCA formulations were built. International LCA studies began

to gain traction in the 1980s, and many countries began to embrace LCA as a tool or mechanism for assessing the environmental impact of products and services concerning their goals towards sustainability. The establishments of LCA studies were pioneered by universities and research institutions, particularly in Europe. LCA gained significant traction in its application across industries during the 1990s, and more of the environmental impact assessment methods became adopted by a wider audience. The year 1997 was another milestone, as the publication of the ISO 14040 standard now offered a methodological framework for LCA, becoming a codified guide for Environmental Impact Assessments [164]. Industrialized application of LCA experienced rapid and widespread adoption, enriching environmental performance in manufacturing processes. In the 2000s, the discussion concerned the revision of the ISO 14040 standard in 2006, which presented a substantial change and update of LCA processes and uses. This revision opened up the use of LCA on international grounds with wider acceptance in various domains such as construction, food, and energy generation. For instance, the construction domain has been able to utilize LCA to assess environmental impacts from various material choices and champion more sustainable practices [161]. Currently, LCA is a critical tool for understanding and reducing the environmental impact associated with products and services. It gained deeper importance with sustainability reporting, environmental impact assessments, and eco-design practices. With the rise in climate change, resource depletion, and environmental degradation, the importance of LCA has achieved even greater heights. Besides, LCA gives valuable insights to policymakers and researchers for fulfilling the objectives of sustainable environmental goals. The history of LCA reflects the growing eminence of environmental sustainability and resource management. From its fledgling applications to its current widespread employments in calibrating environmental impact assessment, LCA has achieved significant progress, allowing it to play a crucial and active role in environmental impact assessment and achieving sustainability goals of industry and policy.

4.4.3 LCA Methodology: Frameworks and Techniques for Comprehensive Evaluation

Life Cycle Assessment (LCA) is a systematic tool for assessing the environmental performance of products and services throughout their entire life cycle. Generally, LCA methodology consists of four main phases: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation of Results. The Goal and Scope Definition stage formally begins the LCA process by establishing the study's objectives and boundaries. It aims to address key questions regarding the environmental impacts of a product or service to minimize subsequent effects. 'Scope' includes the parts of the product life cycle under consideration to be analyzed (extraction of raw materials, production, distribution, use, and disposal). It establishes the methods and procedures for data collection and analysis [161]. In this Life Cycle Inventory stage, resource data and waste generated across the product life cycle are collected. Aspects include energy consumption, raw material use, waste, and emissions. Data collection is conducted through surveys, field studies, literature reviews, and databases to provide the necessary quality and consistency for the data needed to achieve reliable results [161]. The LCI phase generates essential data required for the subsequent impact assessment stages. The Life Cycle Impact Assessment uses LCI data to determine the environmental impacts associated with a product. The focus is on impact categories such as gases emitted, energy consumed, water usage, and other forms of environmental degradation. LCIA involves comparing distinct impact categories and ascertaining the overall environmental performance of a product [161]. LCIA may also determine how choosing different materials and methods impacts the total environmental footprint. Finally, the Interpretation of Results interprets the results and presents findings for decision-making. Recommendations are provided to compare various options addressing a range of environmental issues. This step allows decision-makers to use the results to guide strategies for reducing impacts based on results communicated through methods such as graphs and charts [161].

Table 4.1 LCA methodology [161]

Phase	Objective	Key Activities

Table 4.1 LCA methodology (continued) [161]

Phase	Objective	Key Activities
Goal and Scope Definition	Define objectives and boundaries	Identify questions, specify life cycle stages, establish methods
Life Cycle Inventory	Collect data	Record energy use, materials, emissions, waste using surveys, databases, fieldwork
Life Cycle Impact Assessment	Analyze environmental impacts	Evaluate emissions, resource use, and environmental effects
Interpretation of Results	Present findings for decision-making	Compare options, recommend actions, use visual tools like graphs and charts

Table 4.1 describes the essential phases of Life Cycle Assessment (LCA), along with the specific objectives and activities predominant at each phase (Table 4.1). The prescribed framework is crucial as it enables the systematic evaluation of environmental impact attributes throughout the product's life cycle [161]. In a broader context, LCA offers a comprehensive understanding of a product's environmental effects, contributing to sustainability efforts across various industries.

a) The Goal and Scope Definition

The goal and scope definition phase serves as the foundation of the LCA process. This phase defines the study's goal and establishes the context for evaluating environmental impacts on a product, service, or system basis. The primary goal may take a variety of forms based on the purpose of any given LCA, which may include comparing alternative products or processes and reporting the environmental performance of a certain product. LCA can guide internal decision-making and support regulatory compliance. Strategic sustainability initiatives may also be informed by LCA [161]. The primary aim of the study, whatever LCA aims to achieve, should be properly articulated from the outset. These goals may include comparing design alternatives, identifying opportunities to reduce environmental impacts, or assessing the overall sustainability of a product or operation. Most importantly, a well-defined goal is paramount since it steers the whole assessment process in all its subsequent decisions with regard to the scope and methodology.

The scope of the LCA equally determines the system boundaries that dictate which life cycle stages will be considered in the analysis. Generally, these stages include raw material extraction, production, distribution, use, and end-of-life disposal. The outline of the scope specifies which processes, activities, or systems will qualify for the assessment. A clearly defined boundary lends itself to ensuring that the study remains on task, directing the investigation toward specific goals that ultimately render the results of utmost relevance. The scope may range from the entire life cycle of a product to restricting certain stages, such as transportation, depending on the perspective of an individual study [161]. A well-defined scope also establishes crucial bases for the comparison of different studies and provides directions for the gathering of data. A more important aspect of this particular phase, and one whose implementation may vary with the final product and the general agreement of the project team, is the establishment of the functional unit. In other words, this unit is a measure against which any two or more products—in this case, they've gotten down to making their environmental impacts at various scales—can provide some sort of numerical basis for making the evaluations. For instance, the "functional unit" could be defined as "1 kilogram of a product" or "1 year of service provided." This sort of standardization provides a standardized basis for meaningful comparisons between alternatives, which may differ significantly in scales, weights, or the duration of use for the LCA. The use of the functional unit aims to harmonize the comparative basis between products under analysis so as to avoid biased or misleading results [161]. The goal and scope definition phase also entails the identification of the impact categories to be considered, in addition to the study's goal, scope, and functional unit. These impact categories generally relate to the potential environmental concerns of the study, such as climate change (global warming potential), resource depletion, water consumption, acidification, and human toxicity. Which impact categories need consideration in a study are dependent on the goal of the study and the environmental considerations most pertinent to the product or service under examination.

b) The Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) phase is a critical phase in LCA, systematically gathering and quantifying data related to resource use and environmental emissions

across all stages of a product's life cycle [161]. This phase, in detail, describes the environmental flows, environmental inputs such as raw materials, energy, and water, and outputs like waste, air, water, and soil emissions and byproducts. The data brought together in the LCI phase are crucial for understanding the environmental performance of the product system and thus provide the basis for the subsequent Life Cycle Impact Assessment (LCIA) phase. The LCI phase gathers data from diverse sources such as surveys, field studies, literature reviews, and environmental databases. Because the quality and stringency of data impact the acceptability of LCA results, data collection has to be systematic and representative. Common data sources are manufacturers, suppliers, and established databases such as Ecoinvent. Complex systems require precise representation of environmental flows, as variations in resource use and emissions can significantly affect the overall assessment. Life Cycle Inventory (LCI) examines all aspects associated with industries, involving not merely the extraction and manufacture of raw materials but also through to transportation, usage, disposal, or recycling. Besides accounting for material and energy flows, the LCI also describes the emissions and refuse generated. Such outputs include greenhouse gas emissions, water pollution, and solid waste, which are assessed for their environmental impacts. This phase ensures a complete understanding of all environmental flows related to the product, laying the foundation for the subsequent impact analysis in the next stages of the LCA procedure. The LCI phase allocates environmental flows when multiple products or processes share inputs or outputs, preventing double-counting. For example, in a manufacturing facility producing multiple items, it may be necessary to allocate energy use or emissions among the products based on such criteria as their mass, economic value, or energy content [161]. The choice of allocation methods is pivotal in ensuring proper and transparent distribution of environmental burdens, especially since allocation done improperly can lead to biased results and wrong conclusions. Furthermore, sensitivity analysis is often conducted during this stage to examine how changes in estimates or assumptions affect the overall project outcomes, thus improving the robustness and reliability of LCA results. The LCI phase also provides the most thorough description of the resources a product uses and the emissions it

disposes of, thus creating a detailed product picture whilst contributing toward better environmental elucidation, hence better-informed and sustainable decision-making.

c) The Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) phase, also regarded as the evaluation, uses the quantitative data available in the preceding LCI phase to evaluate its potential environmental impacts. Notably, it offers critical insights into the overall consequences of resource use and emissions [161]. In this, the resource flows and emissions identified in the LCI are assigned to various environmental impact categories such as global warming potential (GWP), ozone depletion, acidification, eutrophication, photochemical smog, human toxicity, and resource depletion. The LCIA phase links the inputs and outputs of a system to specific impact categories and converts raw inventory data into meaningful environmental effects, facilitating interpretation and comparison [165]. Under LCIA, classification, characterization, and sometimes normalization or weighting represent three main steps of the process. Classification assigns one or more impact categories to each resource or emission based on its environmental effects. Hence, carbon dioxide emissions represent global warming potential, whereas sulfur dioxide emissions result in acidification [166]. During characterization, within each category, the impact intensity is quantified using established scientific models. For instance, the contribution of carbon dioxide to global warming may equal that of a reference gas like CO_2 [167]. The application of normalization and weighting will provide valuable insights for decision-making on the relative importance of impacts across categories. This phase is especially beneficial in identifying life cycle stages that provide the greatest contribution to specific environmental burdens, allowing targeted mitigation actions to be put into place. An example would be the production phase of goods with respect to GWP, where high energy usage can be observed. In contrast, the disposal phase would contribute to human toxicity through hazardous waste generation [168]. LCIA also allows comparisons between different alternatives for products, processes, or scenarios and indicates which options are more sustainable. A change from virgin feed that is produced from raw materials into one made from recycled materials will likely have dramatic reductions in GWP and resource depletion, despite a slight

increase in energy consumption. A critical evaluation of trade-offs between categories is yet another important aspect for LCIA. For instance, a process might lower greenhouse gas emissions but create more solid waste, which requires comprehensive analysis as to which impact categories match best with sustainability goals. Such analyses highlight the importance of comprehensive perspectives in environmental decision-making. Having determined a systematic comparison of environmental impacts, the LCIA phase gives politicians useful insights into developing sustainable products, processes, and policies.

d) The Interpretation of Results

The interpretation of the results phase, representing the closure of the LCA process, integrates data from the LCI and LCIA phases into meaningful insights and actionable recommendations. This phase is crucial in developing active approaches to minimizing environmental impacts within a product service [161]. It explicitly evaluates the significance of identified impacts across life cycle stages to identify areas with the greatest potential for intervention. For instance, if the LCIA indicates that the manufacturing stage of the product is a primary contributor to greenhouse gas emissions, this knowledge may allow targeted process optimizations or material substitution. In this stage, decision-makers evaluate a number of possible scenarios and pursue enhancements like introducing energy-efficient technology, adopting renewable materials, or introducing better waste management practices [167]. Comparisons are usually made to define how sustainable an alternative product or design choice may prove to be against others. Such comparisons will serve to prioritize changes in line with organizational goals or requirements laid out in regulations. The interpretation phase also addresses trade-offs between impact categories, allowing stakeholders to prioritize competing environmental objectives—for example, between reducing carbon emissions and minimizing water use. Addressing uncertainties is a critical component of this phase. LCA results may be affected by data quality, method assumptions, or definitions of system boundaries. The effect of these varied factors on results is commonly assessed by sensitivity analysis to guarantee the robustness of conclusions derived [166]. Transparent reporting of uncertainties enhances confidence in the findings and supports

decision-making. Visual tools like charts, graphs, and comparative tables effectively communicate assessment findings to stakeholders. These instruments effectively facilitate complex data and information, pinpointing and drawing attention to areas for action and specific issues [168]. The next step is documenting the steps, sources of data, and limitations of a study that will enhance the reliability and repeatability of any LCA conclusions and facilitate transparency in the phase. The final phase of this analysis provides a bridge between technical interpretation and practical implementation. The findings from this analysis support the development of more sustainable products and processes while advancing common environmental goals like carbon neutrality, resource conservation, and regulatory compliance [169]. This phase underscores the critical role of LCA in promoting sustainability across industries and informs clear solutions for reducing environmental impacts.

4.4.4 Challenges and Future Perspectives of LCA: Navigating the Path Ahead

Life Cycle Assessment (LCA) is used to systematically assess the environmental impacts of products and processes and faces a series of challenges partly limiting its application. Some of the challenges are quite limiting in their own right; some others, however, raise questions and sometimes present opportunities for growth and improvement. As sustainability grows in importance, numerous occasions for growth and development of LCA become present in a number of initiatives that could eventually enhance its role in environmental decision-making [170]. The section elaborates more on the overarching challenges facing LCA while analyzing the potential enhancements for defining the most relevant future use of LCA. Accessibility and quality of data are among the main challenges faced by LCA. Quality and detailed data play a significant role in providing reliable LCA results, wherein many industries do not have enough, up-to-date, or consistent information on their products' life cycles. A lack of good-quality data may render environmental impact assessments unreliable and lead to possibly misleading conclusions [171]. The problem of data collection and evaluation is particularly alarming in developing countries, where very often, the infrastructure for monitoring or reporting on the collection or analysis of the data is severely inadequate. In order to help improve this situation in developing countries, further developments should seek to increase

access to much more user-friendly data thanks to the establishment of digital platforms, data-sharing networks, and collaborative international databases, making LCA data easier to access and standardized across industries and regions[172]. Among the major challenges that LCA faces are the quality and accessibility of the data. The quality and depth of the data in question are some of the most significant contributors to the reliability of any given LCA. Many industries, however, do not have adequate, updated, or shareable information regarding the life cycles of their products. Secondly, poor-quality data could lead environmental impact assessments to become less reliable and provide misleading conclusions. The facet of data collection and evaluation becomes particularly distressing in developing countries, where commissioned infrastructures for monitoring, reporting on, or analyzing data are usually deplorably lacking. In order to improve the current situation in developing countries, further developments should look to increase access to much more user-friendly data. Urban Asia is particularly well-placed to lead these efforts in such areas as improved digital platforms, the establishment of regional data-sharing networks, collaborative international databases, and, in general, the standardization of LCA data across industries and regions [166]. To satisfy the critical needs of an LCA, enrolled businesses and consumers alike should develop a comprehensive understanding of an LCA and, consequently, LCA. The major obstacle to the adoption of sustainable practices is a lack of understanding on the part of companies either as to how to interpret and work towards developing socially and environmentally responsible choices based on the results of LCA or how to incorporate them into their decision-making processes, thereby facilitating environmental performance improvement [169]. Likewise, it is highly important that consumers are informed about how to select products with 'lower' environmental impacts, as determined by LCA results. This requires a broad range of awareness and educational initiatives in terms of LCA and its use. In the future, a commitment to formal training programs on LCA concepts in school curricula, public awareness campaigns, and business sustainability will allow both businesses and consumers to participate actively in sustainability goals. A relationship between LCA and policy and regulation is another area that would require some refinements. While LCA may offer certain useful insights to decision-makers, clear policies on mechanisms for the

integration of LCA findings into regulatory frameworks seem to be lacking. The absence of any guidelines as to the ways to actually build LCA into the policy-making process disables it from serving fully its purpose in influencing higher-order environmental policies [161]. In the future, much more concerted effort should be given to establishing policies that engage LCA in all its phases, from product design and manufacturing to waste management and recycling. Besides, policymakers should encourage the use of LCA to set measurable sustainability targets and to track progress so as to provide a more effective scheme for environmental regulation. Technological advancement presents an excellent opportunity for the improvement of lifecycle assessment capabilities. The growing prospect of developing technologies, for example, AI, big data analytics, and automation, indicates that LCA could be sped up, made more accurate, and optimized with promoting excellence. These advancements certainly have the potential to enable real-time data collection and analysis, which will allow for the dynamic completion of an LCA assessment at any point within the lifecycle of a product or process. The advances in materials science and technologies of production in construction and manufacturing will ensure a more efficient use of resources, thereby serving to further lessen environmental impacts [173]. It shall become increasingly clear, as technology advances and the LCA has gained further traction, that opportunities exist to identify means of further implementation into LCA-based tools and processes to make the methodology more accessible, efficient, and relevant. Equally significant will be global coordination and standardization to tackle the limiting challenges for LCA. Differentiation in terms of the LCA practices and methods that exist in different regions of the world complicates data sharing and limits comparative assessments across borders. Establishing international LCA standards would produce assessments with more consistency and reliability, encouraging global cooperation to tackle environmental challenges. In establishing similarities in practice between nations and across regions, LCA would thus have the opportunity to become a truly universal tool for sustainable development, with more consistent and reliable data to fit into policy-making, business strategy, and scientific research. Alongside this, international cooperation could further develop a comprehensive global network of LCA data repositories, thereby enabling the

transfer of knowledge and best practices throughout industries and regions [174]. LCA is undoubtedly a robust tool for assessing environmental impacts arising from products and processes; nonetheless, it consequently faces significant challenges. The shortcomings on account of data unavailability and quality, uncertainties related to methodology, conceptual gaps in awareness, policy integration, and cooperation on a global scale are big pitfalls that ought to be attended to for the proper application of LCA. Challenges turned into opportunities through high-tech solutions, along with establishing a venue for international cooperation with stronger policy frameworks, assisting in the success of LCA. Moving forward with LCA is paramount for the optimal realization of the global sustainability development agenda and a way for policymakers, industries, and consumers to take further needed action to ensure the votes go in favor of better environmental results.

4.5 Life Cycle Assessment in Architecture: From Concept to Construction

The built environment has significant implications for global sustainability, heavily impacting resource consumption, energy usage, and greenhouse gas emissions. Architecture, in this regard, is central to shaping the spaces in which we live, one that firmly affects the environmental footprint of construction and operational processes. Life Cycle Assessment (LCA) has become an essential tool for architects and engineers to assess and methodically reduce these impacts. Assessment of the environmental impacts of materials, energy use, and emissions from raw material extraction through to the demolition of building components provides LCA with a robust framework for decision-making within the realm of sustainability. In architecture, the use of the LCA ranges from conceptual design through material selection and methods of construction. Application of LCA early in the design phase gives architects a set of options from which they can choose alternatives superior in environmental terms and more optimized building performance, consistent with sustainability goals. An increasing demand for green certification and compliance with regulation has further propelled LCA into primary importance towards the development of sustainable architectural solutions. This section examines the application of LCA in architecture, exploring its methodologies, benefits, and

obstacles. It details how LCA drives decisions during various stages of the building's life cycle, with an emphasis on mitigating environmental impacts while providing for functionality and aesthetic value. This analysis further reveals how LCA holds the potential to shift architectural practice into a far more sustainable domain and thus provides a road map for integrating environmental considerations into every facet of what is commonly referred to as the building process.

4.5.1 LCA in Architecture: Understanding Its Role and Relevance

LCA has gained significant recognition in the architecture and construction industries, being a systematic approach to scrutinizing the environmental impacts of buildings during their entire lifecycle. With the rise in climate change and environmental degradation concerns, the architecture sector increasingly recognizes the need to assess the sustainability of its practices. The application of LCA enables understanding and quantifying the environmental impacts occurring at several stages of building life, including raw material extraction, transportation, construction, operation, and end-of-life scenarios. LCA is the instrument through which architects and designers get to decide between different materials and strategies that minimize adverse effects on the environment and enhance sustainability [175]. Various phases of a building's lifecycle from conception to demolition and disposal offer opportunities for LCA application in an architectural firm. During the early design phases, LCA could be used by architects to assess differing materials and systems focused on reducing the environmental burden. By determining energy consumption and carbon emissions of materials like concrete, steel, or timber, LCA allows architects to select the most sustainable alternatives. For instance, using sustainably sourced timber as the building material reduces the total environmental impacts compared to concrete, which has a high embodied energy [176]. This early decision into the design phase has a direct bearing on long-term performance with respect to that of the building since LCA provides input during the design phase to settle the choice of structural systems, energy performance, and resource use into place. Energy-efficient strategies can be encouraged to include passive solar design, use of natural ventilation, and selection of energy-efficient mechanical systems. Energy consumption for a building can be predicted and simulated even before construction,

ensuring that it functions appropriately in terms of performance throughout its occupancy phase [177]. This preemptive approach urged by LCA includes minimizing operational energy use and reducing reliance on nonrenewable resources. The construction phase is perceived as being quite a consumptive one with regard to the natural resource sphere, but there remains serious potential for LCA in this instance. By identifying the most environmentally significant activities during construction, such as energy use and waste generation, LCA allows architects and contractors to implement strategies that reduce such impacts. For instance, modular or prefabricated components reduce construction waste due to on-site construction and improve efficiencies owing also to lesser requirements for machinery and labor. Immediately after the completion of construction, LCA can help guide the selection of low-impact building methods that reduce carbon emissions and other pollutants. Using a prefabricated steel frame rather than a concrete frame, those items can be considered to reduce the energy for a level during assembly to diminish the environmental impact of construction [176]. Beyond the construction phase, LCA actively engages during operation when a building's energy use and emissions become relatively high. Even at the end of a building's viable life cycle, LCA continues to provide insight into what approach to demolition, renovation, or reuse is the most sustainable. The circular economy closely mirrors LCA principles; both express interest in the concept of reused materials and waste minimization. It assesses the possibilities for recycling building materials or reusing components, including windows, doors, and load-bearing structures. Its formula also compares demolition against refreshment as far as environmental costs and benefits are concerned. The end of the building life cycle impacts can be significantly lessened when there is an allowance for designing for disassembly, where materials can be segregated more conveniently for recycling [177]. The primary rationale for which LCA is brought into architecture is its holistic nature. In contrast to conventional design approaches that consider phases or components of a building, LCA takes a more systemic view, thus ensuring decisions taken at one stage of a building's lifecycle do not elicit negative environmental dragging effects at another stage. For instance, employing more sustainable materials may lessen their embodied energy, but if poor energy-efficient design is employed in creating a building, this might

mean an increase in the operational demands for energy. LCA helps identify trade-offs between embodied energy and operational energy demand since it enables the designer to create truly sustainable buildings over their entire life cycle [175]. However, as an effective tool to assist with sustainable architecture, LCA also has limitations. Barriers like data availability and quality, methodological uncertainties of different LCA methodologies, and the complexity of integrating LCA into the overall design and manufacturing process still exist. However, with the emergence and evolution of digital and computational tools, LCA is becoming more accessible and effective, enabling architects to make better and more sustainable design decisions.Finally, the Life Cycle Assessment in architecture is not only a technical tool but also a mindset to think about the long-term environmental impact of our design decisions. LCA allows professionals to consider the entire life cycle of a building, including raw material extraction and demolition, allowing for the reduction of the ecological footprint of buildings, energy efficiency improvements, and provisioning for sustainable options in construction usage. As experts on something you would normally only hear about for architecture in much more technical settings, the implications of this time period most likely mean ensuring that the built environment does not adversely affect the natural environment.

4.5.2 LCA Applications in Architecture: From Materials to Design, Waste to Sustainability

Assessment is applied to assess energy efficiency during the design phase[161]. The passive design principles provide a feasible means to improve the energy performance of buildings. The use of natural ventilation, daylighting, and improved heating and cooling systems can significantly reduce energy consumption levels. The Passive House standard, for example, offers design guidelines for energy-efficient buildings and serves as a model example for energy use reduction. LCA is also useful for evaluating the integration of renewable energy sources. Solar, wind, and geothermal energy systems are efficient ways to minimize energy consumption and maintain energy production at sustainable levels. For example, the use of solar panels helps mitigate energy consumption while also reducing operational costs. Building automation, monitoring energy consumption, and optimizing energy efficiency

systems are examples of energy management strategies. LCA analyses help understand the environmental impacts of these systems, making building operations more sustainable. For instance, in the area of smart energy management, systems can optimize energy consumption when usage is not required through energy monitoring [178]. LCA can evaluate the potential of such systems in achieving energy-saving aspects, contributing to reducing the environmental impacts of building operations [178]. For sustainability, waste management in architecture is of vital importance. Life Cycle Assessment, which accounts for the environmental performance of the waste generated throughout the construction and utilization process, assists in constructing waste control techniques[161]. Reducing the quantity of waste is one of the key factors in sustainable construction. LCA identifies various strategies for reducing construction site waste generation. Modular building systems minimize waste, which in turn reduces construction time [179]. Modular structures minimize environmental impacts as they generate less waste and contribute to sustainable construction practices [179]. Recycling, reuse, and reduction are the three R's, and they play a significant role in waste management. LCAs assess the potential of building materials to be recycled and reused. Recovery of materials during demolition contributes to reducing environmental impacts. Sustainable waste management strategies are imperative to mitigate the environmental impacts of construction projects. LCA assists in advising waste management plans on construction works. Source separation, recycling, and reuse of wastes are important means to mitigate environmental impacts [180]. LCA can also evaluate storage and disposal methods of construction waste. The environmental impacts of these processes [180] enable the formulation of more sustainable waste management approaches. Life Cycle Assessment is a key point for integrating the principles of sustainability in architectural design processes. It minimizes environmental impacts and, simultaneously, can optimize economic and social benefits. Strategic planning and decision-making are the essence of sustainable design. LCA provides architects with a framework for assessing changes throughout the design process. Factors such as site selection, building design, and materials can be evaluated using LCA, which offers a framework for identifying sustainable solutions [161]. Siting of buildings can be influenced by climatic and environmental factors. [181] contributed to

creating sustainable settlements through understanding the environmental impacts of site selection. Architectural design processes usually involve complex systems; systematic LCA-based analyses can examine environmental impacts and provide recommendations to improve sustainability performance [161]. For example, analyzing building automation systems through LCA reveals their potential for energy management and user comfort. The introduction of such systems improves building energy performance and reduces operating costs [178]. The application of LCA in architecture is crucial for achieving environmental sustainability. LCA in areas like material selection, energy efficiency, waste management, and the integration of sustainable design principles helps architects make informed, sustainable design decisions. These processes either reduce environmental impacts or yield economic and social benefits. Proper use of LCA thus presents an important tool for achieving sustainability goals in architecture, and further integration of these methods will be implemented in future projects.

CHAPTER 5

WALLS THAT SHAPE THE FUTURE: THE IMPACT OF SCHOOL BUILDINGS ON CHILD GROWTH

School buildings are among the most critical constructions whose existence extend beyond being mere educational venues by shaping children's social, physical, and academic development. The design and physical characteristics of school buildings are, therefore, some of the most vital determinants of school quality because children spend a large portion of their day in these spaces. In such instances, planning schools according to aspects of ergonomic design, sustainability, safety, and accessibility directly contributes to students' individual and social development. Natural light, ventilation, acoustic regulation, and other elements are core determinants of students' concentration, motivation, and learning performance [182]. In Türkiye, standardized projects sketch the building of school structures and offer insight into a close evaluation of the physical and social impacts of the educational environment. The schema models used by the Turkish Ministry of National Education (MEB) have traditionally ranged in design for schools according to size and capacity (8, 12, 24, and 32 classrooms). These projects offer various design and functional advantages but must be evaluated within the framework of prevailing sustainability and ergonomic criteria. This section seeks to analyze the physical and psychological effects of school buildings on students and to present an in-depth analysis of the standardized projects prevalent in Türkiye. This research will assist in identifying the strengths in the design of school buildings and areas that need work on them. It will also suggest how to adjust the buildings within the frame of green sustainability and contemporary educational needs. This section will briefly discuss the influences of physical and psychological comfort on learning, assessment of design features for the standard projects in Türkiye, and their contributions to the performance of the school.

5.1 Learning Spaces: How School Buildings Influence Child Development and Education

Schools are not only places where students learn but also environments that significantly influence their social, physical, and psychological development. School buildings occupy a significant part of children's daily lives, contributing substantially to their personal, academic, and social development. In this context, the psychological and physical effects of school buildings become some of the most pivotal contributors to the quality of the educational environment. Educational settings are responsible for determining the learning processes of their students, encouraging behaviors, and influencing emotional states and health. According to [183], design and comfort of educational environments affect students' learning processes, health, and social interactions, emphasizing that the working conditions of school buildings can influence learning performance. Factors including the physical dimensions of school structures indirectly impact and directly influence students' academic achievements. Such attributes include ingress of natural light, acoustic adjustments, air quality controls, heating, cooling, and ergonomic design elements. [182] believe that natural light, ventilation, acoustic adjustments, and ergonomic features of school buildings indeed improve student focus, motivation, and achievement and thus provide more efficient training spaces. Because of these features, the learning environment becomes more comfortable and may improve students' psychological dispositions, thus making their time in school more productive. More particularly, the effects of school building air quality, temperature control, and sound on student attention and information processing seem to be well documented. [184] emphasize that classroom air quality continues to be a crucial factor influencing students' concentration and learning processes. Likewise, temperature level and environmental acoustic modifications also have direct effects on students' attention spans. Students who learn in healthy and sustainable educative environments gain not only educational success but also improvements in their physical and psychological health [184]. It is therefore the design of school buildings that is not just needed for functional purposes and aesthetics but for health as well as performance in students. Further, safety and accessibility in school buildings

guarantee equal educational opportunities among the students and encourage social participation. According to the [185], safe school buildings minimize psychological stress on students, fostering more active participation in learning processes by providing safer, more inclusive learning environments. Safe and accessible buildings create equal opportunities for disabled people and others with differing learning needs and contribute toward achieving educational equity. An additional point to note is that safety features in schools ensure physical and emotional security for any student. Students who feel safe will interact more socially, which in turn assists emotional growth. School buildings and their designs play a significant role in the social development of students. For students, schools are not only an academic setting but also a platform for developing and reinforcing social relationships and communication skills. A well-designed school building promotes social interaction among the students, facilitates group working, and promotes belongingness with a higher quality of school life. [186] note that proper building design helps students feel safe and increases their sense of belonging, thereby allowing for healthier social relationships and better expression. The development of flexible spaces responsive to psychological and social needs enhances the quality of education and encourages healthy student development, as [186] emphasize in their analysis of learning environments. A key aspect of the improvement of educational quality is to provide for child-friendly, flexible, and ergonomic healthy spaces in the design of school buildings. Such designs help not only in the learning processes of the students but also in their physical, emotional, and social development. Educational environments are more than mere physical structures; they include the social environment that meets students' psychological and social needs. Thus, in the design of educational buildings, attention must be paid not only to the physical necessities of students but also to the psychological net security and social interaction. Giving cognizance to these mandates in the preparation and designing of educational buildings provides students with efficiency, safety, and hygiene of a greater degree, all of which serve toward optimizing their growth and development in all facets.

5.1.1 Classrooms of Comfort: Enhancing Physical and Psychological Well-being in School Architecture

Physical and psychological comfort afforded by school buildings is a basic requirement determining students' learning processes and overall development. Since school-related activities take a good amount of time in the day, appropriate consideration must be given to open space in designing these environments that work best for students. In these situations, combining methods like adequate lighting, proper ventilation, sound control, comfortable seating, and a sense of safety helps create better learning spaces. This improves students' academic performance and overall happiness. Natural light, as a physical factor that greatly influences student performance, is an important element. On one hand, classrooms with penetration of natural light help with the regulation of the student's biological rhythms; melatonin levels stabilize, which extends the time of concentration for students while engaged in learning tasks [182,187]. Unlike artificial lighting, natural light sources increase the energy amongst students and enhance their emotional well-being. On top of this, proper light conditions ensure visual comfort, reduce eyestrain in students, and enhance employees' health at work [187]. Ventilation in the classroom and indoor air quality are yet another critical determinant of students' cognitive functions. Adequate air circulation should enable some retention of the normal level of carbon dioxide in classrooms, in turn optimizing students' concentration and learning [188]. Higher indoor air quality, mainly in enclosed settings, avoids undesirable consequences like headaches, fatigue, and attentional deficits, which are multifactorial causes of health impairment. Furthermore, proper ventilation lowers transmission of the virus causing respiratory infections, which decreases the age- and cohort-approximated student absenteeism [188]. Acoustic arrangements form an equally significant physical factor determining the efficacy of learning environments. Some authors claim that noise pollution diverts students, hindering the process of learning. Echo-free classrooms and the installation of proper sound-absorbing material enhance the ability of students to comprehend course content, thus enhancing their learning experiences [189]. They also empower teachers to exert less effort to communicate ideas, thus supporting classroom communication and learning processes. It has been shown that a reduction in ambient noise significantly increases information retention, especially in the youngest students [189]. Therefore, ergonomics has a direct relationship with the design of furniture and equipment in school buildings that can hamper students'

physical health in the long term. Desks and chairs that are at the appropriate heights and provide proper sitting support assist the musculoskeletal system in eliminating common disorders, such as back-neck pains [190]. Moreover, a well-arranged ergonomic environment allows students freedom of movement; therefore, students participate more actively in class and concentrate for long periods. In addition to physical comfort, school buildings must provide students with at least basic psychological support. That atmosphere promotes a sense of safety and belonging. Such environments facilitate the formation of social relationships, enhance communication skills, and build self-esteem [191]. Besides that, supportive learning environments reduce stress, allowing students to learn more effectively.In conclusion, such physical and psychological attributes of the school building would have direct implications for the academic success of pupils. Accordingly, due to these important reasons, during the design phase, more importance should be given to physical factors, such as lighting, ventilation, proper acoustic arrangement, and ergonomics, along with elements reinforcing psychological security and a sense of belonging. This approach offers to nourish a stronger human being at both personal and community levels.

5.1.2 Designing Connection: Social Interaction and Belonging in Schools

A school is not just a building for the supervision of the academic process; it accounts for all the significant space where children's social development is molded and the foundations of community building are built upon. Education is not only the delivery of academic content; it also includes the social, emotional, and psychological development of students. Flexible space for children to stimulate their interaction, develop social skills, form friendships, and express themselves freely in school: They all take place in a temporal context wherein peculiarities of location become a factor [191]. In this context, building design should be arranged so as to contribute to students' social development by providing a supportive physical environment. Creating a safe and approachable surrounding fosters a sense of belonging in children, thereby enhancing the development of community spirit [191]. The areas designed for social interaction, such as those within and outside the school building, are essential factors shaping students' experiences in schools. They provide

students with opportunities to get to know each other, make friends, and cultivate social relationships. For instance, providing safe spaces for children to develop social skills with others and improve their capability for collaboration and unity enables the emergence of a favorable social atmosphere in the school [192]. It is essential to develop open-air areas, social relaxation spaces, group work areas, and dynamic movement spaces; these should be integrated and designed according to the students' needs. Their placement concerning the overall structure of the school and their accessibility are also critical. Poor design of these spaces can lead to reduced utilization, and a sense of belonging may not develop [193]. Central placement of these areas encourages their use by students, thereby contributing to the establishment of the school as a social forum [194]. Interaction areas help children nurture personal relationships and develop a sense of social responsibility, empathy, and teamwork skills. The focus of the school should ideally help students play together, know each other better, and share ideas. This contributes to their development as they apply skills learned within the school to their lives beyond, instilling important values like social cohesion and respect for cultural diversity [191]. Additionally, social spaces at school allow for the fulfillment of students' emotional needs within a nurturing and safe environment. A supportive social environment minimizes student anxiety levels and allows them to focus on their learning processes. Community building entails the social, behavioral, emotional, and psychological development of students in school. The school building caters to a sense of belonging and positively impacts emotional well-being by providing students with opportunities to express themselves in a safe environment [192]. In conclusion, school facilities must be built not only for educational purposes but also as places of social interaction and community building. Such environments lead to the development of students' social skills and their understanding of the community—the foundation for their entire social lives. Therefore, when designing school buildings and surrounding areas, it is important to promote student interaction, social connectivity, and teamwork skills.

5.1.3 Final Reflections: Integrating Well-being, Environment, and Social Connection in School Design

School has been emphasized as the most important foundation of education in the life of a child. These are buildings that are meant for learning but are multifaceted centers of children's psychological, social, and environmental skills enhancement. Equally, the design of school buildings and facilities has a pronounced influence on students' academic achievements, psychological health, and social interactions. The modern school philosophy expects such things as school buildings not only to be the mediation between teaching and learning but also a conducive environment for emotional and social development among the children. In that sense, school buildings should be designed with features that would enable students to become healthier, socially skilled, and environmentally aware. Such factors in the design of school buildings can be internal physical comfort, the use of natural light, acoustics, temperature, and air quality. Other factors conducive to the educational processes include the building conditions, which enhance attention and motivation, subsequently increasing student success. In this context, sustainability approaches foster students' awareness of the environment by establishing a healthy school environment. The design of well-planned buildings provides for purposefully designed spaces to ease social interactions among students, enhancing community feeling, thereby tightening the bond for a possible personal development into more responsible members of society. The new school buildings should be constructed as educational spaces with respect to sustainability and health, thereby improving education quality. The learning environment should be one where children from different backgrounds support the development of eco-friendly, healthy, and efficient environments. When such designs provide support in academics, they equally teach children to be aware of the environment and their roles as active members of their communities. Finally, the design of school buildings should be incorporated as an integral part of the educational process, where these buildings are seen as an essential element contributing toward the development of students and a more sustainable future.

5.2 School Building Design: Conceptual Foundations and Practical Applications of Standardized Projects in the Context of Türkiye

The educational structures should be regarded as primary drivers in determining the future of societies. The design and construction of school buildings affect not only the students' learning environments and teachers' working conditions but also communities' social and environmental sustainable development objectives. Therefore, consideration must be given to aspects of functionality, aesthetics, durability, and the optimal use of resources in an educational structure. In addition to conventional design techniques, the use of standardized school building designs sometimes referred to as "type projects," has gained widespread acceptance by both the public and private sectors in recent years. Standardized school building designs provide repeatable, standardized solutions that respond to a limited range of uses. Replacing the standard user program with a set of required building characteristics acknowledges the necessity for a timely, cost-effective response to an increasing demand for buildings without compromising quality. The use of standardized school building designs for educational buildings has presented a possible solution in relation to other countries—and in particular Türkiye—where, by space limitations, a burgeoning student populace demands immediate attention. This section will first look into a definition of standardized school building designs and their strategic approach. Following that, the historical development and use of these designs in school buildings in Türkiye shall be extensively examined. Last, the advantages offered by this typology will be appraised, with discussions of the economic, social, and environmental return on school-building investment. The assessment is intended to provide a broad conceptual framework for understanding standardized school building designs and possible areas of their intervention.

5.2.1 Definition and Basic Principles of Standardized Projects : Focus on School Building Design

Standardized projects generally refer to modular, repeatable design templates devised for structures with similar functions. Their primary goal is to provide optimized, pre-tested design solutions that streamline construction processes and reduce both time and cost. In this approach, the architectural, structural, electrical, mechanical, and additional infrastructural elements are formulated according to predetermined templates [195]. A principal advantage of standardized projects lies in their

systematic nature. Each implementation phase draws upon previous experiences, allowing for improved methods and designs in subsequent applications. By minimizing uncertainties and offering a proven design framework, these projects enable a more efficient utilization of materials, labor, and financial resources [196]. Particularly in school buildings, standardized projects are utilized to address educational needs while promoting the swift construction of similar facilities across multiple regions. This approach accelerates the development of school infrastructures and reduces delays or technical setbacks. Since standardized school-building designs are typically pre-approved for safety and functionality, compliance with national regulations—including earthquake and fire codes—becomes more straightforward [197,198]. Nevertheless, standardized models may not always be ideal for every local context. Türkiye's geographical, climatic, and cultural diversity necessitates adaptable and flexible solutions. In cold regions, for example, enhanced thermal insulation is critical, whereas hot regions require an emphasis on natural ventilation and shading solutions. Rural communities often need smaller or more basic facilities, while urban centers may demand larger schools or those with boarding arrangements. Consequently, standardized templates should allow enough flexibility for regional and cultural modifications [199]. Despite these challenges, standardized projects provide considerable benefits in terms of rapid construction, reduced costs, and quality assurance. By adopting designs that have undergone initial testing, public authorities and local stakeholders can rely on the safety, functionality, and regulatory compliance of the resulting school buildings. This is particularly relevant in earthquake-prone regions of Türkiye, where robust structural and architectural measures are critical [198]. In conclusion, standardized (typical) projects for school buildings in Türkiye offer economic and time-saving benefits while aiding in upholding national design and safety standards. Nonetheless, it is essential to incorporate local conditions—such as climate, cultural practices, and varied educational needs—into these templates. When appropriately adapted, standardized designs can effectively balance uniformity in construction with flexibility to address regional differences, ensuring that each school structure meets the community's and students' needs [199,200].

5.2.2 Historical Development and Application Areas of Standardized Projects for School Buildings in Türkiye

The use of standardized projects for school buildings in Türkiye has shown significant development, particularly since the 1980s. During this period, the rapidly growing population and urbanization processes increased the demand for educational infrastructure. In the context of swiftly expanding cities, existing school buildings were insufficient, necessitating the construction of new ones. Within this context, standardized projects accelerated school-building construction and made it more cost-effective. Standardizing school buildings through such projects also helped address gaps in educational infrastructure. Since the 1980s, these projects have offered a solution to the growing institutional infrastructure needs, facilitating fast-track construction of school buildings [201]. Standardized projects play a key role in advancing school-building standardization. In Türkiye, projects for school buildings are generally determined by the number of classrooms, building type, and local requirements. The Ministry of National Education (MEB) has sought to propose functional solutions to meet educational needs in designing these projects. The most widely used standardized projects in Türkiye are for school buildings of 8, 12, 24, and 32 classrooms. These designs have enabled rapid school construction in different geographic regions, contributing to the country's educational infrastructure development. Notably, these projects have been devised to fulfill the functional needs of school buildings while significantly reducing time and costs [202]. One significant advantage of standardized projects is that they allow for swift and efficient governmental action on educational infrastructure, especially when there is a rapid increase in school demand. With these projects, local authorities and the state can quickly construct educational facilities and address the urgent need for classrooms. However, a major challenge facing standardized projects is the need for adapting each school building to local conditions and the unique needs of students. School-building designs in Türkiye's different geographies would diverge based on climate, demographics, and cultural contexts. Hence, it becomes evident that national projects cannot serve as a one-size-fits-all solution under all local conditions, making adaptation an essential design step for each school [203]. Addressing standardized projects in contemporary times involves considerations of environmental

sustainability, which has become a pivotal theme in the construction sector. Such standardized projects should not only accelerate implementation and reduce costs but also incorporate eco-friendly materials and energy-efficient solutions. Environmental sustainability thus directly influences a school building's long-term performance and energy consumption. Consequently, to mitigate potential ecological risks, it is necessary for standardized project designs to adopt sustainability principles throughout the project lifecycle [204]. Furthermore, it is crucial to minimize the environmental impact of standardized projects by sourcing materials locally and employing energy-efficient technologies during construction [205]. In brief, amid rapid population growth and urbanization since the 1980s, standardized school-building projects have been central to developing Türkiye's educational infrastructure. These projects have sped up the construction of school facilities and improved efficiency in addressing infrastructure deficiencies. Nevertheless, evidence from site-specific requirements suggests that besides providing a uniform blueprint, standardized projects demand local adaptations. Designing standardized projects in line with sustainability principles is vital for reducing environmental impact and ensuring the long-term efficiency of educational buildings [205].

5.2.3 The Benefits of Standardized Designs: Streamlining School Architecture

Standardized projects favored for the design and construction of school buildings provide many advantages. They speed up the building process and are cost-effective. Standardized projects offer safety and accessibility to school buildings as well as functionality, while also intended to improve the quality of education. With an increasing student body and the construction of schools in Türkiye, the advantages of standardized projects have, thus, become essential tools for addressing infrastructure challenges in education. Among the most prominent benefits is the high speed of construction. All standardized projects come from pre-signed and already-approved architectural plans. Consequently, there are minimal uncertainties and delays in the construction works. Given the fast construction process, educational demands can be met swiftly, which is a significant advantage in addressing the immediate needs of schools. Time savings generate other benefits that ensure the quick availability of school buildings, thus minimizing disruptions in children's education. Moreover, a

fast construction process allows for better control over expenditures. Projects completed on time typically incur less resource waste, thus enhancing the efficiency of public budget use [206]. Standardized projects also possess a competitive advantage in terms of cost-effectiveness. They often utilize conventional methods and materials; thus, the overall building cost is much lower. In addition, bulk purchasing of materials and the use of local labor can significantly reduce costs while promoting efficient resource utilization [207]. Cost-effectiveness is vital in the public sector, where limited resources need to be allocated to a wide range of services. In such situations, standardized projects stand out as effective strategies for improving the educational infrastructure. By following predefined quality standards, these projects help curb unexpected expenses, thus lowering the total project cost. Another advantage of standardized projects is structural safety. They are designed to meet both local regulations and international construction standards. Structural integrity is crucial, and construction materials undergo safety testing before use [208]. This approach provides robust protection for school buildings against potential disasters. Structural safety is of paramount importance for safeguarding students and teachers, especially in a country like Türkiye, which is situated in an earthquake zone. By employing standardized methods and tested materials, the impact of environmental risks is mitigated, ensuring each school's longevity and resilience against possible hazards [209]. The accessibility advantages of standardized designs are similarly significant. During the various stages of design, physical accessibility within educational settings is a top priority. Standardized designs incorporate necessary modifications that enable all learners to participate fully in education. For instance, accessible paths, ramps, and bathrooms suitable for individuals with disabilities help ensure a barrier-free, equitable educational environment for all students [210]. These accessibility features have made schools more inclusive, contributing to social equity. This overall process significantly supports equality in education by creating school settings that facilitate every student's growth. Standardized projects also confer another major benefit: an improvement in the quality of education. They are developed to align strictly with educational methodologies and pedagogical approaches. Classroom layouts, along with the use of natural light, ventilation, and acoustics, influence students' learning experiences within school buildings. Studies

have shown that increased exposure to natural light improves students' mental well-being, while better indoor air quality positively affects their physical health and attention levels. Proper ventilation and adequate lighting are integral to providing a healthy learning atmosphere. Furthermore, fine-tuning a room's acoustic properties (for instance, through sound insulation) helps ensure that students remain focused and are not distracted by ambient noise. These factors serve as fundamental components that boost learning efficiency [211]. Accordingly, the elements incorporated into the design of standardized projects help create an environment conducive to improved academic performance and a more productive learning experience. On the whole, standardized projects have demonstrated considerable benefits in the design of school infrastructure—faster completion times, cost-effectiveness, guaranteed quality and safety, ease of accessibility, and support for educational quality. These advantages confirm that standardized projects are a vital tool in developing educational infrastructure. They not only meet educational needs but also reflect environmental and social responsibility. Hence, safe, functional, comfortable, and efficient school buildings enhance the overall educational process. The design and implementation of these projects will, therefore, contribute significantly to strengthening a nation's educational framework.

5.2.4 Feasibility of Standardized Projects in School Building Designs: A Brief Overview

The design of educational buildings should combine functional requirements and relevance across different geographical, climatic, and cultural contexts. Each region has a unique profile defined by varying climatic conditions, social structures, and geographical features. These differences critically inform how school buildings should be designed. Consequently, it is essential to create standardized projects that maintain a modular and flexible structure to address this diversity. These projects need to be assessed and adapted to meet local needs for successful implementation. Moreover, climate is among the most fundamental factors in school building design. For instance, thermal insulation measures become crucial in colder regions, whereas natural ventilation and sun protection become critical in hotter climates [212]. While standardized designs may not directly solve all climate-related challenges, their

effectiveness depends on adaptability to specific climates and local circumstances. For example, an adaptable project may incorporate double-glazed windows, insulated walls, and efficient heating systems in cold climates, while features such as strategic window positioning for natural airflow, shading, and the use of local natural materials are particularly advantageous in hot climates [213]. Furthermore, geographical factors influence the design of school buildings in regions prone to natural disasters. Standard design approaches afford significant advantages here by integrating local ground analysis, disaster-response measures, and modular structural elements [214]. Specifically, hybrid or flexible structures built on earthquake-resistant designs enhance durability, calling for improved foundation systems to withstand seismic events. Another key consideration is cultural and social needs in school building design. Differences in socio-cultural contexts may require particular adaptations of the standard design. For instance, in certain areas, schools might need to host community activities and thus require multipurpose halls with gyms or spaces for extracurricular programs. These can be added to standardized projects without undermining the overall building plan [215]. The outcome of a standardized design that acknowledges local culture is critical, given that the physical setting of schools often correlates with students' engagement in the learning process. Incorporating local elements is, therefore, essential for the success of standardized projects. When a school design fails to incorporate the educational and cultural requirements of the area, efficiency and effectiveness can suffer. Accordingly, standardized solutions can become modular frameworks capable of adapting to local conditions. This approach enables schools to meet regional needs yet still accelerates project delivery [216]. Such flexibility, achieved through detailed local adaptations, renders standardized projects viable in diverse settings. However, one must ensure these designs reflect local culture and community structures, thereby aligning economic and time-saving benefits with cultural relevance. Consequently, standardized projects can enhance the quality of educational infrastructure, shaping it to address each region's unique demands.

5.2.5 Fundamental Design Principles of Standardized Projects for School Buildings

The design of school buildings is crucial to the quality of education. In Türkiye, standardized projects developed by the Ministry of National Education (MEB) play a significant role in the design of educational buildings. They are standardized designs made to meet various educational needs. They are designed based on fundamental design principles, including function, flexibility, sustainability, safety, health, and aesthetics, with the goal of providing the students with a proper learning environment that is healthy, safe, and functional. More than physically bettering school buildings, the intention of these standardized projects is to boost educational processes. The principles in the design of school buildings, ensuring effective use of space while considering the environment and greater social factors, play a crucial role. Some principles are functionalism, flexibility, and sustainability, which are deemed requisite to maintaining efficacy in school buildings over the extreme run. This will therefore include safety and health as significant, which in turn relates to increasing social responsibility for school buildings. The above-mentioned principles will be discussed in greater detail in this section regarding sentiments concerning the different criteria that require significant attention when the construction of school buildings is in consideration

a. Functionality

One of the principal aspects determining the effectiveness of educational environments is the functional design of a school building. Functionality here refers to a design that assists educational processes, sustaining optimal academic and social development for children. In Türkiye, standardized school designs are meticulously planned across various specialties to support these tasks. Each design feature of the school building is shaped by student and teacher needs, and the efficient functional arrangement of facilities supports extended learning processes [217]. A school's functional arrangement must be guided by a detailed plan in which every section of the building corresponds to an educational need. Such considerations include classroom size for specific student numbers and social spaces. Classroom capacity plays a significant role in shaping the overall educational process: rooms proportionally arranged to their student populations ensure enough movement space for learners and ease for teachers to conduct lessons. Additionally, the classroom

ambience should address acoustics, lighting, and air quality. Proper classroom orientation toward natural light has a positive effect on students' psychological and physical health, and sufficient air circulation in indoor areas promotes a conducive learning environment [218].

Acoustic arrangements also form an important feature for educational efficiency. Structural elements that prevent sound transmission between classrooms, as well as sound insulation systems, must be included. Such arrangements enable more engaging learning processes and ensure that students are not distracted by external noise [219]. Beyond classrooms, functionality requires considering teachers' and administrators' needs. Offices, meeting rooms, libraries, and laboratories are crucial to supporting school operations and the quality of instruction. These areas provide pedagogical and administrative support, ensuring that teachers can quickly access teaching materials and respond to educational needs without hindrance. Consequently, functional layouts in a school's administrative units help ensure efficient daily operations [220]. In designing school buildings, social and cultural amenities also hold great importance. Providing social spaces enables students to engage in both individual and group work. Common areas that encourage socializing, hosting events, or extracurricular activities align with the school's pedagogical objectives. Besides fostering a sense of community, these areas support students' psychological development by allowing them to practice social skills. Many school buildings, therefore, include sports halls, art workshops, music rooms, and playgrounds. The design of these spaces should be flexible, accommodating the age range and physical abilities of students [221]. Another essential component is accessibility. Accessibility ensures that quality education is available to all, particularly to students with disabilities [222]. This includes provisions such as wheelchair ramps, sufficiently wide doors, and restrooms adapted for individuals with limited mobility. Accessibility is not merely a matter of physical design; it also reflects the social responsibility of schools. By guaranteeing equality in education and every student's right to learn, specialized adaptations increase inclusivity. Flexible spaces in school buildings further support both individual and collaborative tasks, allowing teaching methods to become dynamic and interactive. By redesigning classrooms into various learning contexts, these environments promote collaborative

thinking, idea-sharing, and problem-solving. Such flexibility also provides teachers with areas to experiment with different teaching methods and effectively manage the learning process[223]. Ultimately, functional design aims to boost educational efficiency, foster the best possible student growth, and facilitate the smooth running of school operations. These requirements have been carefully integrated into the standardized projects developed in Türkiye, ensuring a comprehensive approach to students' educational experience [207]. Observing developments and needs in education while tailoring school buildings to functional criteria is an effective method of elevating the overall quality of learning [206].

b. Flexibility

The flexibility of school buildings refers to their ability to swiftly adapt to changes in educational requirements. Shifts in the education system, diverse student populations, and varying pedagogical approaches underscore the necessity for flexible school buildings. Standardized school project designs, therefore, incorporate modular spaces and flexible layouts to respond to these educational shifts. Flexibility not only enables schools to effectively address today's teaching practices, but it also ensures that school buildings can adapt to future needs. This approach strengthens the long-term functional viability of educational facilities by enabling them to adjust as circumstances evolve [224]. Flexible design implies that classrooms can be utilized for different pedagogical methods and needs. In this arrangement, not only can classroom layouts be reconfigured, but social spaces can also be utilized for multiple purposes, facilitating a multidisciplinary restructuring of common areas. A gymnasium might occasionally be converted into a concert hall, while a library may be used for reading sessions or other activities. This multi-usage promotes more effective and responsive learning environments for students. Moreover, it promotes innovative and interactive educational practices across various teaching environments [225]. A key aspect of flexibility lies in modular construction methods. These components can be rearranged or replaced around the school over time to reorganize its environment. With modular designs, school buildings can be tailored to contemporary educational demands while also reducing long-term maintenance costs and extending the lifespan of buildings [226]. Additionally, modular systems

enhance adaptability in a cost-effective manner. By eliminating unnecessary maintenance expenses and enabling continuous reshaping of school facilities, flexible design ensures that buildings remain aligned with evolving educational needs [227]. Flexibility further relates to the digitalization of educational processes. A school should be built so that its infrastructure seamlessly accommodates modern technology. Classrooms need to be arranged for the interactive use of digital learning tools, and essential technological elements—such as wireless internet access and smart boards—should be readily available. Digitalization can boost the efficiency of schooling by providing students with interactive avenues for learning [228]. Moreover, sufficient flexibility in classroom design allows digital tools to be used effectively for both individual and group work, facilitating potential future educational models as these evolve [229]. Flexibility extends beyond the purely physical characteristics of school buildings; it involves a design philosophy that accounts for pedagogical and digital transformations while anticipating future educational shifts. Thus, school structures are able to address current academic demands while remaining prepared for emerging needs. Flexible and modular designs respond quickly to changes in education, ensuring the long-term sustainability of school buildings [230].

c. Sustainability

Aspects of sustainable school design aim to mitigate the adverse environmental impacts of school buildings while promoting the efficient use of natural resources. In Türkiye, standardized school projects increasingly incorporate environmentally friendly solutions that reduce the long-term ecological footprint of educational facilities. The core principles of sustainable design address both functionality and architectural appeal, all while ensuring ecological safety. From both educational and environmental standpoints, developing a sustainable model for schools is of paramount importance. Designing a sustainable school involves high energy efficiency, water conservation, recyclable materials, and natural resource protection [231]. Energy efficiency ranks among the top priorities in school building design. Standardized school projects can incorporate renewable energy sources—such as solar or wind power—that contribute to meeting energy demands while reducing the

school's environmental impact. Additionally, the materials used often come from local and low-impact sources. Relying on locally sourced materials lowers transportation-related carbon emissions, while recycled or recyclable components help manage waste [232]. Natural lighting and ventilation systems in school buildings are equally crucial in promoting sustainability. Maximizing daylight reduces energy consumption and simultaneously creates a healthier, more efficient indoor environment. Effective ventilation systems further improve air quality, which benefits students' well-being and lowers overall energy usage [233]. Durability is another cornerstone of a sustainable school building, as long-lasting materials minimize both environmental impact and maintenance costs. By using robust materials, schools can ensure that the facility remains a healthy setting for students throughout their academic years, requiring fewer repairs and less ongoing maintenance. In addition, sustainable school designs integrate green areas, landscaping, and nature-friendly architectural elements. Green spaces help capture carbon and provide opportunities for students to interact with the natural environment, fostering environmental awareness. Preserving the surrounding ecosystem not only contributes to biodiversity but also supports students' understanding of ecological issues [234]. Consequently, the importance of sustainable school buildings in education becomes evident. By interacting with these environments, students learn about environmental stewardship and adopt eco-friendly habits. In combining environmental construction with environmental education, sustainable school buildings function as exemplars in promoting sustainable lifestyles—protecting nature while meeting the educational needs of future generations [235].

d. Safety and Health

The design of school buildings also involves multi-dimensional design principles that protect students' mental health and environmental safety. In Türkiye, standardized projects contribute to ensuring the security of school facilities by laying out detailed plans for comfortable and healthy environments. Safety measures can vary from fire safety and emergency exits to security cameras and trained security personnel. Fire safety is particularly critical; school buildings should include fire-resistant materials,

properly installed fire alarm systems, and emergency exits. Each school must also be equipped with effective fire suppression devices, staffed with fire-trained personnel, and have clear evacuation routes. Thus, students are safeguarded during their studies and are prepared for unforeseen emergencies. Protecting students in case of a fire incident is a key consideration in educational building design [236]. Security cameras and on-site security personnel represent another important dimension of safety measures. Cameras act as essential instruments for monitoring and mitigating potential risks, whereas trained staff provide continuous oversight. These measures help swiftly identify and address potential threats within and around the school environment. Furthermore, extracurricular activities should also be planned with student safety in mind, extending protective measures beyond the classroom [237]. The interior design of school buildings directly influences students' health. In standardized projects, air quality, climate control, sound insulation, and lighting are incorporated for health-related reasons. A well-designed interior contributes significantly to both the physical and psychological well-being of students. Adequate sunlight in school buildings promotes overall health and mental alertness. Exposure to natural light supports vitamin D synthesis, strengthens the immune system, and improves students' concentration levels. Additionally, ensuring proper ventilation and clean airflow is essential for protecting students' physical health. Fresh air contributes to reducing indoor air pollution in school buildings, thereby maximizing the effectiveness of learning time [238]. Sound insulation stands out as another vital aspect affecting students' health in school buildings. Noise negatively impacts the learning process; hence, classrooms should be acoustically designed to enhance instructional quality. Effective soundproofing minimizes external noise, particularly important in large classrooms. Finally, hygiene standards are critical in maintaining student health. Routine cleaning protocols in classrooms, restrooms, and cafeterias help prevent the spread of infectious diseases, ensuring a safe educational setting [239]. Through these health and safety measures, standardized designs promote students' well-being in every corner of the school building. Fire safety systems, security measures, indoor air quality controls, sound insulation, and hygiene standards collectively yield a positive influence on students' physical and mental

health. Ultimately, such design elements minimize risk, foster health-promoting learning environments, and support high-quality education.

e. Aesthetic design

The design relevance of school buildings—particularly those created within standardized projects in Türkiye—not only fosters students' educational well-being but also promotes harmony within the school environment. Standardized projects refer to building types developed to meet specific educational standards and local needs. In such endeavors, aesthetics is not merely about visual appeal but also about functionality and ecological compatibility. A school's aesthetic design hinges on the exterior, material selection, colors, structural form, and spatial arrangement, all of which are key elements in standardized projects. Materials and colors that align with environmental compatibility enhance the interaction between the school building and its surrounding community [240]. In designing standardized projects, durable and aesthetically pleasing materials—such as natural stone—are often preferred. Materials such as wood and metals contribute to a modern aesthetic while also enhancing a school's longevity. The interiors, especially in classrooms and common areas, are planned with an eye toward aesthetics that can positively influence students' health and psychological well-being. Choices in classroom color schemes may impact students' mental state: vivid colors like yellow and blue can attract students' attention, whereas more earthy tones such as green can have a soothing effect. Meanwhile, lighting design should aim to maximize natural light in order to create student-centered learning settings [241]. Beyond the interior, landscape design around the school contributes to environmental awareness as well as aesthetic appeal. Green spaces provide opportunities for outdoor play and support local biodiversity when integrated thoughtfully with natural vegetation. Such landscaping enhances the visual context of the school and reinforces its role as an educational hub that also promotes social and environmental consciousness [242]. A design approach that harmonizes aesthetics with environmental factors thereby benefits both the school's educational mission and its community engagement.

5.2.6 Conclusion

The design principles of standardized school projects in Türkiye rely on several fundamental premises directed toward enhancing the physical premises of education, viz., sevenfold: functionality, flexibility, sustainability, safety, health, and beauty. School buildings are designed to perform not only educational functions but also to provide students with a safe, healthy, and enriching environment. A detailed design process for standardized projects attempts to provide students with the best learning experience while considering environmental protection and social responsibility features. Basically, the physical configuration of the environment seems to significantly influence the development of educational processes. Hence, every element organized in a design should be selected with utmost care in order for the school building to serve its educational function as effectively and efficiently as possible. The safety of a school building is considered to be one of the paramount features that directly affect both the physical and psychological health of children. Essentials immediately affecting safety for every school building include fire safety, emergency exits, CCTV cameras, and personnel. Health considerations pertaining to a school building cover indoor air quality, heating and cooling systems, lighting, and any other element ensuring that the education process is conducted in an environment conducive to good health for students. The appointed conditions for hygiene and relevant acoustics in school building designs also contribute to the position of creating this healthy environment. Sustainability fundamentally ensures the least environmental impact of a building under standardized conditions. In standardized projects, features like energy-efficient designs, the maximum use of recyclable materials, and the conservation of natural resources will be applied. Not only do these principles make the school building environmentally friendly, but they also ensure its continued efficient operation into the future. The design also integrates many facets of stand-alone and passive energy designs; therefore, both energy use and environmentally detrimental impacts from school buildings are diminished. In addition to these, sustainable design helps reduce the maintenance cost of school buildings for many years, thus freeing school budgets for better efficacy. Aesthetics plays a critical role in the improvement of students' mental and psychological health in the sense that visual-aesthetic features strengthen students' connections with the ambiance of their school environment. Colors, arrangement of

interiors, landscape design, and applicable use of natural elements positively define the atmosphere of a school. The aesthetic design thus provides an environment not just functional, but also consonant with the neighboring surroundings and inspirational for the child. In conclusion, the design principles set down by standardized school projects in Türkiye ensure that while meeting all functional needs, they also cater to environmental, social, and pedagogical needs with a view to upgrading teaching environments for children in cleaner, more secure, and sustainable settings. Besides, they also ensure that the school buildings continue to be effective and efficient for long, firm support toward furthering sustainability in society. Perhaps underlining the way the environment plays a role in an education program would strengthen the idea that any approach must adequately plan these projects from the outset to the end. During the first planning stages of construction, such coordinated projects can prove to be helpful towards the attainment of better education standards and good communities.

CHAPTER 6

STANDARDIZED ELEMENTARY SCHOOL DESIGNS IN TURKIYE: A COMPARATIVE PROJECT ANALYSIS

In this section, standardized elementary school projects developed by the Ministry of National Education (MEB) of the Republic of Türkiye will be examined. These elementary schools aim to provide physical environments appropriate to the needs of primary education in terms of various group sizes and educational demands. The projects are categorized into four main typologies: 8, 12, 24, and 32 classroom layouts. These typologies are diversified according to student capacity and educational needs, incorporating classrooms, social spaces, administrative units, and technical facilities. The designs respond to modern educational requirements in order to provide a safe, healthy, and conducive learning environment. This section offers an in-depth presentation concerning the architectural design and spatial organization of each elementary school typology. The evaluation of the distribution and functionality of spaces is the floor plan study and highlights common features and unique characteristics of these projects.

6.1 8-Classroom School Project: General Features and Spatial Analysis

The section provides an overview of the 8-classroom school project in light of structural features and spatial functions. The project represents a primary school model with a capacity of 270 students, designed to address the educational needs of residential areas. Aiming to meet modern educational requirements, the project stands out with its versatile and functional spatial organization.

6.1.1 Structural Features



Figure 6.1 8-classroom school project - exterior perspective (sourced from the MEB archive)

As shown in Figure 6.1, this rendering presents an exterior perspective of the 8-Classroom school project. The design includes a multi-functional outdoor area that complements the building's architectural structure (Figure 6.1).

The project consists of a three-story building, including a basement. Its architectural design incorporates units that support both educational activities and social and cultural events:

Total Area: 2461 m²

Ground Area: 594 m²

Floor Plans: Basement + Ground + 2 Floors + Roof

Student Capacity: 270

Number of Classrooms: 8



Figure 6.2 Exterior perspective of the 8-classroom school project (sourced from the MEB archive)

As shown in Figure 6.2, this rendering illustrates the exterior of the 8-classroom school, highlighting its modern design, colorful facade, and surrounding outdoor spaces for recreational activities (Figure 6.2).

6.1.2 Floor Plans



Figure 6.3 8-classroom school project basement floor plan (sourced from the MEB archive)

Figure 6.3 illustrates the basement floor plan of the building. The basement includes service areas supporting the building's operations, such as technical spaces, a shelter, a kitchen, and a physical education hall. Additionally, horizontal circulation areas ensure the effective utilization of this floor (Figure 6.3).



Figure 6.4 8-classroom school project ground floor plan (sourced from the MEB archive)

As shown in Figure 6.4, the ground floor plan features shared spaces for educational and social activities. This floor includes a dining hall, canteen, activity and playroom, as well as a library and classrooms. This layout is designed to meet students' needs at both educational and social levels (Figure 6.4).



Figure 6.5 8-classroom school project first floor plan (sourced from the MEB archive)

As shown in Figure 6.5, the first floor plan emphasizes educational areas. This floor includes classrooms, administrative offices, and a prayer room. The layout is organized to facilitate simultaneous educational and administrative activities (Figure 6.5).



Figure 6.6 8-classroom school project second floor plan (sourced from the MEB archive)

As Figure 6.6 illustrates, the second floor plan is designed with a focus on education. In addition to classrooms, it features a multi-purpose hall that provides flexible space for various events and meetings (Figure 6.6).

6.1.3 Spatial Distribution and Functions

The project includes various units designed to support the holistic development of students:

Educational Spaces: Classrooms, visual arts and music classrooms, kindergarten classroom, science classroom, physical education hall.

Support Areas: Library, support education room, counseling service.

Social Spaces: Dining hall, multi-purpose hall, student canteen, prayer room.

Administrative Areas: Administration offices, teachers' rooms.

Each space is planned to meet the needs of users in terms of functionality and design. These spatial arrangements, particularly aimed at integrating educational, social interaction, and cultural activities, support contemporary educational approaches.

The 8-classroom school project goes beyond meeting the needs of students and teachers by emphasizing the social and cultural functions of an educational building. In this context, the building's design promotes both multi-purpose use of spaces and a user-friendly approach. The solutions offered by the project provide a significant example for the development of educational structures in residential areas.

6.2 12-Classroom School Project: General Features and Spatial Analysis

This section offers a comprehensive overview of the 12-classroom school project, focusing on its structural features and spatial functions. The project represents a primary school model with a capacity of 288 students, designed to address the educational needs of residential areas. Designed to align with contemporary

educational needs, the project is distinguished by its adaptable and practical spatial arrangement.

6.2.1 Structural Features



Figure 6.7 Exterior perspective of the 12-classroom school project (sourced from the MEB archive)

As shown in Figure 6.7, this rendering showcases the exterior design of the 12-classroom school, highlighting its modern architecture and the surrounding outdoor recreational spaces, including sports courts and parking areas (Figure 6.7). The project consists of a three-story building, including a basement. Its architectural design incorporates units that support both educational activities and social and cultural events:

Total Area: 2839 m²

Ground Area: 721.m²

Floor Plans: Basement + Ground + 2 Floors + Roof

Student Capacity: 288

Number of Classrooms: 12



Figure 6.8 Main entrance view of the 12-classroom school project (sourced from the MEB archive)

As shown in Figure 6.8, this image presents the main entrance of the 12-classroom school, emphasizing the building's welcoming facade and organized outdoor area (Figure 6.8).

6.2.2 Floor Plans



Figure 6.9 12-classroom school project basement floor plan (sourced from the MEB archive)

Figure 6.9 showcases the basement floor, including essential technical areas, storage spaces, and service rooms designed to support the operational needs of the school.

The layout ensures easy access to service facilities while minimizing student interaction in these areas (Figure 6.9).



Figure 6.10 12-classroom school project ground floor plan (sourced from the MEB archive)

As shown in Figure 6.10, the ground floor features key social and educational spaces, including classrooms, a dining hall, and a library integrated with a computer lab. The main entrance connects seamlessly to the central hallway, ensuring smooth circulation and accessibility (Figure 6.10).



Figure 6.11 12-classroom school project first floor plan (sourced from the MEB archive)

As Figure 6.11 illustrates, first floor is dedicated primarily to educational activities, with classrooms distributed strategically to optimize light and reduce noise. Administrative areas, such as offices for teachers and counselors, are also located on this floor to ensure close interaction with students (Figure 6.11).



Figure 6.12 12-classroom school project second floor plan (sourced from the MEB archive)

As shown in Figure 6.12, second floor includes additional classrooms and a multi-purpose hall, which serves as a flexible space for various activities, meetings, or events. The layout emphasizes functionality while maintaining an organized flow between different areas (Figure 6.12).

6.2.3 Spatial Distribution and Functions

The project includes various units designed to support the holistic development of students:

Educational Spaces: Classrooms, visual arts and music classrooms, physics classroom, technology design classroom, science classroom, physical education hall.

Support Areas: Library, physical education hall counseling service.

Social Spaces: Dining hall, multi-purpose hall, student canteen, prayer room.

Administrative Areas: Administration offices, teachers' rooms.

Each space is planned to meet the needs of users in terms of functionality and design. These spatial arrangements, particularly aimed at integrating educational, social interaction, and cultural activities, support contemporary educational approaches. The 12-classroom school project goes beyond meeting the needs of students and teachers by emphasizing the social and cultural functions of an educational building. In this context, the building's design promotes both multi-purpose use of spaces and a user-friendly approach. The solutions offered by the project provide a significant example for the development of educational structures in residential areas.

6.3 24-Classroom School Project: General Features and Spatial Analysis

This section offers a comprehensive examination of the 24-classroom school project, focusing on its structural characteristics and spatial functionalities. The project

represents a primary school model with a capacity of 576 students, designed to address the educational needs of residential areas.In pursuit of contemporary educational standards, the project distinguishes itself through its adaptable and practical spatial arrangement.

6.3.1 Structural Features



Figure 6.13 Exterior perspective of the 24-classroom school project-view 1 (sourced from the MEB archive)

As shown in Figure 6.13, This image showcases the modern design and welcoming entrance of the 24-classroom school project, complemented by vibrant colors and open spaces (Figure 6.13). The project consists of a four-story building, including a basement. Its architectural design supports both educational and social functions, providing versatile spaces for students and staff:

Total Area: 4020 m²

Ground Area: 780 m²

Floor Plans: Basement + Ground + 3 Floors

Student Capacity: 576

Number of Classrooms: 24



Figure 6.14 Exterior perspective of the 24-classroom school project-view 2 (sourced from the MEB archive)

As shown in Figure 6.14, rendering highlights the colorful facade, landscaped surroundings, and outdoor sports areas of the 24-classroom school Project (Figure 6.14).

6.3.2 Floor Plan



Figure 6.15 24-classroom school project basement floor plan (sourced from the MEB archive)

As Figure 6.15 illustrates, basement floor plan contains technical areas, storage spaces, and service rooms essential for the school's operational needs. These spaces

are strategically placed to avoid interference with student activities while ensuring accessibility (Figure 6.15) .



Figure 6.16 24-classroom school project ground floor plan (sourced from the MEB archive)

As shown in Figure 6.16, ground floor includes primary educational and social spaces such as classrooms, a dining hall, and a library. The central hallway is designed to connect functional spaces seamlessly, facilitating easy movement (Figure 6.16).



Figure 6.17 24-classroom school project first floor plan (sourced from the MEB archive)

As shown in Figure 6.17, first floor focuses on academic activities, featuring classrooms, administrative offices, and additional support areas. The design prioritizes natural light and minimizes distractions for optimal learning conditions (Figure 6.17).



Figure 6.18 24-classroom school project second floor plan (sourced from the MEB archive)

As Figure 6.18 illustrates, second floor provides additional classrooms and specialized spaces, accommodating diverse educational activities while maintaining efficient circulation patterns (Figure 6.18).

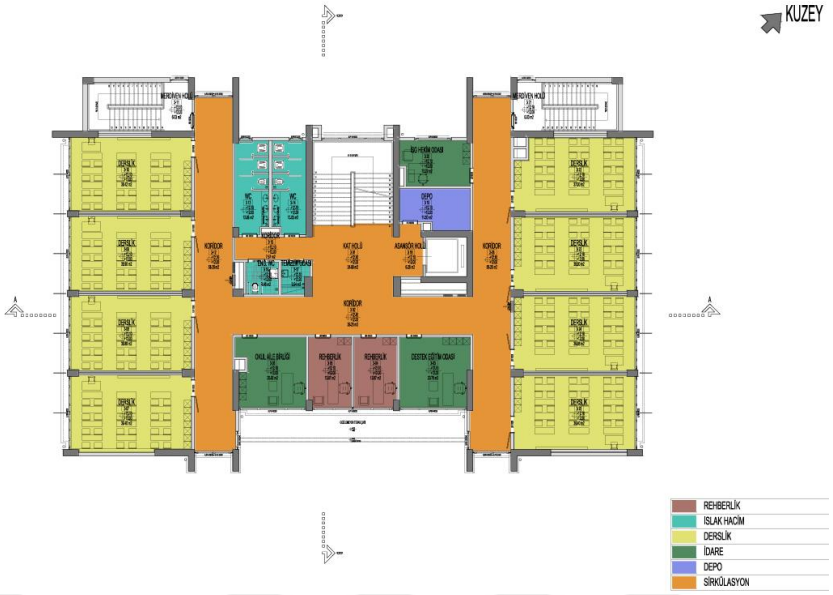


Figure 6.19 24-classroom school project third floor plan (sourced from the MEB archive)

As shown in Figure 6.19, third floor includes further classrooms and multi-functional spaces designed to adapt to various academic and extracurricular needs. The layout ensures the best use of available space while supporting flexibility (Figure 6.19).

6.3.3 Spatial Distribution and Functions

The project includes various units designed to support the holistic development of students:

Educational Spaces: Classrooms, visual arts and music classrooms, science classroom, technology design classroom, physical education hall.

Support Areas: Library, support education room, counseling service.

Social Spaces: Dining hall, multi-purpose hall, student canteen, prayer room.

Administrative Areas: Administration offices, teachers' rooms.

The 24-classroom school project goes beyond basic educational functions by emphasizing both academic and social development. In this context, the building's design promotes both multi-purpose use of spaces and a user-friendly approach. The solutions offered by the project provide a significant example for the development of educational structures in residential areas.

6.4 32-Classroom School Project: General Features and Spatial Analysis

This section evaluates the 32-classroom school project based on its structural features and spatial functions. designed to accommodate 960 students, the project addresses the educational needs of diverse urban areas. In pursuit of contemporary educational standards, the project distinguishes itself through its adaptable and practical spatial arrangement.

6.4.1 Structural Features



Figure 6.20 Exterior perspective of the 32-classroom school project (sourced from the MEB archive)

As shown in Figure 6.20, This rendering showcases the exterior design of the 32-classroom school project, highlighting its modern architecture, spacious courtyard, and adjacent sports facilities, designed to support both educational and recreational activities (Figure 6.20).

The project consists of a four-story building, including a basement. Its design ensures compatibility with local conditions across all 81 provinces and incorporates solutions suitable for school age groups:

Total Area: 7280 m²

Ground Area: 1681 m²

Floor Plans: Basement + Ground + 3 Floors

Student Capacity: 960

Number of Classrooms: 32



Figure 6.21 Main entrance view of the 32-classroom school project (sourced from the MEB archive)

As shown in Figure 6.21, rendering highlights the main entrance of the 32-classroom school project, showcasing its modern design, functional layout, and adjacent sports facilities that enhance both accessibility and utility (Figure 6.21).

6.4.2 Floor Plans



Figure 6.22 32-classroom school project basement floor plan (sourced from the MEB archive)

As Figure 6.22 illustrates, basement floor includes essential service and operational areas such as a multi-purpose hall, physical education hall, preparation rooms, storage spaces, ablution areas, prayer rooms, and technical spaces. These facilities are strategically designed to support the building's functionality without interfering with student activities (Figure 6.22).



Figure 6.23 32-classroom school project ground floor plan (sourced from the MEB archive)

As shown in Figure 6.23, ground floor houses key educational and administrative spaces, including six classrooms, a visual arts classroom, a technology design classroom, a library, a dining hall, a canteen, and administrative offices. The layout ensures efficient movement and accessibility for all users (Figure 6.23).

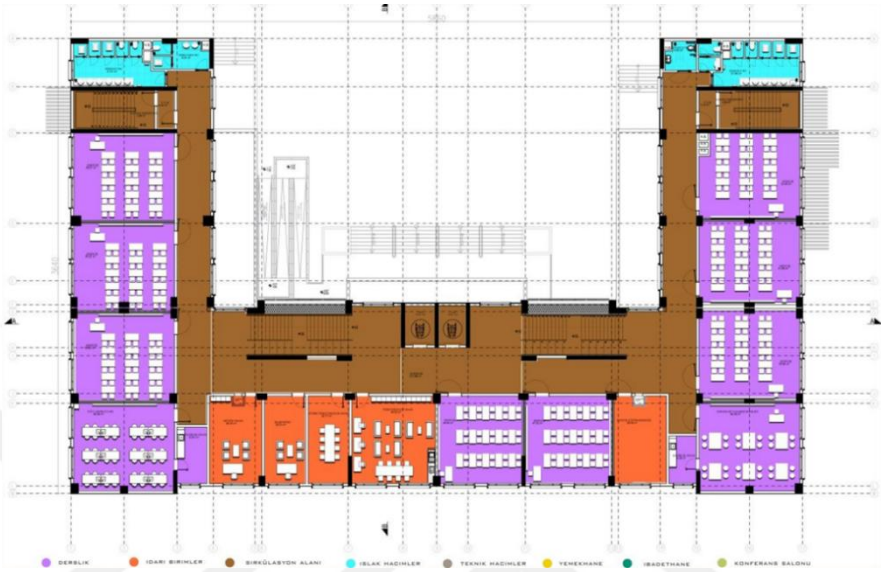


Figure 6.24 32-classroom school project first floor plan (sourced from the MEB archive)

As Figure 6.24 illustrates, first floor focuses on educational activities, featuring eight classrooms, a science laboratory, a technology design classroom, administrative offices, a support education room, and teacher lounges. The design prioritizes optimal lighting and a conducive learning environment (Figure 6.24).

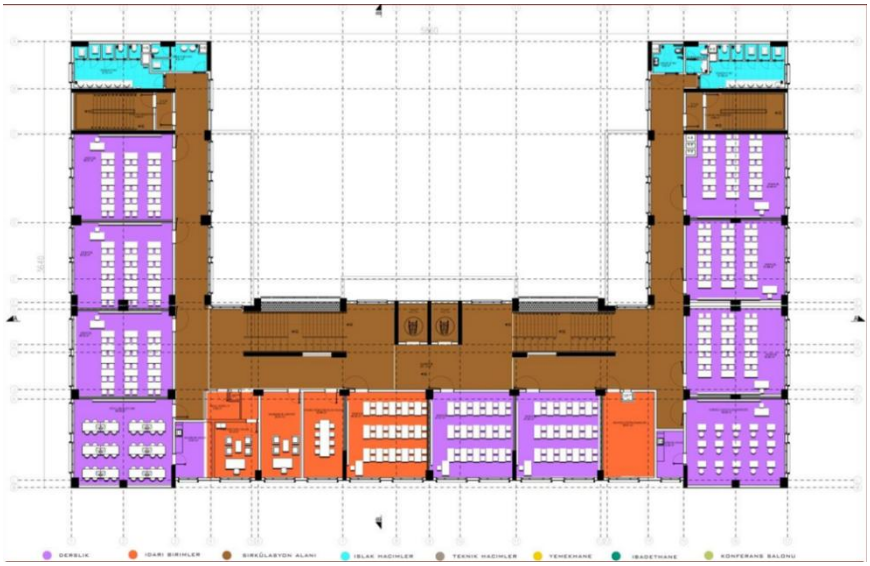


Figure 6.25 32-classroom school project second floor plan (sourced from the MEB archive)

As shown in Figure 6.25, second floor includes nine classrooms, a science laboratory, a visual arts classroom, administrative offices, a support education room, and teacher lounges. The spatial arrangement enhances functionality and accessibility for various academic needs (Figure 6.25).

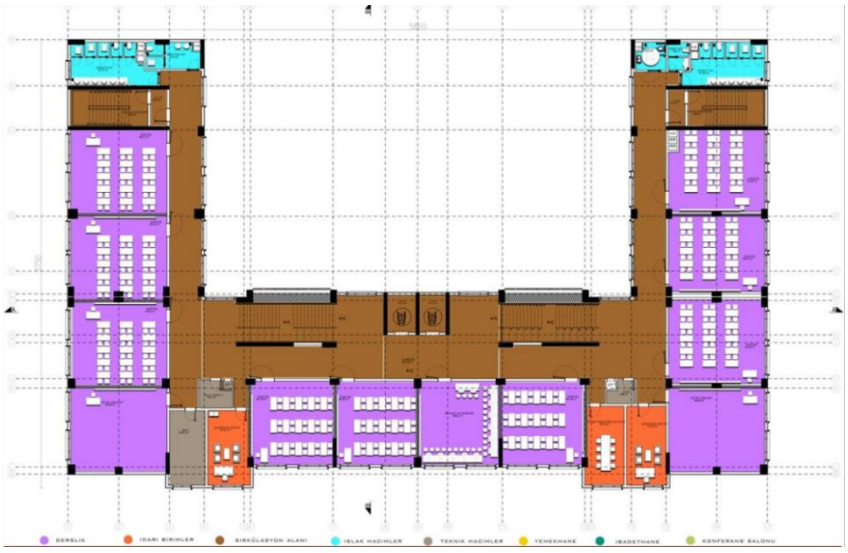


Figure 6.26 32-classroom school project third floor plan (sourced from the MEB archive)

As Figure 6.26 illustrates, third floor accommodates nine classrooms, two music classrooms with storage, a computer classroom with storage, and two counseling rooms. This layout ensures ample space for specialized educational activities and administrative support (Figure 6.26).

6.4.3 Spatial Distribution and Functions

The project includes various units designed to support the holistic development of students:

Educational Spaces: Classrooms, science laboratories, technology design classrooms, visual arts classrooms, music classrooms, computer classrooms, physical education hall.

Support Areas: Library, support education room, counseling service.

Social Spaces: Dining hall, multi-purpose hall, student canteen, prayer room.

Administrative Areas: Administration offices, teachers' rooms.

The 32-classroom school project provides a well-balanced solution for educational and social needs, emphasizing safety, functionality, and adaptability. The design incorporates modern materials and construction techniques to ensure sustainability and cost-efficiency.

6.5 Structural Details and Material Selection Process

The choice of structural materials and design details plays a pivotal role in shaping a building's environmental footprint. Appropriate material selection is essential to achieve sustainability goals and reduce the environmental impacts of construction. This study conducted a comprehensive analysis of the standardized school projects. This section will provide a comprehensive analysis of the material selection and matching process, explaining the criteria used for defining materials for each building component, such as walls, ceilings, and floors, and detailing how these materials were evaluated and matched in Tally to ensure both environmental sustainability and functional compatibility. The environmental impacts of material

types were assessed throughout their life cycle, and these assessments were documented alongside their corresponding position numbers. Each selection was detailed in terms of both environmental sustainability and building performance.

6.5.1 Wall Systems

This section provides a detailed examination of the wall systems employed throughout the project, highlighting their alignment with the building's structural, functional, and environmental requirements. Based on the project details, wall types were identified and categorized using specific codes to represent walls with varying characteristics and functions. For example, BDV-1 refers to a reinforced concrete basement wall designed for below-ground levels, while DV-1 represents an interior brick wall commonly used in partitioning indoor spaces. These codes ensure clarity and consistency in defining the structural and functional differences among the walls used in the project. Each wall system has been meticulously designed to optimize structural stability, acoustic and thermal insulation, and overall performance. Advanced materials and innovative construction techniques were integrated to ensure durability, sustainability, and compliance with diverse functional needs. To enhance environmental performance, an LCA of the materials was conducted using the Tally Environmental Impact Tool. This comprehensive evaluation demonstrates the walls' critical role in improving the building's energy efficiency, occupant comfort, and long-term resilience, underscoring their contribution to modern architectural standards and sustainable design goals.

Table 6.1 Wall systems: material composition and functional attributes (sourced from the MEB archive)

Code	Material	Thickness	Finishing Details	Additional Features
BDV-1	Reinforced concrete shear wall, HDPE drainage sheet, 5 cm XPS	200-250 mm	Interior: Satin plaster and paint; Exterior: Waterproofing, thermal insulation	Load-bearing system; resistance to water and moisture ingress; HDPE protection sheet for exterior insulation

Table 6.1 Wall systems: material composition and functional attributes (continued) (sourced from the MEB archive)

Code	Material	Thickness	Finishing Details	Additional Features
DV-1	Brick wall (hollow vertical bricks), satin plaster	190-290 mm	Painted interior surface	Lightweight structure element; acoustic performance-enhancing satin plaster; fire resistance
DV-2	Brick wall, ceramic cladding, rough plaster	190-290 mm	Interior: Ceramic cladding; Exterior: Limewash	Water and moisture-resistant surface; surface preparation with rough plaster; slip-resistant ceramic cladding
DV-3	Brick wall, ceramic cladding150 cm (height)	190-290 mm	Interior: Ceramic cladding	Cladding only at a specific height; combined with floor waterproofing
DV-4	Protective wall pad (150 cm high)	190-290 mm	Interior: Protective padding; Exterior: Paint	Protective against impacts; padding thickness between 3-5 cm; fire-resistant material

Table 6.1 provides an overview of various wall systems, detailing their material composition, dimensions, finishing details, and additional features. The table outlines the functional roles and technical properties of each wall type within the context of the building's structural and environmental requirements (Table 6.1). This table captures the technical and functional diversity of wall systems, offering a comparative understanding of their applications and contributions to building performance. BDV-1 (basement wall type) is a reinforced concrete retaining wall system designed to withstand challenges such as water, humidity, and soil pressure encountered in underground structures. This system features a layered design that combines waterproofing and mechanical durability. Each layer is meticulously crafted to enhance the safety and longevity of the structure.

Table 6.2 Layer composition and functional attributes of BDV-1: basement wall type (sourced from the MEB archive)

Layer	Material	Code	Thickness	Purpose and Features
1. HDPE Drainage and Protection Sheet	High-density polyethylene (HDPE) sheet	152.001.002	50-70 mm	Reduces mechanical pressure from soil, facilitates drainage, and extends the system's lifespan.
2. Geotextile Felt	Nonwoven geotextile felt (250 gr/m²)	152.451.002	2-5 mm	Provides moisture retention and enhances the efficiency of insulation layers.
3. Double-Layer Waterproofing	Bituminous membrane or PVC-based material	152.551.009	2-5 mm	Fully protects the reinforced concrete wall against water.
4. 5 cm XPS Thermal Insulation	Extruded polystyrene (XPS)	153.351.003	5 cm	Provides high thermal insulation and prevents moisture penetration.
5. Reinforced Concrete Wall	Reinforced concrete (C30/37 class)	Static project-specific	250-300 mm	Offers high strength, fire resistance, and earthquake resilience while serving as the primary structural element.

Table 6.2 outlines the detailed layer composition of the BDV-1 basement wall system, including material specifications, thickness, and functional purposes. Each layer contributes to the overall performance, durability, and resilience of the system, ensuring suitability for basement applications (Table 6.2). BDV-1 is a layered system that provides protection against water, humidity, and soil pressure in underground structures. The combination of 5 cm XPS thermal insulation, double-layer waterproofing, HDPE drainage sheet, and geotextile felt enhances the structure's durability while ensuring safety. The reinforced concrete wall acts as the primary load-bearing system, offering a long-lasting solution.

Table 6.3 Layer composition and functional attributes of DV-1: interior wall type (sourced from the MEB archive)

Layer	Material	Code	Thickness	Purpose and Features
1. Satin Finish	Satin plaster with primer and water-based paint	155.401.256	1 mm	Smooth and durable interior surface with water-based matte paint.
2. Satin Plaster	Satin plaster application	152.801.011	1 mm	Creates a uniform and aesthetic finish.
3. Perlite Plaster	Perlite-based smoothing plaster	152.801.010	5 mm	Levels the surface and improves adhesion for subsequent layers.
4. Cement-Lime Plaster	Cement-lime mixture plaster	152.751.107	Various	Provides a solid, durable base for finishing layers.

Table 6.3 presents the detailed composition and characteristics of the DV-1: interior wall type system. Each layer serves a specific function, contributing to the overall durability, aesthetic quality, and functionality of the wall system (Table 6.3).

Table 6.4 Layer composition and functional attributes of DV-2: wet area wall type (sourced from the MEB archive)

Layer	Material	Code	Thickness	Purpose and Features
1. Ceramic Finish	Matte, unglazed porcelain tiles (30x60 cm)	153.901.050	10-12 mm	Water-resistant, hygienic surface for wet areas with 1 mm grout lines.
2. Base Plaster	Cement-lime plaster	152.751.106	Various	Ensures smooth and sturdy surface for tile application.
3. Lime Wash	Lime-based coating (3 coats)	155.401.212	Various	Adds moisture protection and finishes the exposed wall surface.

Table 6.4 presents the detailed composition and characteristics of the DV-2: wet area wall type system. Each layer serves a specific function, contributing to the overall durability, aesthetic quality, and functionality of the wall system (Table 6.4).

Table 6.5 Layer composition and functional attributes of DV-3: lower wet area wall type (sourced from the MEB archive)

Layer	Material	Code	Thickness	Purpose and Features
1. Ceramic Finish	Matte, unglazed porcelain tiles (30x60 cm)(150cm height)	153.901.050	10-12 mm	Provides a water-resistant and hygienic surface for lower wet area walls with 1 mm grout lines.
2. Base Plaster	Cement-lime plaster for ceramic application	152.751.106	Various	Ensures a solid base for ceramic tile installation and enhances durability.
3. Satin Finish	Satin plaster with water-based paint	155.401.256	1 mm	Creates a smooth, aesthetic, and durable surface for interior areas above the tile height.
4. Satin Plaster Layer	Satin plaster for leveling	152.801.011	1 mm	Provides a uniform surface for finishing layers and improves adhesion.
5. Perlite Plaster	Perlite-based plaster for smoothing	152.801.010	5 mm	Smooths the surface and ensures compatibility with finishing layers.
6. Cement-Lime Plaster	Cement and lime mixture plaster	152.751.107	Various	Provides a durable and stable base for all wall layers.

Table 6.5 presents the detailed composition and characteristics of the DV-3: lower wet area wall type. Each layer serves a specific function, contributing to the overall durability, aesthetic quality, and functionality of the wall system (Table 6.5).

Table 6.6 Layer composition and functional attributes of DV-4: protective padded wall (sourced from the MEB archive

Layer	Material	Code	Thickness	Purpose and Features
1. Protective Layer	Foam-padded protective sheet (150cm height)		150 cm height	Provides impact resistance and safety for high-risk or sports areas.
2. Satin Finish	Satin plaster with water-based paint	155.401.256	1 mm	Creates a smooth, durable, and aesthetic surface for interior walls.
3. Satin Plaster Layer	Satin plaster application	152.801.011	1 mm	Ensures a uniform and aesthetic surface, enhancing the paint finish.
4. Perlite Plaster	Perlite-based smoothing plaster	152.801.010	5 mm	Smooths the surface and ensures compatibility with top layers.
5. Cement-Lime Plaster	Cement and lime mixture plaster	152.751.107	Various	Provides a durable and stable base for all wall layers.

Table 6.6 presents the detailed composition and characteristics of the DV-4: protective padded wall type. Each layer serves a specific function, contributing to the overall durability, aesthetic quality, and functionality of the wall system (Table 6.6).

Table 6.7 Wall thickness and material specifications (sourced from the MEB archive)

Wall Thickness	Material	Code	Explanation
19 mm	Hollow Clay Brick (240x190x235 mm)	152.201.114	Walls constructed with hollow clay bricks of 19 mm thickness.
145 mm	Hollow Clay Brick (240x145x235 mm)	152.201.112	Walls constructed with hollow clay bricks of 145 mm thickness, providing structural and acoustic benefits.
115 mm	Hollow Clay Brick (240x115x235 mm)	152.201.111	Walls made with hollow clay bricks of 115 mm thickness for partitioning and lightweight construction.

Table 6.7 outlines the specifications for walls constructed using hollow clay bricks of varying thicknesses. Each entry provides details about the material's dimensions, code, and functional benefits, emphasizing the adaptability of these materials for different construction purposes (Table 6.7).

Table 6.8 Exterior facade application and materials specifications (sourced from the MEB archive)

Material	Code	Thickness	Description	Function and Advantages
Silicone-Based Textured Exterior Paint	155.401.305		A silicone-based, textured exterior paint applied to the building's outer surface.	Enhances facade aesthetics, provides excellent environmental protection, is durable, and requires minimal maintenance.
Thermal Insulation with Stone Wool	153.401.006	8 cm	An 8 cm thick layer of stone wool insulation installed on the facade to enhance energy efficiency.	Offers superior thermal performance and fire resistance, improves indoor comfort, and reduces energy consumption.
Rough Plaster	152.751.101		Rough plaster applied beneath the insulation layer to smooth the surface and provide structural support.	Secures insulation materials and optimizes the overall facade system performance.
20 cm Brick Wall Construction	152.201.114	20 cm	The main structural walls consist of 20 cm thick brickwork.	Enhances structural integrity and contributes to thermal insulation.

Table 6.8 presents the key materials used in the exterior facade system, including their item codes, thickness, descriptions, and functions. The materials are selected to enhance the building's energy efficiency, durability, and aesthetic appeal (Table 6.8). This design has been carefully developed to meet environmental sustainability goals, improve energy efficiency, and achieve a visually appealing exterior. The specified layers work in harmony to deliver a durable, high-performing facade system.

Table 6.9 Wall types for project zones (sourced from the MEB archive)

Zone Name	Wall Type
Classrooms, Training Rooms, Library, Tool Rooms	DV-1
Wet Areas	DV-2
Kitchen, Service Area	DV-3
Cafeteria, Canteen, Corridors	DV-1
Administrative Offices	DV-1
Multi-Purpose Room	DV-1
Gymnasium / Physical Education Hall	DV-4
Prayer Room	DV-1
Staircases	DV-1
Mechanical Room	DV-3
Technical Room and Storage	DV-1
Preparation Rooms for Classrooms	DV-1
Shelter	DV-1

Table 6.9 outlines the assigned wall types for various zones within the project. Each wall type is defined based on the functional requirements of the zone, considering factors such as durability, moisture resistance, and aesthetic needs (Table 6.9). The material compositions and features of the wall types are tailored to meet the specific demands of each space, ensuring optimal performance and compliance with design standards.

a) Material Selection

In this section, material selection for the project is addressed in detail, focusing on aligning each component with the structural, functional, and environmental requirements of the design. The process involves matching suitable materials using the Tally Environmental Impact Tool, ensuring compatibility with the project's

sustainability and performance goals. Each material is carefully chosen to optimize durability, energy efficiency, and environmental impact, contributing to a holistic and responsible approach to building construction. For the paint, brillux, acrylic facade paint was selected as the exterior paint in the Tally software. The selection is compatible with the project's item code 15.540.1305 exterior paint gren, fulfilling both aesthetic and functional requirements of the design. Mineral wool, knauf, was selected in the Tally software as the insulation material for its superior thermal and acoustic performance. This selection is compatible with the project's item code stone wool insulation (15.340.1006), fulfilling both the technical and environmental requirements of the design. Portland cement stucco was selected in the Tally software for cement lime plaster (15.275.1101). This material was chosen for its high durability and resistance to external weather conditions, making it ideal for exterior applications. Synthetic stucco was selected in the Tally software for perlite based plaster (15.280.1010). This material was chosen due to its lightweight and flexible properties, which align with the functional characteristics of perlite based plaster. The selection is compatible with the project's item code 15.280.1010, ensuring alignment with technical requirements and design considerations. Portland cement stucco was selected in the Tally software for base plaster (15.275.1106). This material was chosen due to its cement-based composition, which provides a durable and reliable foundation layer for subsequent finishes. Portland cement stucco ensures strong adhesion and compatibility with other materials, fulfilling both the technical and functional requirements of the project. This selection aligns with the project's item code 15.275.1106, making it an ideal choice for the base plaster application. In the project, porcelain ceramic tile, glazed was selected in the Tally software for ceramic finish (15.390.1050). This material was chosen for its high durability, low water absorption, and aesthetic appeal. The selection aligns with the project's technical and design requirements, ensuring long-lasting performance and functionality. Polyethylene sheet vapor barrier (HDPE) was selected in the Tally software for HDPE Protection (15.200.1002). This material was chosen due to its superior moisture resistance and vapor barrier properties, ensuring effective protection for the structure against water ingress. HDPE's durability and mechanical strength make it an ideal choice for safeguarding waterproofing layers and enhancing

the longevity of the overall system. This selection aligns with the project's item code 15.200.1002, meeting both technical and functional requirements. In the project, XPS insulation, foamular 250 was selected in the Tally software for XPS insulation (15.335.1003). This material was chosen for its optimal balance between thermal insulation performance and mechanical strength, making it suitable for a wide range of applications. The selection aligns with the project's item code 15.335.1003, fulfilling both technical and sustainability requirements. PVC rigid sheet, inpro, pvc rigid sheet was selected in the Tally software for DV-4 protective padded wall. This material was chosen for its high impact resistance, durability, and ease of maintenance, making it an ideal choice for high-traffic areas such as sports halls. This selection fulfills both functional and environmental requirements, ensuring long-term performance and safety.

6.5.2 Flooring Systems

In this section, the flooring systems utilized throughout the project are examined in detail. The analysis focuses on matching the flooring types (DS-1 to DS-9) with the functional and aesthetic requirements of different spaces while ensuring compliance with the Ministry of Education (MEB) standards. Based on the project details, porcelain tile flooring systems were identified and categorized using specific codes to represent variations in functional requirements and installation areas. For example, DS-1 refers to a standard porcelain tile system designed for general areas, offering durability and aesthetic appeal, while DS-2 represents a waterproof porcelain tile system tailored for wet zones such as bathrooms and kitchens. These codes ensure clarity and consistency in defining flooring systems, facilitating precise material selection and effective communication throughout the project. Each flooring type has been carefully selected based on its durability, functionality, and compatibility with the specific needs of the spaces.

Additionally, the LCA of the materials, conducted using the Tally Environmental Impact Tool, ensures that an environmentally responsible approach has been maintained throughout the material selection process. This study aims to provide a comprehensive evaluation of the flooring systems, balancing performance, functionality, and sustainability.

Table 6.10 Flooring systems and their layered structures (sourced from the MEB archive)

Layer	Material	Code	Purpose and Features
Porcelain Tile Example (DS-1)			
1	Porcelain Tile (mat, unglazed, 60x60 cm)	153.901.008	Durable and aesthetically pleasing surface for general areas.
2	Screed	152.501.101	Provides a level surface for tile installation.
3	Leveling Layer	152.501.001	Ensures a smooth and stable foundation for upper layers.
Waterproof Porcelain Tile Example (DS-2)			
1	Porcelain Tile (mat, unglazed, 60x60 cm)	153.901.008	Durable and aesthetically pleasing surface for wet areas.
2	Cement-Based Waterproofing Mortar	152.701.005	Provides waterproofing and durability for wet zones.
3	Screed (400 doz)	152.501.101	Provides a level surface for tile installation.
4	Leveling Layer	152.501.001	Ensures a smooth and stable foundation for upper layers.
Laminate Flooring Example (DS-3)			
1	Laminate Flooring (AC3, 23-31 class)	154.901.002	Durable and easy-to-maintain surface for classrooms and office areas.
2	Screed (400 doz)	152.501.101	Provides a level surface for laminate installation.
3	Leveling Layer	152.501.001	Ensures a smooth and stable foundation for upper layers.
Heavy-Duty Laminate Flooring Example (DS-4)			
1	Laminate Flooring (AC3, 23-31 class)	154.901.002	Durable and easy-to-maintain surface for gymnasiums and assembly halls.

Table 6.10 Flooring systems and their layered structures (continued) (sourced from the MEB archive)

Layer	Material	Code	Purpose and Features
2	Screed (400 doz)	152.501.101	Provides a level surface for laminate installation.
3	Leveling Layer	152.501.001	Ensures a smooth and stable foundation for upper layers.
Stage			
1	Laminate Flooring (AC4, 23-31 class)	154.901.002	High-durability laminate for stages and performance areas.
2	Cement-Based Board	15.300.1006 A	Provides structural stability and durability for heavy loads.
3	Antirust and Synthetic Paint	155.401.102	Protects metal surfaces and enhances durability.
4	Box Profile Construction (50x50x3 mm)	155.501.202	Ensures structural support and longevity for stage flooring.
Marble Tile Example (DS-5)			
1	Marble Agglomerate Terrazzo Tile	154.001.004	Adds aesthetic appeal and durability for interior spaces.
2	Leveling Layer	152.501.001	Ensures a smooth and stable foundation for upper layers.
Turquoise Carpet Tile Example (DS-6)			
1	Turquoise Carpet Tile	771.151.005	Enhances acoustic and thermal comfort, suitable for libraries and quiet spaces.
2	Screed (400 doz)	152.501.101	Provides a level surface for carpet tile installation.
3	Leveling Layer	152.501.001	Ensures a smooth and stable foundation for carpet tiles.
PVC Sports Flooring Example (DS-7)			
1	PVC Sports Flooring	153.651.008	Durable, slip-resistant, and suitable for sports areas.

Table 6.10 Flooring systems and their layered structures (continued) (sourced from the MEB archive)

Layer	Material	Code	Purpose and Features
2	Screed (400 doz)	152.501.101	Provides a level surface for PVC flooring installation.
3	Leveling Layer	152.501.001	Ensures a smooth and stable foundation for PVC sports flooring.
Marble Tile Example (DS-8)			
1	Marble Tile	154.101.104	Adds luxury and durability to high-traffic areas.
2	Leveling Layer	152.501.001	Ensures a smooth and stable foundation for marble tiles.
Marble Terrazzo Tile Example (DS-9)			
1	Marble Agglomerate Terrazzo Tile	154.001.004	Adds aesthetic appeal and durability for interior spaces.
2	Screed (400 doz)	152.501.101	Provides a level surface for tile installation.
3	Leveling Layer	152.501.001	Ensures a smooth and stable foundation for upper layers.
4	PVC Membrane	152.501.002	Provides waterproofing and prevents moisture infiltration.

Table 6.10 presents a comprehensive analysis of the flooring systems utilized in the project. Each flooring type (DS-1 to DS-9) is meticulously designed to meet the functional requirements of different spaces. The table includes details about the materials, their codes and the purpose and features of each layer (Table 6.10). The selected materials ensure durability, aesthetic compatibility, and environmental performance. The use of screed and leveling layers guarantees stability and even surfaces for the final flooring finishes. Moreover, waterproofing solutions are applied where necessary to enhance the longevity of the structures. The flooring systems used in this project have been meticulously designed with a focus on durability, performance, and sustainability. Each system incorporates carefully selected

materials, layers, and finishes to achieve optimal functionality and aesthetic compatibility.

Table 6.11 Flooring types for project zones (sourced from the MEB archive)

Room/Space	Ceiling Type
Classrooms, Support Education Rooms, Game Rooms, Library, Tool Rooms	DS-1
Wet Spaces	DS-2
Kitchen/Service	DS-2
Dining Hall, Corridors	DS-4
Administrative Offices	DS-3
Multi-purpose Hall	DS-4
Sports Hall, Physical Education Hall	DS-7
Stairs	DS-8
Mechanical Room	DS-9
Technical Room/Storage	DS-5
Classroom Preparation Rooms	DS-1

Table 6.11 illustrates the assignment of flooring types (DS-1 through DS-9) to their respective spaces within the project. This allocation was meticulously planned to align with the functional requirements, aesthetic preferences, and performance characteristics of each area. The selection process prioritized durability, safety, and environmental sustainability, ensuring that each flooring type complements the specific operational needs of its designated space. The flooring materials were chosen to meet the Ministry of Education's (MEB) standard building specifications while reflecting the project's commitment to sustainable practices. Each material underwent a thorough evaluation through LCA using the Tally Environmental Impact Tool. This analysis enabled the optimization of material choices to minimize environmental impact while maintaining essential features such as slip resistance, acoustic comfort, and ease of maintenance. By linking the flooring types to their

respective applications, Table 6.11 underscores the project's focus on functional design and environmental responsibility. The systematic classification ensures that spaces such as classrooms, sports halls, and wet areas are equipped with flooring systems tailored to their specific requirements (Table 6.11). This approach not only enhances the building's operational efficiency but also aligns with the principles of sustainable architecture, supporting the project's long-term goals of durability, safety, and reduced environmental footprint.

a) Material Selection

In this project, unglazed ceramic tiles (15.390.1008) were chosen for their durability and aesthetic appeal, ideal for high-traffic educational spaces. For Tally modeling, similar ceramic tiles and cement mortar were selected to align with project requirements and ensure accurate environmental impact assessments. This approach ensures consistency between the materials used on-site and the LCA modeling process. Cast-in-place concrete, structural concrete, 2500 psi was selected for the screed layer (15.250.1101) due to its compatibility with the performance requirements of the flooring systems. This material offers sufficient durability and strength for general screed applications, ensuring a stable and even surface for subsequent layers. The choice of cast-in-place concrete also aligns with the project’s sustainability goals, as it can be effectively analyzed in Tally for its environmental impact. The fiber cement construction panel was selected for the leveling layer (15.250.1001) in this project due to its suitability for flooring underlays and its alignment with the project's performance and sustainability goals. This material's waterproof nature ensures long-lasting durability and resistance to moisture, making it an optimal choice for supporting upper flooring layers. Cement-based waterproofing mortar (15.270.1005) was specified for wet areas due to its durability, compatibility with cementitious substrates, and reliable waterproofing properties. However, for Tally modeling purposes, modified bituminous waterproofing membrane was used as a substitute to facilitate accurate environmental impact analysis. The selected bituminous membrane offers robust waterproofing performance and adheres effectively to a variety of substrates. While the Cement-based waterproofing mortar meets the practical construction requirements of

the project, the modified bituminous waterproofing membrane was chosen in Tally to represent a comparable material with similar performance features. This substitution ensured consistency in the environmental assessment without compromising the accuracy of the project's specifications. In this project, Laminate Flooring (15.490.1002) was chosen for its durability, ease of maintenance, and aesthetic suitability for educational spaces. For Tally modeling, the same laminate flooring material was selected to maintain consistency with the project's design and ensure accurate environmental impact assessments. This alignment guarantees that both the construction and modeling processes reflect the project's sustainability and performance goals. Cement-based chipboard (15.300.1006/A) was chosen for the stage area due to its structural performance and durability. For Tally modeling, the fiber cement construction panel was selected as it closely matches the project specifications. This material provides the required strength and impact resistance while ensuring environmental compliance through its EPD certification. The alignment between the project and Tally choices ensures accurate LCA analysis and consistency with the project's functional and sustainability goals. This selection, Steel Protection (15.540.1102), was chosen in the Tally model for the stage area due to its compatibility with the project's structural requirements. The metal plating material ensures durability and corrosion resistance, essential for maintaining the integrity of steel components over the building's lifecycle. This choice aligns with the project's focus on long-term performance and environmental sustainability while accurately reflecting the stage area's functional demands in the LCA analysis. Steel rectangular tubing was selected in Tally as the most suitable material for the stage's box profile (15.550.1202) construction. This material offers excellent structural integrity and durability, meeting the high load-bearing requirements of stage areas.The choice of Steel Rectangular Tubing aligns with the project's focus on structural stability and safety, particularly for critical components like the stage. In this project, marble agglomerate terrazzo tile (15.400.1004) was selected for its aesthetic appeal and durability, making it suitable for high-traffic areas and spaces requiring enhanced design elements. For the Tally modeling process, concrete tile was chosen as an equivalent substitute. This decision was based on the similarity in mechanical properties and the ability of concrete tiles to reflect the performance

characteristics of terrazzo tiles. The use of concrete tiles in the Tally model ensures accurate environmental impact assessments while maintaining consistency with the project's sustainability objectives. In this project, turquoise carpet tile (15.270.1005) was selected for its acoustic and thermal comfort properties, making it ideal for interior spaces such as libraries and prayer rooms. For Tally modeling, the Nylon Carpet material was chosen as a suitable alternative. This material aligns with the project's environmental assessment goals while maintaining performance requirements. In this project, the PVC sports flooring (15.365.1008) was specified for its durability, slip resistance, and suitability for sports areas. For Tally modeling, foamed pvc flooring was selected as a substitute to ensure compatibility with the LCA process while maintaining the intended material's performance characteristics. In this project, stone cladding (15.410.1104) was selected for its durability, aesthetic appeal, and suitability for high-traffic and visually prominent areas. For Tally modeling, this material was chosen to ensure alignment with project requirements and accurate life cycle assessment (LCA) results. The stone cladding's robust properties and long service life make it an ideal choice for spaces requiring enhanced structural and visual performance.

6.5.3 Ceiling System

Educational buildings pose specific challenges in construction, as they must accommodate a high volume of users while ensuring durability, acoustic comfort, and hygienic conditions. The ceiling systems included in this analysis were carefully selected and structured to address these requirements. They reflect the standardized approach used in MEB projects, which ensures consistency and adaptability across various school typologies in different regions. The materials and methods employed in these systems take into account the climatic conditions of Türkiye and the specific demands of educational facilities, including sustainability, ease of maintenance, and long-term performance. In this section, the ceiling systems utilized throughout the project are examined in detail. The analysis focuses on matching the ceiling types (TV-1 to TV-5) with the functional requirements of different spaces while considering sustainability and compliance with the Ministry of Education (MEB) standards. Each ceiling type was selected based on its acoustic properties, durability,

and aesthetic compatibility. Additionally, LCA of the materials, conducted using the Tally Environmental Impact Tool, ensures an environmentally conscious approach to material selection. This study aims to provide a balanced evaluation of performance, functionality, and sustainability for the ceiling systems.

Table 6.12 Ceiling systems and their layered structures (sourced from the MEB archive)

Layer	Material	Code	Thickness	Purpose and Features
TV-1 - Acoustic and Mineral Wool Ceiling Example				
1	Lime Wash	155.401.212	3 Coats	Breathable, durable coating, provides a natural appearance.
2	Gypsum Panel Ceiling	155.301.904	10-15 mm	Water and fire-resistant, lightweight, and safe.
3	Satin Plaster	152.801.011	1-2 mm	Provides smooth and aesthetic surfaces.
4	Antibacterial Paint	155.401.256	2 Coats	Hygienic, durable, water-based matte paint.
5	Mineral Wool Acoustic Tile	485.351.001	60x60x1.5 cm	Provides acoustic insulation and fire resistance.
TV-2 - Acoustic Gypsum Board Ceiling Example				
1	Lime Wash	155.401.212	3 Coats	Breathable, durable coating, provides a natural appearance.
2	Gypsum Panel Ceiling	155.301.904	10-15 mm	Water and fire-resistant, lightweight, and safe.
3	Satin Plaster	152.801.011	1-2 mm	Provides smooth and aesthetic surfaces.
4	Antibacterial Paint	155.401.256	2 Coats	Hygienic, durable, water-based matte paint.
5	Electrostatic Powder-Coated Perforated Aluminum Ceiling System	48.535.1030	60x60x9.5 mm	Provides acoustic adjustment and modern appearance.

Table 6.12 Ceiling systems and their layered structures (continued) (sourced from the MEB archive)

Layer	Material	Code	Thickness	Purpose and Features
TV-3 - Gypsum and Acoustic Panel Ceiling Example				
1	Lime Wash	155.401.212	3 Coats	Breathable, durable coating, provides a natural appearance.
2	Gypsum Panel Ceiling	155.301.904	10-15 mm	Water and fire-resistant, lightweight, and safe.
3	Satin Plaster	152.801.011	1-2 mm	Provides smooth and aesthetic surfaces.
4	Antibacterial Paint	155.401.256	2 Coats	Hygienic, durable, water-based matte paint.
5	Perforated Acoustic Gypsum Panel	485.351.003	60x60x9.5 mm	Provides acoustic properties and aesthetic design.
TV-4 - Fast and Economical Ceiling Example				
1	Antibacterial Paint	155.401.256	2 Coats	Hygienic, durable, water-based matte paint.
2	Satin Plaster	152.801.011	1-2 mm	Provides aesthetic surfaces, final preparation for painting.
3	Machine-Applied Gypsum Plaster	152.801.012	15 mm	Enables fast application and provides a homogeneous surface.
TV-5 - Simple and Practical Ceiling Example				
1	Antibacterial Paint	155.401.256	2 Coats	Hygienic, durable, water-based matte paint.
2	Ceiling Plaster	152.751.103	5-10 mm	Used for smoothing ceiling surfaces.

Table 6.12 presents a a detailed overview of five ceiling systems (TV-1 to TV-5) designed based on the data obtained from the standardized typologies of the Ministry

of National Education (MEB) projects in Türkiye. These systems were developed to meet the functional, aesthetic, and environmental needs of educational buildings while maintaining cost-efficiency and compliance with national construction standards. The ceiling types selected for different room types in the project are presented in the table below. Each room's intended use, required performance features, and aesthetic requirements were considered to determine the most suitable ceiling types. The ceiling types were evaluated based on criteria such as durability, acoustic performance, fire resistance, and hygiene.

Table 6.13 Ceiling types for project zones (sourced from the MEB archive)

Room/Space	Ceiling Type
Classrooms, Support Education Rooms, Game Rooms, Library, Tool Rooms	TV-4
Wet Spaces	TV-2
Kitchen/Service	TV-1
Dining Hall, Corridors	TV-1
Administrative Offices	TV-1
Multi-purpose Hall	TV-3
Sports Hall, Physical Education Hall	TV-1
Prayer Room	TV-4
Stairs	TV-4
Mechanical Room	TV-5
Technical Room/Storage	TV-5
Classroom Preparation Rooms	TV-4
Shelter	TV-5

Table 6.13 presents the correspondence between the designated ceiling types (TV-1 through TV-5) and their respective application areas in the project (Table 6.13) .This classification was made based on the functional requirements, aesthetic considerations, and performance features specific to each type of space. The ceiling types were carefully selected to align with the intended use of each room and to meet the design and sustainability goals of the project. This allocation ensures that the material performance matches the operational demands of each room while maintaining compliance with the Ministry of Education's (MEB) standard building specifications. The selections also reflect a focus on sustainability, with all materials

subjected to life cycle assessment (LCA) using the Tally Environmental Impact Tool. This analysis optimized material choices, prioritizing low environmental impact without compromising on functionality or safety. By detailing the spatial allocation of ceiling types, Table 6.13 supports the project's emphasis on tailored material selection for diverse building functions. It underlines the project's adherence to sustainable architecture principles while addressing practical considerations such as durability, safety, and acoustics. This systematic approach ensures that the ceiling materials align with the overall goals of the building's environmental performance and operational efficiency.

a) Material Selection

In this project, lime wash (15.540.1212) was chosen for its eco-friendly and breathable qualities. However, for the modeling process in Tally, synthetic stucco was used as a substitute. This choice was made to facilitate accurate calculations and reflect the finish and performance required for the project. In this project, gypsum panel ceiling (15.530.1904) was chosen for its fire-resistant properties and suitability for educational buildings. For the modeling process in Tally, wall board, gypsum (fire-resistant type x) was used to ensure accurate representation of the material. This gypsum board provides enhanced fire safety and durability, aligning with the building's lifecycle and long-term performance goals. It was selected for its balance of safety, functionality, and sustainability, making it an ideal choice for this project.

In this project, satin plaster (15.280.1011) was chosen for its smooth finish and aesthetic appeal. Among the available options in Tally, portland cement stucco was identified as the most suitable substitute due to its similar characteristics and compatibility with lifecycle assessment. In this project, mineral wool acoustic tile (48.535.1001) was selected for its acoustic insulation and fire resistance. For Tally modeling, acoustic ceiling system, mineral fiber board was chosen as the most suitable substitute due to its similar properties. In this project, electrostatic powder-coated perforated aluminum ceiling system (15.535.1030) was selected for its acoustic performance, lightweight structure, and durability. For Tally modeling, the acoustic ceiling tile (act) was chosen as the most suitable substitute. This selection accurately represents the perforated design and material properties required

for the project, ensuring both functional and aesthetic alignment with the system's objectives. In this project, perforated acoustic gypsum panel (48.535.1003) was selected for its superior acoustic performance and modern appearance. For Tally modeling, acoustic ceiling system was chosen as the most suitable substitute. In this project, machine-applied gypsum plaster (15.280.0121) was selected for its efficiency and consistent application on large surfaces. For Tally modeling, wall board, gypsum, natural was chosen as the most suitable substitute due to its compatibility with the specified thickness and material properties. In this project, tile ceiling (15.275.1103) was selected for its durability, aesthetic appeal, and suitability for ceiling applications. For Tally modeling, ceramic tile, glazed was chosen as the most appropriate substitute. In this study, the materials specified in the project were carefully matched with the most suitable alternatives in Tally for accurate life cycle assessment. Each material was selected based on its performance, durability, and compatibility with the functional and environmental requirements of the educational building. By aligning the project's design intent with Tally's database, the selected materials provide a comprehensive representation of the building's sustainability features while maintaining accuracy in environmental impact calculations. This process ensures that the analysis reflects the project's goals of durability, efficiency, and environmental responsibility.

6.5.4 Roof System

In this section, the roofing system utilized throughout the project is examined in detail. The analysis focuses on aligning the roofing components (ÇT-1) with the functional and environmental requirements of the structure while adhering to sustainability and Ministry of Education (MEB) standards. Each layer in the roofing system was selected for its contribution to thermal insulation, water resistance, and structural integrity. Additionally, the life cycle assessment (LCA) of the materials, performed using the Tally Environmental Impact Tool, underscores an environmentally responsible approach to material selection. This study aims to provide a comprehensive evaluation of the roofing system's performance, functionality, and sustainability.

Table 6.14 Roof system and layered structures (sourced from the MEB archive)

Layer	Material	Code	Thickness	Purpose and Features
CT-1 Standard Roof System Example				
1	Clay Roof Tiles	153.051.004	Standard	Durable, weather-resistant, provides a traditional aesthetic.
2	Waterproofing Membrane	153.301.005	2 mm	Ensures water resistance and protects underlying layers.
3	Wooden Roof Frame (OSB/3 Panel)	153.001.002	Standard	Provides structural stability and forms the base for the roof covering.
4	Roof Cavity			Enhances thermal performance and ventilation.
5	Stone Wool Insulation	153.401.407	8 cm	Provides thermal and acoustic insulation, complies with mechanical codes.
6	Vapor Barrier	153.301.003	Standard	Prevents moisture accumulation in insulation layers.

Table 6.14 presents a comprehensive analysis of the roofing system utilized in the project (Table 6.14). The roof system (CT-1) is meticulously designed to meet the functional requirements of educational buildings while prioritizing durability, thermal performance, and environmental responsibility. The table includes details about the materials, their codes, thicknesses, and the specific purposes and features of each layer. The roofing system in this project emphasizes functionality and sustainability, incorporating carefully selected materials and layers to achieve optimal performance and protection against environmental elements. This roofing assembly is designed to comply with building standards, combining resilience, thermal efficiency, and weatherproofing to meet the demands of educational structures. By integrating these carefully chosen layers, the system achieves both functional excellence and environmental sustainability.

a) Materials selections

In this project, clay roof tiles (15.305.1004) were chosen for roofing purposes. In Tally, terracotta tile was selected to represent this material. Terracotta tiles are known for their natural aesthetic appeal and durability, offering a weather-resistant structure with high performance. This choice aligns with the real project's selection, ensuring functionality and environmental performance while contributing to the sustainability goals of the project. For this project, (15.330.1005) waterproofing membrane was represented in Tally using the EPDM sheet, waterproofing material. This selection was based on the material's proven durability and flexibility in both vertical and horizontal applications. The EPDM sheet provides superior elastomeric properties, ensuring long-term waterproofing performance essential for roofing systems. This choice ensures a reliable and sustainable waterproofing solution for the roofing system modeled in Tally. In this project, wood framing was selected in Tally as a substitute for OBS board (15.300.1002) due to its compatibility with the structural and environmental requirements. In this project, rock wool insulation (15.340.1407) was specified for its high thermal resistance and fireproof characteristics, aligning with the project's sustainability and energy efficiency goals. To model this layer in Tally, mineral wool board, was selected, with a manually specified thickness of 8 cm. This selection ensures the insulation meets the required performance for the building's roof, providing both environmental and functional benefits while maintaining compliance with the design requirements. In this project, EPDM, reinforced membrane, 60 mils, SPRI - EPD was selected as the vapour barrier (15.330.1003) for its durability, flexibility, and compatibility with the overall roofing system. This material offers excellent waterproofing performance and is specifically designed to enhance the roof's resistance to moisture ingress. Its lightweight and reinforced structure make it an optimal choice for ensuring the longevity and functionality of the roofing assembly, while also aligning with the project's sustainability goals and life cycle assessment considerations conducted using Tally.

6.5.5 Foundation System

In this section, the foundation system utilized throughout the project is examined in detail. The analysis focuses on aligning the foundation components (BDS-1) with the structural, functional, and environmental requirements of the building. Each layer in the foundation system was selected for its contribution to load-bearing capacity, water resistance, thermal insulation, and overall structural integrity. Each classroom typology features variations in the dimensions and design of the raft foundations, tailored to the specific structural requirements and load distributions of the respective building configurations. Additionally, the life cycle assessment (LCA) of the materials, conducted using the Tally Environmental Impact Tool, ensures that the selected components meet sustainability and durability goals. This approach provides a comprehensive evaluation of the foundation system's performance and its role in supporting the long-term functionality and resilience of the structure.

Table 6.15 Foundation system and layered structures (sourced from the MEB archive)

Foundation System	Layer	Material	Code	Thickness	Purpose and Features
Foundation System Example -1					
	1	Reinforced Concrete Slab	151.501.006	15 cm	Provides load-bearing capacity, structural stability, and durability.
	2	Double Reinforced Steel	151.601.001	Standard	Ensures structural integrity and distributes loads evenly.
	3	XPS Thermal Insulation	153.551.305	5 cm	Enhances thermal performance and prevents heat transfer.
	4	Crushed Stone Fill	151.251.008	20 cm	Serves as a stable base layer that improves drainage, reduces soil pressure, and prevents water accumulation.
	5	Raft Foundation Concrete	151.501.006	50 cm	Distributes structural loads and provides a stable base for the building.

Table 6.15 Foundation system and layered structures (continued) (sourced from the MEB archive)

Foundation System	Layer	Material	Code	Thickness	Purpose and Features
	6	Protective Concrete Layer	151.501.003	5 cm	Protects waterproofing and insulation layers from mechanical damage.
	7	Geotextile Membrane	152.401.002	250 g/m²	Prevents soil infiltration into drainage systems and enhances foundation stability.
	8	Waterproofing Membrane	152.551.009	2 mm	Ensures water resistance and protects the foundation from groundwater infiltration.
	9	Blinding Concrete (C16/20 Concrete)_	151.501.003	10 cm	Provides a clean, level surface for subsequent construction layers, prevents contamination from soil, and enhances the durability of the foundation.

Table 6.15 presents a comprehensive analysis of the foundation system utilized in the project (Table 6.15). The foundation system employed in this project, identified is a comprehensive assembly designed to meet stringent structural, thermal, and environmental requirements while ensuring long-term durability and performance. This multi-layered system integrates advanced materials and techniques to provide a stable and efficient base for the building. Each layer in the system has been meticulously selected and designed to meet specific functional requirements, ensuring optimal structural performance, thermal efficiency, and environmental protection. This foundation system exemplifies a holistic approach to sustainable construction, balancing technical excellence with environmental responsibility, and ensuring the building's long-term stability and efficiency.

a) Materials selections

In this project, cast-in-place structural concrete (4000 psi, national regional average) was selected to replace the C30/37 reinforced concrete (15.150.1006) specified in the project documentation. This choice was made due to its high compressive strength, durability, and compatibility with the building's long-term requirements. For reinforcement, steel welded wire mesh was chosen as a substitute for the double reinforced steel (15.160.1001) listed in the project. This combination of materials ensures a durable and stable foundation, capable of supporting the building's load-bearing requirements while aligning with the sustainability and performance goals outlined in the project. In this project, extruded polystyrene (XPS) board was selected for the XPS Insulation layer (15.335.1003). This material provides exceptional thermal insulation, moisture resistance, and durability, making it a suitable choice for the foundational insulation layer. This selection aligns with the specified insulation requirements, replacing standard insulation while maintaining high environmental performance, as supported by its EPD certification. For the crushed stone fill (15.125.1008), stone slab, granite with mortar type s was selected to ensure durability, stability, and compliance with project standards. The materials, modeled using the Tally Environmental Impact Tool, align with the project's sustainability goals and long-term performance requirements. For the raft foundation (C30/37 Concrete, 15.150.1006) specified in the project, we selected lightweight structural concrete (4000 psi, national regional average) from Tally. This material ensures compliance with structural and load distribution requirements while maintaining sustainability standards. The protective concrete layer was selected as "lightweight concrete, 3000 psi, national regional average" from the Tally database. This choice aligns with the project requirements. In the project, polypropylene geotextile fabric was selected in Tally to replace the project-defined material geotextile fabric (15.245.1002). This synthetic geotextile fabric, compatible with Tally's database, was chosen for its excellent separation, filtration, and reinforcement properties. For the waterproofing layer of the foundation system, self-adhering sheet waterproofing, modified bituminous sheet was selected in the Tally Environmental Impact Tool. This material was chosen as an equivalent to Waterproofing Membrane (Bituminous Membrane, 15.255.1009) specified in the project. Blinding concrete (C16/20 Concrete), the initial layer in foundation construction, was selected as

cast-in-place concrete, structural concrete, 2500 psi from the Tally database. This choice aligns with the project's requirements for providing a stable and level base for subsequent structural layers.

6.5.6 Structural Systems

The structural systems for the project were carefully designed to ensure stability, load distribution, and compliance with the functional and architectural requirements of each school typology. The chosen systems align with the project's overall goals of safety, durability, and efficiency. For each school typology, column and beam systems were applied according to the specific dimensions and load requirements of the design. These systems were tailored to accommodate the structural needs of the 8, 12, 24, and 32-classroom layouts, ensuring optimal performance and resilience. In this project, reinforced concrete columns with varying dimensions, such as 30x120, 40x40, and 30x70, are utilized as part of the structural system. The design and material selection for these columns were aligned with the Ministry of Education (MEB) guidelines and the structural requirements of the building. For the concrete material, 4000 psi cast-in-place structural concrete was selected in Tally, representing a balance between strength and durability. The chosen option is based on the National regional average mix to ensure consistency with local material properties and environmental considerations. The reinforcement for the columns is specified as steel reinforcing rod (GLO), providing the required tensile strength to support the structural loads. Moderate reinforcement levels were selected in Tally® to meet the demands of typical column applications within the building's design specifications. This selection, modeled and analyzed in Tally®, ensures that the structural system performs efficiently under various load conditions while adhering to the project's sustainability goals and local standards. The integration of Tally into the material selection and environmental analysis process underscores the project's commitment to a sustainable and scientifically grounded approach.

In the project, beams were designed using cast-in-place structural concrete with a strength of 4000 psi (national regional average). This material was selected from the Tally database as it aligns with the structural and durability requirements of the design. For reinforcement, "Column or beam, moderate reinforcement" was chosen,

reflecting the standard practice for ensuring the structural integrity of beam systems. This reinforcement level provides sufficient support for load distribution and compliance with relevant building codes. This combination ensures that the beam system achieves the necessary balance between strength, durability, and material efficiency, contributing to the overall sustainability goals of the project. The roof framing system in this project was meticulously designed and modeled to align with the functional and structural requirements outlined in MEB building standards. Softwood lumber was chosen as the primary material for key load-bearing components, such as eaves, purlins, and other structural elements, due to its strength, durability, and ease of application in roof construction. This selection ensures the roof's stability while offering a sustainable and efficient solution.The use of softwood lumber was matched with Tally's database to provide an accurate environmental impact assessment. This process involved selecting wood framing options that best represented the material used in the project, ensuring a precise alignment between the physical model and digital analysis. The integration of this material in Tally not only validates its suitability for the roof structure but also highlights its contribution to the project's overall sustainability and performance objectives. Through this careful approach, the roof system achieves both technical excellence and environmental responsibility.

6.5.7 Door and Window Systems

a) Doors

The project includes both laminated MDF doors and durable steel doors. Laminated doors feature MDF panels covered with laminate and are supported by DKP steel frames, reinforced with concrete filling at the back of the frames for enhanced durability. These doors are coated with anti-corrosive primer and synthetic paint for corrosion resistance. Additionally, they are equipped with matte chrome stainless steel handles and kick plates made of stainless steel.

The steel doors are designed to be fire-resistant, with galvanized steel reinforcements inside. They are fitted with intumescent seals that expand under heat and certified fire-resistant filling materials, providing significant fire protection.

b) Windows

The windows in the project are made of thermally insulated aluminum profiles and fitted with double-glazed, heat-controlled glass. The window frames are complemented by exterior sills and parapets finished with colored marble. Espagnolette window handles and secure locking mechanisms enhance both usability and safety.These details ensure that the door and window systems contribute to both durability and energy efficiency, supporting a sustainable approach throughout the project.

CHAPTER 7

FINDINGS FROM TALLY ANALYSIS: ENVIRONMENTAL IMPACT EVALUATION

This section presents the findings derived from the Tally analysis conducted on the selected school building typologies. The analysis evaluates the environmental impacts of the materials and construction processes across various life cycle stages, including production, construction, use, and end-of-life. The results are categorized based on material types and environmental impact categories, providing a detailed comparison of the four typologies. By examining these findings, insights are gained into the most significant contributors to environmental impacts and potential areas for improvement in sustainable design strategies.

7.1 Introduction to Environmental Impact Analysis

The following section provides the evaluation of the Life Cycle Assessment (LCA) results of the four school building typologies (8, 12, 24, and 32 classrooms) established by the Ministry of National Education (MEB). This considers the total environmental impact of a building, starting with raw material extraction to its post-life cycle, or in other words, "from cradle to grave." The scopes of analysis include the product stage, transportation, use and maintenance, end-of-life, and recycling. All those analyze the environmental impacts of construction materials from the production of construction materials to their end of service life. The analysis is based on a methodology compliant with international standards such as ISO 14040-14044, ISO 21930:2017, ISO 21931:2010, EN 15804:2012, and EN 15978:2011. All calculations were performed using Tally software, and the environmental impacts were assessed according to the TRACI 2.1 methodology. The custom LCA database of Tally was based on the data from GaBi 8.5 LCI 2018. The quality of the data was assessed according to criteria such as measurement precision, completeness, and geographic-temporal consistency. In cases where missing data were replaced, the appropriate proxy data were used to help ensure the reliability and

accuracy of the results. The functional unit used in the study was defined based on the services provided by each building typology throughout its lifespan (e.g., educational use) and performance requirements. A 60-year service life was assumed for all building typologies, and the analysis included architectural, structural, and finishing systems. Reference units provide a modeling framework for assessing the environmental impacts of building components over all life cycle stages and allow for comparability and consistency. The life cycle assessment (LCA) outlines the life cycle stages as: product stage (A1-A3), transport or transportation stage (A4), maintenance and replacement (B2-B5), and end-of-life stages (C2-C4) and recycling (module D). The functional unit consists of the durability service and the technical performance offered by the building along its life span. The reference unit was designed to provide the consistent and comparable evaluation of the environmental impacts of building components, using 2018 GaBi LCI data to enhance the representativeness of the analysis. Missing data were supplemented with proxy datasets that adhered to geographic, technological, and temporal alignment. Environmental impact categories analyzed include global warming potential (GWP), which measures carbon emissions; acidification potential (AP), which assesses the impact of sulfur and nitrogen oxides on ecosystems; eutrophication potential (EP), which evaluates the effects of nitrogen and phosphorus accumulation; smog formation potential (SFP), which examines the creation of ground-level ozone; and primary energy demand (PED), which measures total energy consumption. These categories comprehensively evaluate the environmental impacts of construction materials across their life cycle. System boundaries were defined broadly to include all life cycle stages, from raw material extraction to the disposal of building materials. The study aims to provide a comparative analysis of the environmental impacts of four different school building typologies and to develop strategies for minimizing these impacts.

The evaluation includes several key components:

i. Total and Per m² Evaluation: The environmental impacts of the school buildings are assessed both in total and on a per square meter basis. This dual perspective

enables a clearer understanding of absolute environmental burdens and facilitates comparisons across building types and scales.

ii. Lifecycle Stage Contributions: Impacts are analyzed across life cycle stages, including the Product Stage (A1–A3), Transportation (A4), Maintenance and Replacement (B2–B5), End of Life (C2–C4), and Recycling/Reuse (Module D). This approach highlights the contribution of each stage to key impact categories, such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED).

iii. Material and Division Analysis: By categorizing materials into divisions like Concrete, Masonry, Metals, Wood/Plastics/Composites, and others, the study identifies the most impactful material groups. This breakdown provides a clear understanding of how specific materials contribute to overall environmental burdens.

iv. Revit Category Evaluation: The impacts are further itemized based on Revit building components, such as Ceilings, Floors, Walls, Windows, and Structures, allowing for detailed insights into the environmental performance of different architectural and structural elements.

Each of these analyses aims to inform sustainable design and construction practices by identifying the critical areas where interventions can significantly reduce the environmental footprint of school buildings. The findings not only offer a basis for selecting low-impact materials and optimizing life cycle stages but also guide decision-making for more sustainable and efficient educational facilities.

7.2 Environmental Impact Analysis of 8-Classroom School Building

This section focuses on the detailed environmental impact assessment of the 8-classroom school building. The analysis evaluates the building's performance across various life cycle stages. The aim is to uncover critical areas for improvement, offering actionable insights to enhance sustainability and reduce environmental

burdens. The findings from this analysis are intended to guide the design and construction of more environmentally efficient educational facilities.

7.2.1 Total and Per m² Evaluation

In this section, the environmental impacts of the 8-classroom school building are analyzed from two different perspectives:

Total Environmental Impacts: The total impacts at each life cycle stage.

Environmental Impacts Per m²: The same impacts, but evaluated per square meter of the building.

These two perspectives are crucial for understanding the overall environmental burden and for facilitating the comparison of buildings of different sizes. They provide insights into both the absolute environmental effects and the relative impact per unit area, which is important for scaling and comparison across various building types. The following tables provide a detailed assessment of the environmental impacts associated with the 8-classroom school building. Table 7.1 presents the total impacts for each life cycle stage, while Table 7.2 shows the per area impacts (impacts per m²). These analyses aim to identify the most significant contributors to environmental burdens across the building's life cycle and provide a basis for sustainable design strategies.

Table 7.1 Total environmental impacts analysis of 8-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

Environmental Impact Category	**Product Stage (A1–A3)**	**Construction Stage (A4)**	**Use Stage (B2–B5)**	**End of Life Stage (C2–C4)**	**Module D (D)**
Global Warming (kg CO_2eq)	1.660.231	48.053	53.251	187.427	-102.554
Acidification (kg SO_2eq)	6,770	222.7	258.5	504.7	-251
Eutrophication (kg Neq)	306,9	18,13	13,43	32,47	-8,18

Table 7.1 Total environmental impacts analysis of 8-classroom school building(continued). Environmental impact data derived from Tally software's analysis conducted in 2025

Environmental Impact Category	Product Stage (A1–A3)	Construction Stage (A4)	Use Stage (B2–B5)	End of Life Stage (C2–C4)	Module D (D)
Smog Formation (kg O_3eq)	105.279	7.358	3.594	9.479	-2.421
Ozone Depletion (kg CFC-11eq)	0,05099	1,646E-009	1,453E-004	1,057E-005	6,495E-004
Primary Energy (MJ)	1,846E+007	698.788	1.105.450	1.746.654	-1.023.543
Non-Renewable Energy (MJ)	1,685E+007	682.066	984.691	1.633.307	-1.001.831
Renewable Energy (MJ)	1.623.720	16.898	121.481	115.227	-22.129

Table 7.2 Per area environmental impacts analysis of 8-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

Environmental Impact Category	Product Stage (A1–A3)	Construction Stage (A4)	Use Stage (B2–B5)	End of Life Stage (C2–C4)	Module D (D)
Global Warming (kg CO_2eq/m²)	674,6	19,53	21,64	76,16	-41,7
Acidification (kg SO_2eq/m²)	2,751	0,09048	0,105	0,2051	-0,1019
Eutrophication (kg Neq/m²)	0,1247	0,007367	0,005455	0,01319	-0,003322
Smog Formation (kg O_3eq/m²)	42,78	2,990	1,460	3,852	-0,9837
Ozone Depletion (kg CFC-11eq/m²)	2,072E-005	6,687E-013	5,905E-008	4,293E-009	2,639E-007
Primary Energy (MJ/m²)	7.502	283,9	449,2	709,7	-416
Non-Renewable Energy (MJ/m²)	6.846	277,1	400,1	663,7	-407
Renewable Energy (MJ/m²)	659,8	6,866	49,36	46,82	-8,99

Table 7.1 and Table 7.2 highlight the critical role of life cycle analysis in pinpointing opportunities for reducing environmental impacts and fostering sustainable building practices (Table 7.1 and Table 7.2). The total environmental impacts highlight the contributions of each life cycle stage. The product stage (A1–A3) emerges as the dominant contributor, accounting for the highest values across most categories, such as Global Warming Potential and Primary Energy Use. This underscores the significant environmental burden of material production and manufacturing processes. In contrast, Module D demonstrates environmental benefits, reflected in negative values for Global Warming Potential, emphasizing the role of reuse and recycling beyond the system boundary. The End of Life stage (C2–C4) also presents notable impacts, highlighting the importance of sustainable disposal and recovery strategies. Per area environmental impacts provide a standardized perspective, allowing for scalability and comparison across building types. For instance, Global Warming Potential per m² serves as a benchmark for evaluating similar structures. The product stage remains the largest contributor on a per area basis, reinforcing the need for sustainable material choices. These per m² values facilitate understanding the relative impact and enable informed decisions for future designs.Overall, the total and per m² evaluations of the 8-classroom school building emphasize the critical environmental impacts of material production and the potential benefits of recovery strategies. These insights provide a foundation for optimizing sustainable design and material selection in educational buildings.

7.2.2 Results per Life Cycle Stage

The chart illustrates the environmental impacts of the 8-classroom school building across various life cycle stages, including the Product Stage (A1-A3), Transportation (A4), Maintenance and Replacement (B2-B5), End of Life (C2-C4), and Module D (Recycling/Reuse). Key impact categories such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED) are represented, providing insight into the contribution of each stage (Figure 7.1).

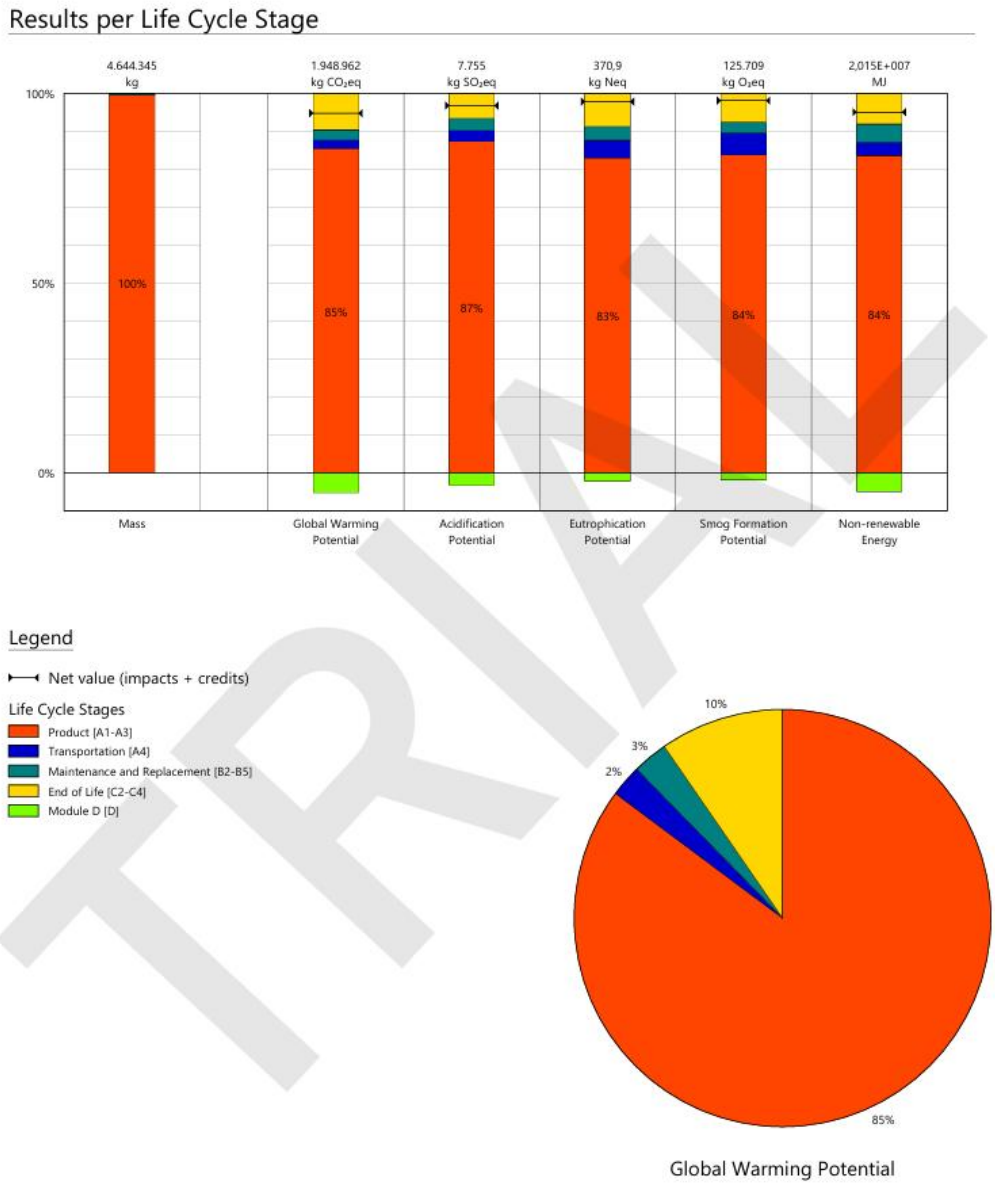


Figure 7.1 Results per life cycle stage analysis of 8-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

The chart clearly highlights the environmental impacts across different life cycle stages (Figure 7.1). In all impact categories, the Product Stage (A1–A3) has the largest contribution, accounting for 85% of the Global Warming Potential. Similarly, its share in other categories such as acidification, eutrophication, smog formation, and non-renewable energy consumption ranges from 84% to 87%. This emphasizes that improvements in material selection, optimization of production processes, and the use of low-carbon energy sources could have a significant sustainability impact

during this stage. The Transportation Stage (A4) has relatively lower contributions, with impacts below 3% across all categories. These impacts could be further minimized through strategies such as reducing transport distances and prioritizing locally sourced materials. The Maintenance and Replacement Stage (B2–B5) also accounts for approximately 3% of the total impacts. However, the use of durable and long-lasting materials could further reduce the environmental burdens of this stage. The End of Life Stage (C2–C4) contributes 10% to the Global Warming Potential, making it the second-largest contributor to environmental impacts. Proper waste management and improved recycling processes could significantly reduce the burdens during this phase. Recycling (Module D) provides environmental credits, as represented by the negative values in the chart. These credits help offset impacts from other life cycle stages by promoting material recovery and reuse, leading to reduced energy consumption and emissions. These findings emphasize the need to implement sustainability practices across all life cycle stages to minimize environmental impacts effectively.

7.2.3 Results per Life Cycle Stage, Itemized by Division

The chart provides a detailed breakdown of the environmental impacts of the 8-classroom school building, categorized by material divisions, including Concrete, Masonry, Metals, Wood/Plastics/Composites, and others. The life cycle stages analyzed are the Product Stage (A1-A3), Transportation (A4), Maintenance and Replacement (B2-B5), End of Life (C2-C4), and Module D (Recycling/Reuse). Key environmental impact categories such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED) are assessed to highlight the contributions of each division (Figure 7.2).

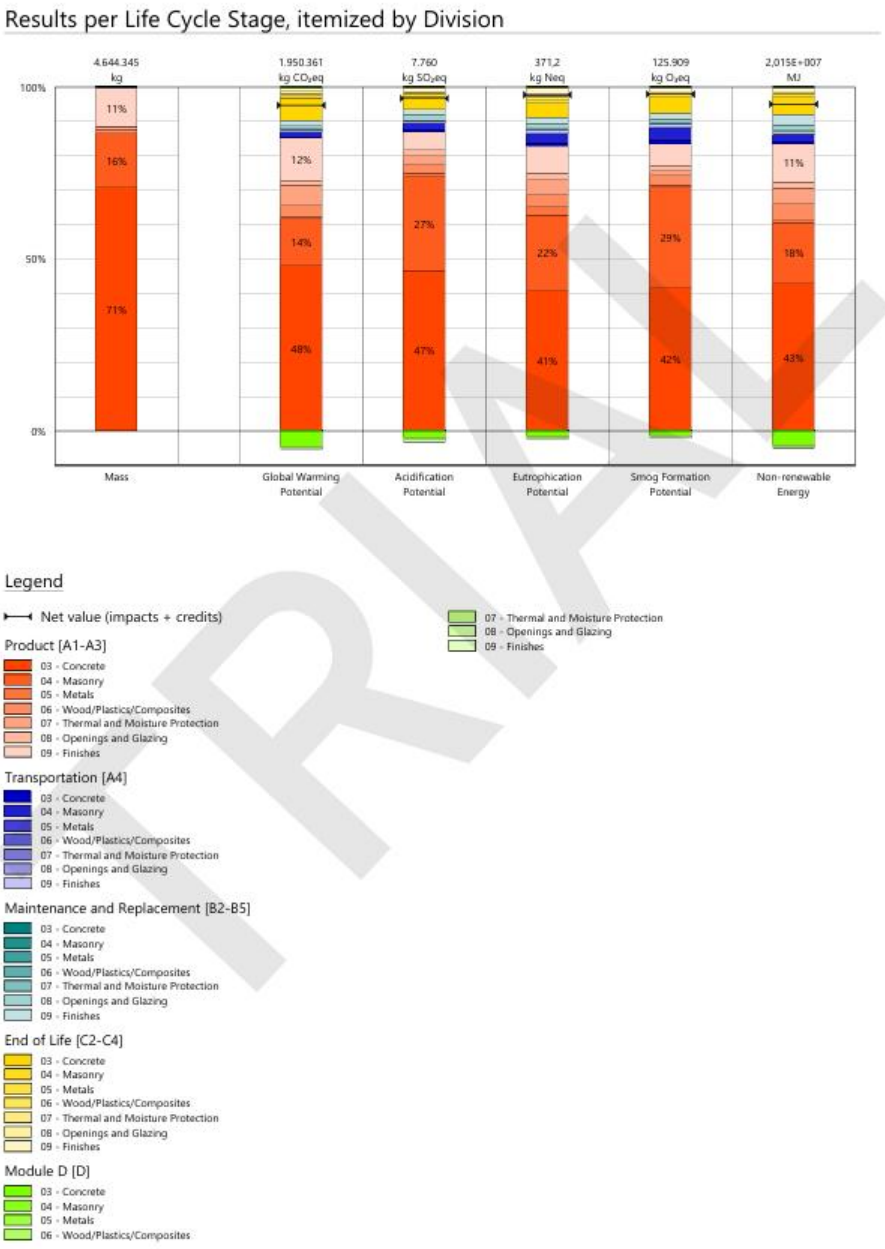


Figure 7.2 Results per life cycle stage, itemized by division analysis of 8-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

The chart illustrates the environmental impacts of the life cycle stages and material divisions for the building. The Product Stage (A1–A3) dominates across all categories, with concrete being the most impactful material. Concrete contributes 71% of the total mass and 48% of the Global Warming Potential (GWP), while its

energy-intensive production processes lead to high contributions to Acidification Potential (47%) and Non-Renewable Energy Demand (43%). Masonry materials, such as bricks, add significant impacts, especially in Smog Formation Potential (29%) and Eutrophication Potential (22%), largely due to manufacturing and transportation processes. Other materials, such as Metals, Wood/Plastics/Composites and Thermal and Moisture Protection, have smaller but still notable contributions to environmental burdens. The Transportation Stage (A4) primarily reflects the impacts of moving heavy materials like concrete and masonry. Optimizing logistics and prioritizing locally sourced materials could mitigate these impacts. The Maintenance and Replacement Stage (B2–B5) sees significant contributions from openings, glazing, and finishes, which require periodic maintenance and replacements. Using durable, low-maintenance materials could help reduce these impacts over time. Module D highlights the environmental benefits of recycling, particularly for concrete and masonry, which provide substantial offsets to other life cycle stages. Recycling reduces the demand for virgin raw materials and energy in future production cycles, underscoring its critical role in minimizing overall environmental impacts. This analysis emphasizes the importance of optimizing high-impact materials like concrete and masonry while leveraging recycling benefits to improve the sustainability of the building throughout its life cycle.

7.2.4 Results per Division

The chart provides a detailed analysis of the environmental impacts of the 8-classroom school building, categorized by material divisions such as Concrete, Masonry, Metals, Wood/Plastics/Composites, and others. Environmental impact categories include Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED) (Figure 7.3).

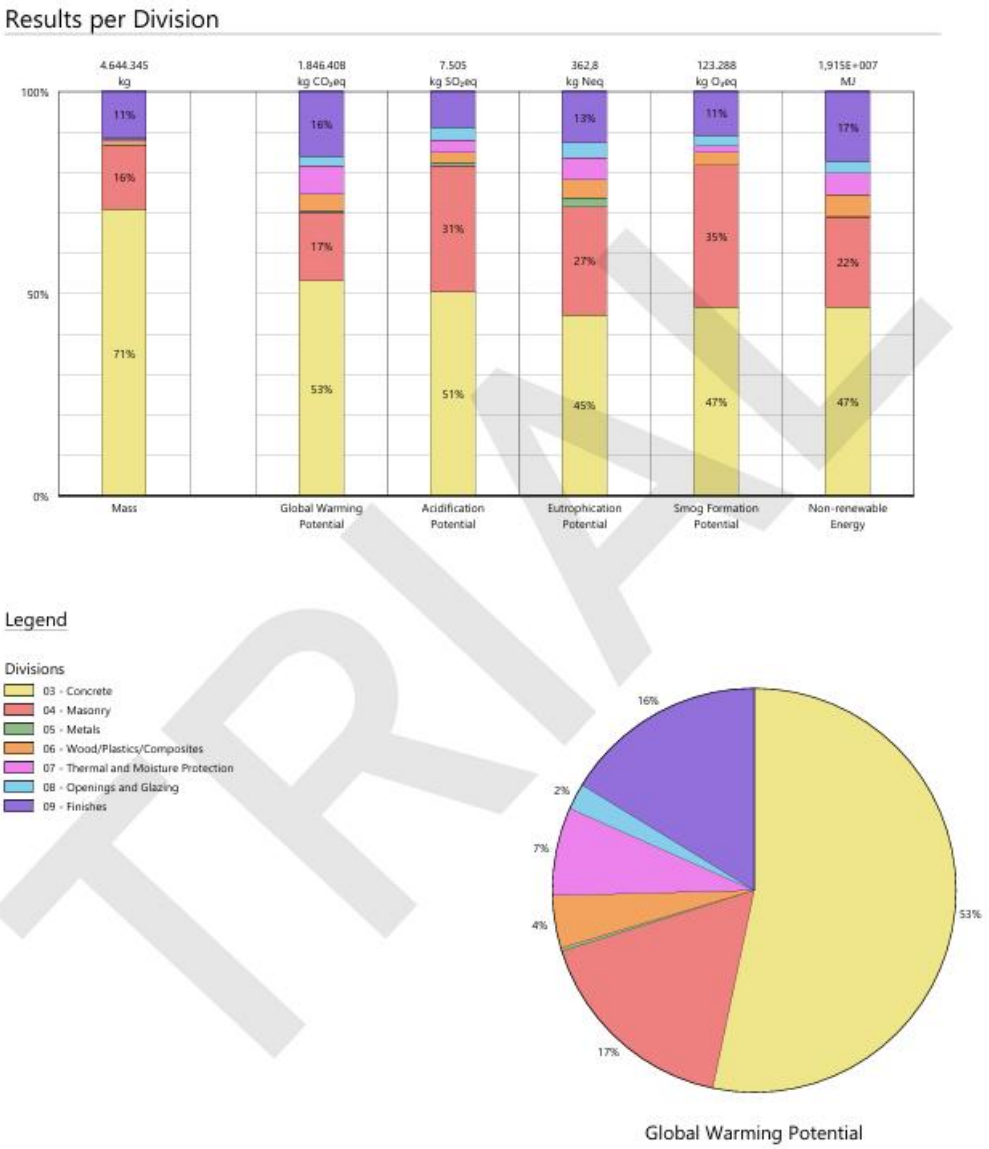


Figure 7.3 Results per division analysis of 8-classroom school building.
Environmental impact data derived from Tally software's analysis conducted in 2025

The chart provides an analysis of the environmental impacts for the 8-classroom building, itemized by material divisions. The Concrete category dominates most impact categories, contributing 71% of the total mass, 53% of the Global Warming Potential (GWP), 51% of the Acidification Potential (AP), 45% of the Eutrophication Potential (EP), and 47% of the Smog Formation Potential (SFP). This highlights the significant environmental burden of concrete production, emphasizing the need for optimization and low-carbon alternatives. Masonry materials are the second-largest

contributor, accounting for 17% of GWP, 31% of AP, 27% of EP, and 35% of SFP. These impacts primarily result from the energy-intensive processes involved in masonry production and transportation. Other materials, such as Metals, Wood/Plastics/Composites, Thermal and Moisture Protection, Openings and Glazing, and Finishes, contribute smaller but notable shares to specific impact categories. This analysis highlights that concrete and masonry together account for the majority of environmental impacts across most categories. Recycling strategies and sustainable material alternatives will be essential to mitigate these impacts effectively.

7.2.5 Results per Revit Category

The chart illustrates the environmental impacts of the 8-classroom school building, categorized by Revit components such as Ceilings, Doors, Floors, Roofs, Stairs and Railings, Structure, Walls, and Windows. The analysis encompasses multiple life cycle stages: the Product Stage (A1-A3), Transportation (A4), Maintenance and Replacement (B2-B5), End of Life (C2-C4), and Module D (Recycling/Reuse). Key environmental impact categories include Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED), with contributions itemized per category (Figure 7.4).

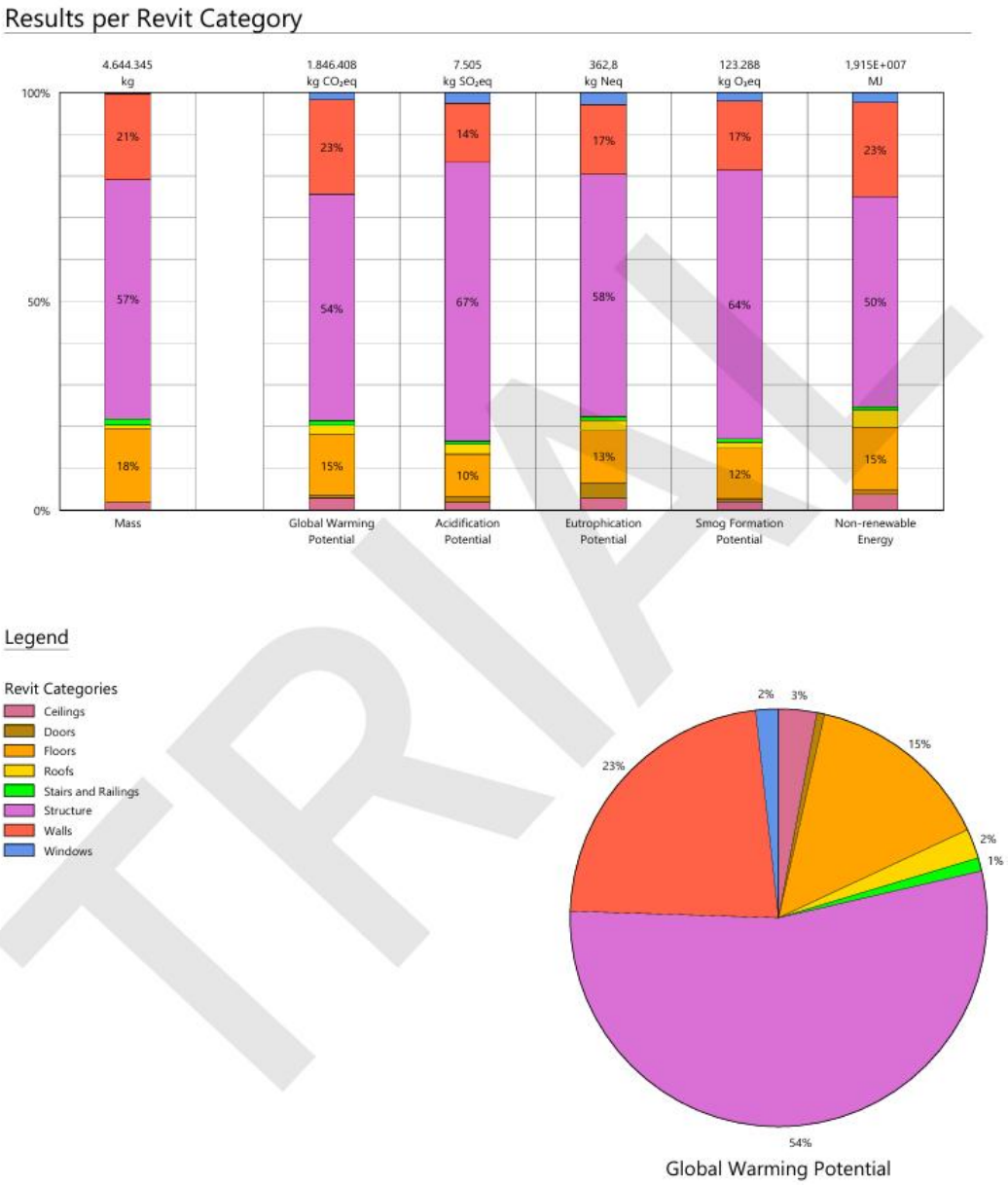


Figure 7.4 Results per Revit category analysis of 8-classroom school building.
Environmental impact data derived from Tally software's analysis conducted in 2025

The chart provides an analysis of the environmental impacts for the 8-classroom building, categorized by Revit components. The Structure category dominates most impact categories, accounting for 57% of the total mass and 54% of the Global Warming Potential (GWP). This reflects the extensive use of structural materials and their significant environmental burden. Walls are the second-largest contributor, comprising 21% of the total mass and 23% of GWP, highlighting their environmental

impact due to their material composition and thermal performance role. Floors follow, contributing 18% of the total mass and 15% of GWP, showcasing their importance in interior finishes. The pie chart for GWP further highlights the dominance of structural elements, walls and floors. These findings emphasize the importance of optimizing material selection, improving production processes, and exploring sustainable alternatives to reduce the environmental impacts of the 8-classroom building.

7.3 Environmental Impact Analysis of 12-Classroom School Building

This section focuses on the detailed environmental impact assessment of the 12-classroom school building. The analysis evaluates the building's performance across various life cycle stages. The aim is to uncover critical areas for improvement, offering actionable insights to enhance sustainability and reduce environmental burdens. The findings from this analysis are intended to guide the design and construction of more environmentally efficient educational facilities.

7.3.1 Total and Per m² Evaluation

In this section, the environmental impacts of the 12-classroom school building are analyzed from two perspectives:

Total Environmental Impacts: Evaluating the overall environmental burdens across each life cycle stage.

Per m² Environmental Impacts: Normalizing these impacts per square meter of the building area for comparative purposes.

These dual perspectives provide insights into both absolute environmental impacts and relative efficiencies, facilitating the identification of focus points and opportunities for improvement in building design. The following tables outline the detailed environmental assessment for the 12-classroom school building. Table 7.3 summarizes the total impacts at each life cycle stage, while Table 7.4 presents the per area impacts. These analyses form the foundation for strategies aimed at improving

sustainability and minimizing environmental burdens throughout the building's life cycle.

Table 7.3 Total environmental impacts analysis of 12-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

Impact Category	Product Stage (A1–A3)	Construction Stage (A4)	Use Stage (B2–B5)	End of Life Stage (C2–C4)	Recycling (D)
Global Warming (kg CO_2eq)	2.349.073	56.481	41.696	244.679	-107.189
Acidification (kg SO_2eq)	11.999	261,7	167,8	654,8	-242
Eutrophication (kg Neq)	508,4	21,31	9,119	38,92	-7,79
Smog Formation (kg O_3eq)	191.140	8.648	2.793	12.577	-2.041
Ozone Depletion (kg CFC-11eq)	0,07756	1,934E-009	1,565E-004	1,606E-005	7,067E-004
Primary Energy (MJ)	2,694E+007	821.354	986.015	2.236.858	-1.044.706
Non-Renewable Energy (MJ)	2,422E+07	801.700	903.329	2.175.866	-1.029.814
Renewable Energy (MJ)	2.726.094	19.861	82.781	153.55	-15.332

Table 7.4 Per area environmental impacts analysis of 12-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

Impact Category	Product Stage (A1–A3)	Construction Stage (A4)	Use Stage (B2–B5)	End of Life Stage (C2–C4)	Recycling (D)
Global Warming (kg CO_2eq/m²)	827,4	19,89	14,69	86,18	-37,8
Acidification (kg SO_2eq/m²)	4,226	0,09219	0,05911	0,2306	-0,08513
Eutrophication (kg Neq/m²)	0,1791	0,007506	0,003212	0,01371	-0,002743
Smog Formation (kg O_3eq/m²)	67,33	3,046	0,9837	4,430	-0,7188

Table 7.4 Per area environmental impacts analysis of 12-classroom school building(continued) . Environmental impact data derived from Tally software's analysis conducted in 2025

Impact Category	Product Stage (A1–A3)	Construction Stage (A4)	Use Stage (B2–B5)	End of Life Stage (C2–C4)	Recycling (D)
Ozone Depletion (kg CFC-11eq/m²)	2,732E-005	6,814E-013	5,511E-008	5,659E-009	2,489E-007
Primary Energy (MJ/m²)	9.491	289,3	347,3	819,6	-368
Non-Renewable Energy (MJ/m²)	8.533	282,4	318,2	766,4	-363
Renewable Energy (MJ/m²)	960,2	6,996	29,16	54,09	-5,40

Table 7.3 and Table 7.4 highlight the critical role of life cycle analysis in pinpointing opportunities for reducing environmental impacts and fostering sustainable building practices (Table 7.3 and Table 7.4). The total environmental impacts highlight the contributions of each life cycle stage. Among these, the product stage (A1–A3) emerges as the dominant contributor, as it involves material extraction, production, and transportation processes that demand significant energy and resources. Categories such as Global Warming Potential and Primary Energy Use are particularly affected during this stage, emphasizing the need to prioritize sustainable material sourcing and efficient manufacturing processes. Additionally, the construction stage (A4) adds to the environmental load through transportation and on-site assembly activities, while the End of Life stage (C2–C4) underscores the environmental impacts associated with demolition, waste processing, and disposal. Module D represents environmental benefits, showcasing the potential for reuse, recycling, and energy recovery beyond the building's lifecycle. Per area environmental impacts provide a standardized perspective, allowing for scalability and comparison across building types. For instance, the Global Warming Potential per m² during the product stage serves as a benchmark for evaluating the efficiency and environmental performance of similar structures. The dominance of the product stage in per m² impacts reinforces the importance of material efficiency and life cycle thinking during the design phase. Furthermore, these metrics help identify

specific areas for improvement, such as reducing construction waste, optimizing material use, and incorporating renewable energy solutions.

7.3.2 Results per Life Cycle Stage

The chart illustrates the environmental impacts of the 12-classroom school building across various life cycle stages, including the Product Stage (A1-A3), Transportation (A4), Maintenance and Replacement (B2-B5), End of Life (C2-C4), and Module D (Recycling/Reuse). Each impact category, such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED), is assessed to highlight the contributions of these stages (Figure 7.5).

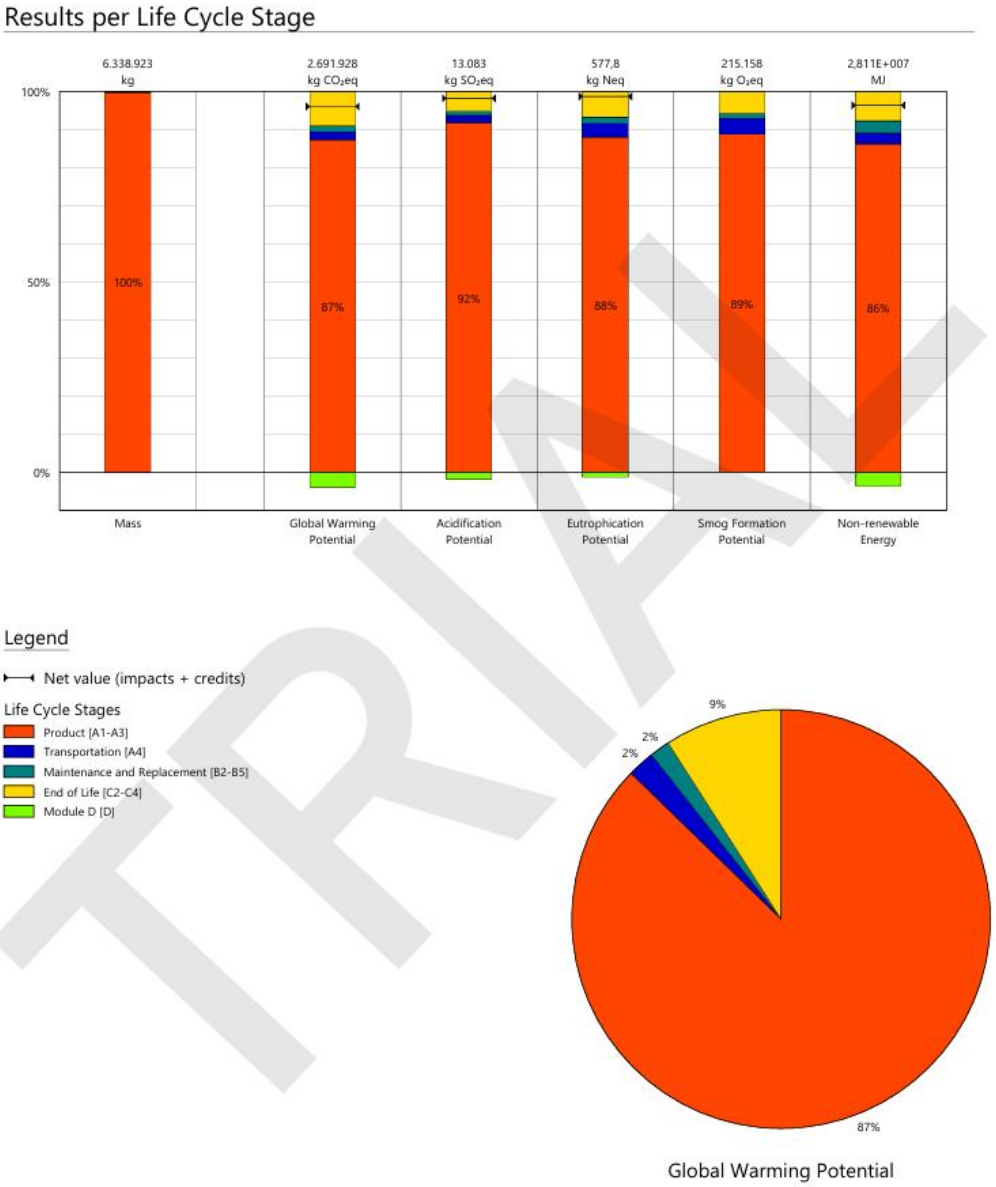


Figure 7.5 Results per life cycle stage analysis of 12-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

The chart illustrates the environmental impacts of the life cycle stages for the 12-classroom building (Figure 7.5). The Product Stage (A1–A3) has the highest contribution across all impact categories. It accounts for 87% of the Global Warming Potential, 92% of the Acidification Potential, 88% of the Eutrophication Potential, 89% of the Smog Formation Potential, and 86% of Non-Renewable Energy Consumption. These results indicate that the extraction, processing, and manufacturing of materials in the Product Stage are the primary drivers of

environmental impacts. Improvements in material selection, energy-efficient production, and reducing fossil fuel reliance during this stage could yield significant sustainability benefits. The Transportation Stage (A4) contributes approximately 2–3% of the impacts across most categories. While its contribution is relatively small, optimizing transportation logistics and prioritizing local materials could further reduce emissions and energy demand. The Maintenance and Replacement Stage (B2–B5) accounts for about 2% of the total impacts. These impacts could be minimized by using durable, low-maintenance materials that reduce the need for frequent replacements throughout the building's lifecycle. The End of Life Stage (C2–C4) contributes 9% to the Global Warming Potential, making it the second-largest contributor after the Product Stage. Proper waste management and enhanced recycling processes during this stage are critical for mitigating its environmental burdens. Recycling (Module D) provides negative values across all impact categories, representing environmental credits. These credits offset impacts from other life cycle stages by promoting material recovery and reuse, thereby reducing the demand for raw materials and energy in future production cycles. This analysis highlights the importance of focusing sustainability efforts on the Product Stage while leveraging recycling benefits to mitigate overall life cycle impacts.

7.3.3 Results per Life Cycle Stage, Itemized by Division

The chart provides a detailed breakdown of the environmental impacts of the 12-classroom school building, categorized by divisions such as Concrete, Masonry, Metals, Wood/Plastics/Composites, and other material types. The life cycle stages analyzed include the Product Stage (A1-A3), Transportation (A4), Maintenance and Replacement (B2-B5), End of Life (C2-C4), and Module D (Recycling/Reuse). Key environmental impact categories—such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED)—are examined to highlight the contribution of each division (Figure 7.6).

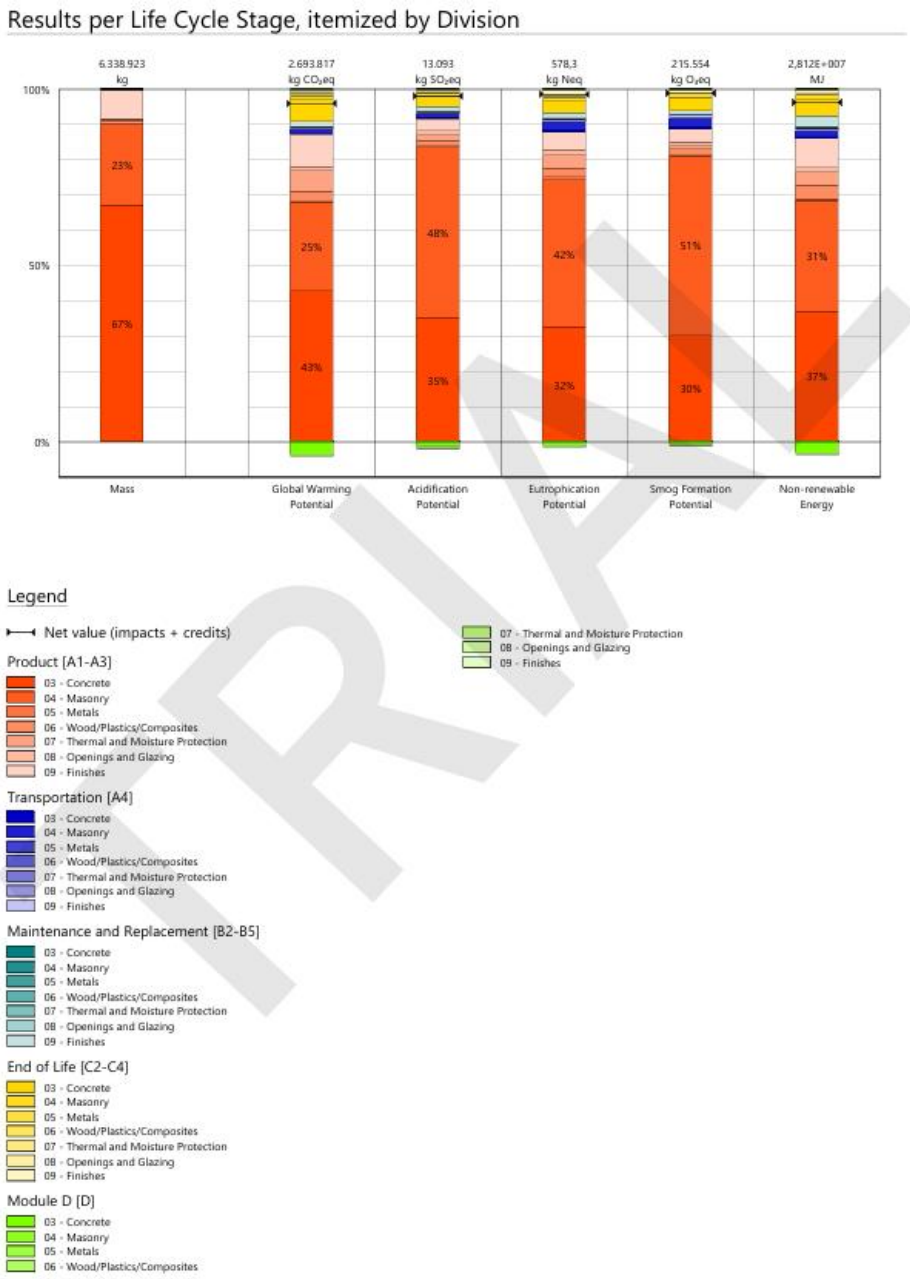


Figure 7.6 Results per life cycle stage, itemized by division analysis of 12-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

The chart illustrates the environmental impacts of the life cycle stages for the 12-classroom building, itemized by material divisions. The Product Stage (A1–A3) dominates across all categories, with concrete being the largest contributor. Concrete accounts for 67% of the total mass, 43% of the Global Warming Potential (GWP),

35% of the Acidification Potential (AP), and 37% of Non-Renewable Energy Demand (NRED). This highlights the energy-intensive nature of concrete production and its significant role in environmental impacts. Optimizing concrete usage or adopting alternative low-carbon materials could reduce these effects. Masonry materials, such as bricks, contribute significantly to Smog Formation Potential (SFP, 51%), Eutrophication Potential (EP, 42%), and Acidification Potential (AP, 48%), due to their production and transportation processes. Other materials, such as Metals, Wood/Plastics/Composites and Thermal and Moisture Protection, have smaller but notable contributions, particularly in material-specific environmental categories.This analysis underscores the importance of material selection, lifecycle planning, and recycling to enhance the environmental performance of the 12-classroom building.

7.3.4 Results per Division

The chart provides a breakdown of the environmental impacts of the 12-classroom school building by material divisions, including Concrete, Masonry, Metals, Wood/Plastics/Composites, Thermal and Moisture Protection, Openings and Glazing, and Finishes. Key impact categories such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED) are examined to highlight the contributions of each division (Figure 7.7).

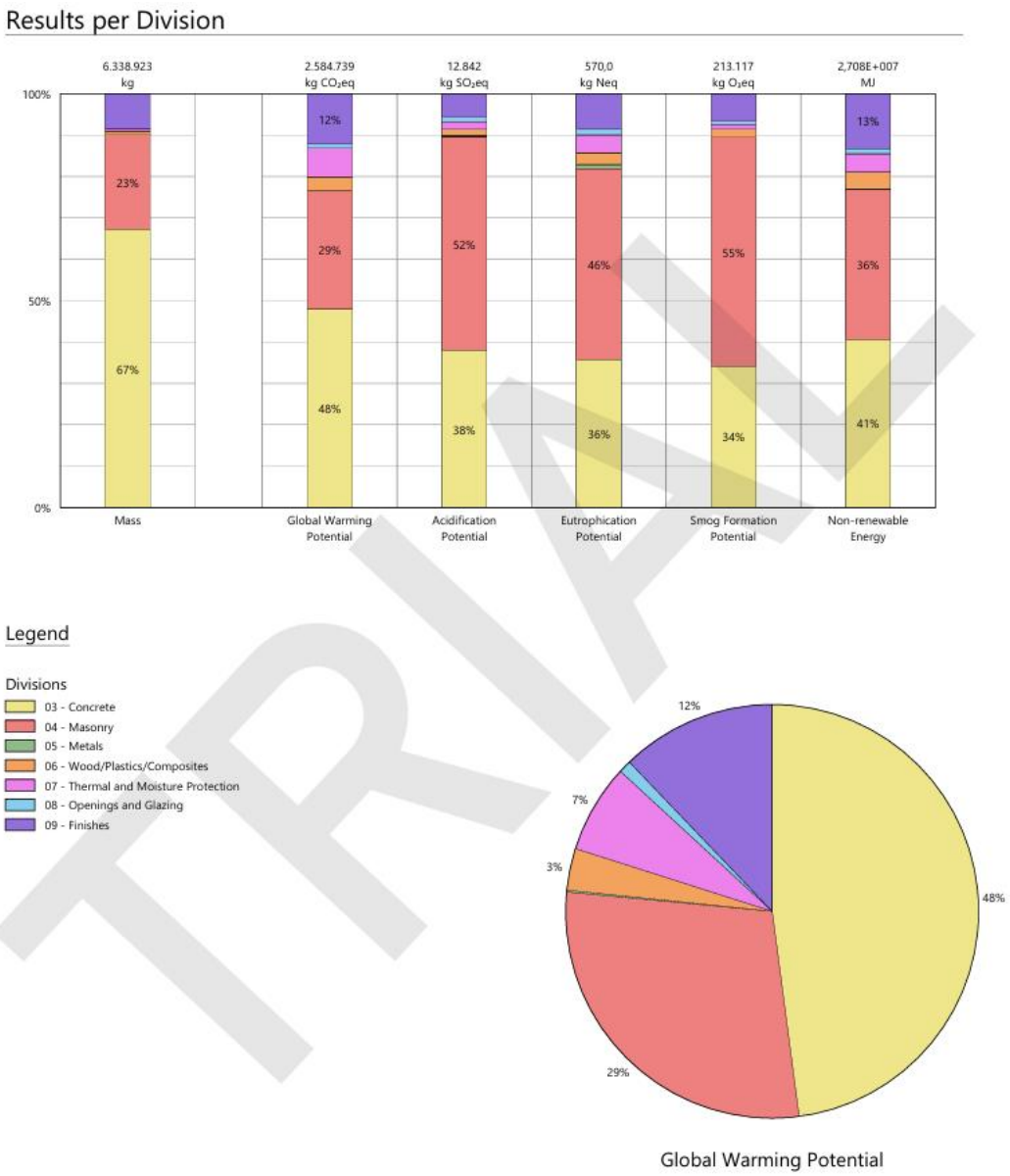


Figure 7.7 Results per division analysis of 12-classroom school building.
Environmental impact data derived from Tally software's analysis conducted in 2025

The chart provides an analysis of the environmental impacts for the 12-classroom building, itemized by material divisions. The Concrete category dominates most impact categories, contributing 67% of the total mass, 48% of the Global Warming Potential (GWP), 38% of the Acidification Potential (AP), and 41% of the Non-Renewable Energy Demand (NRED). This reflects the significant energy and resource demands of concrete production and its role as the primary material in the building. Masonry materials are the second-largest contributor, accounting for 29%

of GWP, 52% of AP, and 46% of Eutrophication Potential (EP). These impacts primarily arise from the energy-intensive processes involved in producing and transporting masonry products. Other materials, including Metals, Wood/Plastics/Composites, Thermal and Moisture Protection, Openings and Glazing, and Finishes, contribute smaller but notable shares to specific impact categories. For instance, Concrete and Masonry dominate Smog Formation Potential (SFP), accounting for 55% and 34%, respectively. Metals, Wood/Plastics, and other divisions have minimal contributions, ranging from 1% to 7%. These materials influence specific environmental categories due to their unique production characteristics and usage requirements. The pie chart for Global Warming Potential highlights that concrete and masonry together account for the majority of emissions. This emphasizes the need for more sustainable material choices and production efficiencies to reduce the overall environmental burden.

7.3.5 Results per Revit Category

The chart illustrates the environmental impacts of the 12-classroom school building across various Revit categories, including Ceilings, Doors, Floors, Roofs, Stairs and Railings, Structure, Walls, and Windows. The analysis evaluates multiple impact categories, such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED), and presents the contributions of each category to the building’s overall environmental performance (Figure 7.8).



Figure 7.8 Results per Revit category analysis of 12-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

The chart provides an analysis of the environmental impacts for the 12-classroom building, categorized by Revit components. The Structure category dominates most impact categories, accounting for 64% of the total mass and 67% of the Global Warming Potential (GWP). This highlights the extensive use of structural materials and their significant environmental burden.Walls are another contributor, comprising 15% of the total mass and 17% of GWP, reflecting their material composition and

role in thermal performance. Floors contributing 17% of the total mass, and 11% of GWP. These results emphasize the importance of these categories in building performance and their associated environmental impacts. The pie chart for GWP illustrates the dominance of structural elements, walls, floors. These findings emphasize the importance of optimizing material selection, improving production processes, and exploring sustainable alternatives to reduce the environmental impacts of the 12-classroom building.

7.4 Environmental Impact Analysis of 24-Classroom School Building

This section focuses on the detailed environmental impact assessment of the 24-classroom school building. The analysis evaluates the building's performance across various life cycle stages. The aim is to uncover critical areas for improvement, offering actionable insights to enhance sustainability and reduce environmental burdens. The findings from this analysis are intended to guide the design and construction of more environmentally efficient educational facilities.

7.4.1 Total and Per m² Evaluation

In this section, the environmental impacts of the 24-classroom school building are analyzed from two different perspectives:

Total Environmental Impacts: The total impacts at each life cycle stage.

Environmental Impacts Per m²: The same impacts, but evaluated per square meter of the building.

These dual perspectives provide insights into both absolute environmental impacts and relative efficiencies, facilitating the identification of focus points and opportunities for improvement in building design. The following tables outline the detailed environmental assessment for the 24-classroom school building. Table 7.5 summarizes the total impacts at each life cycle stage, while Table 7.6 presents the per area impacts. These analyses form the foundation for strategies aimed at improving sustainability and minimizing environmental burdens throughout the building's life cycle.

Table 7.5 Total environmental impacts analysis of 24-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

Environmental Impact Category	Product Stage (A1–A3)	Construction Stage (A4)	Use Stage (B2–B5)	End of Life Stage (C2–C4)	Recycling (D)
Global Warming (kg CO_2eq)	3.900.544	84.649	53.121	369.430	-191.017
Acidification (kg SO_2eq)	19.959	392,2	218,4	1.008	-440
Eutrophication (kg Neq)	808,8	31,94	11,24	61,22	-14,6
Smog Formation (kg O_3eq)	301.622	12.961	3.572	19.285	-4.101
Ozone Depletion (kg CFC-11eq)	0,091	2,899E-009	2,076E-004	1,896E-005	0,001238
Primary Energy (MJ)	4,341E+007	1.230.975	1.266.710	3.566.842	-1.842,.41
Non-Renewable Energy (MJ)	3,917E+007	1.201.518	1.160.015	3.335.347	-1.838.227
Renewable Energy (MJ)	4.252.417	29.767	106.815	235.386	-5.140

Table 7.6 Per area environmental impacts analysis of 24-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

Environmental Impact Category	Product Stage (A1–A3)	Construction Stage (A4)	Use Stage (B2–B5)	End of Life Stage (C2–C4)	Recycling (D)
Global Warming (kg CO_2eq/m²)	970,3	21,06	13,21	91,90	-47,5
Acidification (kg SO_2eq/m²)	4,965	0,09757	0.05432	0.2507	-0.1095
Eutrophication (kg Neq/m²)	0.2012	0.007945	0.002796	0,01523	-0,003636
Smog Formation (kg O_3eq/m²)	75,03	3,224	0,8885	4,797	-1,02
Ozone Depletion (kg CFC-11eq/m²)	2,264E-005	7,212E-013	5,164E-008	4,717E-009	3,079E-007

Table 7.6 Per area environmental impacts analysis of 24-classroom school building (continued). Environmental impact data derived from Tally software's analysis conducted in 2025

Environmental Impact Category	Product Stage (A1–A3)	Construction Stage (A4)	Use Stage (B2–B5)	End of Life Stage (C2–C4)	Recycling (D)
Primary Energy (MJ/m²)	10.799	306,2	315,1	887,3	-458
Non-Renewable Energy (MJ/m²)	9.743	298,9	288,6	829,7	-457
Renewable Energy (MJ/m²)	1.058	7,405	26,57	58,55	-1,28

Table 7.5 and Table 7.6 highlight the critical role of life cycle analysis in pinpointing opportunities for reducing environmental impacts and fostering sustainable building practices (Table 7.5 and Table 7.6). The total environmental impacts reveal significant contributions from each life cycle stage. The product stage (A1–A3) dominates across most impact categories, including Global Warming Potential and Primary Energy Use, emphasizing the resource-intensive nature of material extraction and production. The construction stage (A4) also contributes to the environmental load through transportation and assembly activities, albeit to a lesser extent. The End of Life stage (C2–C4) adds considerable environmental burdens, highlighting the importance of sustainable disposal and recovery practices. Module D demonstrates potential environmental benefits, as recycling and reuse strategies offset the overall impacts. Per area environmental impacts provide a standardized perspective, enabling scalability and meaningful comparisons. For instance, Global Warming Potential per m² serves as a critical benchmark for assessing the environmental efficiency of the building. The product stage remains the most impactful on a per m² basis, which underscores the need for material efficiency and innovative design solutions to reduce environmental burdens. These per m² metrics also highlight opportunities for improvement, such as incorporating renewable energy sources and minimizing construction waste.

7.4.2 Results per Life Cycle Stage

The chart illustrates the environmental impacts of the 24-classroom school building across various life cycle stages: Product Stage (A1-A3), Transportation (A4), Maintenance and Replacement (B2-B5), End of Life (C2-C4), and Module D (Recycling/Reuse). Key environmental impact categories include Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED). The contributions of each stage are highlighted to provide insights into the building's overall environmental performance (Figure 7.9).

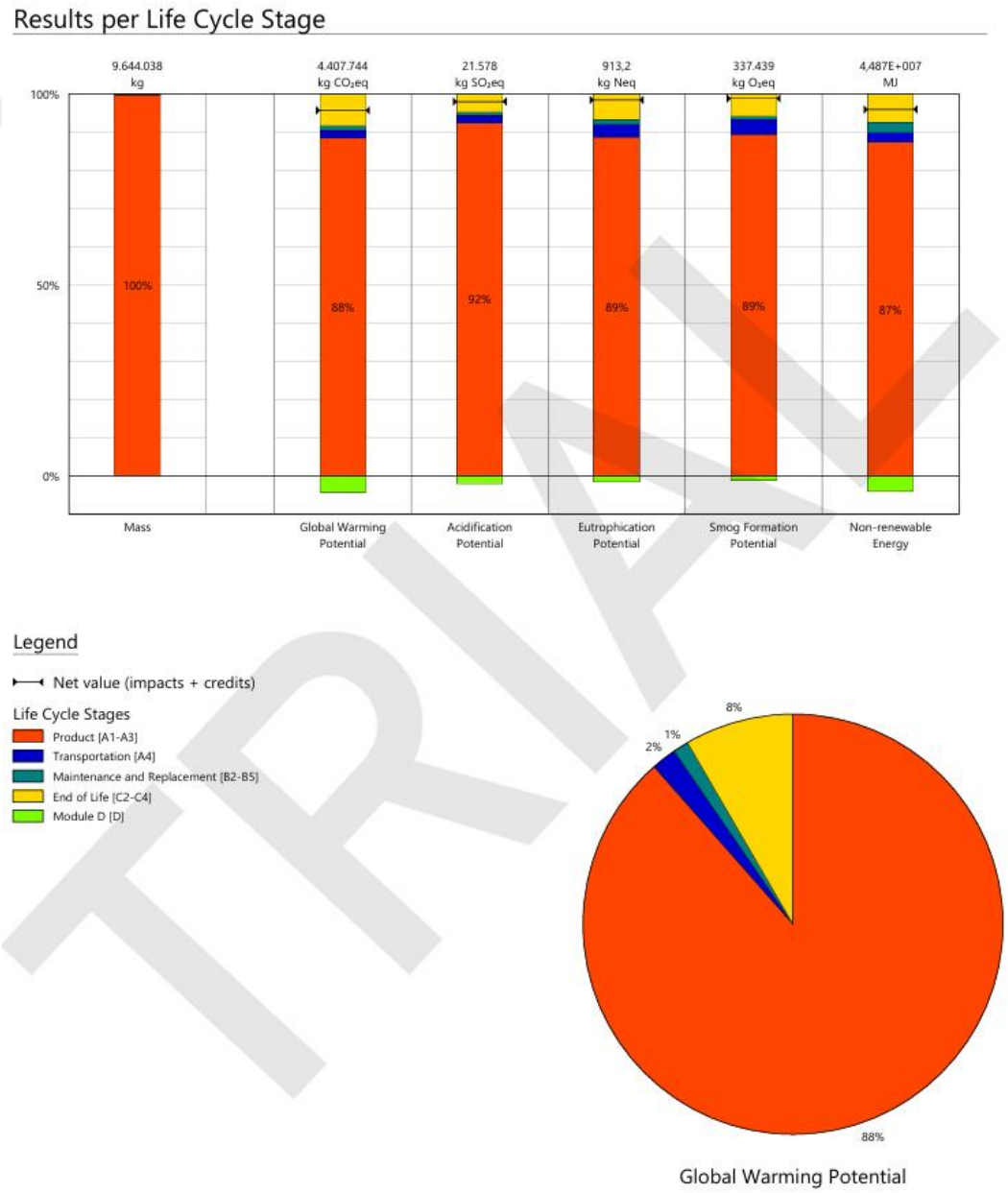


Figure 7.9 Results per life cycle stage analysis of 24-classroom school building.
Environmental impact data derived from Tally software's analysis conducted in 2025

The chart illustrates the environmental impacts of the life cycle stages for the 24-classroom building (Figure 7.9). The Product Stage (A1–A3) accounts for the highest contribution across all categories, making up 88% of the Global Warming Potential, 92% of the Acidification Potential, 89% of the Eutrophication Potential, 89% of the Smog Formation Potential, and 87% of Non-Renewable Energy Consumption. These results highlight that the extraction, processing, and manufacturing of materials are the primary drivers of environmental impacts in this stage. Improvements in material selection and production efficiency could significantly enhance sustainability. The Transportation Stage (A4) contributes approximately 2–3% of the total impacts across all categories, indicating a relatively small but noteworthy contribution. Optimizing logistics and sourcing materials locally can help further reduce its impacts. The Maintenance and Replacement Stage (B2–B5) has a minimal contribution, representing around 1–2% of the total impacts. Using durable and low-maintenance materials could further reduce these effects over the building's lifecycle. The End of Life Stage (C2–C4) accounts for 8% of the Global Warming Potential, making it the second-highest contributor after the Product Stage. Proper waste management and improved recycling processes during this phase could significantly reduce the environmental burdens. Recycling (Module D) provides environmental credits, as indicated by the negative values across all categories. These credits offset impacts from other life cycle stages by promoting material recovery and reuse, reducing the demand for raw materials and energy in future production cycles. This analysis reinforces the importance of focusing on the Product Stage for sustainability improvements while leveraging the benefits of recycling to mitigate impacts across the entire lifecycle. Overall, the analysis underscores the importance of material selection, optimized transportation, and enhanced recycling systems in reducing the environmental footprint of the 24-classroom school building. Sustainable design strategies focusing on these areas can significantly improve the building’s life cycle environmental performance.

7.4.3 Results per Life Cycle Stage, Itemized by Division

The chart presents a detailed breakdown of the environmental impacts of the 24-classroom school building, categorized by divisions such as Concrete, Masonry, Metals, Wood/Plastics/Composites, and other material types. The life cycle stages include the Product Stage (A1-A3), Transportation (A4), Maintenance and Replacement (B2-B5), End of Life (C2-C4), and Module D (Recycling/Reuse). Key environmental impact categories—such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED)—are itemized to highlight the contribution of each division (Figure 7.10).

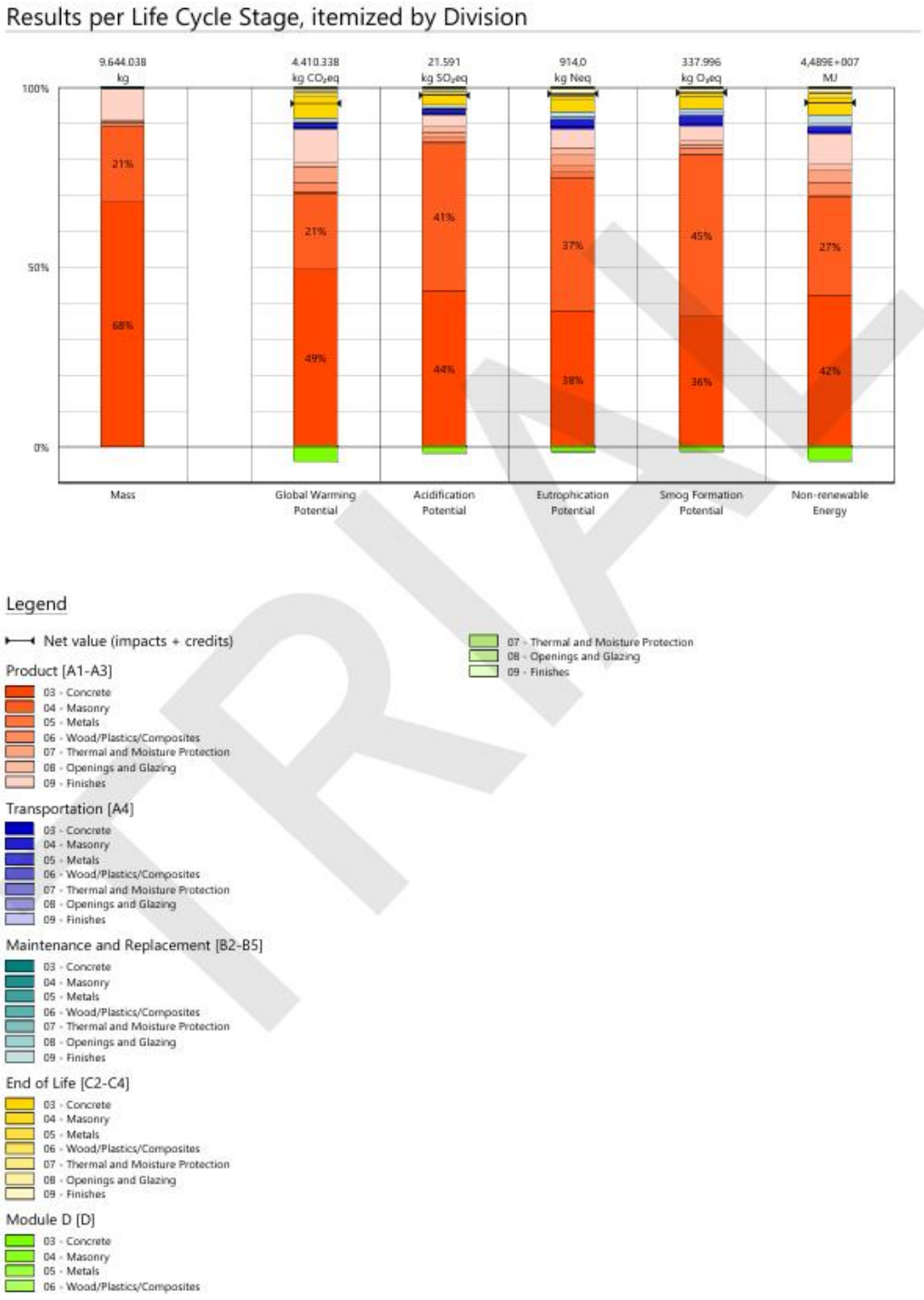


Figure 7.10 Results per life cycle stage, itemized by division analysis of 24-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

The chart illustrates the environmental impacts of the life cycle stages for the 24-classroom building, itemized by material divisions. The Product Stage (A1–A3) remains the dominant contributor across all categories. Concrete is the most impactful material, accounting for 68% of the total mass, 49% of the Global Warming Potential (GWP), 44% of the Acidification Potential (AP), and 42% of Non-Renewable Energy Demand (NRED). Its energy-intensive production process highlights the need for optimized use or low-carbon alternatives to reduce its environmental burden. Masonry materials contribute significantly to Smog Formation Potential (SFP, 45%), Eutrophication Potential (EP, 37%), and Acidification Potential (41%), driven by their manufacturing and transportation processes. Other materials, including Metals, Wood/Plastics/Composites and Thermal and Moisture Protection, provide smaller but meaningful contributions to material-specific environmental burdens. The Transportation Stage (A4) reflects impacts primarily from moving heavy materials such as concrete and masonry, emphasizing the importance of sourcing materials locally and optimizing logistics. The Maintenance and Replacement Stage (B2–B5) shows significant contributions from openings, glazing, and finishes, which require regular maintenance or replacements. Choosing durable materials could reduce these impacts over the lifecycle of the building. The End of Life Stage (C2–C4) sees significant impacts from concrete and masonry, emphasizing the need for improved waste management and recycling practices. Module D highlights the environmental credits provided by recycling, particularly for metals and wood/plastics, which offset impacts from other life cycle stages and reduce raw material demand in future production cycles. This analysis highlights opportunities for material efficiency, lifecycle planning, and recycling to improve the environmental performance of the 24-classroom building.

7.4.4 Results per Division

The chart illustrates the environmental impacts of the 24-classroom school building, categorized by material divisions such as Concrete, Masonry, Metals, and other components. Key impact categories analyzed include Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED) (Figure 7.11).

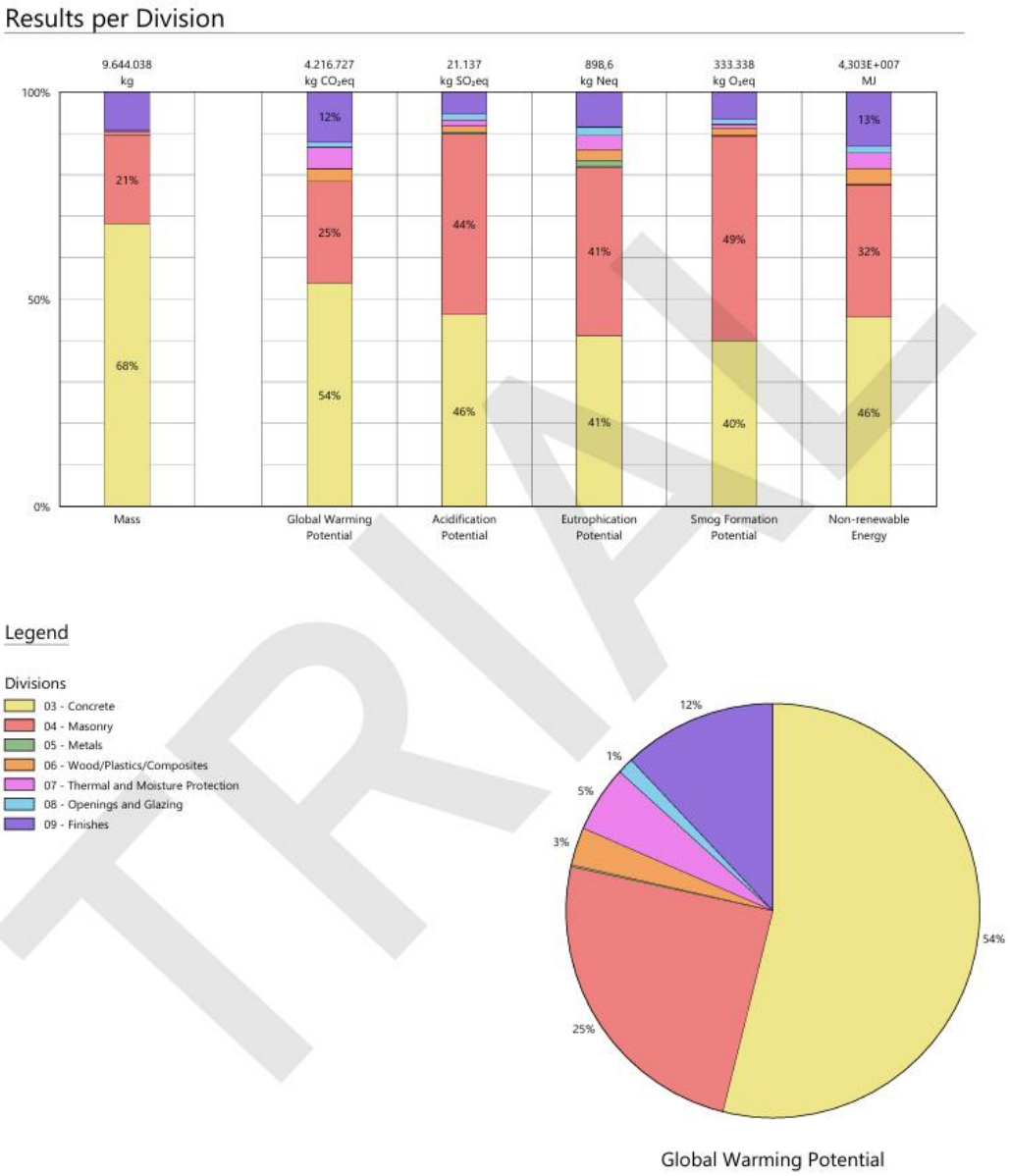


Figure 7.11 Results per division analysis of 24-classroom school building.
Environmental impact data derived from Tally software's analysis conducted in 2025

The chart provides an analysis of the environmental impacts for the 24-classroom building, categorized by material divisions. The Concrete category dominates most impact categories, contributing 68% of the total mass, 54% of the Global Warming Potential (GWP), 46% of the Acidification Potential (AP), 41% of the Eutrophication Potential (EP), and 40% of the Smog Formation Potential (SFP). These results highlight the significant environmental impact of concrete production, emphasizing the importance of optimizing its use and exploring sustainable alternatives. Masonry

materials are the second-largest contributor, accounting for 25% of GWP, 44% of AP, 41% of EP, and 49% of SFP. These impacts arise from the energy-intensive processes associated with masonry manufacturing and transportation. Other materials, such as Metals, Wood/Plastics/Composites, Thermal and Moisture Protection, Openings and Glazing, and Finishes, contribute smaller but noteworthy shares to specific impact categories. For instance, Wood/Plastics/Composites contribute 3% to GWP and 2% to EP, while Thermal and Moisture Protection accounts for 5% across most categories. These contributions reflect the specialized usage and material properties influencing environmental impacts. The pie chart for Global Warming Potential illustrates that concrete and masonry together dominate emissions, underscoring the importance of prioritizing material efficiency and sustainable production methods. These findings highlight the critical role of sustainable material selection, efficient production processes, and recycling strategies in minimizing the lifecycle impacts of the 24-classroom school building.

7.4.5 Results per Revit Category

The chart illustrates the environmental impacts of the 24-classroom school building across various Revit categories, including Ceilings, Doors, Floors, Roofs, Stairs and Railings, Structure, Walls, and Windows. The analysis evaluates multiple impact categories, such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED), and presents the contributions of each category to the building’s overall environmental performance (Figure 7.12).



Figure 7.12 Results per revit category analysis of 24-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

The chart provides an analysis of the environmental impacts for the 24-classroom building, categorized by Revit components. The Structure category dominates most impact categories, accounting for 67% of the total mass and 65% of the Global Warming Potential (GWP). This dominance reflects the extensive use of structural materials and their significant environmental burden. Walls are another contributor, comprising 15% of the total mass and 16% of GWP, highlighting their environmental

impact due to their material composition and role in thermal performance. Floors closely contributing 15% of the total mass, and 16% of GWP. These results emphasize the importance of these components in the building's environmental profile. The pie chart for GWP further highlights the dominance of structural elements, walls, floors. These findings underscore the importance of optimizing material usage, improving production methods, and adopting sustainable alternatives to reduce the environmental impacts of the 24-classroom building.

7.5 Environmental Impact Analysis of 32-Classroom School Building

This section focuses on the detailed environmental impact assessment of the 32-classroom school building. The analysis evaluates the building's performance across various life cycle stages. The aim is to uncover critical areas for improvement, offering actionable insights to enhance sustainability and reduce environmental burdens. The findings from this analysis are intended to guide the design and construction of more environmentally efficient educational facilities.

7.5.1 Total and Per m² Evaluation

In this section, the environmental impacts of the 32-classroom school building are analyzed from two different perspectives:

Total Environmental Impacts: The total impacts at each life cycle stage.

Environmental Impacts Per m²: The same impacts, but evaluated per square meter of the building.

These dual perspectives provide insights into both absolute environmental impacts and relative efficiencies, facilitating the identification of focus points and opportunities for improvement in building design. The following tables outline the detailed environmental assessment for the 32-classroom school building. Table 7.7 summarizes the total impacts at each life cycle stage, while Table 7.8 presents the per area impacts. These analyses form the foundation for strategies aimed at improving sustainability and minimizing environmental burdens throughout the building's life cycle.

Table 7.7 Total environmental impacts analysis of 32-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

Environmental Impact Category	Product Stage (A1–A3)	Construction Stage (A4)	Use Stage (B2–B5)	End of Life Stage (C2–C4)	Recycling (D)
Global Warming (kg CO_2eq)	6.663.878	155.439	100.253	699.046	-382.988
Acidification (kg SO_2eq)	32.777	720,3	420	1.859	-781
Eutrophication (kg Neq)	1.412	58,65	21,94	107,7	-27,4
Smog Formation (kg O_3eq)	531.975	23.8	6.931	35.979	-7.476
Ozone Depletion (kg CFC-11eq)	0,1957	5,32E-009	2,695E-004	4,105E-005	0,002654
Primary Energy (MJ)	7,664E+007	2.260.416	2.373.358	6.667.371	-3.555.968
Non-Renewable Energy (MJ)	6,928E+007	2.206.325	2.170.272	6.234.657	-3.626.140
Renewable Energy (MJ)	7.386.918	54.660	203.241	440.013	68.610

Table 7.8 Per area environmental impacts analysis of 32-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

Environmental Impact Category	Product Stage (A1–A3)	Construction Stage (A4)	Use Stage (B2–B5)	End of Life Stage (C2–C4)	Recycling (D)
Global Warming (kg CO_2eq/m²)	915,4	21,35	13,77	96,02	-52,6
Acidification (kg SO_2eq/m²)	4,502	0,09894	0,05769	0,2554	-0,1073
Eutrophication (kg Neq/m²)	0,194	0,008056	0,003013	0,01479	-0,003759
Smog Formation (kg O_3eq/m²)	73,07	3,269	0,9521	4,942	-1,03
Ozone Depletion (kg CFC-11eq/m²)	2,688E-005	7,313E-013	3,702E-008	5,639E-009	3,645E-007
Primary Energy (MJ/m²)	10.528	310,5	326,0	915,8	-488

Table 7.8 Per area environmental impacts analysis of 32-classroom school building (continued). Environmental impact data derived from Tally software's analysis conducted in 2025

Environmental Impact Category	Product Stage (A1–A3)	Construction Stage (A4)	Use Stage (B2–B5)	End of Life Stage (C2–C4)	Recycling (D)
Non-Renewable Energy (MJ/m²)	9.517	303,1	298,1	856,4	-498
Renewable Energy (MJ/m²)	1.015	7,508	27,92	60,44	9,424

Table 7.7 and Table 7.8 highlight the critical role of life cycle analysis in pinpointing opportunities for reducing environmental impacts and fostering sustainable building practices (Table 7.7 and Table 7.8).The environmental impacts of the 32-classroom school building are analyzed from two perspectives: total impacts and impacts per m². These evaluations provide insights into the overall burden and enable meaningful comparisons across buildings. The product stage dominates most categories, including Global Warming Potential and Primary Energy Use, due to resource-intensive material production. The construction stage adds impacts through transportation and assembly, while the End of Life stage contributes significantly to Global Warming and Acidification. Module D highlights the benefits of recycling and reuse, offsetting some impacts. Per m² evaluations emphasize efficiency and underscore opportunities to reduce material usage and optimize energy performance. Key metrics such as Acidification, Eutrophication, and Smog Formation reflect the need for cleaner production processes and better material choices. These findings show that focusing on material efficiency, renewable energy integration, and recovery strategies can reduce the ecological footprint of educational facilities. The 32-classroom school building illustrates the potential for sustainable practices throughout the building life cycle.

7.5.2 Results per Life Cycle Stage

The chart illustrates the environmental impacts of the 32-classroom school building across various life cycle stages: Product Stage (A1-A3), Transportation (A4), Maintenance and Replacement (B2-B5), End of Life (C2-C4), and Module D

(Recycling/Reuse). Key environmental impact categories include Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED). The contributions of each stage are highlighted to provide insights into the building's overall environmental performance (Figure 7.13).

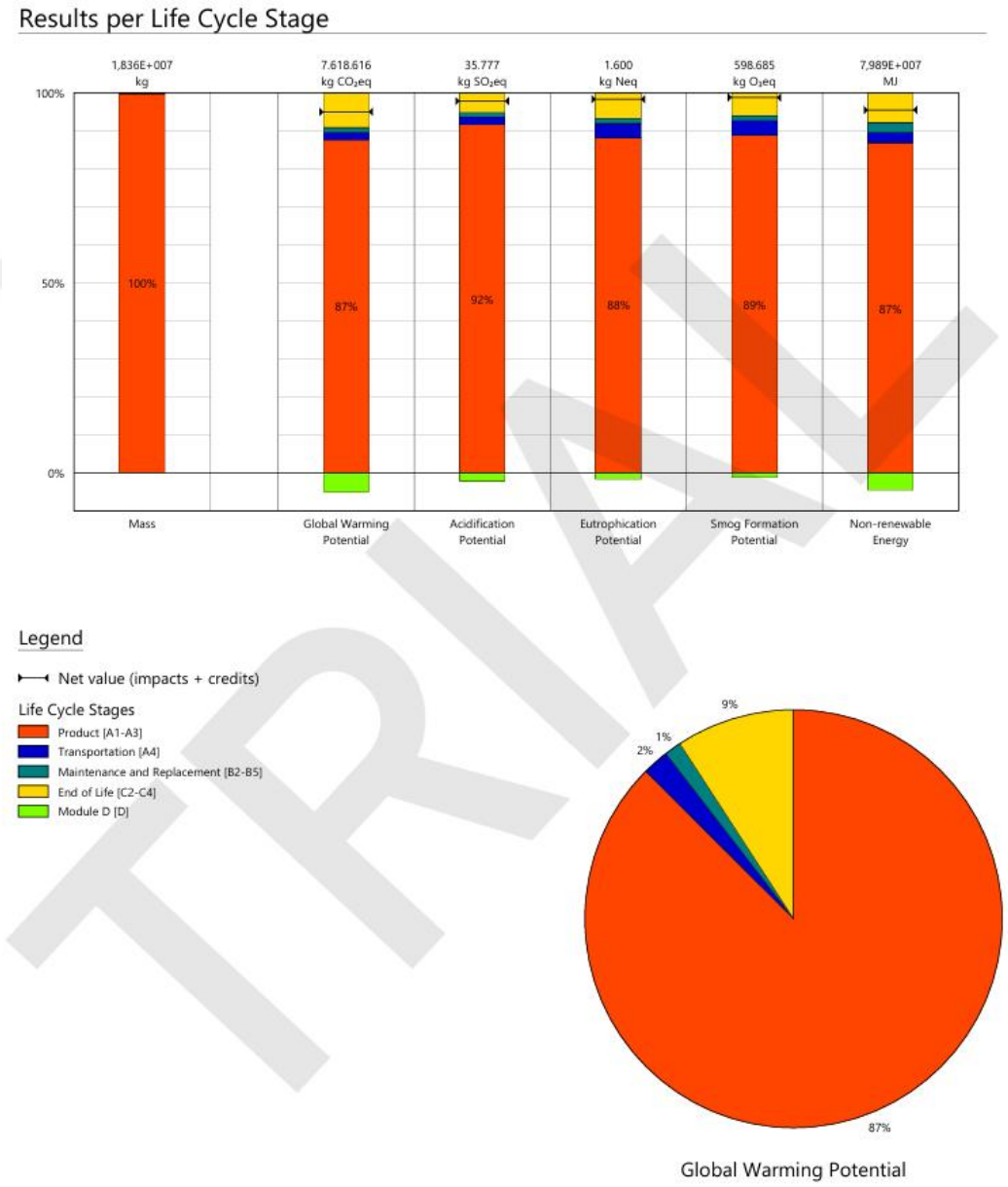


Figure 7.13 Results per life cycle stage analysis of 32-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

The chart illustrates the environmental impacts of the life cycle stages for the 32-classroom building (Figure 7.13). The Product Stage (A1–A3) contributes the highest share across all categories, accounting for 87% of the Global Warming Potential, 92% of the Acidification Potential, 88% of the Eutrophication Potential, 89% of the Smog Formation Potential, and 87% of Non-Renewable Energy Consumption. These results emphasize that material extraction, processing, and manufacturing are the primary drivers of environmental impacts during this stage. Enhancements in material efficiency, production processes, and energy sources could significantly reduce the overall environmental footprint. The Transportation Stage (A4) contributes approximately 2–3% of the total impacts across all categories, reflecting a relatively minor impact. However, optimizing transportation logistics and prioritizing local material sourcing could further reduce its effects. The Maintenance and Replacement Stage (B2–B5) has a negligible contribution of about 1–2%. Using durable and low-maintenance materials would further minimize these impacts over the building's life cycle.The End of Life Stage (C2–C4) accounts for 9% of the Global Warming Potential, making it the second-highest contributor after the Product Stage. Effective waste management strategies and recycling processes during this phase could significantly reduce the environmental burdens. Recycling (Module D) provides environmental credits, as indicated by the negative values across all categories. These credits help offset impacts from other life cycle stages by enabling material recovery and reuse, ultimately reducing the need for raw materials and energy in future production cycles. This analysis highlights the need to prioritize sustainability improvements during the Product Stage while maximizing the benefits of recycling to mitigate impacts across the entire life cycle of the building. Overall, this analysis highlights the importance of sustainable material selection, efficient logistics, and robust recycling practices in mitigating the environmental impacts of the 32-classroom school building. Implementing these strategies can significantly improve its life cycle environmental performance.

7.5.3 Results per Life Cycle Stage, Itemized by Division

The chart presents a detailed breakdown of the environmental impacts of the 32-classroom school building, categorized by divisions such as Concrete, Masonry,

Metals, Wood/Plastics/Composites, and other material types. The life cycle stages include the Product Stage (A1-A3), Transportation (A4), Maintenance and Replacement (B2-B5), End of Life (C2-C4), and Module D (Recycling/Reuse). Key environmental impact categories—such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED)—are itemized to highlight the contribution of each division (Figure 7.14).

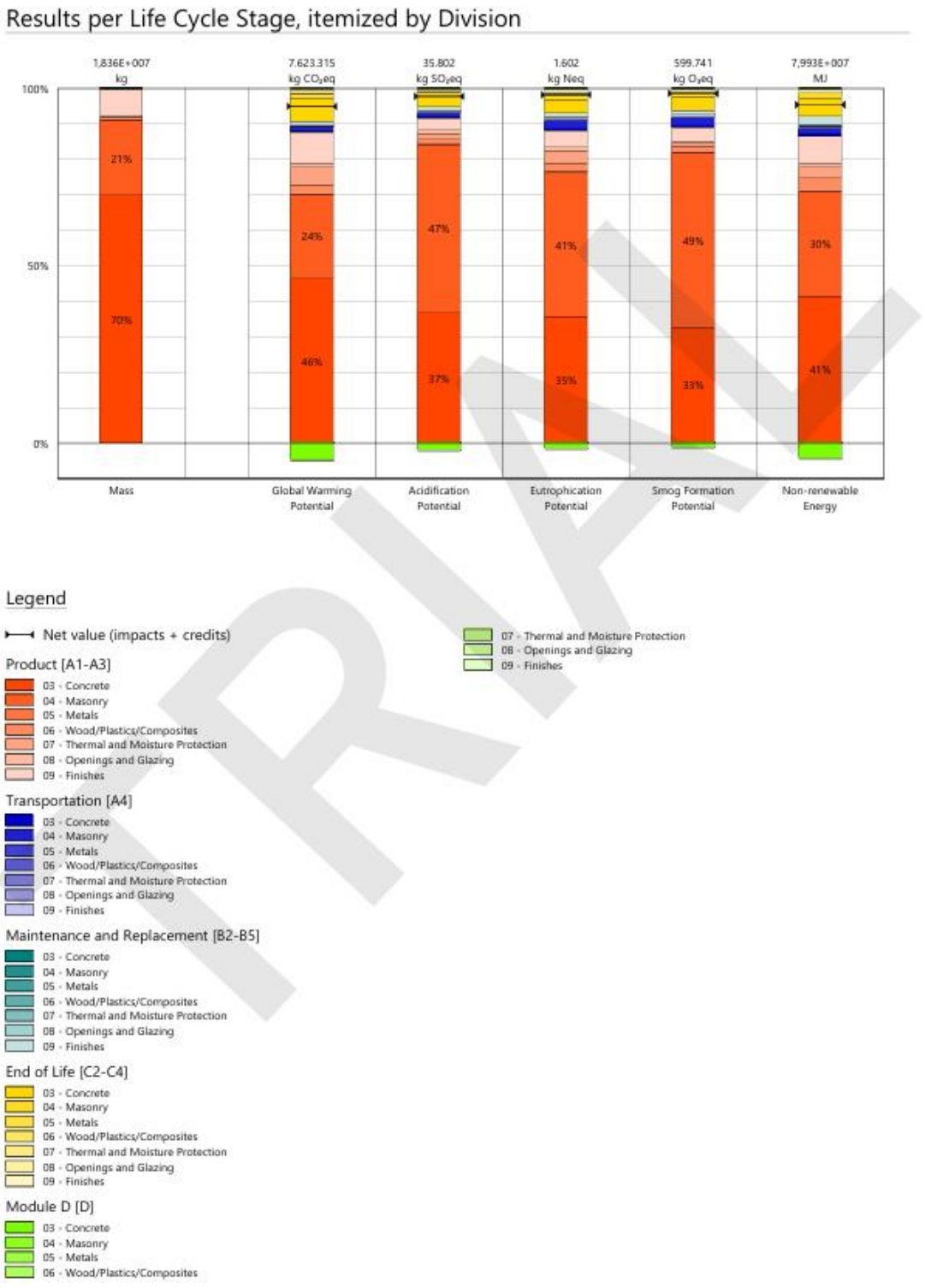


Figure 7.14 Results per life cycle stage, itemized by division analysis of 32-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

The chart illustrates the environmental impacts of the life cycle stages for the 32-classroom building, itemized by material divisions. The Product Stage (A1–A3) dominates across all impact categories, with concrete being the largest contributor. Concrete accounts for 70% of the total mass, 46% of the Global Warming Potential (GWP), 37% of the Acidification Potential (AP), and 41% of Non-Renewable Energy Demand (NRED). Its energy-intensive production highlights the need for optimized use or low-carbon alternatives to reduce environmental burdens. Masonry materials contribute significantly to Smog Formation Potential (SFP, 49%), Eutrophication Potential (EP, 41%), and Acidification Potential (47%), primarily due to their production and transportation processes.Other materials, such as Metals, Wood/Plastics/Composites and Thermal and Moisture Protection, provide smaller yet meaningful impacts in specific categories. The Transportation Stage (A4) reflects impacts from moving heavy materials, especially concrete and masonry. Local sourcing and efficient logistics could reduce these contributions. The Maintenance and Replacement Stage (B2–B5) sees significant impacts from openings, glazing, and finishes, which require periodic replacements and maintenance. Durable material choices could minimize life cycle impacts in this stage. The End of Life Stage (C2–C4) is primarily influenced by the disposal and recycling of materials like concrete and masonry. Proper waste management strategies and recycling practices are essential to reduce environmental burdens. Module D showcases the environmental credits from recycling, particularly for metals and wood/plastics, which offset impacts from other life cycle stages and reduce the demand for raw materials in future production cycles.This analysis highlights opportunities for material efficiency, life cycle optimization, and recycling to enhance the environmental performance of the 32-classroom building.

7.5.4 Results per Division

The chart illustrates the environmental impacts of the 32-classroom school building, categorized by material divisions, including Concrete, Masonry, Metals, and other components. Key impact categories analyzed are Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED) (Figure 7.15).

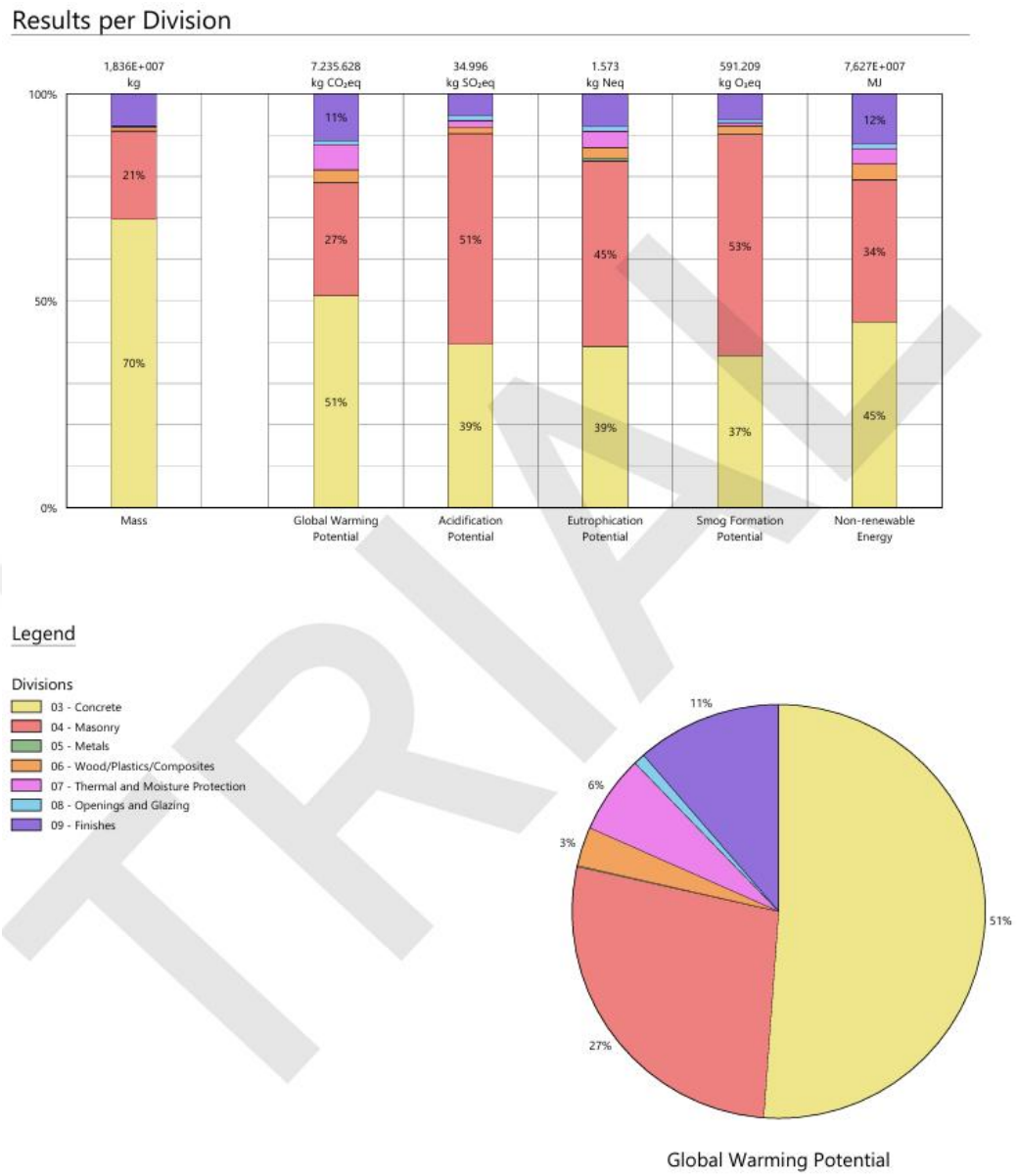


Figure 7.15 Results per division analysis of 32-classroom school building.
Environmental impact data derived from Tally software's analysis conducted in 2025

The chart provides an analysis of the environmental impacts for the 32-classroom building, categorized by material divisions. The Concrete category dominates most impact categories, contributing 70% of the total mass and 51% of the Global Warming Potential (GWP). These results highlight the significant environmental impact of concrete production, emphasizing the need for optimizing its use and adopting sustainable alternatives. Masonry materials are the second-largest contributor, accounting for 21% of the total mass and 27% of GWP. These impacts

are driven by the energy-intensive manufacturing and transportation processes associated with masonry products. Other materials, such as Metals, Wood/Plastics/Composites, Thermal and Moisture Protection, Openings and Glazing, and Finishes, make smaller but notable contributions. The pie chart for Global Warming Potential illustrates that concrete and masonry together dominate emissions, underscoring the importance of prioritizing material efficiency and improving production methods. These findings emphasize the critical role of sustainable material selection, efficient construction practices, and recycling strategies in reducing the environmental impacts of the 32-classroom school building. These results underscore the need for sustainable material selection, energy-efficient production processes, and robust recycling systems to minimize the environmental footprint of the 32-classroom school building.

7.5.5 Results per Revit Category

The chart presents the environmental impacts of the 32-classroom school building distributed across different Revit categories, including Ceilings, Doors, Floors, Roofs, Stairs and Railings, Structure, Walls, and Windows. Key environmental impact categories such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-Renewable Energy Demand (NRED) are analyzed to highlight the contributions of each category (Figure 7.16).

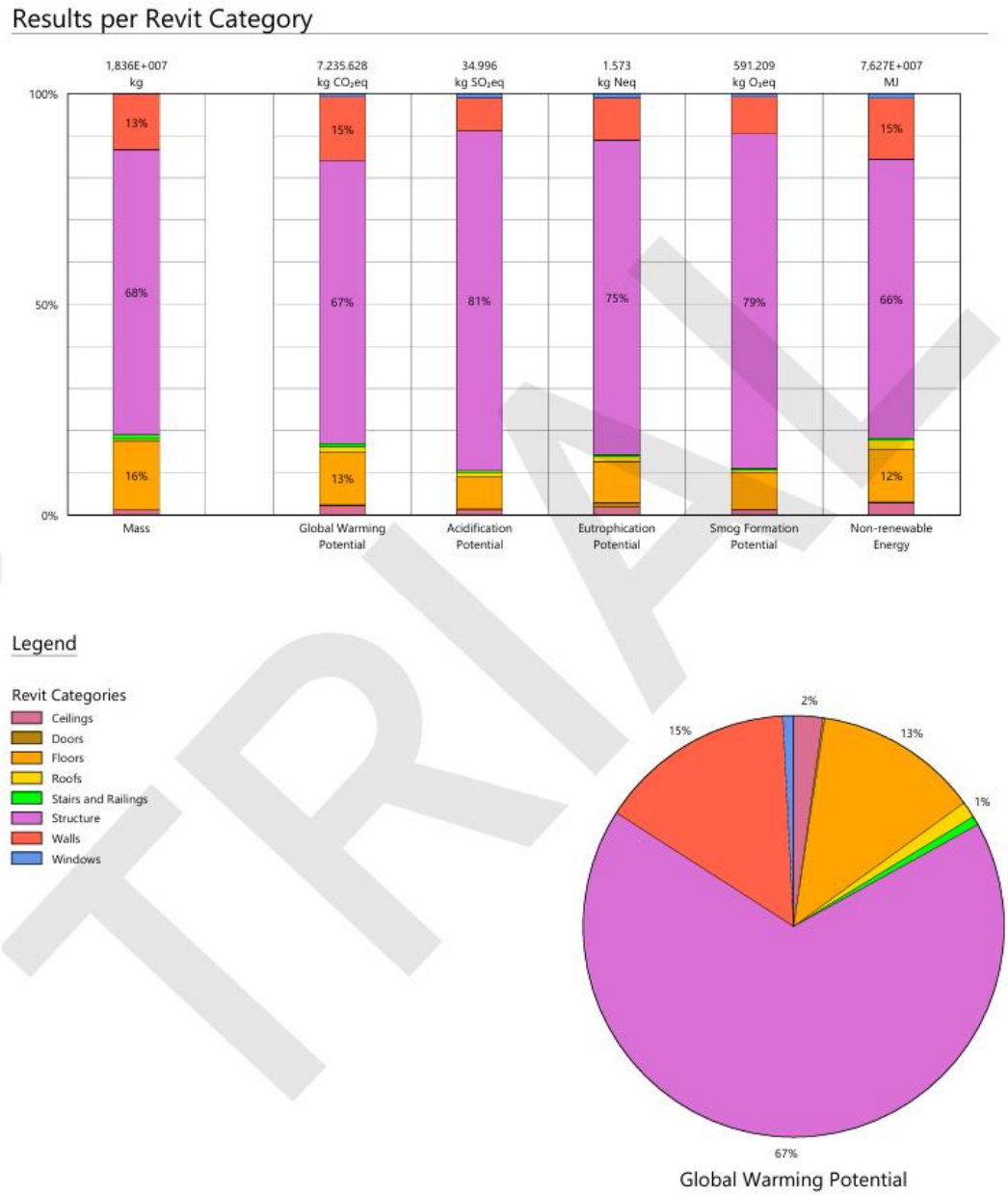


Figure 7.16 Results per revit category analysis of 32-classroom school building. Environmental impact data derived from Tally software's analysis conducted in 2025

The chart provides an analysis of the environmental impacts for the 32-classroom building, categorized by Revit components. The Structure category dominates most impact categories, accounting for 68% of the total mass and 67% of the Global Warming Potential (GWP). This dominance reflects the extensive use of structural materials and their significant environmental burden. Walls are the another

contributor, comprising 13% of the total mass and 15% of GWP, highlighting their environmental impact due to their material composition and role in thermal performance.Floors contributing 16% of the total mass, and 13% of GWP. These results emphasize the importance of these components in the building's environmental profile. The pie chart for GWP further highlights the dominance of structural elements, walls, floors. These findings underscore the importance of optimizing material usage, improving production methods, and adopting sustainable alternatives to reduce the environmental impacts of the 32-classroom building.

CHAPTER 8

DISCUSSION AND CONCLUSION

In this section, the findings from the analysis are synthesized and critically evaluated to provide a comprehensive understanding of the environmental impacts associated with the school building typologies. The discussion highlights key insights, identifies patterns, and interprets the results in the context of sustainability and life cycle assessment principles. Finally, the conclusion summarizes the main outcomes and offers recommendations for future studies and practical applications.

8.1 General Review of the Research

This thesis aims to comprehensively analyze the environmental impacts of four different school typologies (8, 12, 24, and 32 classrooms) determined by the Ministry of National Education, using the Life Cycle Assessment (LCA) method. The research was conducted to deepen the understanding of the environmental performance of buildings and provide a scientific contribution to sustainable design processes. The LCA method examines the environmental impacts of buildings throughout all stages of their life cycle, from raw material extraction to recycling processes. In this context, the study evaluated the Product Stage (A1–A3), Transportation Stage (A4), Use and Maintenance Stage (B2–B5), End-of-Life Stage (C2–C4), and Recycling/Reuse (Module D) in detail. The methodology was designed in accordance with international standards such as ISO 14040, ISO 14044, EN 15804, and EN 15978. All analyses were performed using the Building Information Modeling (BIM)-based software Tally. Tally, integrated with Autodesk Revit, served as a key tool for assessing the material properties, quantities, and environmental impacts of building components. Using the GaBi LCI 2018 database, the software provided accurate and representative life cycle inventory data for construction materials, enhancing the reliability of the results. Missing data were supplemented with suitable proxy datasets, evaluated under geographic, technological, and temporal alignment criteria. The research focused particularly on key environmental impact categories such as

Global Warming Potential (GWP), Primary Energy Demand (PED), and Acidification Potential (AP). These categories were selected to assess the environmental impacts of buildings on both a global scale (e.g., carbon emissions) and a regional scale (e.g., acid rain and energy consumption). The analyses were conducted to quantitatively compare the environmental performance of each school typology and determine which typology had the lowest environmental impact.This study primarily assesses the environmental impacts of construction materials, and operational energy consumption was not included in the analysis. As a result, the energy-related impacts appear lower than in studies that incorporate heating, cooling, and lighting emissions. The methodological scope of this research was deliberately set to focus on the material-based environmental burdens of school building typologies, rather than the operational phase, to enable a detailed comparison of material impacts. The findings revealed that the Product Stage is the largest source of environmental impacts. During this stage, energy consumption and carbon emissions from the extraction, production, and processing of building materials accounted for 80-90% of the total environmental impacts. This highlights the decisive role of materials such as concrete, masonry, and other energy-intensive materials in shaping environmental outcomes. In larger typologies (e.g., 24- and 32-classroom schools), the impacts of the Product Stage became more pronounced due to the increased quantity of materials used. The research demonstrated that recycling and reuse processes (Module D) have significant potential to reduce environmental impacts. Recycling processes, especially in large-scale projects, provided considerable environmental benefits by significantly reducing carbon emissions and energy consumption. For instance, in the 32-classroom typology, the recycling stage offered an environmental credit by reducing total carbon emissions by approximately 382 tons of CO_2eq. Similarly, the effects of recycling processes were observed in other typologies, though the magnitude of these benefits varied depending on the project scale and the recyclability of the materials used. Although the Transportation Stage (A4) plays a relatively limited role in total environmental impacts, it can be further optimized by using local supply chains. Prioritizing local materials can shorten transportation distances, thereby reducing carbon emissions and energy consumption. The Use and Maintenance Stage (B2–B5) encompasses the impacts from renovation

and maintenance activities throughout the building's lifecycle. These impacts can be minimized by using more durable and long-lasting materials. As school size increases, total environmental impacts also rise, with the highest values observed in the 32-classroom school. However, when examining environmental impacts per square meter, the 8-classroom school is found to have the lowest impact, making it a more efficient option. A significant portion of environmental impacts originates from material production and construction processes, with concrete use contributing the most across all categories. Transportation-related impacts increase with school size, but utilizing local resources can help mitigate these effects. Larger schools have higher energy demands during the use phase, leading to greater environmental impacts; however, energy-efficient technologies play a vital role in reducing these effects. At the end-of-life and recycling stages, larger schools generate more waste, yet recycling processes significantly reduce overall environmental impacts. Concrete emerges as the material with the highest share of environmental impacts across all categories, highlighting the critical importance of using sustainable alternatives to reduce its footprint. Masonry materials, such as bricks, have notable impacts, particularly in categories like smog formation and eutrophication potential. Thermal insulation materials, despite having high production impacts, provide long-term benefits by reducing energy consumption during the operational phase. Lastly, recycling processes, especially for concrete and metals, offer substantial opportunities to mitigate environmental impacts. This analysis demonstrates that optimizing material selection, enhancing energy efficiency, and improving recycling strategies can significantly reduce environmental impacts across all school typologies.

In conclusion, this thesis comprehensively examines the environmental impacts of school buildings, identifying which stages contribute the most to environmental burdens and which strategies can mitigate these impacts. Particularly, the decisive role of material selection during the product stage and the effects of recycling processes emphasize the importance of sustainable design decisions. The research clearly highlights the key considerations that should be addressed during both the design and construction phases to minimize environmental impacts.

8.2 Key Results and Comparative Analysis

This section will present the environmental impacts of the 8, 12, 24, and 32 classroom school typologies based on a Life Cycle Assessment (LCA) approach. The analysis will compare the environmental impact categories for each school typology and explore how these impacts vary according to the size of the schools.

The environmental impact categories examined in this study include Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Smog Formation Potential (SFP), and Non-renewable Energy Demand. These categories assess the environmental impacts of school typologies across each life cycle stage, from production to post-use, and evaluate the sustainability potential of school designs. This section analyzes the environmental impacts of the school typologies in a comparative manner. The study investigates the environmental impacts of each school type across the product phase, transportation, usage, end-of-life, and recycling stages, revealing the differences according to school size. The results serve as a guide for developing strategies to reduce environmental impact. The main findings present data on the magnitude of the environmental impacts for each school typology and highlight the stages where these impacts are most concentrated. Based on these findings, the overall effect of school size on environmental impact is discussed. Comparative analyses clarify how different school typologies perform and identify which design parameters are more sustainable. Ultimately, this study provides valuable insights into how the environmental impacts of school designs can be optimized, offering recommendations for more sustainable school projects.

8.2.1 Total and Per m² Evaluation

This section presents the comparative environmental impacts of the 8, 12, 24, and 32-classroom school typologies. The analysis focuses on two aspects: the total environmental impacts and the environmental impacts per square meter (m²). The data provided in Table 8.1 and Table 8.2 helps evaluate the absolute environmental burden of each school type and offers insights into the differences between the

school sizes. This comparison is essential to understand how the size of the school influences its environmental footprint across different categories.

Table 8.1 Total environmental impacts analysis of school typologies. Environmental impact data derived from Tally software's analysis conducted in 2025

Impact Category	8-Classroom	12-Classroom	24-Classroom	32-Classroom
Global Warming (kg CO_2eq/m²)	1,660,231	2,349,073	3,900,544	6,663,878
Acidification (kg SO_2eq/m²)	6,77	11,999	19,959	32,777
Eutrophication (kg Neq/m²)	306.9	508.4	808.8	1,412
Smog Formation (kg O_3eq/m²)	105,279	191,14	301,622	531,975
Non-Renewable Energy (MJ/m²)	16,850,000	26,940,730	43,410,000	76,648,000

Table 8.2 Per area environmental impacts analysis of school typologies. Environmental impact data derived from Tally software's analysis conducted in 2025

Impact Category	8-Classroom	12-Classroom	24-Classroom	32-Classroom
Global Warming (kg CO_2eq/m²)	674.6	827.4	970.3	915.4
Acidification (kg SO_2eq/m²)	2.751	4.226	4.965	4.502
Eutrophication (kg Neq/m²)	0.1247	0.1791	0.2012	0.1940
Smog Formation (kg O_3eq/m²)	42.78	67.33	75.03	73.07
Non-Renewable Energy (MJ/m²)	7,502	9,491	10,799	10,528

As seen in Table 8.1 and Table 8.2, the total environmental impacts generally increase with the size of the school, reflecting the greater material usage, energy consumption, and waste generation associated with larger buildings(Table 8.1 and

Table 8.2). However, Table 8.2, which analyzes impacts per m², helps to better assess the relative sustainability of each school type by adjusting for size. Notably, larger schools, such as the 32-classroom school, do not necessarily have the highest impacts per unit area, making the 8-classroom school the most environmentally efficient in terms of per square meter impact. In both tables, the largest environmental impacts are found in the product phase (A1-A3), which includes material extraction and construction processes. Other significant impacts are observed in transportation (A4) and usage (B2-B5), particularly for the larger school types. Conversely, the recycling phase (D) offers a reduction in overall environmental impact, as it helps to offset some of the negative effects of the other stages.The results presented in Table 8.1 and Table 8.2 highlight the importance of considering both total environmental impacts and impacts per square meter when assessing the sustainability of different school typologies. The findings underscore the need to optimize material selection, energy efficiency, and waste management strategies to reduce environmental impacts across all stages of the life cycle.

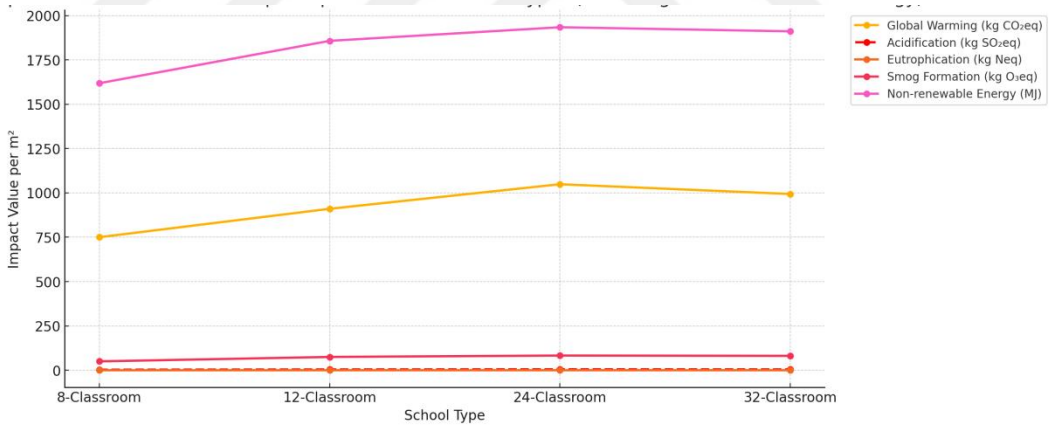


Figure 8.1 Environmental impacts per square meter for different school types. Environmental impact data derived from Tally software's analysis conducted in 2025

The graph above shows environmental impacts per square meter across different school typologies (Figure 8.1). The primary environmental indicators are shown with distinct colors, and a dual-axis system is used to differentiate the impact scales for better readability. This visualization allows for a clearer comparison of how school size affects sustainability metrics.

8.2.2 Results per Life Cycle Stage

This analysis observes how environmental impacts are distributed across various life cycle stages of the school building typologies. Each life cycle stage, from Product Stage (A1-A3) to Module D, contributes differently to the overall environmental footprint of the building. The results from this analysis apply to all four school typologies (8, 12, 24, and 32 classrooms), though the intensity of impacts may vary depending on the school size.

a. Product Stage (A1-A3): The Most Significant Impact

The Product Stage (A1-A3), which includes the extraction of raw materials, manufacturing, and transportation of materials, represents the largest share of environmental impacts across all school typologies. The extraction of raw materials such as metals, timber, and stone requires substantial energy input and results in high emissions, especially CO_2, sulfur oxides (SO_2), and other pollutants. Larger-scale schools require more materials, exacerbating these environmental impacts. Manufacturing construction materials like concrete, masonry is energy-intensive, and this process contributes significantly to environmental impacts. Larger schools demand more materials, which increases emissions and energy consumption.

b. Construction Stage (A4): Increasing Impact with Scale

The Construction Stage (A4) involves the delivery of materials to the construction site and the transportation of other necessary resources during construction. Larger schools, which require more materials, naturally result in higher transportation impacts.The amount of material required for larger-scale schools (24 and 32 classrooms) increases the need for more transportation, leading to greater fuel consumption and higher emissions. The environmental impact from transportation is significant across all school types but becomes more substantial in larger schools due to the increased material demand and more frequent transportation activities. The environmental impact increases with size in this phase, as larger schools require more transportation resources, leading to greater fuel consumption and higher environmental costs.

c. Use Stage (B2-B5): Impact from Energy Consumption

The Use Stage (B2-B5) represents the environmental impacts related to the operational energy demand of buildings throughout their life cycle, including heating, cooling, lighting, and other operational needs. Larger schools generally consume more energy due to their increased size and occupancy. While advancements in energy-efficient technologies can reduce some of these impacts, operational energy remains a significant contributor to a building's overall environmental footprint. However, this study is a material-based Life Cycle Assessment (LCA) and does not account for operational energy consumption, including heating, cooling, lighting, or any other use-phase energy demand. The analysis is limited to the embodied environmental impacts of construction materials, focusing solely on the environmental burdens associated with material production, transportation, and construction.

d. End of Life Stage (C2-C4): Waste Generation

The End of Life Stage (C2-C4) involves the demolition of the building and disposal or recycling of its materials. This phase contributes significantly to the environmental footprint, though Module D can help reduce some of these impacts. Larger schools generate more waste, which has a higher environmental cost if not handled efficiently. The larger the school, the more materials need to be deconstructed, generating more emissions from the demolition process.

e. Module D

Module D helps to reduce overall environmental impact by recovering materials and minimizing waste. The more materials that can be recovered and reused, the lower the demand for raw materials, and the lower the environmental impact in subsequent phases. This phase offers substantial potential for environmental mitigation, especially for larger-scale schools, as they generate more materials to recover. All school typologies can benefit from Module D, but larger-scale schools generate more materials to recover, which increases the environmental benefits of the process. Module D plays a vital role in reducing environmental impacts at the end of life. By

recovering materials and reintroducing them into the production cycle, this stage mitigates some of the negative environmental impacts from previous life cycle stages. In all school typologies, Module D offers the opportunity to reduce environmental impacts by recovering valuable materials and ensuring that they are reused, rather than disposed of.

In conclusion, the distribution of environmental impacts across the life cycle stages of the school buildings reveals how each phase contributes to the overall environmental footprint. While the Product Stage (A1-A3) dominates in terms of total impact, the Construction Stage (A4), Use Stage (B2-B5), and End of Life Stage (C2-C4) also play significant roles, particularly for larger-scale school buildings. Module D provides a significant opportunity to reduce overall environmental impact by recovering materials and minimizing waste. The findings highlight that, although the impact of each stage may vary by school size, larger-scale schools tend to have higher environmental impacts across all stages. However, by optimizing material selection, energy efficiency, and Module D strategies, environmental impacts can be significantly reduced for all school types.

8.2.3 Results per Life Cycle Stage, Itemized by Division

a. Product Stage (A1-A3)

This stage is consistently the largest contributor to environmental impacts across all categories, primarily driven by material production processes, especially concrete. Concrete accounts for the largest share of emissions, particularly for GWP and Non-Renewable Energy Demand (NRED), emphasizing the need to focus on reducing the impacts of raw material extraction and production. Concrete is the dominant material, contributing 43%-71% of GWP, and a similar proportion for other categories (e.g., Acidification Potential, Smog Formation). This suggests concrete's environmental burden is significant, warranting its optimization or replacement with more sustainable alternatives.

b. Construction Stage (A4)

The Construction Stage (A4), primarily reflecting the environmental impact of transporting materials to the site, contributes relatively less—around 2%-3% of GWP and other impact categories. However, optimizing transportation logistics and sourcing materials locally can significantly reduce this contribution.

c. Use Stage (B2-B5)

The Use Stage (B2-B5) shows that larger school buildings have a higher environmental impact. Larger buildings have a greater operational demand due to more students and staff, leading to higher Primary Energy and Non-Renewable Energy consumption. Improvements in energy efficiency through technologies like high-performance insulation and low-energy systems can mitigate some of these impacts.

d. End of Life Stage (C2-C4)

The End of Life Stage (C2-C4) highlights that larger buildings generate more waste, with concrete and masonry being the most impactful materials during demolition. Effective waste management and recycling processes can significantly reduce the environmental footprint at this stage. Module D (Recycling) offers a substantial opportunity to reduce the environmental impact, particularly through concrete recycling and metal recovery.

e. Module D

Module D, reflecting the impact of recycling and reuse, shows negative environmental impacts, helping to offset the impacts from other stages. This is particularly beneficial for materials like concrete and masonry, where material recovery and reuse in future production cycles reduce the need for virgin materials and energy.

Concrete contributes the highest environmental impact across all categories, accounting for 43%-71% of GWP and significant shares in other categories like Acidification and Non-Renewable Energy Demand. Masonry materials (bricks, etc.) are the second largest contributors, significantly impacting Smog Formation (SFP),

Acidification Potential (AP), and Eutrophication Potential (EP). Metals, Wood/Plastics/Composites, and other materials contribute more moderately but still have specific impacts in categories like Smog Formation (SFP), Non-Renewable Energy Demand (NRED), and Eutrophication.

The Product Stage (A1-A3) remains the dominant source of environmental impact, particularly for GWP and NRED. Optimizing concrete production or using alternative, more sustainable materials will be essential in reducing overall environmental burdens.

Transportation (A4) and End-of-Life (C2-C4) contribute to environmental impacts but offer opportunities for improvement, such as local sourcing and enhanced recycling processes. Module D (Recycling) offers critical benefits, reducing the need for raw materials and offsetting emissions, especially for metals and concrete. By focusing on material selection, optimizing energy efficiency, and improving recycling practices, significant reductions in environmental impact can be achieved for all school types.

8.2.4 Results per Division

a) Concrete (Division 03)

Contribution: Concrete is the most significant material in all categories, especially in Global Warming Potential (GWP), Acidification Potential (AP), and Non-Renewable Energy Demand (NRED). Impact: Concrete accounts for 43%-71% of the Global Warming Potential (GWP), 35%-51% of Acidification Potential (AP), and 37%-47% of Non-Renewable Energy Demand (NRED). This underscores concrete's role as the largest environmental burden in all building types, particularly in terms of material mass and energy demand.

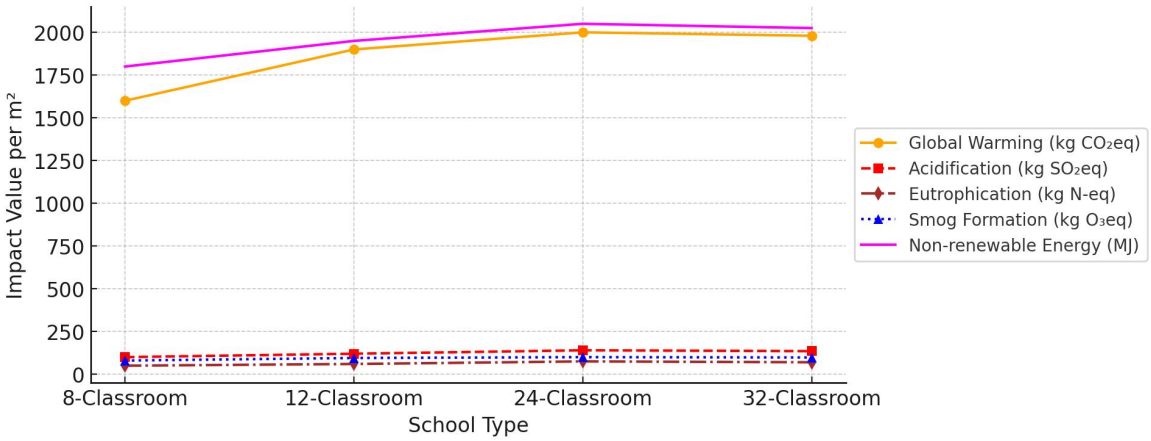


Figure 8.2 Environmental impact of concrete per m² across school types
Environmental impact data derived from Tally software's analysis conducted in 2025

Figure 8.2 presents the environmental impact of concrete per square meter across different school typologies. The global warming potential (kg CO_2eq) and non-renewable energy consumption (MJ) show an increasing trend with larger school sizes. Acidification, eutrophication, and smog formation potential also exhibit slight variations across school types (Figure 8.2).

b) Masonry (Division 04)

Contribution: Masonry materials (such as bricks) contribute notably to Smog Formation Potential (SFP) and Eutrophication Potential (EP), especially during production and transportation. Impact: Masonry materials contribute 17%-29% of the GWP, 31%-52% of Acidification Potential (AP), and 22%-46% of Eutrophication Potential (EP). These impacts highlight the energy-intensive manufacturing and transportation processes associated with masonry materials.

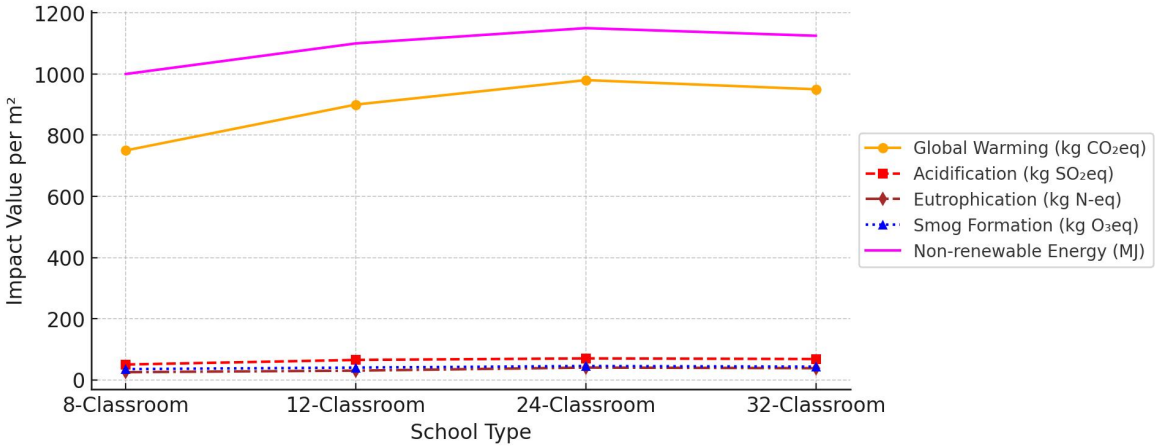


Figure 8.3 Environmental impact of masonry per m² across school types Environmental impact data derived from Tally software's analysis conducted in 2025

Figure 8.3 presents the environmental impact of masonry per square meter across different school typologies. The global warming potential (kg CO_2eq) and non-renewable energy consumption (MJ) increase with school size. Acidification, eutrophication, and smog formation show moderate variations among different school types (Figure 8.3).

c) Finishes (Division 09):

Contribution: Finishes such as paints and coatings contribute significantly to Smog Formation Potential (SFP) and Eutrophication Potential (EP), primarily due to the volatile organic compounds (VOCs) released during their production and application.

Impact: Finishes materials contribute 10%-20% of SFP and EP, and can be minimized with the use of low-VOC paints and eco-friendly finishes.

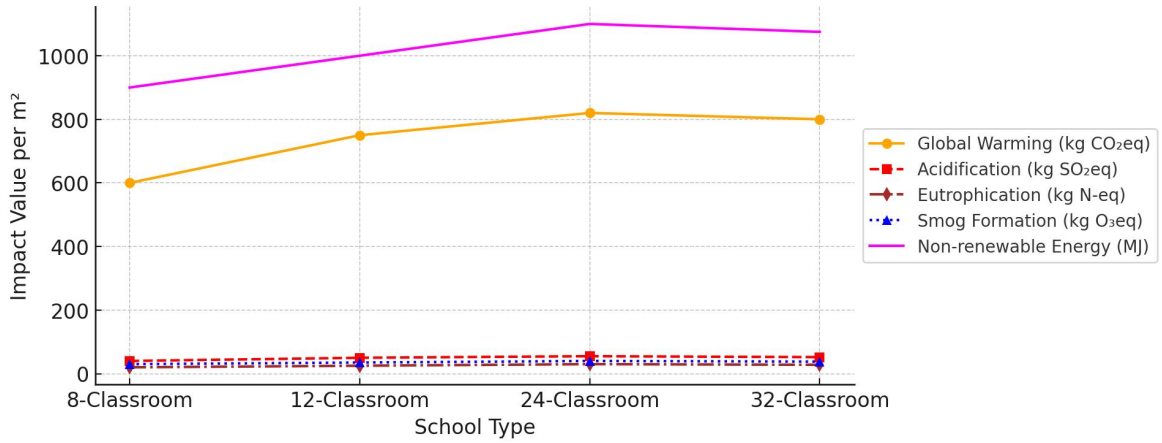


Figure 8.4 Environmental impact of finishes per m² across school types
Environmental impact data derived from Tally software's analysis conducted in 2025

Figure 8.4 presents the environmental impact of finishes per square meter across different school typologies. Global warming potential (kg CO_2eq) and non-renewable energy (MJ) show gradual increases, while acidification, eutrophication, and smog formation display moderate changes across different school types (Figure 8.4).

d) Thermal and Moisture Protection (Division 07):

Contribution: Thermal insulation materials, such as mineral wool and rigid foam boards, contribute to Non-Renewable Energy Demand (NRED) and Global Warming Potential (GWP). Despite the high impact of their production, these materials improve energy efficiency by reducing heating and cooling needs in the building. Impact: Thermal protection contributes significantly to energy demand, but the overall life-cycle benefit of reducing operational energy consumption outweighs the initial environmental impact.

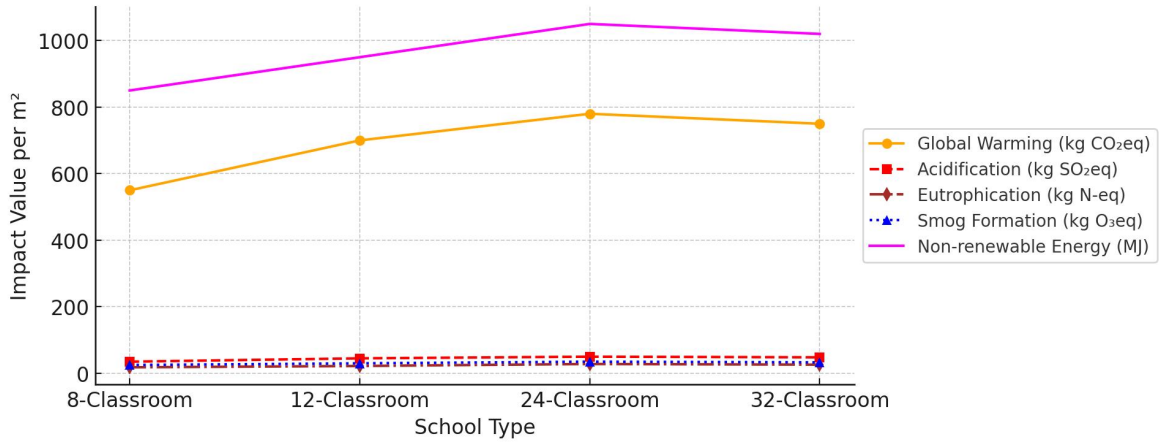


Figure 8.5 Environmental impact of thermal and moisture protection materials per m² across school types Environmental impact data derived from Tally software's analysis conducted in 2025

Figure 8.5 presents the environmental impact of thermal and moisture protection materials per square meter across different school typologies. Global warming potential (kg CO_2eq) and non-renewable energy (MJ) gradually increase, while acidification, eutrophication, and smog formation remain relatively stable (Figure 8.5).

e) Wood/Plastics/Composites (Division 06):

Contribution: Wood, plastics, and composites have a lower environmental burden but still contribute to Non-Renewable Energy Demand (NRED) and Smog Formation (SFP).Impact: These materials account for 1%-7% of GWP and Non-Renewable Energy Demand (NRED), though they help reduce the overall environmental footprint compared to materials like concrete.

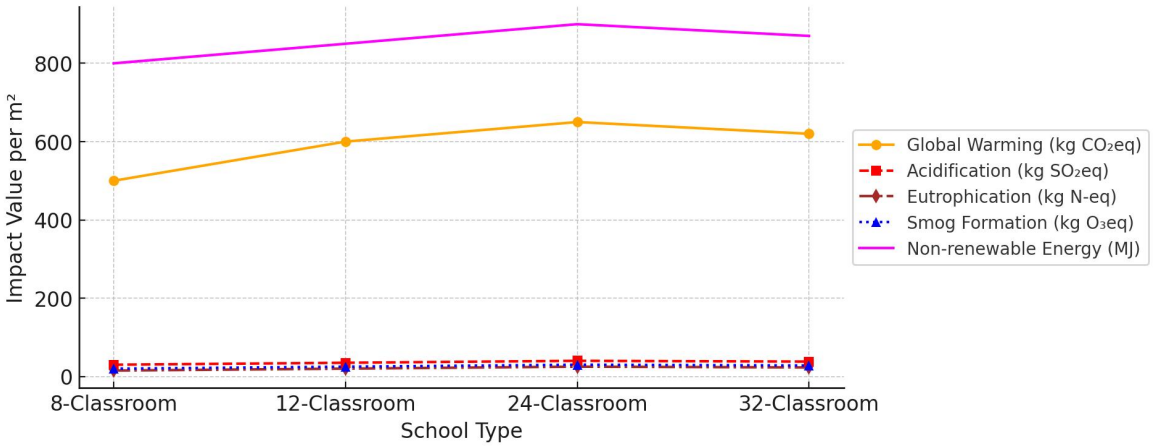


Figure 8.6 Environmental impact of wood/plastics/composites per m² across school types Environmental impact data derived from Tally software's analysis conducted in 2025

Figure 8.6 presents the environmental impact of wood/plastics/composites per square meter across different school typologies. Global warming potential (kg CO_2eq) and non-renewable energy (MJ) exhibit slight variations, while other impact categories such as acidification, eutrophication, and smog formation remain relatively stable (Figure 8.6).

f) Openings and Glazing (Division 08):

Contribution: Windows and doors (glazing) contribute to Global Warming Potential (GWP) and Non-Renewable Energy Demand (NRED) during their production. Impact: Energy-efficient glazing can mitigate the impacts during operation by improving thermal insulation and reducing energy consumption in the building.

Concrete remains the dominant material across all impact categories, with its energy-intensive production processes driving high GWP, AP, and NRED. Masonry and Metals are the second-largest contributors, affecting SFP, EP, and AP. Wood/Plastics/Composites and Thermal Insulation contribute smaller but important environmental impacts, mainly in the categories of NRED and SFP. Openings and Glazing (windows and doors) can significantly improve operational energy efficiency, helping to reduce long-term environmental impacts. Finishes should focus

on sustainable alternatives to reduce their environmental burden, especially in the form of low-VOC paints.

g) Metals (Division 05):

Contribution: Metals (such as steel) contribute significantly to Smog Formation (SFP), Non-Renewable Energy Demand (NRED), and Eutrophication Potential (EP).

Impact: Metals contribute 1%-10% of the GWP and Non-Renewable Energy Demand (NRED), emphasizing the environmental burden associated with their energy-intensive production.

8.2.5 Results per Revit Category

a. Ceilings

Impact: Ceilings are typically made of gypsum board, acoustic tiles, or other lightweight materials. The environmental impact comes from the manufacturing processes of these materials, particularly gypsum and mineral-based insulation. Contribution: The impact is primarily in the form of Global Warming Potential (GWP) and Non-Renewable Energy Demand (NRED) due to the energy required to produce gypsum and mineral wool. Mitigation: Using recycled gypsum or eco-friendly acoustic tiles and incorporating insulation to improve energy efficiency can reduce the environmental footprint of ceiling systems.

b. Doors

Impact: Doors, especially wood and metal, have significant environmental impacts due to their manufacturing processes, contributing to NRED and SFP. Mitigation: Opt for sustainable wood or recycled metals to reduce environmental impacts.

c. Floors

Impact: Floors made of concrete, ceramic tiles, and wood contribute to GWP, NRED, and AP. Mitigation: Use recycled tiles, wood, or bamboo flooring to reduce the environmental impact.

d. Roofs

Impact: Roofs made from bitumen, metal, and concrete contribute to GWP, NRED, and SFP. Mitigation: Solar roofs and green roofs can significantly reduce the environmental footprint.

e. Stairs and Railings

Impact: Stairs and railings made from steel or wood contribute to NRED and SFP. Mitigation: Use recycled steel and sustainable wood for stairs and railings to minimize the environmental impact.

f. Structure

Impact: The structure, composed of steel, concrete, and other materials, is a major contributor to GWP and NRED due to its energy-intensive production.Mitigation: Use recycled steel and lightweight concrete to reduce NRED and GWP.

g. Walls

Impact: Walls made from concrete, brick, and steel contribute to GWP, AP, and NRED. Mitigation: Use insulated wall systems and sustainable materials such as wood and recycled bricks to reduce environmental impacts.

h. Windows

Impact: Windows made from glass and metal framing contribute to GWP and NRED during production. Mitigation: Implement high-performance windows with low-emissivity glass and sustainable framing materials to reduce environmental impacts.

8.3 Future Studies

Future studies should focus on several areas to further enhance sustainable construction practices and environmental impact assessments. The following research areas can contribute to developing strategies that reduce environmental impacts in the construction sector. The concept of circular economy should be

explored more deeply within the construction industry. Studies in this area can investigate the potential for building reuse (adaptive reuse) and recycling, helping to reduce environmental impacts. Furthermore, research can focus on improving waste management and recycling processes during the demolition phase. A comparative analysis of sustainable construction techniques across different regional conditions (such as local material availability, climatic factors) should be conducted. These studies can enable the adaptation of sustainability strategies to local needs, offering more effective solutions. There is a clear need for the development of more advanced Life Cycle Assessment (LCA) methodologies. More accurate methods are required to assess environmental impacts, including energy consumption, carbon emissions, and water usage. The integration of Building Information Modeling (BIM) tools can help track and simulate sustainability performance during construction processes. Research into the integration of smart building technologies and energy management systems to enhance the energy efficiency and overall sustainability of buildings should be expanded. The impact of innovative solutions like smart sensors and energy-saving systems on sustainable building design should be investigated in more detail. Further research should be conducted on the embodied carbon of construction materials. Studies examining the carbon footprint of materials can help identify which materials are most suitable for reducing carbon emissions. This research can also focus on innovative material technologies and alternative green materials.The impact of climate change on the life cycle of buildings should be studied. This research could explore the adaptation potential of materials used in construction to climate change and examine factors like resilience to extreme weather conditions, supporting the design of more sustainable and durable buildings.Research into the economic feasibility of sustainable construction practices should be further developed. These studies can assess the cost-effectiveness of sustainable materials and technologies and develop strategies for broader adoption of these practices within the construction sector. Finally, there should be more focus on stakeholder engagement and the development of policies related to sustainable construction. Involving local governments, investors, and other stakeholders more actively can improve the societal acceptance of sustainable construction practices.

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