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A BIM–LCA Integration Framework for Early-Stage Environmental Assessment in Tunnel Infrastructure

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Abstract

The growing underscore on sustainability in infrastructure development has highlighted the need for accessible and practical tools to assess environmental impacts. This thesis presents a BIM–LCA integration framework, specifically tailored for tunnel infrastructure projects, aiming to support early-stage environmental decision-making through material-based impact evaluation.

The study combines Building Information Modeling (BIM) with Life Cycle Assessment (LCA) to quantify environmental indicators , particularly Global Warming Potential (GWP)by extracting material data from a tunnel model in Revit , matching it with environmental profiles exported from OpenLCA, and sending back the results into the BIM environment. A semi-automated workflow was developed using Dynamo and Excel to manage material quantities, match them with LCA indicators, and visualize the results within the model through shared parameters and color-coded filters.

A case study of a tunnel segment demonstrates the feasibility of this approach. While not focused on detailed environmental optimization, the workflow successfully enables the identification of material contributions to embodied carbon, offering designers immediate visuale feedback to inform sustainability decisions. challenges such as manual material matching and interoperability limitations are also documented , along with practical strategies to address them.

This research contributes to sustainable infrastructure practices by delivering a replicable, transparent methodology using widely accessible tools. Aligned with ISO 14040 and 14044 principles, the framework empowers designers, engineers, and students to embed environmental thinking into digital workflows, even in early design stages and without reliance on proprietary software.

Acknowledgments

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1.Introduction

The integration of Building Information Modeling (BIM) and Life Cycle Assessment (LCA) offers a transformative approach to sustainable building design and construction. BIM serves as a digital framework for managing material information, quantities, and project data, while LCA provides a structured methodology to quantify environmental impacts throughout the lifecycle of a building—from material extraction and construction to operation, maintenance, and end-of-life.

This research presents a simplified, semi-automated framework for connecting BIM and LCA, enabling efficient material matching and environmental impact assessment. The proposed approach leverages automated material extraction from BIM, structured LCA databases, and Excel-based material matching, ensuring a balance between automation and user control. The study follows the principles of ISO 14040:2006 and ISO 14044:2006, ensuring methodological consistency and reliability.

By implementing this framework in a case study of a simple home model in Revit, the research demonstrates how LCA results can be reintegrated into BIM models to support decision-making for sustainable design. The findings contribute to enhancing data interoperability, reducing manual workload, and promoting practical sustainability applications in BIM-based workflows. This study serves as a scalable methodology that can be extended to larger projects, providing architects and engineers with a practical tool for integrating environmental considerations into the design process.

Building Information Modeling (BIM) has evolved beyond geometric modeling (3D) and project management tools (4D-6D) to include 7D BIM, which integrates Life Cycle Assessment (LCA) for environmental sustainability. This new dimension enables data-driven decision-making for material selection, energy efficiency, and carbon footprint reduction, ensuring buildings are designed and constructed with long-term environmental responsibility.

Despite the increasing adoption of green building standards (ISO 14040, LEED, BREEAM), LCA is often conducted separately from BIM models, leading to manual data transfer, inconsistencies, and inefficiencies. This research aims to bridge the gap by developing a semi-automated workflow where BIM models extract material data, match it with an LCA database, and reintegrate environmental impact information back into BIM. This approach simplifies 7D BIM implementation, making sustainability analysis more accessible to designers and engineers.

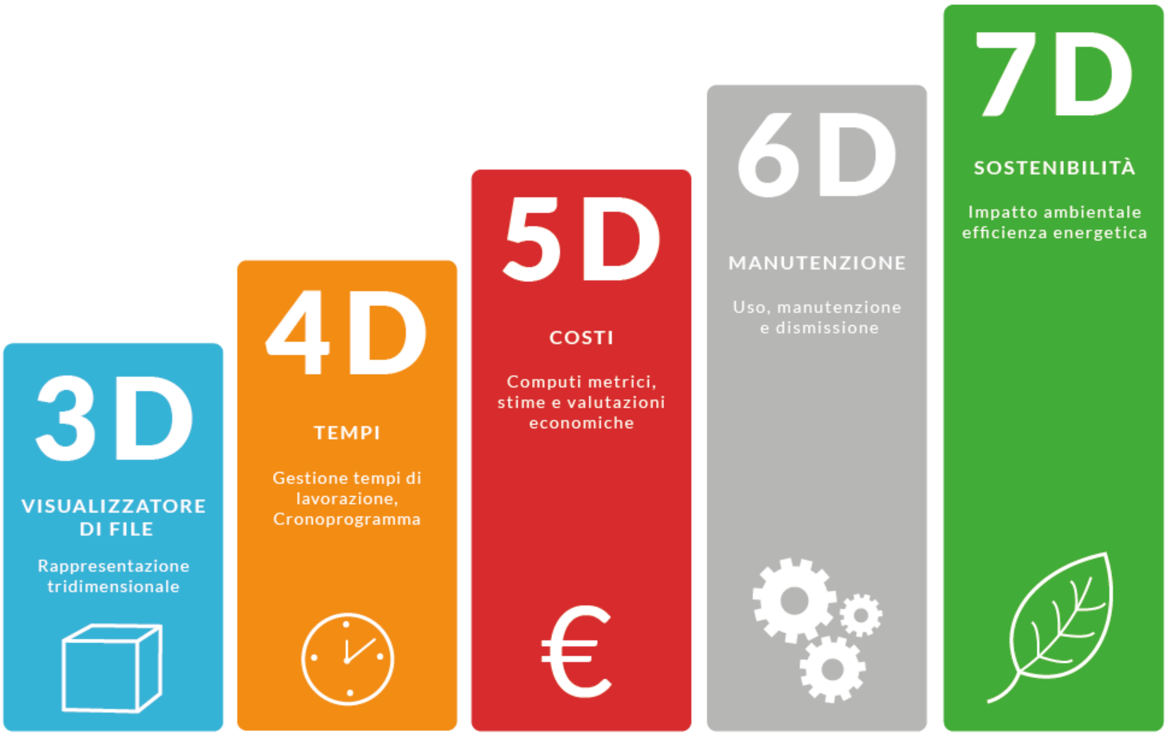


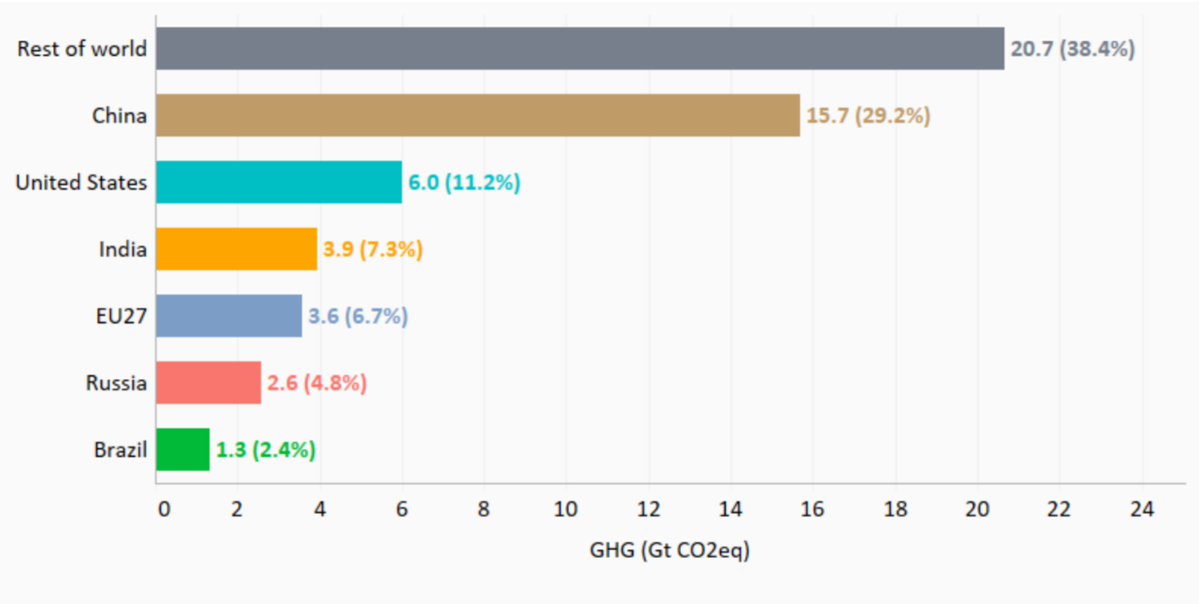
FIG.1 - 7D BIM implementation

1.1 Background and Motivation

Transportation infrastructure plays a pivotal role in fostering economic growth, enhancing mobility, and driving societal development. Roads, bridges, tunnels, railway systems, and airports form the backbone of modern societies, enabling connectivity between urban and rural areas, facilitating trade and commerce, and supporting emergency services. However, these critical infrastructures come at a significant environmental cost. The construction, operation, and maintenance of transportation networks contribute extensively to (GHG) [1]emissions, depletion of natural resources, and ecosystem disruption. According to the IEA[2], transportation infrastructure construction accounts for nearly 10% of global CO_2 emissions,

[1] greenhouse gas
[2] International Energy Agency

with highways, bridges, and tunnels being major contributors to this figure. Furthermore, the operational phase of transportation systems—particularly road traffic and energy consumption—represents one of the largest sources of GHG emissions worldwide.



Source: JRC, 2023

FIG.2- GHG emissions (in Gt CO2eq) and contribution of the major emitting economies and the rest of the world in 2022, (in Gt CO2eq)

	Share in global	Change 2019-2020	Change 2020-2021	Change 2021-2022	Change 2019-2022	Change 2020-2022	CAGR (1990-2022)
China	29.2%	1.9%	5.1%	0.3%	7.4%	5.4%	4.3%
United States	11.2%	-8.7%	5.5%	1.6%	-2.2%	7.2%	-0.1%
India	7.3%	-5.7%	6.7%	5.0%	5.7%	12.1%	3.2%
EU27	6.7%	-7.7%	5.6%	-0.8%	-3.4%	4.7%	-1.0%
Russia	4.8%	-3.9%	7.2%	-1.0%	2.0%	6.1%	-0.5%
Brazil	2.4%	-0.3%	5.1%	-2.4%	2.3%	2.6%	2.0%
Indonesia	2.3%	-4.9%	2.1%	10.0%	6.8%	12.3%	3.4%
Japan	2.2%	-5.3%	1.2%	0.6%	-3.6%	1.8%	-0.3%
Iran	1.8%	-1.6%	3.9%	1.6%	3.9%	5.6%	3.3%
Mexico	1.5%	-6.5%	3.5%	7.1%	3.7%	10.9%	1.8%
Saudi Arabia	1.5%	-0.8%	3.3%	3.9%	6.4%	7.3%	3.9%
Canada	1.4%	-8.2%	3.0%	3.2%	-2.4%	6.4%	0.8%
South Korea	1.3%	-4.3%	4.5%	-0.7%	-0.8%	3.7%	2.5%
Türkiye	1.3%	3.5%	8.5%	3.1%	15.8%	11.9%	3.5%
Australia	1.1%	-3.9%	-2.0%	1.7%	-4.1%	-0.3%	0.7%
South Africa	0.99%	-9.8%	-0.5%	-2.5%	-12.5%	-3.1%	0.8%
Global		-3.7%	4.8%	1.4%	2.3%	6.2%	1.5%
International Aviation	0.8%	-52.3%	15.4%	23.3%	-32.1%	42.3%	1.5%
International Shipping	1.4%	-8.5%	5.7%	5.7%	2.2%	11.7%	2.0%

FIG.4-Shares in 2022 global emissions, yearly GHG emission relative changes over the period 2019-2022 and the CAGR in 1990-2022 (%)

Global GHG emissions from 1970 until 2022[3]

The evolution of global GHG emissions over the period 1970-2022 is illustrated in Figure 2. Emission trends for the main activity sectors (namely power industry, industrial combustion and processes, transport, buildings , agriculture, waste and fuel exploitation) are also shown. Because of the COVID-19 pandemic, global emissions decreased by 3.7% in 2020 compared to 2019 levels, interrupting a more than ten-year increasing trend. Global GHG emissions started to grow after the COVID-19 pandemic, reaching in 2022 the level of 53.8 Gt CO2eq, which is 2.3% higher than 2019 and 1.4% higher than 2021. In 2020, the GHG emissions from transport experienced the largest drop compared with the pre COVID-19 year (-14.1%). However, in 2022, this sector experienced the largest increase, rising by 4.7%. In 2022, GHG emissions from the building sector only saw a marginal decrease of 0.4% compared with 2021, year in which these emissions grew by 4.6%. Global per-capita emissions in 2022 increased by 0.4% to reach 6.76 t CO2eq/cap, a value still 0.8% lower than in 2019.

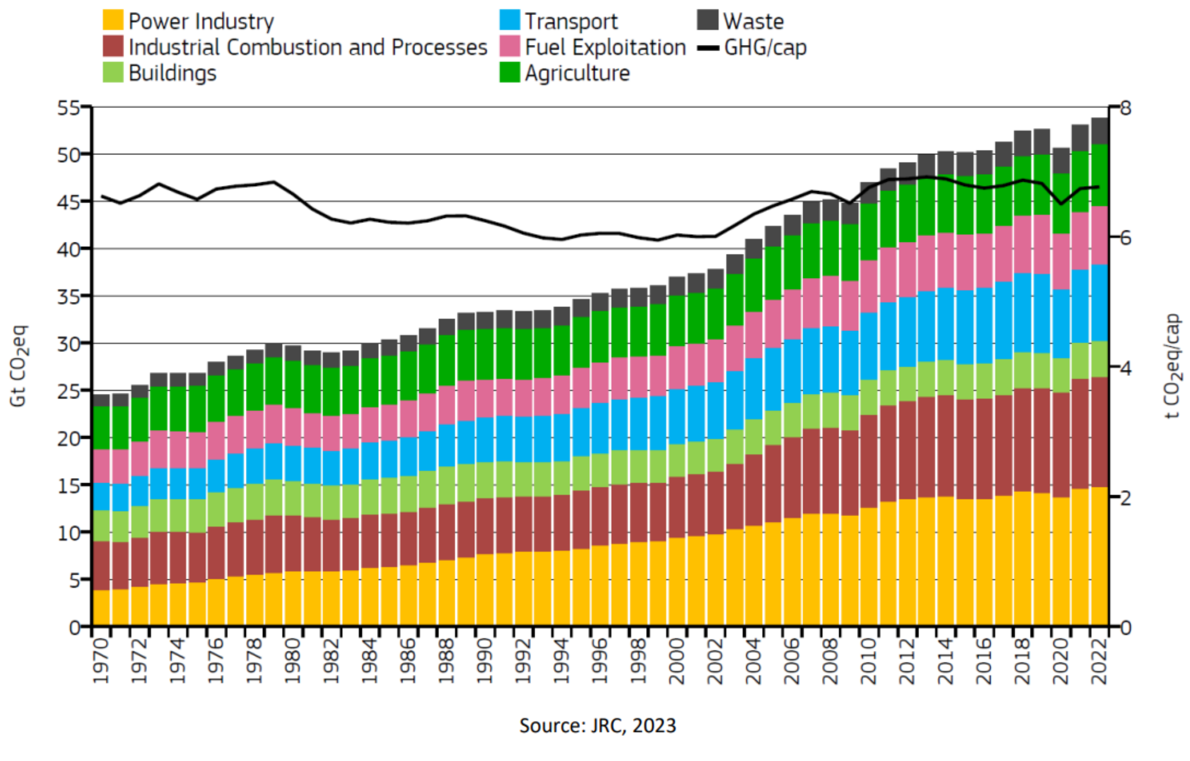


FIG.5- Global GHG emissions by sector (left axis, bars) and per capita (right axis, black line), 1970-2022 (in Gt CO2eq)[4]

[3] All from , (Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf E., Becker, W., Monforti-Ferrario, F., Quadrelli, R., Risquez Martin, A., Taghavi-Moharamli, P., Köykkä, J., Grassi, G., Rossi, S., Brandao De Melo, J., Oom, D., Branco, A., San-Miguel, J., Vignati, E., GHG emissions of all world countries, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/953332, JRC134504.)

In response to these pressing environmental concerns, the construction sector has increasingly adopted sustainability-driven approaches to infrastructure development. Among the various tools and methodologies available, Life Cycle Assessment (LCA) has emerged as a globally recognized framework for evaluating the environmental impacts of construction projects. LCA provides a systematic and standardized method for assessing the energy consumption, carbon footprint, and environmental burden of materials, processes, and end-of-life scenarios across all lifecycle stages. Despite its potential, the traditional implementation of LCA in infrastructure projects has been constrained by several limitations, including:

- **Data-Intensive Procedures:** Traditional LCA requires extensive manual data collection and processing, which can be time-consuming and error-prone, particularly in large-scale transportation projects.
- **Lack of Interoperability:** Limited compatibility between software tools used for BIM modeling and LCA calculations hinders seamless data exchange and integration.
- **Manual Data Collection:** Reliance on manual methods for gathering material quantities, energy usage, and emission factors limits the scalability and accuracy of LCA studies.

Building Information Modeling (BIM) has revolutionized the construction industry by offering a digital representation of infrastructure assets that supports integrated workflows for design, construction, and asset management. With its capacity for real-time data exchange, automated material quantification, and dynamic visualization, BIM presents a valuable opportunity to enhance LCA methodologies. By automating impact assessment processes and ensuring more precise calculations of resource use and emissions, BIM can significantly streamline environmental evaluations in transportation infrastructure projects.

The synergy between BIM and LCA provides an opportunity to bridge the gap between digital design and sustainability assessments, offering a more streamlined and scalable approach to environmental impact evaluation. For instance, BIM models can serve as a centralized repository for material quantities, geometric properties, and lifecycle information,

[4] Data from: (Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf E., Becker, W., Monforti-Ferrario, F., Quadrelli, R., Risquez Martin, A., Taghavi-Moharamli, P., Köykkä, J., Grassi, G., Rossi, S., Brandao De Melo, J., Oom, D., Branco, A., San-Miguel, J., Vignati, E., GHG emissions of all world countries, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/953332, JRC134504.)

which can then be seamlessly linked to LCA databases for automated impact assessments. This integration not only reduces the manual effort required for data collection but also enhances the accuracy and reliability of LCA results.

Despite the growing recognition of BIM-LCA integration, several challenges hinder its widespread adoption in transportation infrastructure projects. These challenges include:

- **Data Interoperability Issues:** Variability in data formats and lack of standardized protocols for exchanging information between BIM and LCA platforms remain significant barriers.
- **Limited Automation:** Current BIM-LCA workflows often rely on semi-automated or manual processes, limiting their efficiency and scalability.
- **Standardization Gaps:** The absence of universally accepted guidelines for integrating BIM and LCA in transportation projects complicates the development of consistent methodologies.

Addressing these challenges is critical for ensuring that BIM-based LCA methodologies can be effectively implemented to drive sustainability in infrastructure development.

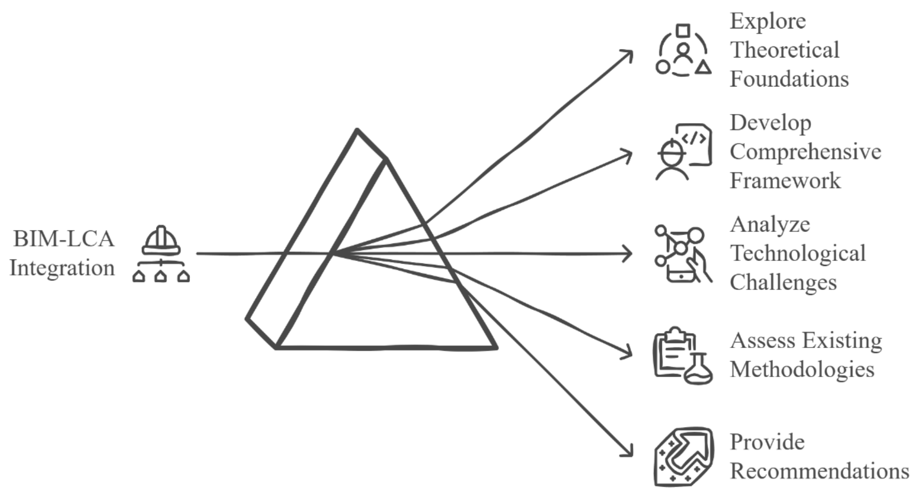
1.2 Research Objectives

This research aims to address the aforementioned challenges and advance the integration of BIM and LCA in transportation infrastructure projects. Specifically, the study seeks to achieve the following objectives:

1. **Explore the Integration of BIM and LCA Methodologies**
   Investigate the theoretical foundations and practical applications of combining BIM and LCA in transportation infrastructure projects. This includes examining how BIM models can be leveraged to automate material quantification, energy usage calculations, and lifecycle impact assessments.
2. **Develop a Comprehensive Framework for Automated LCA Calculations Within BIM Environments**
   Design and implement a robust framework that enables seamless integration of BIM and LCA workflows. The framework will incorporate automation tools, such as

Python scripts and parametric modeling techniques, to streamline data exchange and reduce manual intervention.

3. **Analyze Technological Challenges Related to Data Interoperability and Information Exchange**
   Identify and evaluate the technical barriers to achieving effective data exchange between BIM and LCA platforms. Propose solutions, such as adopting IFC[5] standards and leveraging blockchain technology for secure data provenance.
4. **Assess Existing Methodologies and Identify Gaps in Current BIM-LCA Applications**
   Conduct a thorough review of existing research on BIM-LCA integration, focusing on its application in transportation infrastructure. Highlight gaps in current methodologies and propose strategies for improvement.
5. **Provide Recommendations for Future Adoption of BIM-LCA Frameworks**
   Based on the findings of the study, offer actionable recommendations for practitioners, policymakers, and researchers to facilitate the broader adoption of BIM-LCA frameworks in transportation infrastructure planning and design.



[5] Industry Foundation Classes

1.3 Research Significance

The importance of this research lies in its potential to enhance sustainability assessment methodologies in transportation infrastructure. By integrating BIM and LCA, this study contributes to the following outcomes:

- Improved Environmental Impact Assessments: Through automated data processing and real-time material quantification, the proposed framework enables more accurate and efficient environmental impact assessments.
- Optimized Material Selection and Design Optimization: Enhanced precision in material quantification and lifecycle analysis allows for better material selection and design optimization, reducing embodied carbon and energy consumption.
- Reduction in Time and Cost: Automating LCA calculations within BIM environments significantly reduces the time and cost associated with conducting manual studies, making sustainability assessments more accessible and scalable.
- Compliance with International Standards: The adherence to ISO 14040:2006 and ISO 14044:2006 ensures that the developed framework aligns with globally recognized sustainability standards.
- Support for Regulatory Policies: The research supports the implementation of policies aimed at reducing the environmental impact of transportation infrastructure projects, aligning with global efforts to combat climate change.

Additionally, this research aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 9[6] and SDG 11[7]. By promoting responsible infrastructure development practices, the study contributes to building resilient and sustainable transportation systems that meet the needs of present and future generations.

1.4 Structure of the Thesis

This thesis is organized into five chapters, each addressing a specific aspect of the research:

[6] Industry, Innovation, and Infrastructure
[7] Sustainable Cities and Communities

Chapter 1: Literature Review

This chapter provides a comprehensive review of the theoretical foundations of BIM and LCA integration. It explores key advancements in BIM-LCA methodologies, examines case studies from the transportation sector, and identifies existing research gaps. The literature review lays the groundwork for developing a robust framework for integrating BIM and LCA in transportation infrastructure projects.

Chapter 2: Methodology

This chapter outlines the research design, data collection strategies, modeling techniques, and assessment frameworks employed in the study. It describes the development of a BIM-LCA workflow, detailing the tools and technologies used for automating data exchange and impact calculations. The methodology section emphasizes adherence to ISO standards and highlights the iterative nature of the research process.

Chapter 3: Analysis and Results

This chapter evaluates the implementation of BIM-based LCA workflows in real-world transportation infrastructure projects. It presents case studies demonstrating the effectiveness of the proposed framework in reducing environmental impacts, optimizing material usage, and improving decision-making processes. Quantitative and qualitative analyses are used to assess the performance of the framework under different scenarios.

Chapter 4: Conclusion and Future Research

This concluding chapter summarizes the key findings of the study, discusses their implications for policy and practice, and suggests directions for further research. It highlights the contributions of the research to the field of sustainable transportation infrastructure and underscores the need for continued innovation in BIM-LCA integration.

By addressing the complexities and challenges of integrating BIM and LCA in transportation infrastructure projects, this research aims to provide a foundation for more sustainable and resilient infrastructure development practices. The findings will inform practitioners, policymakers, and researchers in their efforts to mitigate the environmental impact of transportation systems and promote a greener built environment.

2.Literature Review

The integration of Building Information Modeling (BIM) and Life Cycle Assessment (LCA) represents a transformative strategy for advancing sustainable construction practices. BIM provides a digital framework for managing and visualizing a building's design, construction, and operation phases, enabling stakeholders to collaborate effectively throughout the project lifecycle. On the other hand, LCA offers a scientific methodology to quantify environmental impacts across the lifecycle of materials and processes, from material extraction through manufacturing, construction, operation, and end-of-life phases. Together, these methodologies empower architects, engineers, and sustainability experts to make informed decisions from the earliest stages of design, aligning projects with global sustainability goals such as those outlined in the United Nations' Sustainable Development Goals (SDGs).

The principles and guidelines established by ISO 14040:2006 and ISO 14044:2006 form the international foundation for conducting LCAs, ensuring consistency and reliability in evaluating environmental impacts. These standards define the scope, inventory analysis, impact assessment, and interpretation stages of an LCA, creating a robust framework for tools and methodologies. This literature review delves into state-of-the-art research on BIM-LCA integration, drawing insights from notable contributions by Victor Alberto Arvizu-Pina, Jose Francisco et al. (2023), Felippe Pereira Ribeiro, Olubimbola Oladimeji et al. (2025), Guilherme Guignone, Joao Luiz Calmon et al. (2023), Meex et al. (2021), Hui Gao, Donglin Wang, Zhongwei Zhao (2024), and Kaveh Safari, Hessam AzariJafari (2021). The review explores key advancements, challenges, and future directions in this rapidly evolving field.

7D BIM represents a paradigm shift in sustainable construction, integrating Life Cycle Assessment (LCA) into digital design and project management. The core objective of 7D BIM is to evaluate a building's environmental impact across its entire lifecycle, from material extraction to demolition and recycling. This methodology aligns with international sustainability standards such as ISO 14040, ISO 14044, and EU Green Deal policies.

2.1 The Role of LCA in Sustainable Design

Life Cycle Assessment (LCA) has emerged as the gold standard for assessing environmental impacts across the lifecycle of buildings. It encompasses all stages of a building's existence, including material extraction, manufacturing, construction, operation, and end-of-life phases. According to ISO 14040:2006 and ISO 14044:2006, LCA involves four main stages: goal and scope definition, inventory analysis, impact assessment, and interpretation. These stages ensure methodological rigor and transparency in evaluating environmental performance.

Despite its widespread adoption, traditional LCA approaches face criticism for their complexity, which often limits their applicability in early design stages where their insights are most impactful (Victor Alberto Arvizu-Pina, Jose Francisco et al., 2023). For instance, the time-consuming nature of data collection and analysis can delay decision-making during critical phases of the design process. Furthermore, the lack of user-friendly tools has historically restricted LCA to specialized practitioners rather than mainstream stakeholders in the construction industry.

Recent advancements in LCA tools have significantly enhanced their accessibility and usability. For example, Victor Alberto Arvizu-Pina, Jose Francisco et al. (2023) introduced an open-access online tool tailored for bioclimatic buildings. This tool simplifies the process of conducting environmental impact assessments, allowing non-experts to efficiently evaluate embodied carbon reductions. Their case study demonstrated a 15% reduction in embodied carbon when sustainable materials and iterative design processes were applied. By aligning with ISO standards, the tool ensures that simplified LCA processes do not compromise accuracy or consistency, thereby improving accessibility for practitioners at various levels of expertise.

Similarly, the EVAMED framework developed by Meex et al. (2021) integrates region-specific databases, such as MEXICANIUH, to assess environmental impacts within a Latin American context. This tool automates data input for early-stage designs, offering detailed insights into the impacts of production (A1-A3), operation (B6), and deconstruction (C1). Its alignment with ISO 14044:2006 ensures transparency in impact assessment and decision-making, making it particularly suitable for regional applications. Additionally, the modular structure of EVAMED allows for customization based on local regulatory requirements and material availability, enhancing its adaptability to diverse contexts.

Hui Gao, Donglin Wang, Zhongwei Zhao (2024) extended the application of LCA to prefabricated construction by developing a BIM-LCA integrated model. Their approach accounts for emissions associated with the manufacturing, transportation, and installation of prefabricated components, providing precise carbon footprint calculations. By integrating prefab-specific data into BIM workflows, the study identified strategies for achieving carbon neutrality, such as optimizing logistics networks and selecting low-carbon materials. The integration adheres to ISO 14040:2006 principles by considering a cradle-to-grave scope and conducting sensitivity analyses to refine system boundaries and assumptions. Sensitivity analyses are particularly important in prefabricated construction due to the variability in transportation distances and assembly methods, which can significantly influence overall emissions.

2.2 BIM as a Platform for Sustainability

Felippe Pereira Ribeiro, Olubimbola Oladimeji et al. (2025) explored the synergy between BIM and parametric tools to optimize the thermal performance of building envelopes. By leveraging BIM models to simulate design alternatives, the study demonstrated that strategic material choices and geometric configurations could achieve energy savings of up to 20%. This research highlights the iterative nature of parametric design, enabling designers to explore multiple scenarios and balance energy efficiency with aesthetic and functional goals. The adherence to ISO 14044:2006 ensures that inventory analysis and impact assessments are accurately quantified, facilitating meaningful decision-making. Moreover, the use of parametric tools enhances collaboration among multidisciplinary teams, as changes in one parameter can be immediately reflected across all aspects of the design.

Kaveh Safari and Hessam AzariJafari (2021) addressed challenges in data exchange between BIM platforms and LCA tools, particularly in urban high-density construction projects. They proposed a modular data structure framework to enhance interoperability and scalability. Blockchain technology was also identified as a promising solution to ensure data provenance and security in collaborative workflows. By adopting ISO 14040:2006 principles, these frameworks prioritize consistency and transparency in data management across stakeholders. Modular frameworks enable seamless integration of disparate datasets, reducing the risk of errors caused by manual data transfer. Additionally, blockchain-based systems provide an immutable record of all transactions, enhancing trust and accountability among project participants.

2.3 Challenges in BIM-LCA Integration

Guilherme Guignone, Joao Luiz Calmon et al. (2023) identified interoperability as a critical bottleneck in BIM-LCA integration. Variability in data formats across software platforms often leads to inefficiencies and errors, hindering the seamless flow of information. The adoption of Industry Foundation Classes (IFC) was recommended to facilitate seamless data exchange and ensure compatibility between BIM and LCA tools. Aligning with ISO 14044:2006, the emphasis on consistent system boundaries and inventory data ensures more accurate impact assessments. However, despite the potential benefits of IFC, challenges remain in terms of data loss and incomplete mappings, necessitating further refinement of these standards.

The manual effort required to extract, transform, and analyze data remains a significant barrier to the widespread adoption of BIM-LCA integration. Guilherme Guignone, Joao Luiz Calmon et al. (2023) proposed incorporating artificial intelligence (AI) and machine learning techniques to automate repetitive tasks and enhance usability for non-expert users. Automation frameworks aligned with ISO 14040:2006 principles can improve consistency and reduce the potential for human error. For instance, AI-driven algorithms can automatically map material quantities from BIM models to corresponding entries in LCI databases, streamlining the inventory analysis stage. Meex et al. (2021) also emphasized the importance of automation in early design phases, particularly for simplified 3D models with low levels of detail (LOD 200), where rapid feedback is essential for guiding design decisions.

2.3.3 Data Summary Table

Reference	Approach	Results/Findings	LCA Scope	Key Insights
Victor Alberto Arvizu-Pina, Jose Francisco et al. (2023)	Open-access LCA tool for bioclimatic buildings	15% reduction in embodied carbon, optimized material selection	Gate-to-grave	Simplified LCA processes improve accessibility.

Felippe Pereira Ribeiro, Olubimbola Oladimeji et al. (2025)	BIM-based parametric energy analysis	20% energy savings through roof and facade optimization	Cradle-to-operation	Parametric tools enable iterative design refinement.
Guilherme Guignone, Joao Luiz Calmon et al. (2023)	Guidelines for BIM-LCA integration	Identified gaps in interoperability and proposed automation frameworks	Cradle-to-grave	Standardization and AI are key to scalability.
Meex et al. (2021)	EVAMED tool for BIM-LCA integration	Automated BoQ, screening LCA phases (A1-A3, B6), tailored for early design	Cradle-to-grave	Early-phase focus and region-specific databases.
Hui Gao, Donglin Wang, Zhongwei Zhao (2024)	LCA-BIM model for prefabricated buildings	Accurate carbon calculation for prefab components, operational emissions	Cradle-to-grave	Prefab-specific BIM workflows for carbon neutrality.
Kaveh Safari, Hessam AzariJafari (2021)	Challenges and framework for BIM-LCA	Identified interoperability and scalability issues, proposed modular data	Cradle-to-grave	Blockchain and modular frameworks enhance integration.

Guilherme Guignone, Joao Luiz Calmon et al. (2023) and Kaveh Safari, Hessam AzariJafari (2021) stressed the importance of adopting standardized workflows to improve data interoperability and consistency. Standardized workflows would facilitate the development of universal guidelines and best practices, reducing barriers to adoption and enhancing collaboration among stakeholders.
AI-driven tools, as suggested by Guilherme Guignone, Joao Luiz Calmon et al., could automate repetitive tasks, reducing errors and accelerating project timelines. Enhanced automation would empower non-expert users to conduct sophisticated environmental assessments without specialized training, democratizing access to sustainability tools.
Hui Gao, Donglin Wang, Zhongwei Zhao (2024) highlighted the need for prefab-focused BIM-LCA models to achieve carbon-neutral goals effectively. Given the growing demand for prefabricated construction, there is a pressing need for tailored workflows that account for unique lifecycle phases such as transportation and assembly.

The integration of Building Information Modeling (BIM) and Life Cycle Assessment (LCA) represents a pivotal advancement in sustainable construction practices, fundamentally reshaping how infrastructure projects are designed, assessed, and managed. This integration enables stakeholders to evaluate environmental impacts comprehensively, considering factors such as material extraction, energy consumption, emissions, transportation logistics, construction processes, operational efficiency, and end-of-life disposal or recycling. By combining BIM's data-rich digital modeling capabilities with LCA's quantitative environmental assessment framework, project teams can make more informed, sustainability-driven decisions throughout the entire lifecycle of transportation infrastructure projects.

Despite significant progress in BIM-LCA integration, several technical, organizational, and methodological challenges persist, hindering its widespread adoption and full-scale implementation. Interoperability issues remain a major obstacle, as different BIM platforms and LCA tools often operate in silos, lacking standardized data exchange protocols. This inconsistency in data representation leads to inefficiencies in material quantification, impact assessment, and overall sustainability evaluations. Moreover, data accuracy and consistency present challenges, particularly when dealing with regional variations in construction material properties, transportation modes, energy mixes, and regulatory requirements. A lack of standardized LCA databases tailored for transportation infrastructure further complicates impact assessments, introducing uncertainties in carbon footprint calculations and embodied energy estimations.

To address these challenges, increased automation, standardization, and digital integration are necessary. The adoption of Industry Foundation Classes (IFC) and OpenBIM standards can significantly enhance interoperability between BIM and LCA tools, ensuring seamless data transfer across platforms. Furthermore, AI-driven material optimization algorithms **and** parametric modeling techniques can help automate sustainability assessments, reducing manual input errors and enabling more dynamic scenario evaluations. As industry progresses, integrating cloud-based LCA computations, blockchain-powered data validation for environmental reporting, and real-time carbon tracking within BIM environments will further streamline and improve sustainability assessments.

Beyond addressing technical hurdles, a cultural shift within the construction industry is also required. Many stakeholders, including engineers, architects, and policymakers, lack formal training in LCA methodologies, which limits their ability to effectively interpret and utilize

LCA results within BIM workflows. Enhancing education, training, and interdisciplinary collaboration will be essential for promoting BIM-LCA adoption and encouraging a holistic sustainability mindset across project teams. Ultimately, the successful integration of BIM and LCA has the potential to fundamentally transform the construction industry into a more sustainable, resilient, and resource-efficient sector. By embedding life cycle thinking into digital design, construction, and asset management processes, infrastructure projects can better align with global climate action efforts, net-zero carbon targets, and circular economy principles. As regulatory frameworks evolve and digital technologies continue to advance, BIM-LCA integration will become an indispensable tool in ensuring that transportation infrastructure meets both present and future sustainability demands.

3. Methodology

This study adopts a structured methodology aimed at developing a semi-automated framework to establish a seamless connection between Building Information Modeling (BIM) and Life Cycle Assessment (LCA). Rather than merely evaluating BIM-LCA integration challenges, the research focuses on creating a practical workflow that reduces manual work, improves data consistency, and enhances decision-making in transportation infrastructure projects. The proposed methodology leverages a combination of rule-based filtering, automation scripts, and structured workflows to bridge the gap between BIM environments (such as Revit and SketchUp) and LCA databases (such as OpenLCA)

The primary objective is to develop a looped, semi-automated system that allows for efficient material extraction, filtering, selection, and reintegration, enabling iterative sustainability assessments throughout the design and construction phases. The methodology is structured into three key phases:

Phase 1: Extraction of BIM Material Data

Using Dynamo scripts within Revit to automatically extract material quantities, types, and element IDs. The workflow exports this structured data into Excel, creating a reliable inventory of all materials in the tunnel model. This reduces manual data collection errors and ensures consistent formatting for the next phase.

Phase 2: Filtering and Matching with LCA Data

Preparing and simplifying an LCA database (e.g., from OpenLCA) in Excel. The extracted BIM material list is manually matched to LCA profiles using cleaned Excel tables. This semi-automated but accessible approach allows designers to assign Global Warming Potential (GWP) and other environmental indicators to each material, ensuring transparency and adaptability.

Phase 3: Updating the BIM Model with Environmental Data

Reimporting the matched LCA indicators (e.g., GWP values) back into the Revit model using Dynamo. Shared parameters are created or updated to store these values in BIM elements. Designers can then use Revit's filters and color overrides to visualize environmental impact directly in the 3D model, supporting early-stage sustainability decisions.

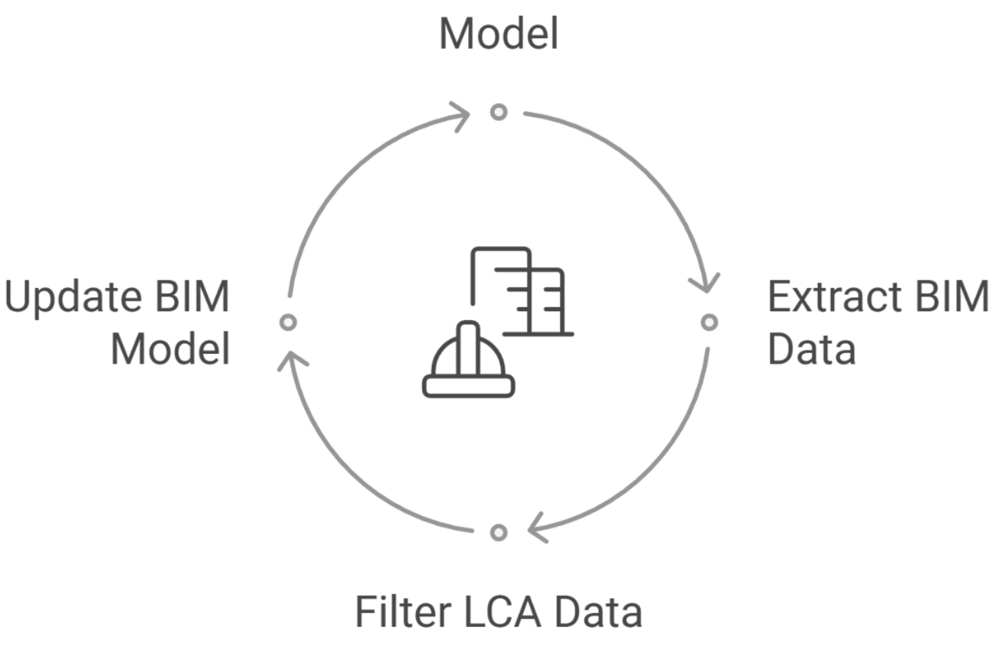


FIG.6 : workflow

The research is firmly grounded in internationally recognized environmental assessment standards, specifically ISO 14040:2006 and ISO 14044:2006, which provide a standardized, structured framework for conducting LCAs. These standards define key methodological steps, including goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment[8] , and results interpretation, ensuring that the study follows a systematic, science-based approach. By aligning with these guidelines, the research maintains a high level of credibility, transparency, and methodological consistency, making its findings both replicable and comparable with existing LCA studies in transportation infrastructure. From a qualitative perspective, the study conducts a thorough literature review, case study analysis, and expert interviews to explore existing BIM-LCA methodologies, industry adoption barriers, and emerging innovations. This approach enables a deeper understanding of context-specific implementation challenges, including interoperability issues, data standardization gaps, and institutional constraints in sustainability-driven project planning. The qualitative component also provides insights into how BIM and LCA integration is being shaped by regulatory frameworks, corporate sustainability goals, and evolving digital construction practices. On the quantitative side, the study employs BIM-driven life cycle inventory (LCI) extraction, parametric environmental impact simulations, and comparative scenario analysis to evaluate material choices, energy consumption patterns, and carbon footprint variations in transportation infrastructure projects. Advanced computational tools such as OpenLCA, One Click LCA, and machine-learning-enhanced sustainability assessment algorithms are leveraged to generate high-resolution, data-driven environmental impact assessments. The study also applies statistical sensitivity analysis to assess the uncertainty and variability in BIM-LCA results, ensuring a robust and scientifically valid evaluation of sustainability trade-offs. By integrating both qualitative and quantitative methods, this research provides a balanced, multi-faceted investigation of BIM-LCA integration, offering insights that are both theoretically rigorous and practically applicable. This dual-methodological approach ensures that findings are not only academically sound but also relevant to industry stakeholders, facilitating evidence-based decision-making for engineers, project managers, policymakers, and sustainability consultants. Through this framework, the study contributes to the ongoing digital transformation of sustainability assessment practices, reinforcing the role of BIM and LCA as essential tools in achieving net-zero carbon goals and next-generation sustainable infrastructure solutions. The research process is divided into 4 key phases:

1. **DataCollection**

   Data sources are utilized to enrich the study. Primary data includes BIM models of

[8] LCIA

real-world transportation infrastructure projects, life cycle inventory[9] datasets, and operational energy usage reports. Some data encompasses ISO standards, government publications, industry guidelines, and peer-reviewed articles. Data collection methods are designed to ensure compatibility with the chosen analytical tools and compliance with international standards.

2. **Development of a BIM-LCA Workflow**

   A structured workflow is created to automate the extraction of material quantities from BIM models and their mapping to LCI databases. This workflow leverages advanced computational techniques, including scripting languages like Python and parametric modeling tools such as Dynamo, to streamline the integration process. The aim is to reduce manual intervention and improve accuracy in quantifying environmental impacts.

3. **Implementation and validation**

   The proposed workflow is evaluated on case studies representing diverse types of transportation infrastructure, such as highways, bridges, and tunnels. These case studies serve as benchmarks for validating the effectiveness and scalability of the developed framework. Real-world data is used to calibrate the model, ensuring that results align with actual conditions observed in practice.

4. **Scenario Analysis and Sensitivity Assessment**
   Multiple design scenarios are evaluated to assess how variations in materials, construction methods, and operational parameters influence lifecycle environmental impacts. Sensitivity analyses are conducted to determine the robustness of the findings under different assumptions and uncertainties. This step is crucial for identifying high-impact areas where interventions can lead to significant reductions in carbon footprints and other negative externalities.

The iterative nature of the research ensures continuous improvement of the BIM-LCA framework based on feedback from each stage. This cyclical process facilitates refinement and optimization of the methodology throughout the study.

[9] LCI

3.2 Data Collection :

- BIM Models: Digital representations of transportation infrastructure projects are generated or imported into BIM software platforms such as Autodesk Revit, Civil 3D, and Infra Works. These models encapsulate detailed information about geometric properties, material specifications, and structural components.
- Material Inventory Data: Material quantities are extracted from the BIM models using automated scripts and linked to established LCI databases such as Ecoinvent, MEXICANIUH, and Environmental Product Declarations (EPDs). This linkage enables precise estimation of embodied impacts associated with specific materials.
- Energy and Emissions Data:[10] Operational energy consumption and emissions data are sourced from project-specific reports and national transportation statistics. These datasets inform the assessment of use-phase impacts, which often constitute a significant portion of a project's total lifecycle emissions.
- ISO Standards: Compliance with ISO 14040:2006 and ISO 14044:2006 ensures that the research adheres to internationally recognized methodologies for conducting LCAs. These standards define requirements for goal definition, scope setting, inventory analysis, impact assessment, and interpretation.
- Existing Case Studies : Previous research on BIM-based LCA applications in infrastructure projects provides valuable precedents and lessons learned.
- Government and Industry Reports : Official documents published by regulatory bodies and industry associations offer authoritative data on transportation emissions, material standards, and sustainability targets. Examples include reports from the International Transport Forum (ITF), the United States Environmental Protection Agency (EPA), and the European Environment Agency (EEA).

3.3 Development of a BIM-LCA Workflow

[10] I used One Click LCA's default and reserve EPD-based detail for future work.

The BIM-LCA integration framework follows a systematic, multi-step workflow designed to facilitate seamless collaboration between BIM and LCA processes. Each step is described below:

Step 1: Infrastructure models are prepared either through de novo creation or importation into BIM software platforms. To enhance efficiency, custom scripts written in Python and Dynamo are employed to automate the extraction of Bill of Quantities[11] and other relevant attributes. This automation minimizes errors and accelerates data preparation.

Step 2: Extracted BoQ data is mapped onto corresponding entries in LCI databases. Materials and energy flows are categorized according to standard life cycle phases defined in EN 15804+A2:2019, including:

- **A1-A3** : Raw material acquisition, processing, and manufacturing.
- **A4-A5** : Transportation and construction activities.
- **B6** : Use-phase energy consumption and maintenance.
- **C1-C4** : End-of-life disposal and recycling.

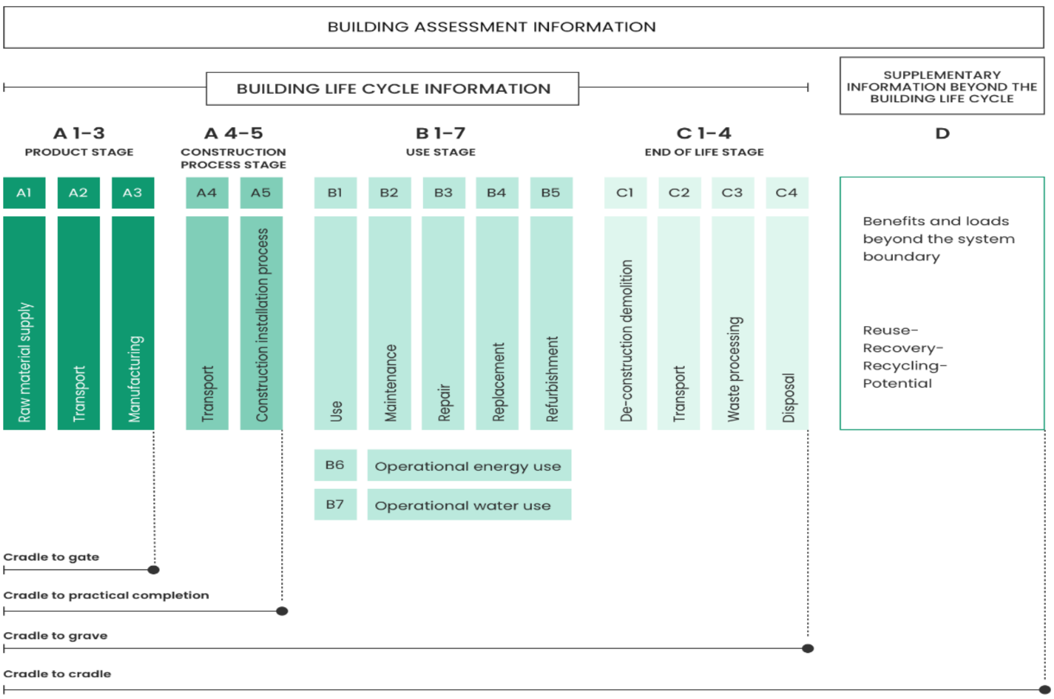


Fig.6 : This categorization ensures that all relevant impacts are accounted for during the assessment.

[11] BoQ

Step 3:Processed data is fed into specialized LCA software tools such as OpenLCA and One Click LCA to compute environmental indicators, including Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Cumulative Energy Demand (CED). Dynamic calculations enable real-time evaluation of alternative design options, empowering decision-makers to select configurations that minimize environmental burdens.

Step 4**:** Design scenarios are systematically evaluated to explore the effects of varying parameters such as material choices, transportation distances, and energy sources. Sensitivity analyses focus on identifying critical variables that exert disproportionate influence on the overall results. For instance, substituting traditional concrete with low-carbon alternatives or optimizing logistics networks could yield substantial reductions in GWP.

3.4 Implementation and Validation

The following table summarizes the software tools and technologies employed in this study[12]:

TOOL	FUNCTION
AUTODESK REVIT	BIM modeling and material quantification
DYNAMO & PYTHON	Automation of BoQ extraction and LCA integration
OPENLCA	Comprehensive LCA computation and impact assessment
ONE CLICK LCA	User-friendly platform for rapid sustainability evaluations
ECOINVENT & MEXICANIUH	Databases containing detailed LCI information

3.5 Scenario Analysis and Sensitivity Assessment

Upon completion, this study is expected to deliver the following outcomes:

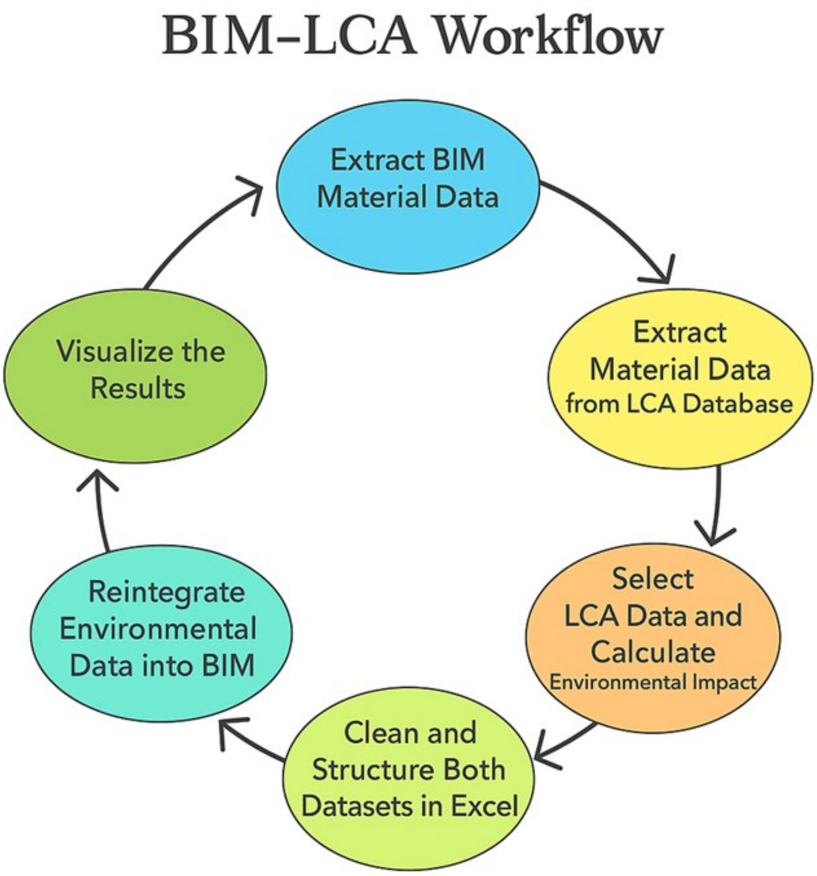
[12] These tools collectively enable efficient execution of the BIM-LCA workflow while maintaining high levels of precision and reliability.

1. Semi-Automated BIM-LCA Workflow: A structured and partially automated system that streamlines the integration of BIM and LCA for transportation infrastructure projects, reducing manual work while maintaining expert decision-making.
2. Optimized Material and Design Selection: A systematic approach for evaluating and selecting materials based on environmental performance, balancing sustainability, technical feasibility, and cost constraints.
3. Framework Validation and Scalability: Demonstration of the framework's effectiveness through compliance with ISO standards, structured case study application, and its adaptability across diverse project contexts.

Future research should address these limitations by exploring emerging digital technologies and data-driven innovations that have the potential to enhance the accuracy, transparency, and accessibility of BIM-LCA workflows. Among these advancements, artificial intelligence (AI)-powered material selection algorithms can play a crucial role in optimizing construction sustainability by automating the identification of low-carbon, energy-efficient, and cost-effective materials. AI-driven predictive models can analyze vast datasets, considering material properties, environmental impacts, lifecycle costs, and structural performance, thereby enabling real-time recommendations for the most sustainable material choices. Additionally, AI can facilitate automated scenario simulations, allowing engineers and designers to assess multiple sustainability alternatives quickly and efficiently within BIM environments.Another promising innovation is blockchain-based data verification systems, which can secure and streamline the tracking of environmental impact data across the entire supply chain. Blockchain technology offers a decentralized and tamper-proof record-keeping system, ensuring that LCA datasets, Environmental Product Declarations (EPDs), and material certifications remain authentic, traceable, and immutable. Furthermore, cloud computing and big data analytics can revolutionize BIM-LCA workflows by enabling real-time, large-scale environmental impact assessments. Cloud-based LCA computation eliminates the need for extensive local processing power, allowing stakeholders to access automated, data-rich sustainability evaluations from anywhere in the world. These advancements will democratize LCA capabilities, making sustainability assessments more accessible to small and mid-sized construction firms that may lack in-house expertise in LCA methodologies.This methodology establishes a robust and scalable foundation for integrating BIM and LCA in transportation infrastructure projects, leveraging the power of cutting-edge digital tools alongside rigorous scientific methods. By creating a standardized, automated, and data-driven approach, the study advances sustainable practices in infrastructure engineering, ensuring that environmental impact assessments are more efficient, reliable, and widely applicable across diverse project types.Ultimately, the findings of this research will empower engineers, designers, policymakers, and construction managers to make informed, data-driven decisions that prioritize both infrastructure functionality and environmental stewardship. By embedding sustainability assessments directly into digital construction workflows, the study contributes to a broader paradigm shift toward net-zero infrastructure, climate resilience, and circular economy principles.

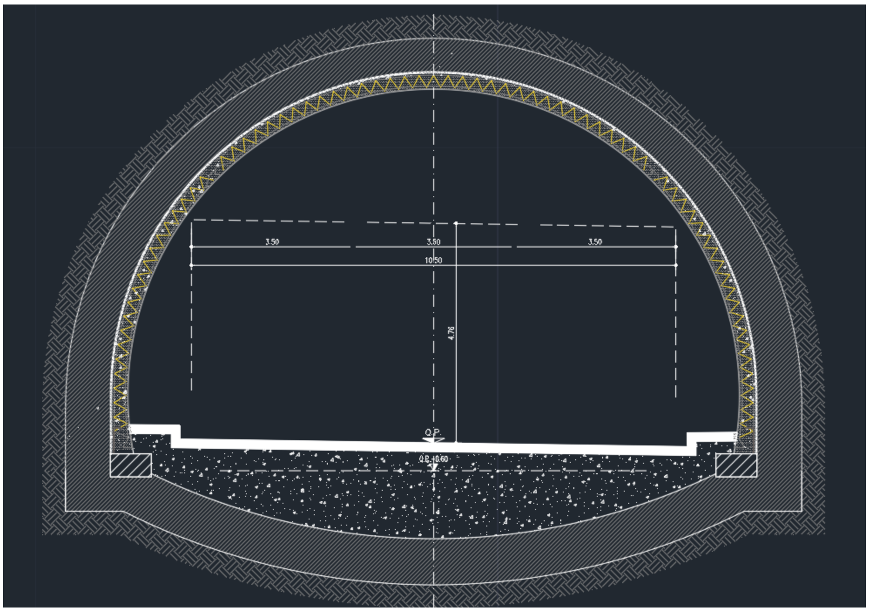
4.Case Study:

This thesis adopts a tunnel infrastructure segment as a representative case study to demonstrate the integration of BIM and LCA workflows for environmental assessment. The chosen tunnel profile is based on a realistic cross-section typically used in transportation engineering projects. The objective of the case study is not to produce a finalized



construction design but to illustrate a replicable workflow that can quantify and visualize environmental impacts at the early stage of design. This study presents a comprehensive BIM-LCA integration framework, designed to establish an automated and structured connection between Building Information Modeling (BIM) models and Life Cycle Assessment (LCA) databases. The objective is to enhance the environmental impact assessment of transportation infrastructure by streamlining the material selection and evaluation process through computational automation.

4.1 Description of the case study



Screenshot num 1: section of the tunnel segment

The tunnel case study used in this thesis is based on a typical tunnel section. Geomeetry reflects real-world design dimensions and structural elements typically adopted in contemporary infrastructure projects across Italy.

The tunnel section includes a semicircular arch with supporting base slabs, waterproofing layers, and a precast concrete lining. The dimensions and materials have been chosen to reflect a realistic construction scenario while keeping the model manageable for BIM–LCA integration.

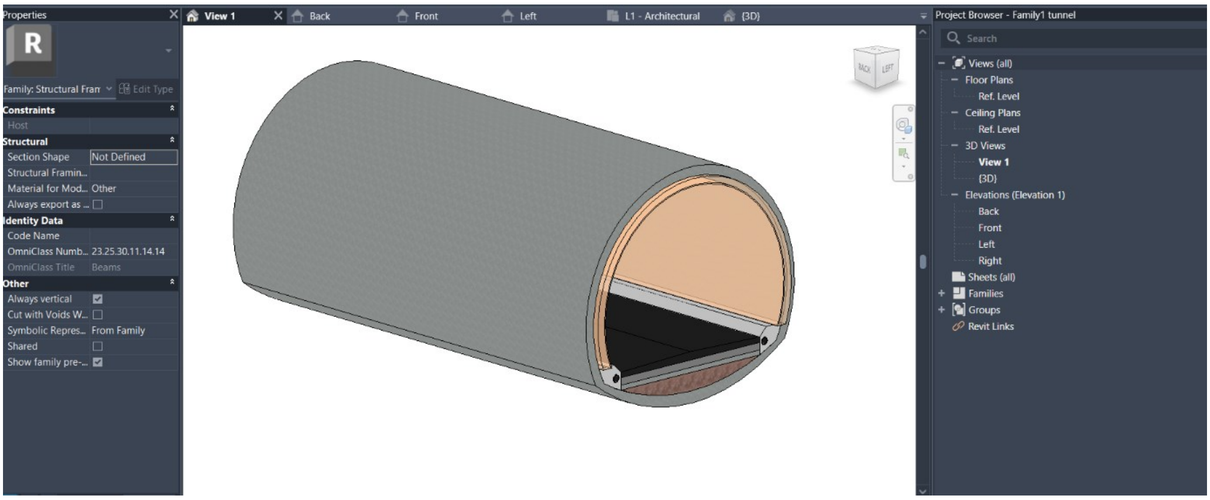
The main characteristics of the tunnel geometry (see section), are:

Element	Description	Value
Inner tunnel width	Distance between interior vertical walls	10.50 m
Tunnel height	From base slab to crown (center of the arch)	~4.75 m
Arch radius (inner)	Internal radius of circular tunnel lining	~5.25 m
Total section height (from foundation)	From base to outer crown (including lining and soil)	~7.5 m
Precast lining thickness	Prefabricated segmental element	0.25 m
Base slab width per side	Supporting slabs extending under each track	3.50 m
Waterproofing layer	Placed between the soil and the lining	~5–10 cm approx.
External revetment	Existing reinforced concrete or sprayed layer	Variable

Structural Element	Material
Tunnel lining (precast + concrete)	Reinforced Concrete (C35/45)
Base slab	Reinforced Concrete (C35/45)
Waterproofing membrane	HDPE membrane (1.5–2mm)
Steel elements (anchors, joints)	Steel Rebar B500C
Existing revetment	Sprayed Concrete / Shotcrete
Pipes or ducts (seen in base)	PVC or HDPE (for drainage)

4.2 Creation of BIM Model for the tunnel

This section was used as a reference to model the tunnel in Revit using sweeps, extrusions, and system families.



Screenshot num 2: modeling in REVIT

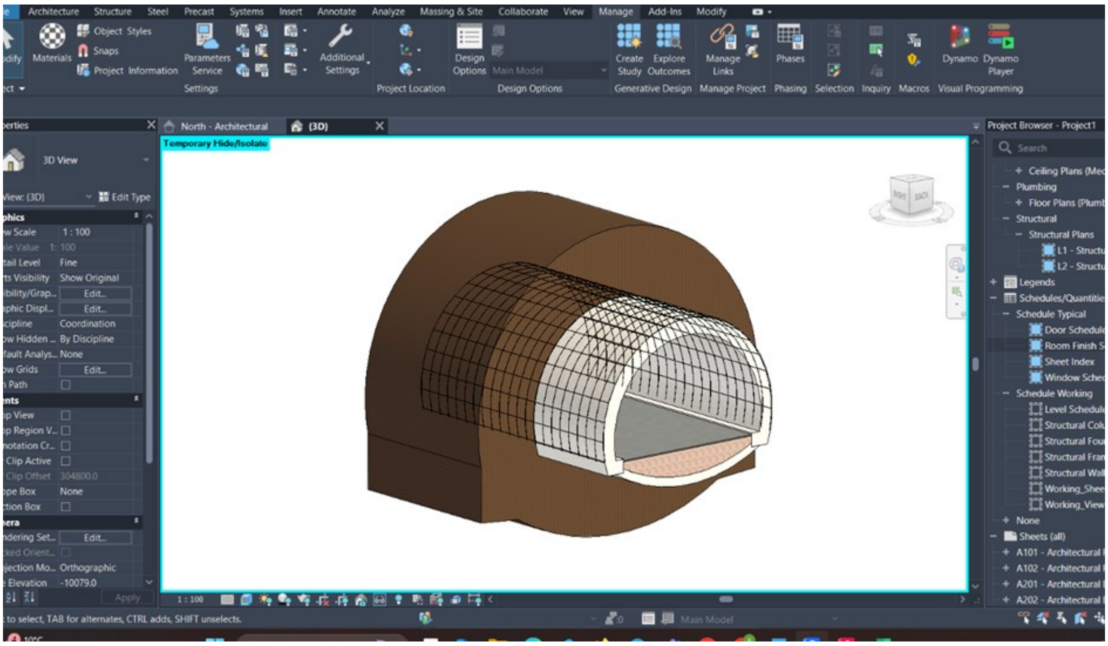
The geometry was simplified slightly for computational manageability but retains all essential environmental contributors:

- Concrete volume (lining + slab)
- Steel content (included through reinforcement proxy)
- Waterproofing and secondary materials

The model was then connected to Dynamo scripts for quantity extraction and environmental analysis Which we will discuss about it in next sections

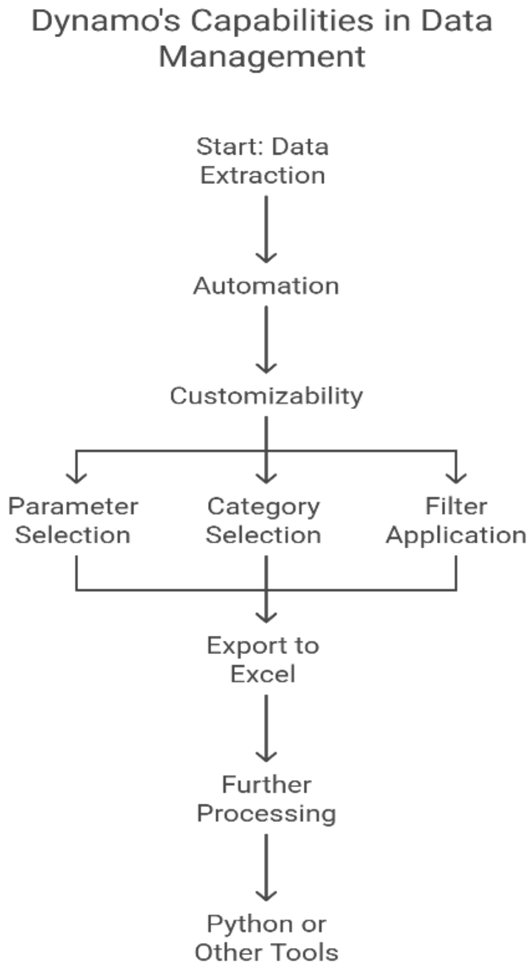
The integration framework follows a structured methodology, ensuring a streamlined connection between BIM models, data extraction, filtering, and LCA-based material assessment.

4.3 Phase 1: Extraction of Material Data from BIM (Revit) Using Dynamo



- The extraction process utilizes a Dynamo script to retrieve key material properties, including:
  - Material names and classifications.
  - Structural and non-structural categorizations (e.g., insulation, finishes, load-bearing components).
  - Densities and volumetric specifications.
  - Unique material identifiers assigned within the BIM model.
- The extracted material data is structured and exported into an Excel file (.xlsx) for further processing.
- The structured format ensures compatibility with LCA datasets and facilitates automated comparison mechanisms.

The primary goal of Step 1 is to automatically extract material-related information from a Revit BIM model using Dynamo scripts and export the data into an Excel (.xlsx) file. This step ensures that all necessary material properties are structured for later comparison with an LCA database. Dynamo is used in this study because it offers key advantages for automating and customizing data extraction within REVIT .



4.3.1Key Data to Extract from Revit

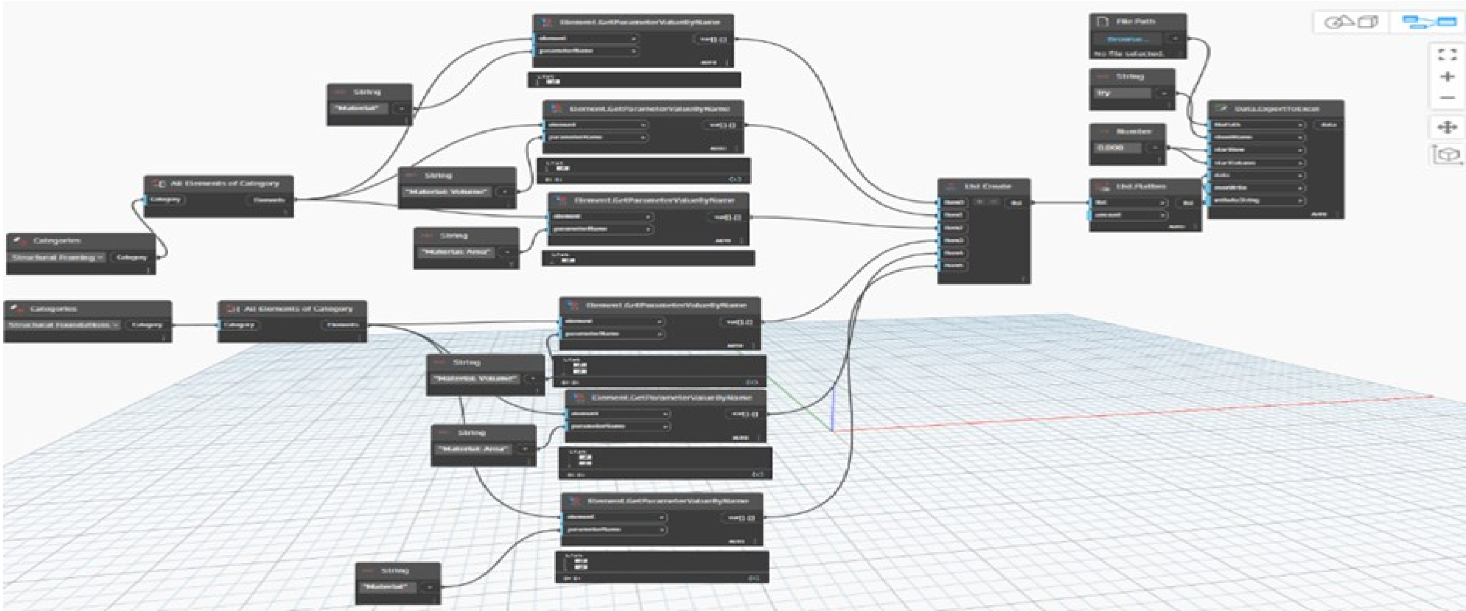
To perform an LCA analysis, the extracted Bill of Materials (BoM) should contain:

Parameter	Description	Unit
Material Name	Name of the material in Revit	-
Material Category	Structural, non-structural, insulation, etc.	-
Volume	Total volume of the material	m^3
Density	Material density	kg/m^3
Mass	Automatically calculated: Volume × Density	kg
Thermal Properties	Conductivity, resistance (if available)	W/(m·K)
Phase	Construction phase (new, existing, demolished)	-
Material ID	Unique identifier for reference	-

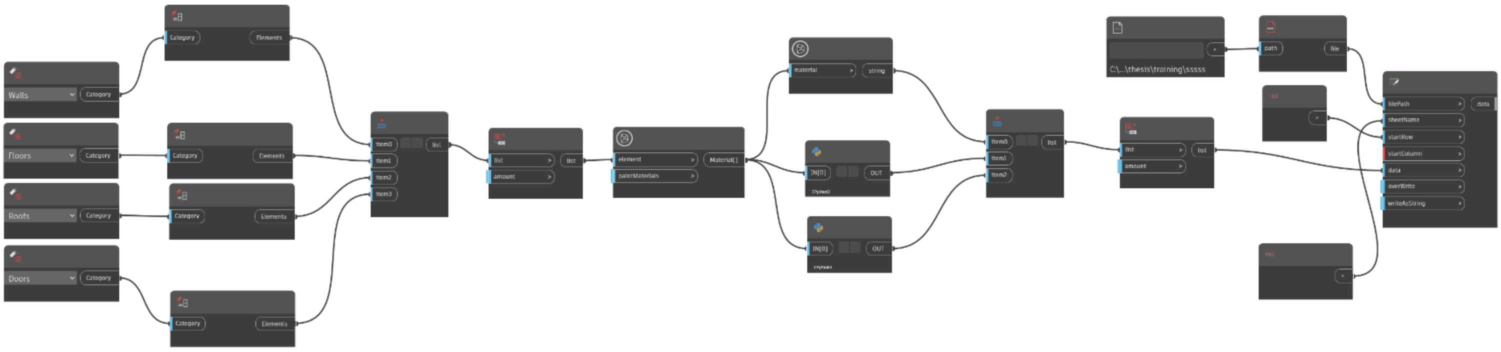
4.3.2 Dynamo Workflow to Extract Data

The following Dynamo workflow extracts these parameters and exports them to an Excel file.

1. **Filter Revit Elements**
    - The "Categories" node to select Walls, Floors, Roofs, and Structural Elements.
    - Extract all elements that contain materials using the "All Elements of Category" node.
2. **Extract Material Properties**
    - The **"**Element.GetMaterialIds" node to retrieve materials linked to each element.
    - Extract key parameters using:
        - **"**Material.Name"
        - "Material.Density"
        - "Element.Volume"
    - Calculate **mass** by multiplying volume with density.
3. **Format Data for Excel**
    - Combine all extracted data into a list of lists format.
    - Create headers for the Excel file (e.g., "Material Name", "Density", "Volume", etc.).
4. **Export Data to Excel**
    - "Excel.WriteToFile" node to write the data to an Excel spreadsheet.
    - Save the file as "BIM_Material_Export.xlsx".



screenshot num 3 : Dynamo Workflow to Extract Data (Element ID + Material Name only + volume/area)

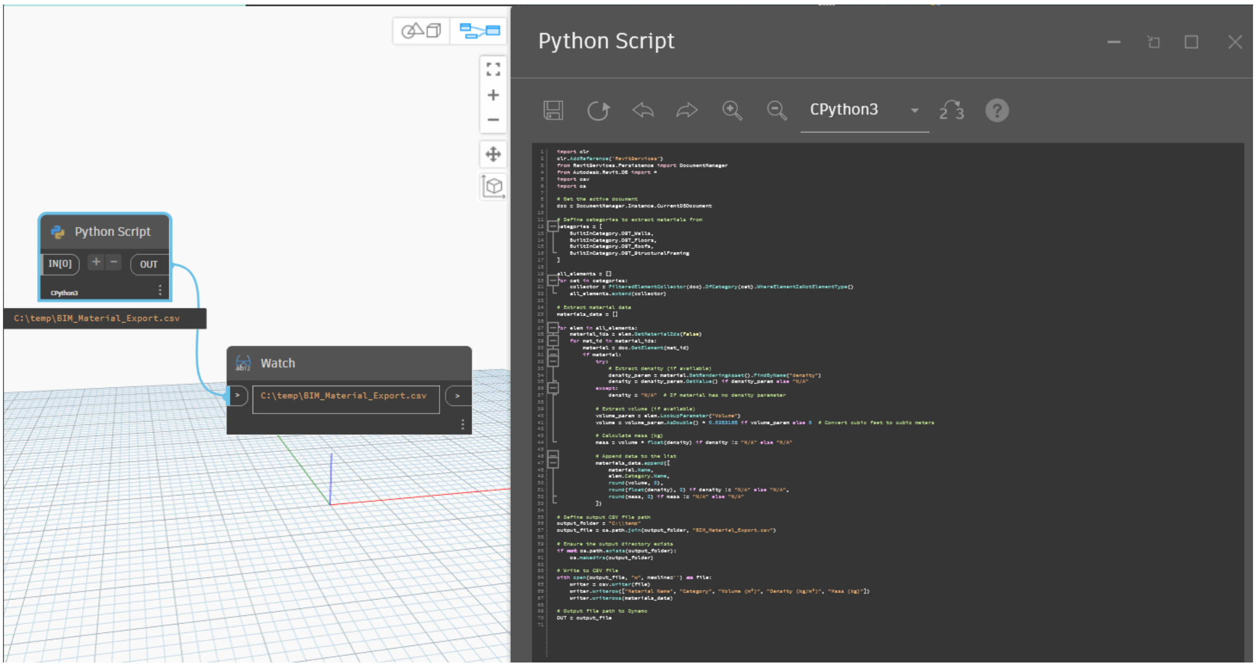


Screenshot num 4 : simple method of extracting materials (Element ID + Material Name only)[13]

[13] Simpler for material inventory rather than impact calculation

4.3.3 Dynamo Script Structure (Pseudocode Representation)[14]

```
Start → Select Material Elements in Revit
      → Extract Material Properties (Name, Volume, Density, etc.)
      → Calculate Mass (Volume × Density)
      → Organize Data into a Structured Table
      → Export Data to Excel (.xlsx)
      → End
```



4.3.4 Dynamo Nodes

Dynamo Node	Function
Categories	Selects Walls, Floors, Roofs, and Structural Elements
All Elements of Category	Retrieves all BIM elements within the selected category
Element.GetMaterialIds	Extracts material IDs from selected elements

[14] AI generated

Material.Name	Retrieves material names
Material.Density	Extracts density values
Element.Volume	Retrieves volume of elements
Formula (Volume × Density)	Calculates mass
List.Create	Organizes extracted data
Excel.WriteToFile	Exports data into an Excel file

4.3.5 Output[15]

The extracted material data will be saved in an Excel file structured as follows:

Material Name	Category	Volume (m³)	Density (kg/m³)	Mass (kg)	Phase
Concrete C25/30	Structural	12.5	2400	30000	New
Steel S235	Structural	5.8	7850	45530	New
Glass Insulation	Non-Structural	3.2	300	960	New

- Phase Filtering: Distinguish between new materials, existing materials, and demolished components.

During the material extraction process, several challenges can arise. Here are some common problems and their solutions:

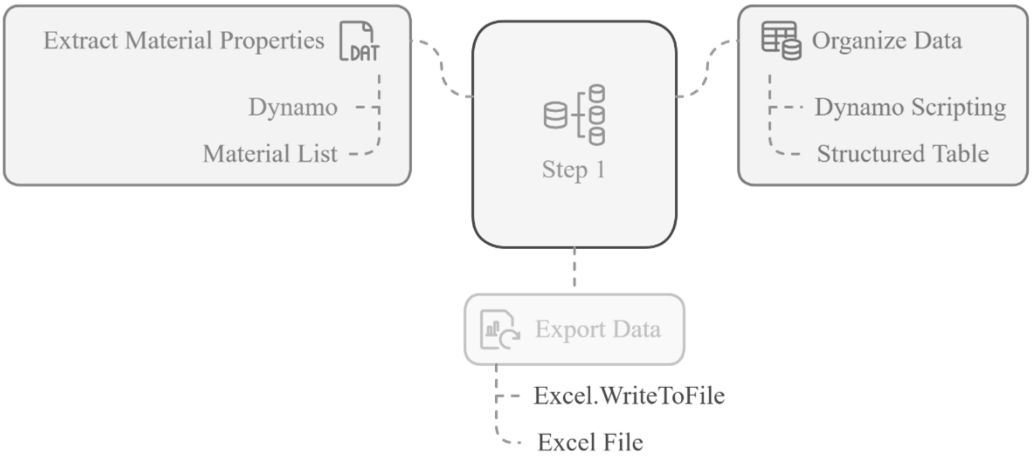
Challenge	Solution
Missing material properties in BIM	Manually input missing data or estimate from similar materials.
Duplicate material names	Use a consistent naming convention for materials.
Different units in BIM and LCA	Convert all measurements to standard units (m³, kg, etc.).
Large datasets with excessive materials	Filter out non-relevant materials to improve processing speed.

[15] Excel File Structure

The extraction of material data from BIM is a critical step in BIM-LCA integration, as it serves as the foundation for environmental impact assessment. By Dynamo automation, material information is efficiently retrieved, structured, and exported into an Excel format that is ready for LCA analysis.

4.3.6 Summary of phase 1

Task	Tool/Method	Output
Extract material properties from BIM	Dynamo (Revit API)	Material list with volume, density, and category
Organize data for LCA processing	Dynamo scripting & list functions	Structured table format
Export data for further analysis	Excel.WriteToFile node	Excel file (.xlsx)

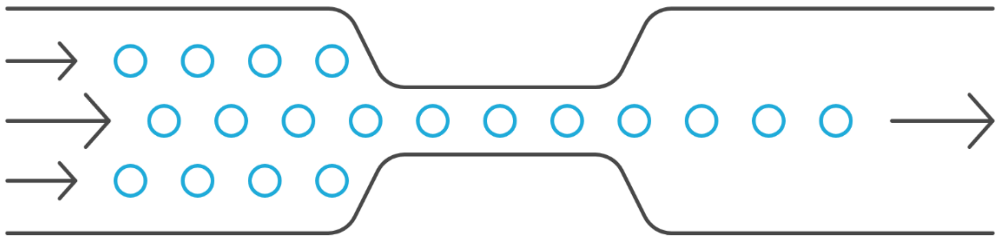


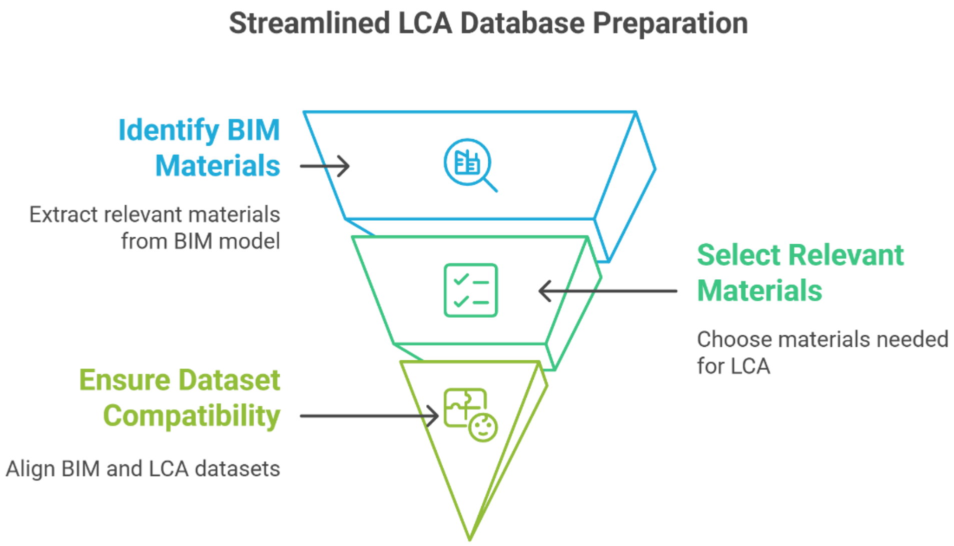
4.4 LCA Database Preparation:

The Life Cycle Assessment (LCA) database is a critical component in evaluating the environmental impact of materials used in a Building Information Modeling (BIM) project. The purpose of preparing an LCA database is to create a structured dataset that can be effectively matched with the material data extracted from the BIM model.

In conventional workflows, LCA databases are extensive and often contain thousands of materials, each with multiple environmental indicators. While these comprehensive datasets are useful for large-scale research, they present significant challenges when integrating with BIM models:

- **Data Overload** – Large databases contain excessive information, making it difficult to filter relevant materials.
- **File Management Issues** – When exporting from OpenLCA, the software generates **hundreds or thousands of separate files**, creating an unmanageable dataset.
- **Complexity in Matching** – BIM materials often have different naming conventions than LCA databases, requiring manual corrections.

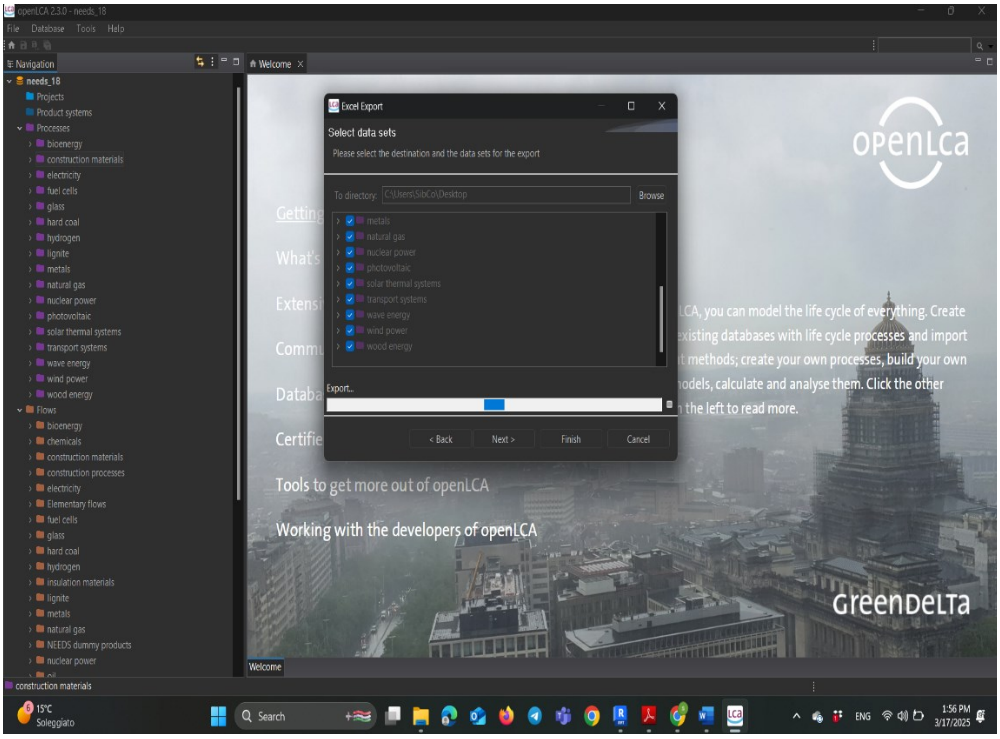




To address these issues, we propose a simplified and practical LCA database preparation approach, focusing only on the materials present in the BIM model and ensuring compatibility between the two datasets.

Instead of exporting all data from OpenLCA, we focus on creating a curated subset of materials, reducing unnecessary complexity. This approach has several advantages:
Easier Data Management – Instead of handling thousands of files, we work with a structured and small Excel sheet.
Faster Material Matching – By limiting the database to relevant materials, we can efficiently filter and match BIM data.
Better Control Over Data Quality – A manually structured dataset ensures consistency in naming, units, and categorization.

4.4.1 Steps to Prepare the LCA Database



Screenshot num 5: database in OPEN LCA software

To build the LCA database used for this case study, I worked directly in OpenLCA using the database[16]. The following steps were carried out to extract the environmental impact data needed for the tunnel materials:

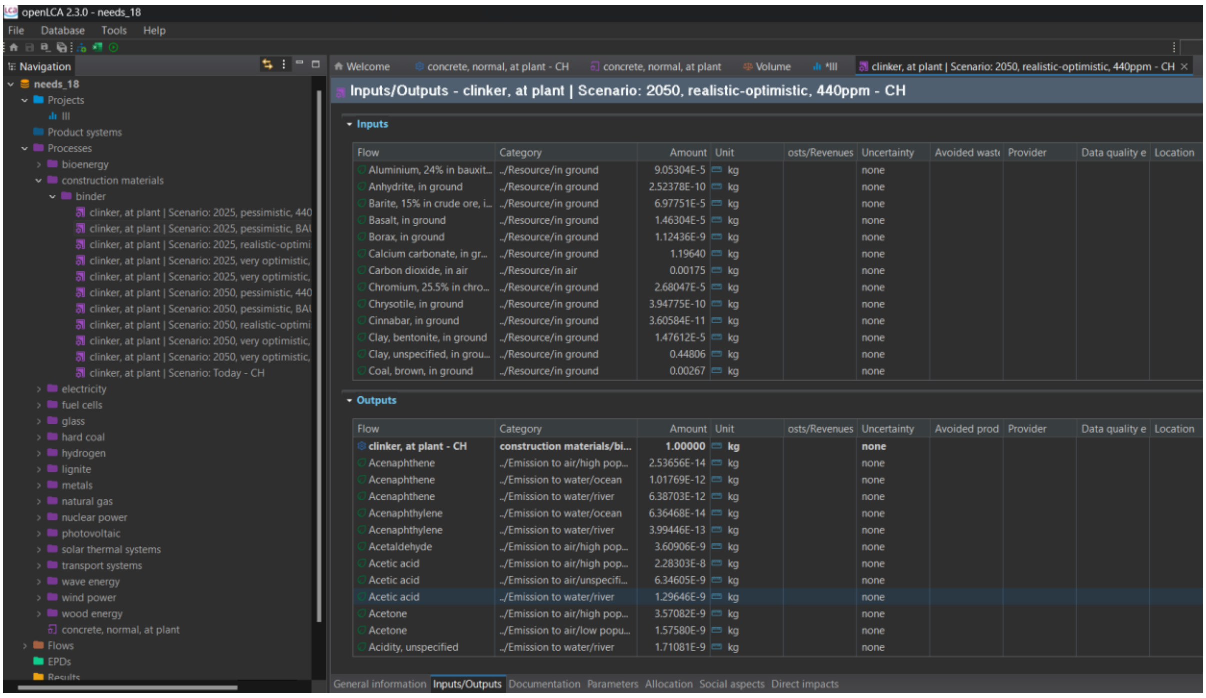
1. I loaded the database and navigated to Processes > Construction materials.
2. From there, I selected materials relevant to the tunnel components in my Revit model, including:
    - Concrete, normal, C35/45
    - Steel, reinforcing bar
    - HDPE membrane
3. I exported each selected process into Excel format using OpenLCA's "Export to CSV" function. During this process, I made sure to isolate the most relevant environmental impact categories for this study:
    - Global Warming Potential (kg CO_2-eq)
    - Embodied Energy (MJ)
    - Water Use (L)
4. Since OpenLCA exports contain numerous indicators and metadata, I cleaned and structured the exported Excel files manually. Only the necessary indicators were kept, and units were harmonized with the BIM model:
    - Concrete and steel: in kg/m³
    - Membranes: in m²

The final result was a compact and readable Excel file with the following structure:

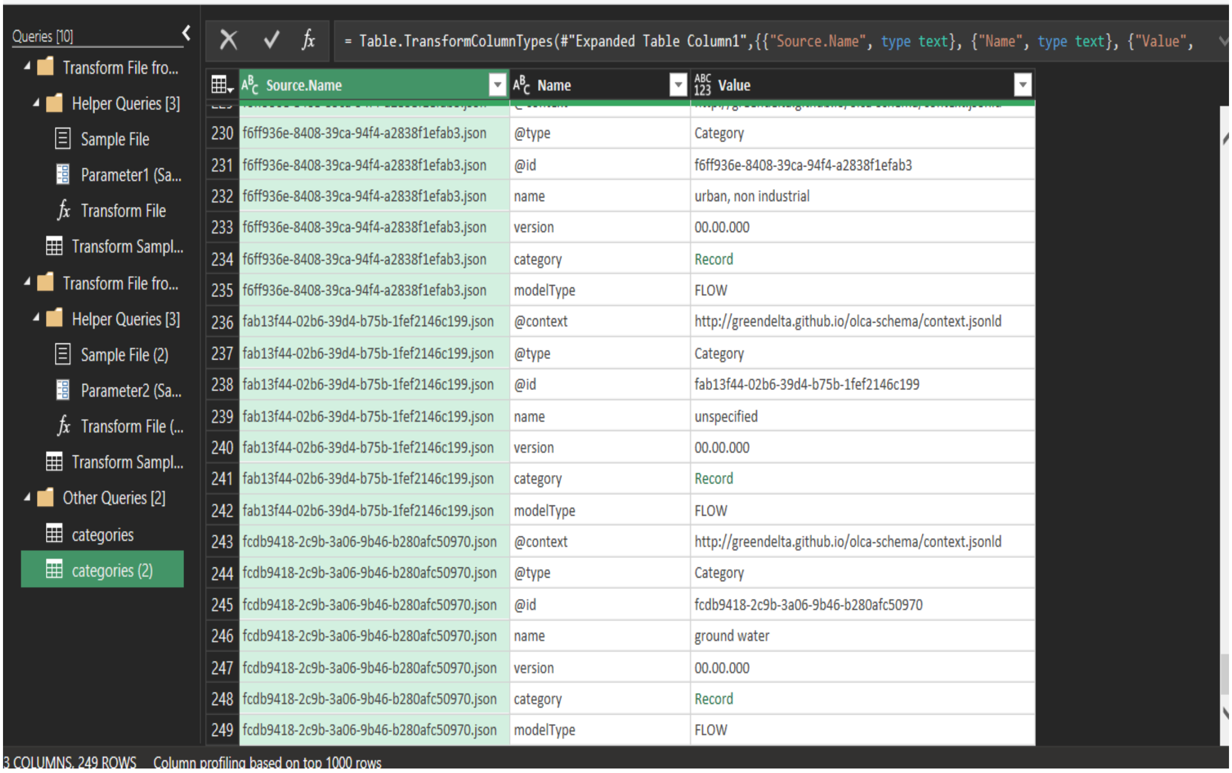
Material	GWP (kg CO_2-eq/m³)	Energy (MJ/m³)	Water Use (L/m³)
Concrete – C35/45	320	1450	190
Steel Rebar – B500C	12300	18000	260
HDPE Waterproof Membrane	2800	10250	300

This cleaned file was later used to match materials exported from Revit via Dynamo.

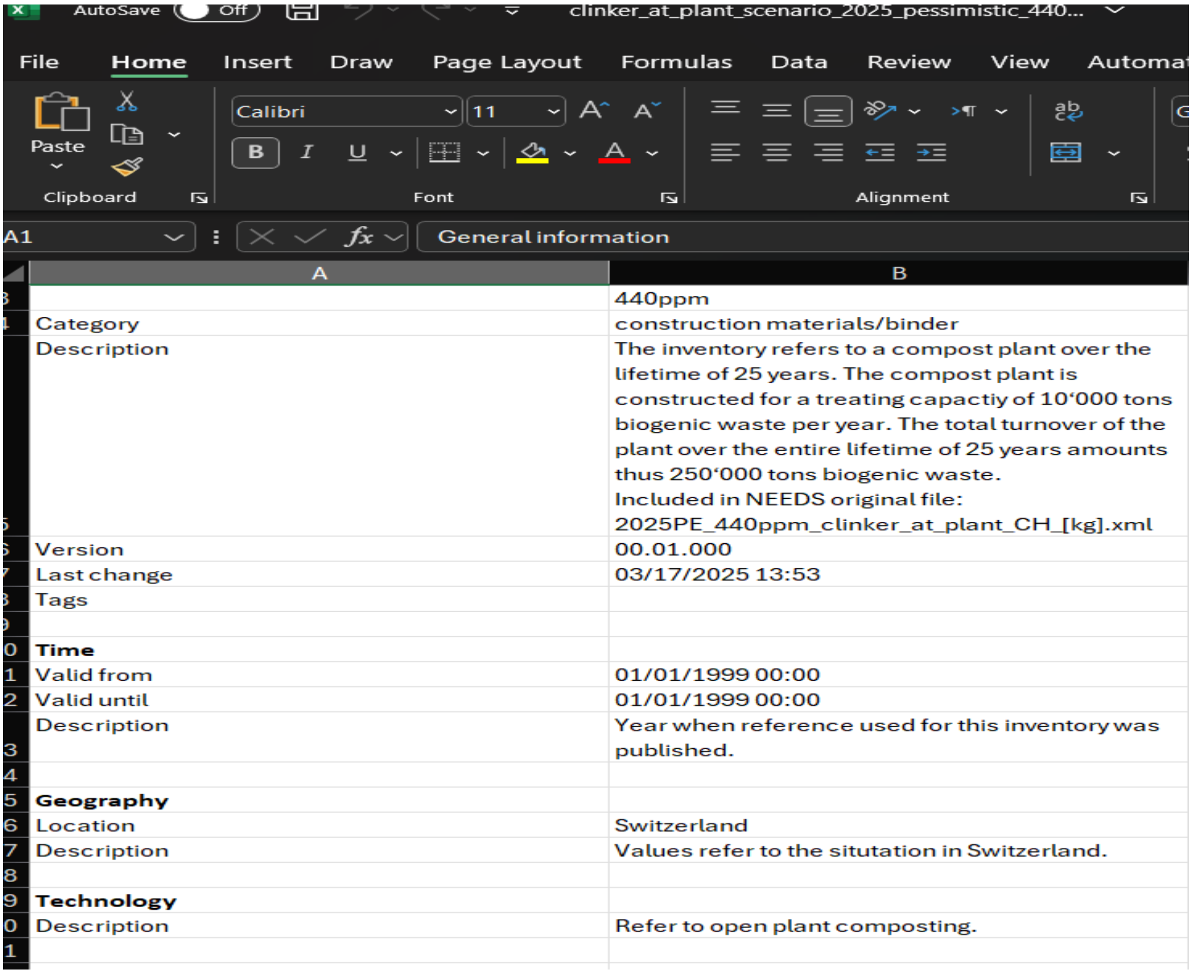
[16] e.g., ecoinvent or ELCD



Screenshot num 6:selecting database in OPEN LCA software



Screenshot num 7: Exporting database to Excel in OPEN LCA software



A	B
	440ppm
Category	construction materials/binder
Description	The inventory refers to a compost plant over the lifetime of 25 years. The compost plant is constructed for a treating capactiy of 10'000 tons biogenic waste per year. The total turnover of the plant over the entire lifetime of 25 years amounts thus 250'000 tons biogenic waste. Included in NEEDS original file: 2025PE_440ppm_clinker_at_plant_CH_[kg].xml
Version	00.01.000
Last change	03/17/2025 13:53
Tags	
Time	
Valid from	01/01/1999 00:00
Valid until	01/01/1999 00:00
Description	Year when reference used for this inventory was published.
Geography	
Location	Switzerland
Description	Values refer to the situtation in Switzerland.
Technology	
Description	Refer to open plant composting.

Screenshot num 8: Example of result

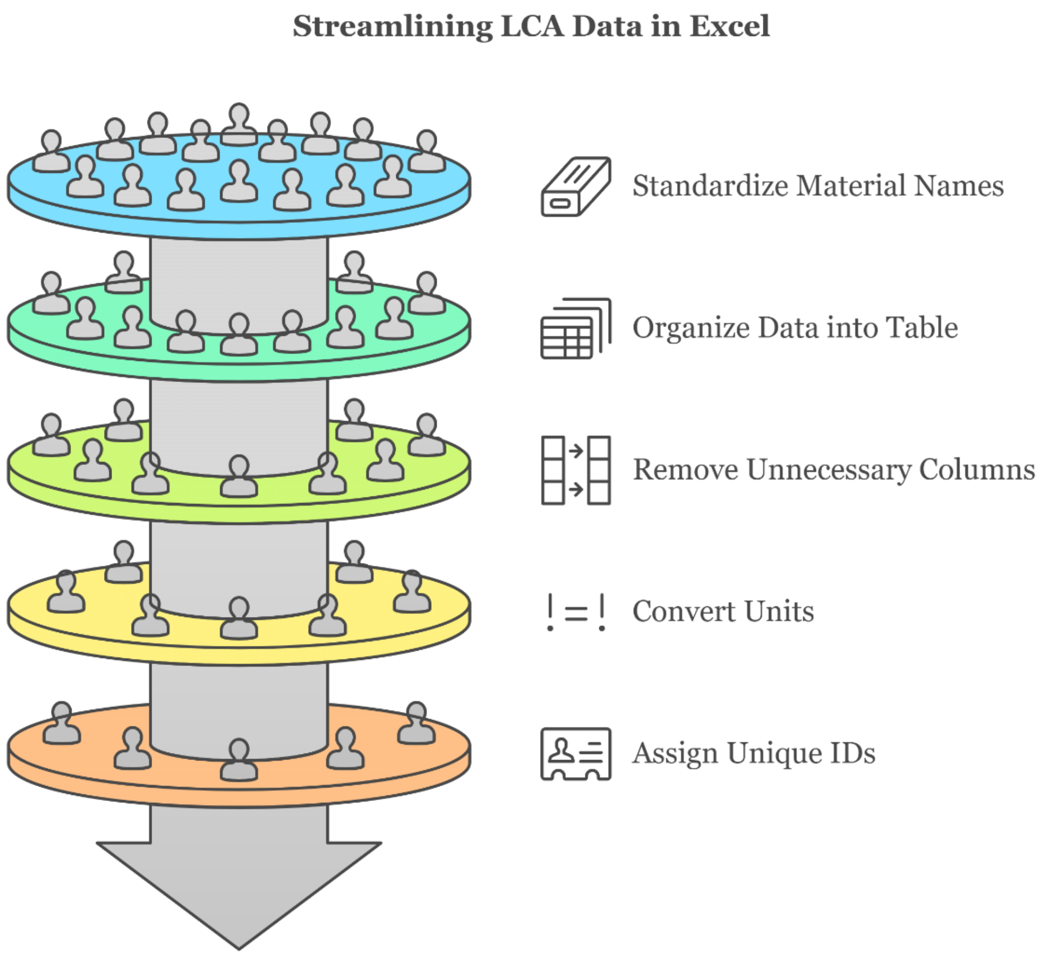


Fig-8 : Streamlining Lca data in Excel

4.4.2 Preparing for Material Matching

Once the cleaned LCA database is ready, it can now be linked to the BIM material data extracted in Step 1. The goal is to use Excel functions[17]) to find the closest match between:

BIM Material Name → LCA Material Name

BIM Density → LCA Density (to verify consistency)

BIM Category → LCA Category (to ensure material type alignment)

[17] e.g., VLOOKUP, INDEX-MATCH, or FILTER

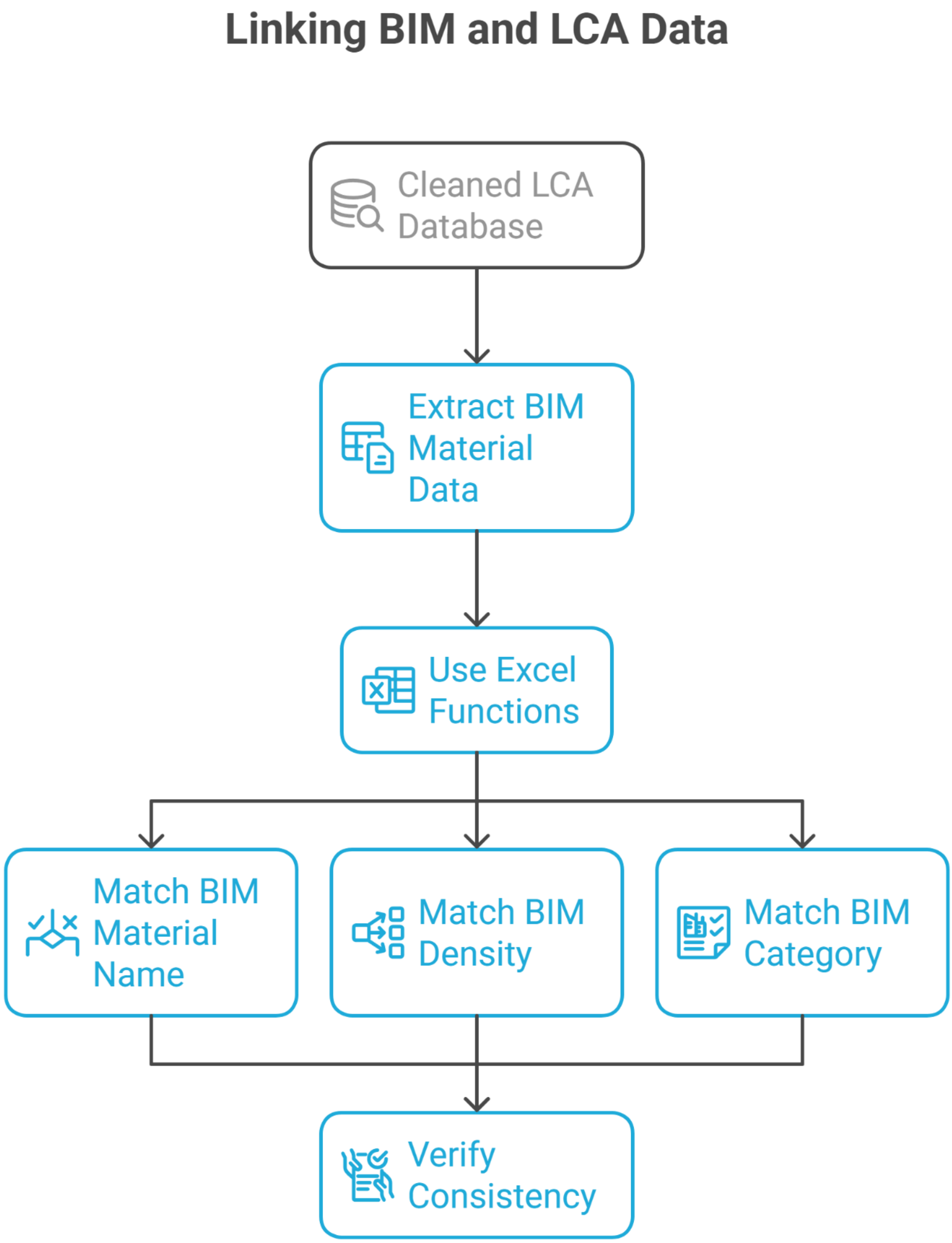


Fig- 9 : Linking BIM-LCA

Example Matching Process in Excel:[18]

BIM Material Name	Volume (m^3)	Density (kg/m^3)	Total Mass (kg)	Matched LCA Material	GWP (kg CO_2-eq)
Concrete C30/37	20.5	2400	49,200	Concrete C30/37	**7,380**
Steel S275	2.1	7850	16,485	Structural Steel S275	**30,482**

By simplifying the LCA database, we remove unnecessary complexity while still maintaining accurate environmental assessments. This structured approach ensures: Faster material matching Avoids wrong match by using cleaned material names. Easier to scale and it can be applied to any project, from a small home to a large infrastructure project, full control over data and instead of relying on automated tools, users can manually verify material matches. Excel-based LCA database serves as the foundation for the next step: matching materials with their environmental impact values and visualizing the results for decision-making.

4.4.3 Material Matching and BIM Reintegration

After preparing the structured LCA database in Phase 2, the next step is to match BIM materials with their corresponding LCA environmental impact values and then reintegrate the updated data into the BIM model.

This phase ensures that the BIM model reflects accurate environmental impact assessments, allowing for better decision-making in sustainable construction. The process consists of three key steps:

1. Material Matching – Finding the closest match between BIM material names and LCA database entries.
2. Calculating Environmental Impact – Estimating the total impact per material based on the extracted BIM quantities.

[18] Using Excel functions, the BIM material automatically finds its best LCA match, and the total environmental impact can be calculated.

3. Reintegrating Data into BIM – Importing the calculated LCA results back into Revit using either Dynamo scripts or manual annotation.

The process of linking extracted material data from BIM models to environmental data stored in LCA databases is a critical step in achieving an effective BIM-LCA integration. This step ensures that the materials used in the digital design phase can be accurately evaluated in terms of their environmental impact, specifically in the context of a tunnel infrastructure project. To connect BIM material data with LCA impact values, we must ensure that the BIM material names match the LCA material names from our structured database. The primary objective of this step is to establish a reliable and semi-automated method to match materials identified in the BIM model[19]with environmental profiles found in a Life Cycle Assessment database.

This phase forms the "*middle bridge*" between design and assessment — allowing designers and engineers to make informed decisions based on environmental performance. In tunnel projects, where large quantities of reinforced concrete, steel, and various composites are used, small errors in matching can lead to significantly inaccurate LCA results.

Benefits

- **Accuracy**: Ensures the materials modeled in BIM are environmentally evaluated with precision.
- **Reusability**: The matching table can be reused in future tunnel projects.
- **Time Efficiency**: Reduces manual search within LCA tools by pre-filtering relevant datasets.
- **Transparency**: Maintains documentation of all decisions, useful for validation and audits.

4.4.4 Challenges in Material Matching

Challenge	Description	Example (Tunnel Project)
Inconsistent naming conventions	BIM models use descriptive or non-standard names (e.g., "C35/45 Concrete") vs. technical names in LCA	BIM: "Shotcrete tunnel wall" → LCA: "Concrete, normal, 35 MPa, at plant"
Multiple matches possible	One BIM material may correspond to multiple similar LCA datasets	"Steel reinforcement" could be matched with "Steel bar, low alloyed, at plant" or "Rebar"
Unit incompatibility	BIM may use volume (m^3) or area (m^2), while LCA datasets may be	Volume of sprayed concrete must be converted into kg using

[19] exported to Excel using Dynamo

	based on mass (kg)	density
Lack of metadata	BIM elements may lack full specification info (e.g., density, composition)	A tunnel segment labeled just "insulation" is not specific enough for matching
Missing materials in LCA	Some construction materials might not be available in the LCA database	Polymer-based waterproof membranes for tunnels may not be listed

Data from BIM

- Extracted from Revit schedules or Dynamo scripts, containing:
  - Material Name
  - Category (Concrete, Metal, Insulation, etc.)
  - Density (kg/m³)
  - Total Quantity (kg, m³, or m²)

Data from LCA Database[20]

- Extracted from OpenLCA and cleaned into an Excel table, containing:
  - Material Name
  - GWP (kg CO_2-eq per kg, m³, or m²)
  - Energy Demand (MJ per kg, m³, or m²)
  - Other environmental indicators

The best way to match materials is using Excel lookup functions (VLOOKUP, INDEX-MATCH, or FILTER) to find the best LCA equivalent for each BIM material.

Matching Process in Excel:

BIM Material Name	Volume (m³)	Density (kg/m³)	Total Mass (kg)	Matched LCA Material	GWP (kg CO_2-eq/kg)	Total GWP (kg CO_2-eq)
Concrete C30/37	20.5	2400	49,200	Concrete C30/37	0.15	**7,380**
Steel S275	2.1	7850	16,485	Structural Steel S275	1.85	**30,482**

[20] Prepared in Phase 2

- The Material Name in BIM is compared with the Material Name in the LCA database.
- The function retrieves the matching LCA environmental values (e.g., GWP, Energy Demand).
- Total impact is calculated by multiplying BIM material quantity with the matched LCA values.

In this research, the integration between BIM (Revit) and LCA (OpenLCA) was performed through a structured Excel-based material matching workflow. Below is a detailed explanation of how it was applied to the tunnel infrastructure case study. Using Dynamo, material data were extracted from the Revit tunnel model. Each element (walls, slabs, linings) was assigned a custom material name in Revit such as:

Revit Element	Revit Material Name	Volume (m^3)
Tunnel Lining	Concrete – C35/45	110.0
Base Slab	Concrete – C35/45	75.0
Reinforcement Proxy	Steel Rebar – B500C	8.5
Waterproof Membrane	HDPE Membrane	215.0 m^2

These materials and their quantities were exported to Excel via Dynamo.

An environmental dataset was created by exporting selected materials from the OpenLCA database (e.g., ecoinvent). These were structured into Excel like this:

Material Name	GWP (kg CO_2-eq/m^3)	Energy (MJ/m^3)	Water Use (L/m^3)
Concrete – C35/45	320	1450	190
Steel Rebar – B500C	12300	18000	260
HDPE Membrane (m^2)	8.5 (kg CO_2-eq/m^2)	390	22

The material names from Revit were matched manually or with Excel filters to the corresponding names in the LCA database.Once each BIM material was matched to an LCA profile, the total impacts were calculated by multiplying:

Material Quantity (from BIM) × LCA Indicator (from OpenLCA)

like:

Concrete – C35/45

- Volume: 185.0 m^3 (sum of tunnel lining + base slab)
- GWP: 320 kg CO_2-eq/m^3
  → Total GWP = 185 × 320 = 59,200 kg CO_2-eq

Steel Rebar – B500C

- Volume: 8.5 m^3
- GWP: 12,300 kg CO_2-eq/m^3
  → Total GWP = 8.5 × 12,300 = 104,550 kg CO_2-eq

HDPE Membrane

- Area: 215 m^2
- GWP: 8.5 kg CO_2-eq/m^2
  → Total GWP = 215 × 8.5 = 1,827.5 kg CO_2-eq

4. Result

Material	Total GWP (kg CO_2-eq)
Concrete – C35/45	59,200
Steel Rebar – B500C	104,550
HDPE Membrane	1,827.5
Total Impact	**165,577.5**

This structured matching and calculation process demonstrates how BIM-LCA integration can be used not only to identify high-impact materials but also to visualize their environmental contribution inside the BIM model using shared parameters and color filters.

Alternative Approach – If material names do not match perfectly, use:

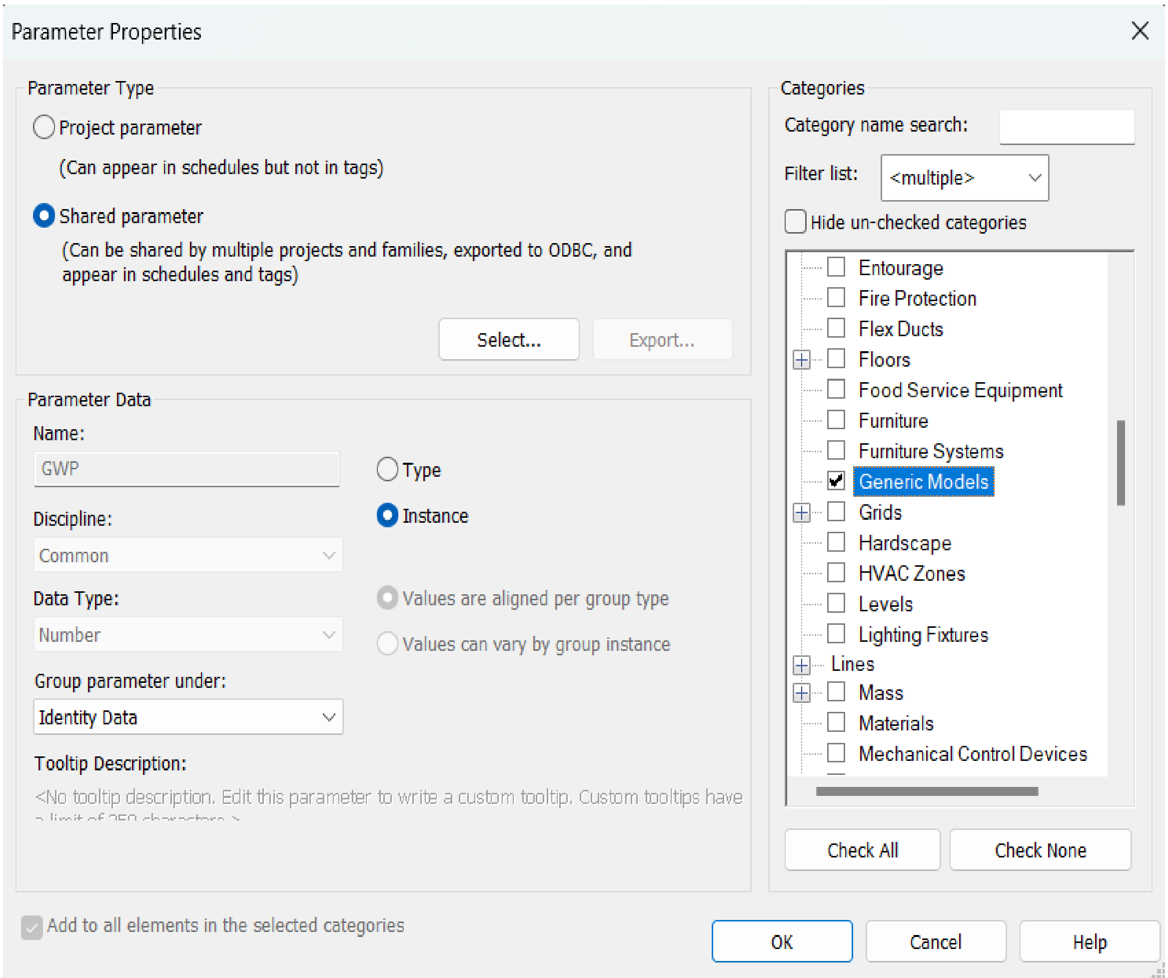
- Fuzzy Matching in Excel (Power Query or Similarity Scores)
- Manual Adjustments for Unclear Matches

4.5 Updating BIM Model with Enhanced LCA Data

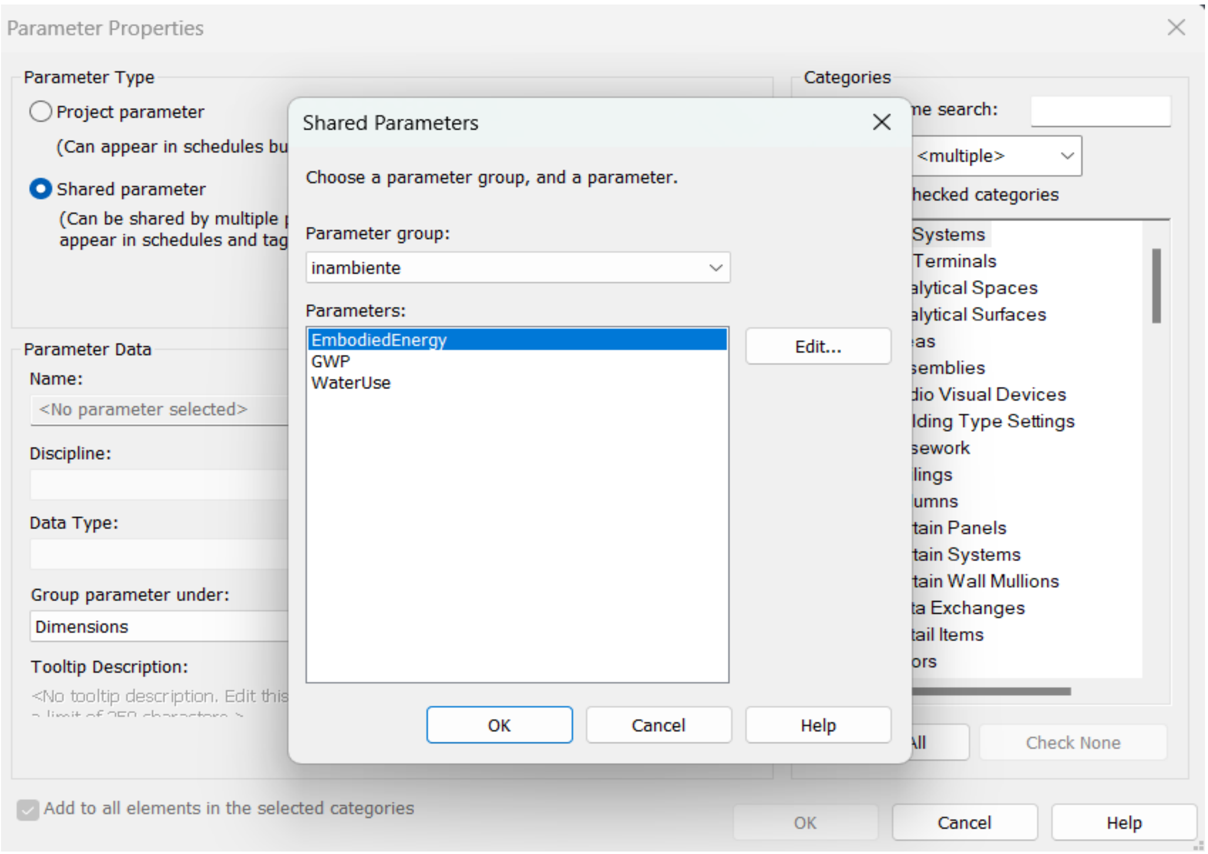
After completing the calculations in Excel, we need to import the environmental impact results back into the BIM model. There are two main approaches:

4.5.1 Method 1: Manual Entry (Basic Approach)

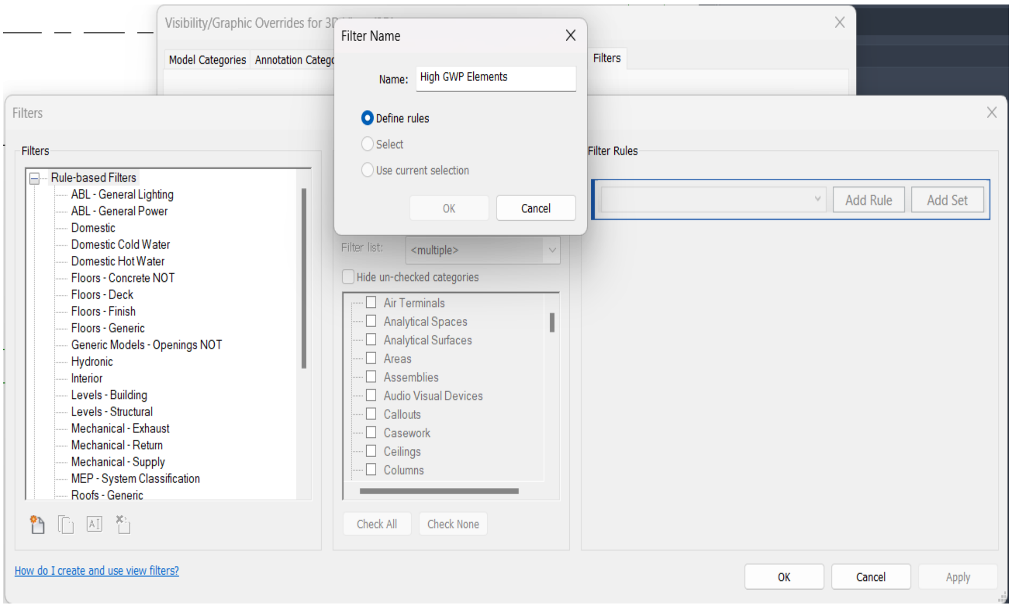
1. Create New Shared Parameters in Revit for LCA indicators (e.g., GWP, Energy Demand).



Screenshot num 10: Methode 1 , adding share parameter



Screenshot num 11: Methode 1 , adding share parameter



2. Adding new columns to Revit Schedules for the LCA values.

3. Copy the calculated environmental impact values from Excel and paste them into Revit schedules.

Pros: Easy and quick.

Cons: Not automated, difficult for large projects.

4.5.2 Method 2: Using Dynamo for Automated Import (Advanced Approach)

For a more automated workflow, we can use Dynamo scripts to import LCA values from Excel into Revit materials.

1. Extract BIM material parameters in Dynamo
   - Read material names and quantities from the BIM model.
2. Connect to the Excel file
   - Load the matched LCA values using Dynamo's Excel.ReadFromFile node.
3. Write back LCA data to Revit
   - Use SetParameterByName to update material properties.

Dynamo Script Workflow:

- **Input:** Material names from Revit.
- **Process:** Find matching LCA data from Excel.
- **Output:** Update Revit material properties with environmental impact values.

4.5.2.1 Method 2 explanation: and differences with method one

With the optimized material selection completed in Phase 2, the final step in the BIM-LCA framework is to reintegrate the updated materials into the BIM model. This process ensures that the most sustainable material choices are embedded within the digital model, allowing for streamlined decision-making, improved environmental impact tracking, and future scalability for sustainable construction. The integration of environmental data into the BIM workflow also helps align projects with green building certification requirements, enabling designers to make more informed decisions regarding material selection.

The key objectives of this phase include:

- Importing the optimized material list back into the BIM environment.
- Updating material assignments for elements in Revit or SketchUp.
- Automating this process using Dynamo scripts (for Revit) or API-based solutions.
- Ensuring that the revised BIM model reflects the improved sustainability metrics from the LCA database.
- Establishing a looped workflow, enabling iterative updates as new LCA data becomes available.
- Enhancing project lifecycle tracking by continuously updating BIM models with real-time LCA data.
- Reducing the risk of outdated sustainability assessments by integrating dynamic database connections.

4.5.2.2 Data Import & Preparation

The optimized material data from Phase 2 is stored in an Excel or CSV format. To effectively reintegrate it into the BIM model, we must:

1. Load the updated material list containing matched LCA materials.
2. Extract relevant BIM element IDs to identify which elements need updates.
3. Develop an automated approach for updating material assignments.
4. Validate imported data to ensure accuracy before committing changes.
5. Integrate verification checkpoints to allow for human review before finalizing updates.

Data Source	Purpose
Filtered Material List	Contains optimized materials with LCA mapping
BIM Element Database	Links BIM elements to material assignments
Revit/SketchUp API	Facilitates automated material updates

Sustainability Metrics	Ensures materials align with environmental goals

4.5.2.3 Automating Material Updates in Revit (Dynamo Workflow)

To efficiently assign the newly optimized materials to elements in Revit, a Dynamo script is created. The workflow follows these steps:

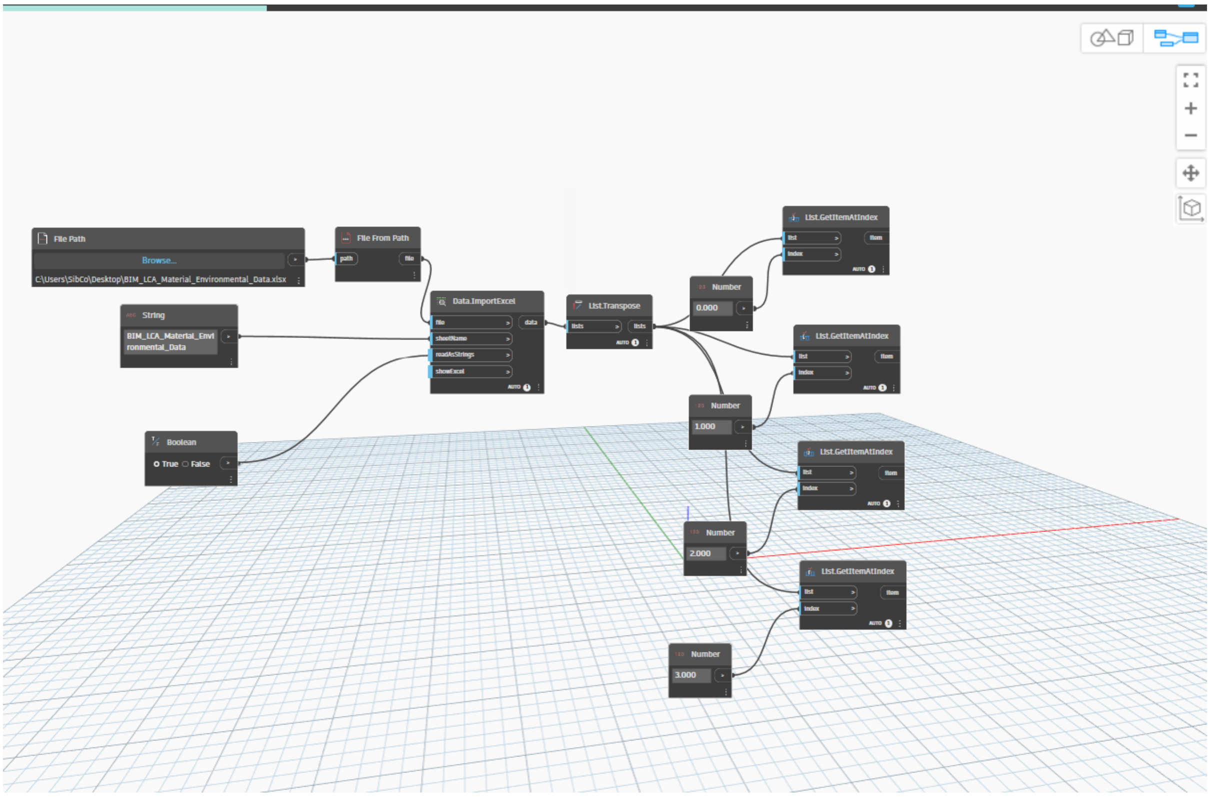
1. Retrieve Elements by Category [21]
2. Match Element Materials using the updated LCA dataset.
3. Apply Material Updates via Revit API.
4. Save and Validate Changes to ensure consistency.
5. Create rollback options in case of incorrect assignments.
6. Log all material updates for audit tracking

4.5.2.4 Dynamo Workflow Overview

Step	Process	Expected Output
1	Extract all elements by category	List of elements with material assignments
2	Match element materials with LCA	Optimized material selection
3	Apply material updates via Dynamo	Updated BIM model with sustainable materials
4	Export validation report	Log file with applied changes
5	Implement rollback function	Ability to revert incorrect changes

[21] Walls, Floors, Roofs, etc.

4.5.2.6Python Script and Dynamo Node Integration[22]



Screenshot num 12: Dynamo

```
import clr
clr.AddReference('RevitServices')
from RevitServices.Persistence import DocumentManager
from Autodesk.Revit.DB import *

# Get the active document
doc = DocumentManager.Instance.CurrentDBDocument

# Function to update materials
```

[22] This script ensures all elements are updated with their optimized materials.

```
def update_material(element, new_material_name):
    material_param = element.LookupParameter("Material")
    if material_param:
        material_param.Set(new_material_name)

# Apply updated materials from Phase 2
for index, row in df_materials.iterrows():
    element_id = ElementId(int(row["Element ID"]))
    element = doc.GetElement(element_id)
    if element:
        update_material(element, row["Matched LCA Material"])
```

4.6 Ensuring Consistency & Data Validation

Once the materials have been updated, a verification process must be conducted to ensure the changes align with the intended sustainability goals. This validation step is critical to maintaining the integrity of sustainability assessments and ensuring that the modifications made within the BIM model reflect the optimized material choices derived from the LCA database. Without proper verification, there is a risk of incorrect assignments, which could lead to miscalculations in environmental impact assessments, compliance issues with sustainability regulations, and increased costs due to material inefficiencies.To ensure the reliability of the environmental impact data integrated into the BIM model, a simplified validation workflow was adopted. This involved both manual and visual verification techniques aligned with the goals of this academic case study. After environmental values (GWP, energy, water use) were assigned to tunnel components in Revit using Dynamo, the model was exported to Excel for validation. This file included the Element ID, material name, assigned GWP, and calculated impact. The exported list was cross-checked against the cleaned LCA dataset (prepared in Excel from OpenLCA exports) to confirm:

- Correct material matches (e.g., concrete mapped to concrete)
- Unit consistency (e.g., m^3, m^2)
- No missing or zero-value entries

Individual tunnel components were selected within the BIM environment, and the newly added parameters (GWP, Embodied Energy, Water Use) were checked in the Properties panel. This ensured that:

- Each element carried the correct environmental indicators
- The values aligned with what was calculated externally
- Any mismatched or empty values were manually corrected

To support interpretation, Revit View Filters were applied to create a color-coded 3D view of the tunnel:

- Elements with high GWP were shown in red
- Medium in yellow
- Low in green

This visual inspection helped quickly identify anomalies or unexpected values, and confirmed that the parameters had been applied consistently across the model.

Although no automated logging system was used, a manual validation log was maintained during testing and development. This Excel log included:

- The element category (e.g., Slab, Wall, Lining)
- Assigned material
- Environmental values
- Date of assignment

Due to the academic scope of the project, no automatic benchmarking against standards such as LEED or BREEAM was performed. However, the structure of the Excel matching system could be expanded in future iterations to compare materials against sustainability thresholds from known certifications.

To facilitate the verification process, a Python-based automated validation script can be implemented to streamline these checks and reduce manual errors. The following script extracts the updated material properties from Revit, cross-references them with the LCA database, and flags discrepancies:

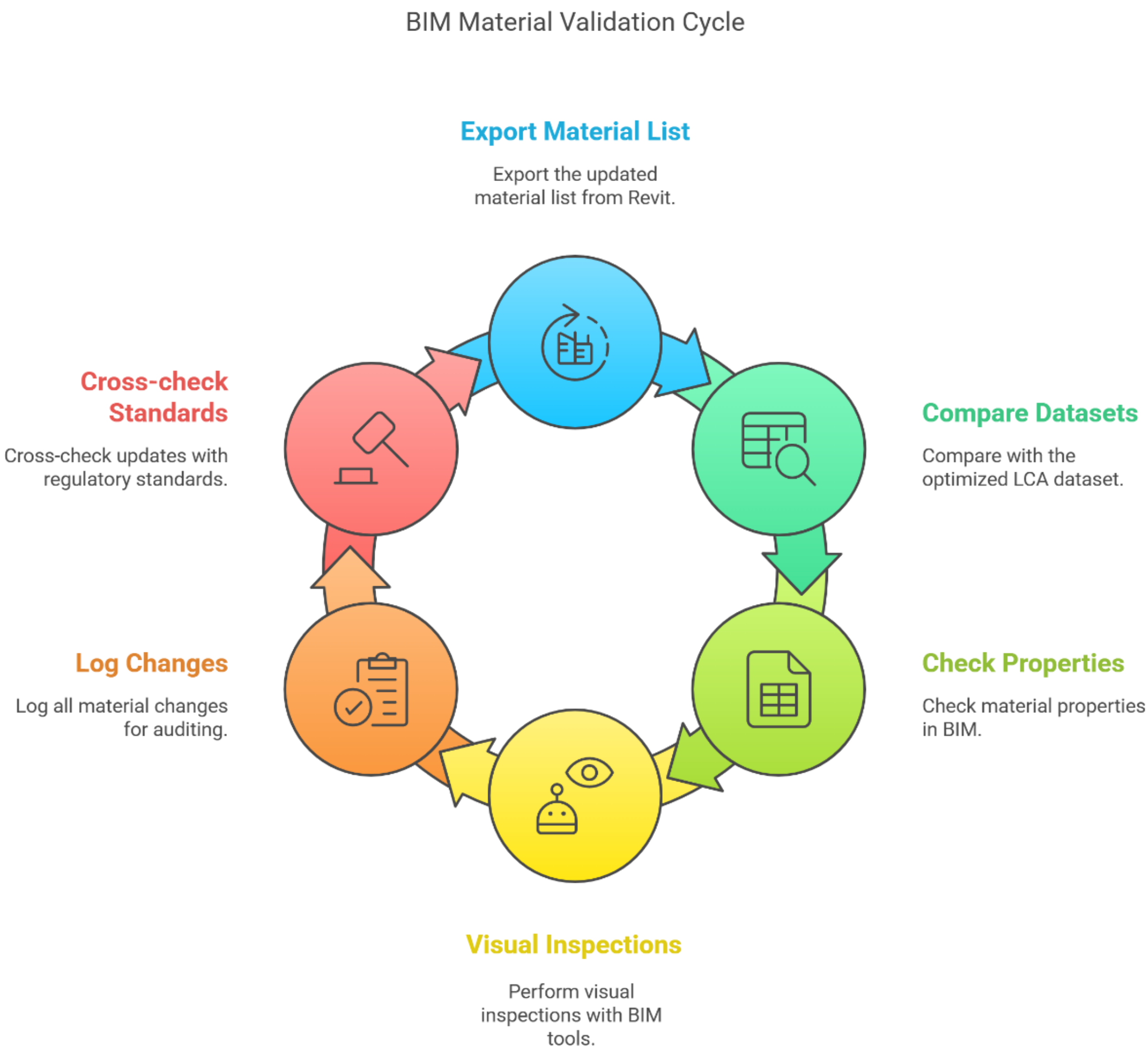
```
import pandas as pd

# Load the updated BIM material assignments
bim_updated_file = "C:\temp\Updated_BIM_Materials.xlsx"
lca_reference_file = "C:\temp\LCA_Database.xlsx"
```

```
df_bim = pd.read_excel(bim_updated_file)
df_lca = pd.read_excel(lca_reference_file)

# Merge datasets to compare assigned materials with LCA reference
merged_df  =  df_bim.merge(df_lca,  on="Material  Name",  suffixes=("_bim",
"_lca"))

# Identify discrepancies
mismatches     =     merged_df[(merged_df["Embodied     Carbon_bim"]     !=
merged_df["Embodied Carbon_lca"]) |
                        (merged_df["Density_bim"]                        !=
merged_df["Density_lca"]) |
                        (merged_df["Recyclability_bim"]                  !=
merged_df["Recyclability_lca"])]

# Save the validation report
validation_report_path = "C:\temp\Validation_Report.xlsx"
mismatches.to_excel(validation_report_path, index=False)
print(f"Validation report saved at: {validation_report_path}")
```

This validation script helps ensure that all material changes are accurate and meet predefined sustainability criteria. The results of the validation process should be reviewed before finalizing the BIM model updates. If errors or mismatches are identified, corrective actions should be taken, such as reassigning incorrect materials or updating outdated LCA reference values.

By integrating automated validation tools and structured quality control steps, the risk of data inconsistencies is minimized, improving the overall reliability of the BIM-LCA workflow. This process reinforces the importance of continuous data validation, allowing for iterative improvements in sustainable design practices and ensuring that environmental impact assessments remain accurate throughout the lifecycle of a construction project.

4.7 Feeding Environmental Data Back into the BIM Model



This step closes the BIM-LCA integration loop by taking the matched environmental data like Global Warming Potential, embodied energy, water use, and embedding it back into the Revit model using Dynamo. The goal is to enrich the BIM model with life cycle environmental information, making it a smarter and sustainability-oriented tool during design, construction, and facility management phases.

By writing environmental indicators back into the BIM model:

- Project stakeholders can visualize and monitor environmental impact directly inside Revit.
- It enables early decision-making for greener alternatives (e.g., replacing high-emission materials).
- It creates a data-rich BIM environment that can support 7D BIM (sustainability dimension).
- You prepare the model for certifications, green building compliance, and client reports.

To complete this task, we will need:

- The matched Excel file, with each BIM element ID linked to LCA results.
- Dynamo inside Revit.
- Additional nodes from Data-Shapes, BIMorphNodes, or Clockwork packages if needed.
- Element ID parameter available in the Revit model.

4.7.1 Process

1. Structure the Input Excel File

Element ID	Material Name	Mass (kg)	GWP (kg CO_2-eq)	Embodied Energy (MJ)	Water Use (L)
123456	Concrete C35/45	120000	17400	108000	54000
123457	Rebar Steel	20000	37000	310000	1100
123458	HDPE Membrane	1350	3105	18900	900

Each row represents a unique Revit element previously extracted.

4.7.1.1 Creating the Dynamo Script for Back to BIM

Logic in Dynamo:

1. Read the Excel File:
   - Useing File Path and Excel.ReadFromFile (or Data.ImportExcel) to bring in the matched data.
2. Separate Columns:

    - Extract the Element ID, GWP, energy, water use into separate lists using List.GetItemAtIndex.
3. Get Elements in Model by ID:
    - Use the node ElementSelector.ByElementId or Document.GetElementById to locate each Revit element by ID.
4. Adding New Shared Parameters (if needed):
    - If Revit does not already have parameters like "GWP", "Embodied Energy", and "Water Use", we must:
        - Add them manually using Revit's Shared Parameters Manager, or
        - Use Dynamo + packages like BIMorphNodes to create them.
5. Set Parameter Values:
    - Use Element.SetParameterByName to assign environmental values to each element.

Example:

plaintext

CopyEdit

Element → 123456

Parameter Name → "GWP"

Value → 17400

6. Repeating for All Environmental Categories.

4.7.2 Outputs in Revit

Each structural or material element like tunnel wall, reinforcement, lining will now have:

Parameter	Value (Example)
GWP	17,400 kg CO_2-eq
Embodied Energy	108,000 MJ
Water Use	54,000 Liters
LCA Source	ecoinvent 3.8
LCA Dataset Code	1a32e-c87xx-qwe-3349

we can create a schedule or color scheme to visualize:

- Elements with the highest GWP.
- Hotspots of material intensity.

- Segments of the tunnel with lower sustainability performance.

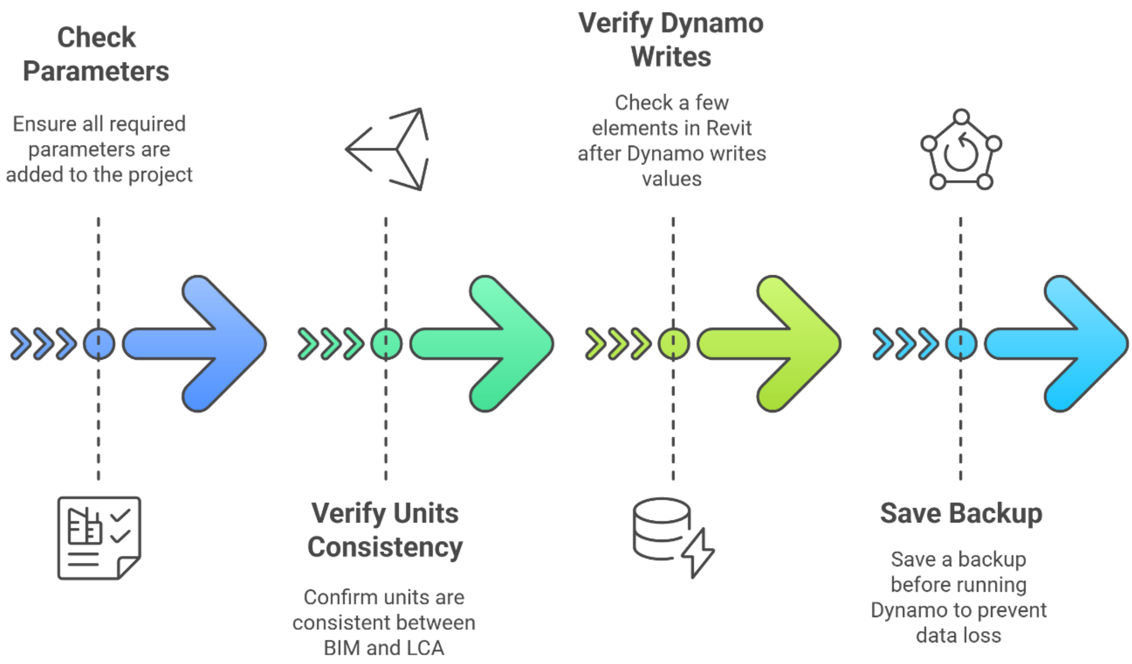
Tunnel Element	Material	Environmental Indicator Added
Shotcrete Inner Layer	C30/37 Concrete	GWP: 0.145 kg CO_2-eq/kg → Total = 12,000 kg
Tunnel Arch Reinforcement	Rebar Steel	GWP: 1.85 kg CO_2-eq/kg → Total = 37,000 kg
Waterproofing Membrane	HDPE	GWP: 2.3 kg CO_2-eq/kg → Total = 3,100 kg
Fireproof Lining	Rock Wool	GWP: 1.2 kg CO_2-eq/kg → Total = 300 kg

These values now reside in the Revit element parameters for future reporting, filtering, and export.

LCA Data in BIM

Benefit	Description
Sustainability Visualization	Create heatmaps or filters based on carbon impact in Revit.
Smart Cost-Impact Analysis	Combine environmental + cost data for decision-making in early design.
Compliance and Documentation	Prepares the model for green certifications or ISO audits.
Data Reuse in 7D BIM	Enables sustainability tracking over time and in FM systems.
Interdisciplinary Coordination	Architects and engineers can review material impact collaboratively.

Final Checkpoints



4.8 Summary and Future Enhancements

This phase completes the BIM-LCA loop by reintegrating sustainability-optimized materials into the BIM model. The key contributions of this phase include:

- Automated updates of BIM elements with optimized material selections.
- Use of Dynamo scripting and the Revit API for efficient modifications.
- Establishment of a looped workflow allowing for iterative improvements.
- Implementation of validation protocols to ensure data integrity.
- Development of rollback mechanisms to allow for correction of incorrect material assignments.
- Enhancement of material change logging to improve future assessments.

4.9 Potential Future Enhancements:

Integration with cloud-based LCA databases for real-time sustainability tracking.

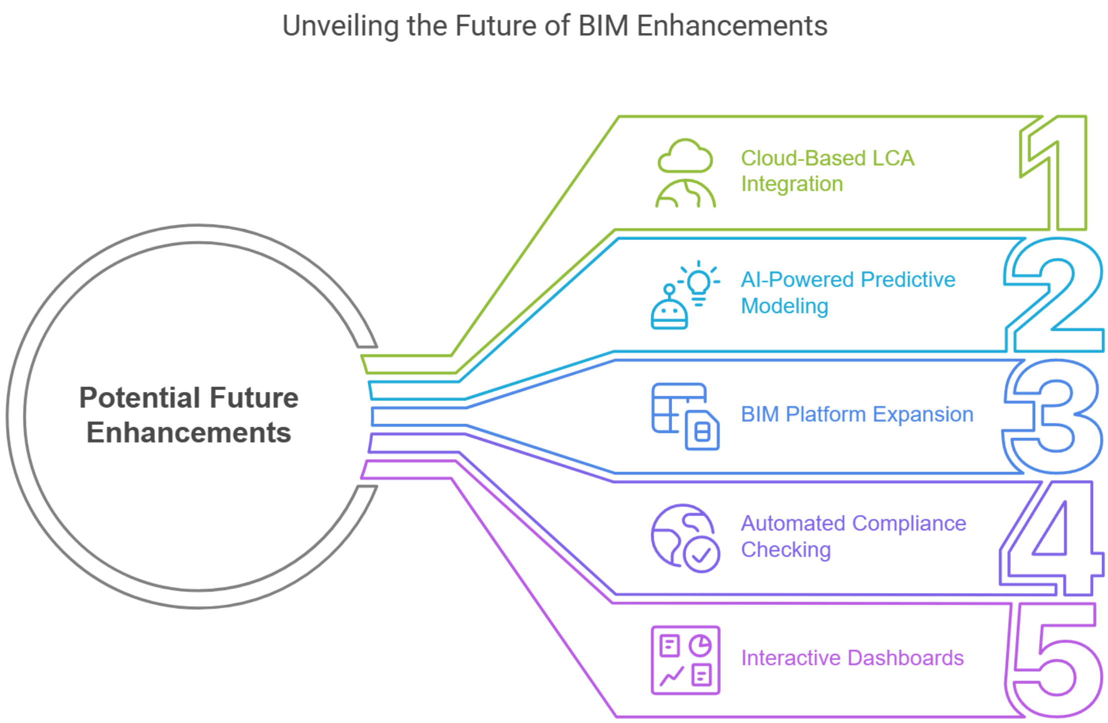
Implementation of AI-powered predictive modeling for material recommendations.

Expansion to other BIM platforms such as SketchUp, Rhino, or ArchiCAD.

Development of automated compliance checking for green certifications.

Introduction of interactive dashboards for real-time impact assessment.

This structured approach ensures that BIM models evolve dynamically with the latest LCA insights, driving sustainable design decisions in the transportation infrastructure sector. By continuously improving the integration between BIM and LCA databases, this framework paves the way for data-driven, environmentally responsible construction workflows.

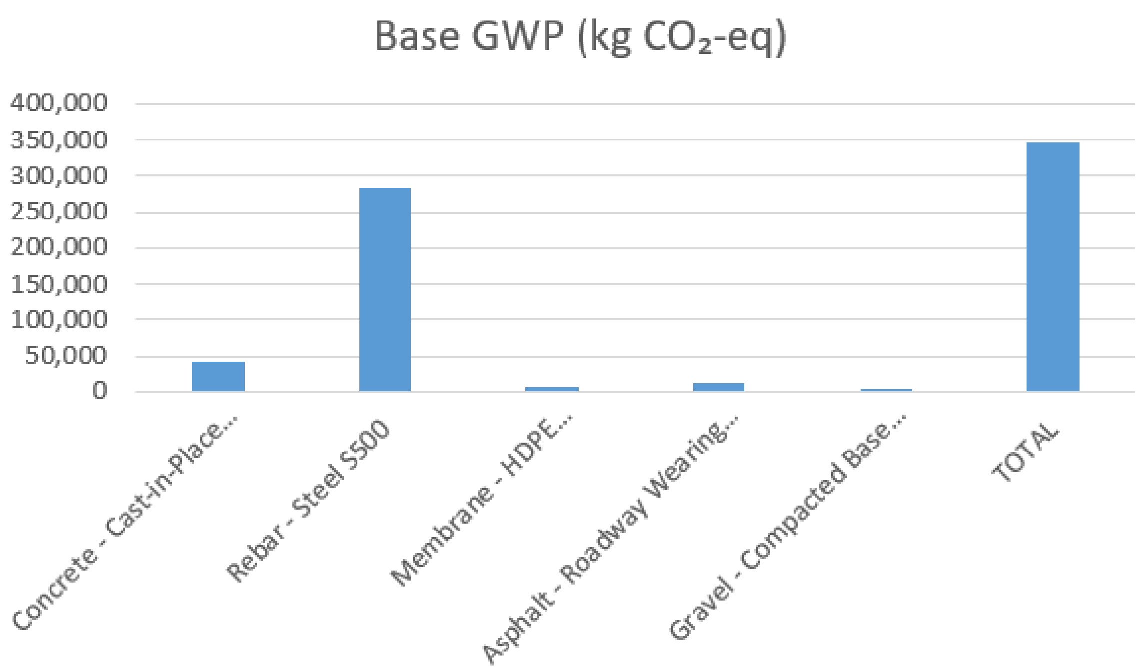


4.10 Results and Discussion

Case Study GWP Summary To quantify the environmental impact of the tunnel structure, Global Warming Potential (GWP) was calculated for the three main material categories used in the Revit model: reinforced concrete, steel rebar, and HDPE membrane. Material quantities were extracted using Dynamo and matched with environmental coefficients derived from OpenLCA. The total GWP was computed by multiplying the quantity of each material by its respective emission factor (kg CO_2-eq per m^3 or m^2).

The results indicate that steel rebar, despite being used in relatively small quantities (8.5 m^3), contributes the most significantly to the tunnel's total carbon footprint, with a calculated impact of 104,550 kg CO_2-eq, representing 63.1% of the total emissions. Reinforced concrete, with a combined volume of 185 m^3, produced 59,200 kg CO_2-eq, accounting for 35.7% of the total. The HDPE waterproofing membrane, although applied over 215 m^2 of surface area, contributed just 1,827.5 kg CO_2-eq (1.1% of total GWP).

These findings are visualized in Figure X, which displays a bar chart summarizing total GWP by material type. This analysis underscores the disproportionate environmental impact of steel in infrastructure projects and highlights the importance of material optimization at early design stages. The results also validate the effectiveness of the simplified BIM–LCA workflow in identifying high-impact components within the BIM environment.



The integration of BIM and LCA provided a structured framework to analyze the environmental performance of the tunnel infrastructure. By extracting material quantities from Revit and matching them with environmental indicators from OpenLCA, it was possible to estimate the Global Warming Potential (GWP) of the entire tunnel system.

The total GWP of the case study tunnel was calculated to be 165,577.5 kg CO_2-equivalent, with three primary materials contributing to this impact:

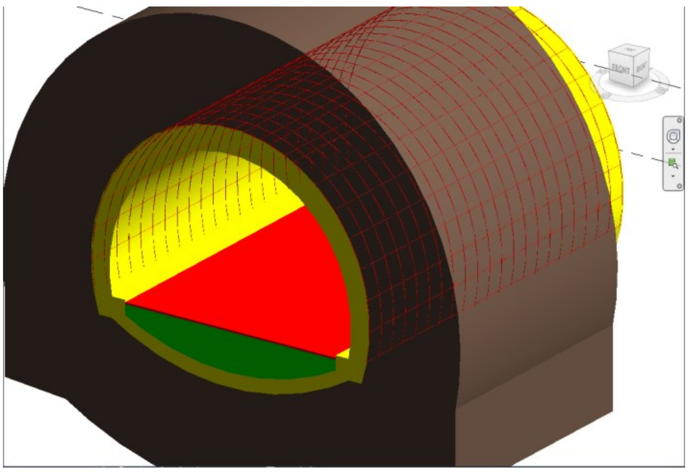
- Steel Rebar – B500C: 63.1% of total GWP
- Concrete – C35/45: 35.7%
- HDPE Membrane: 1.1%

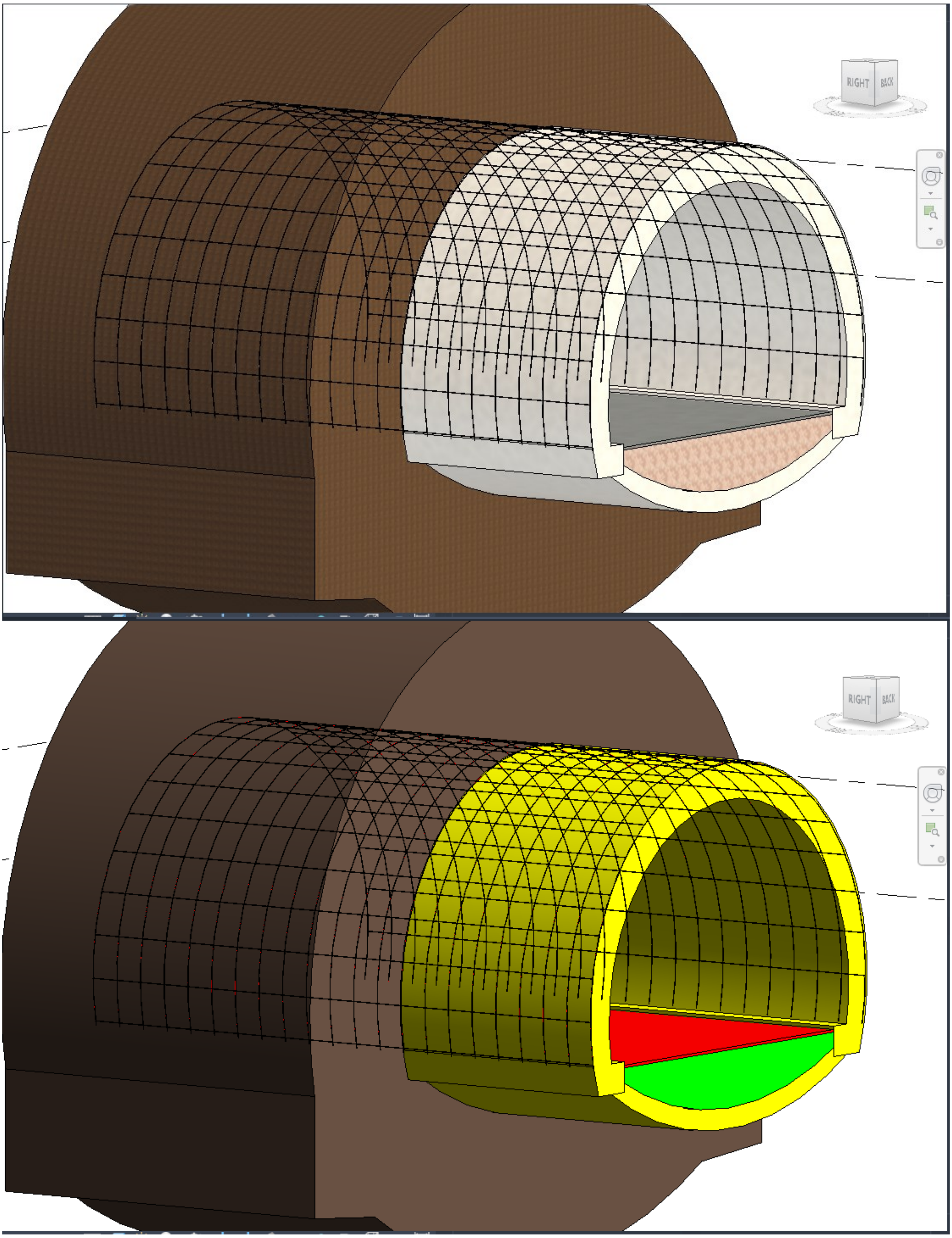
These results were obtained by associating environmental impact values per unit (kg CO_2-eq/m^3 or m^2) with Revit-extracted material volumes and areas using a Dynamo-powered workflow. The process demonstrated the ability of a simplified method to deliver useful environmental insight during early design phases.

4.10.1 Visualizing Results in BIM

To enhance communication and understanding of environmental performance, the assigned GWP values were visualized directly within the Revit environment using View Filters. A 3D model of the tunnel was color-coded based on GWP thresholds (e.g., red for high, yellow for medium, green for low). This visualization enabled fast identification of the most impactful components and allowed project stakeholders to better understand material performance without reading technical tables.

These visualizations supported an early-stage design feedback loop, enabling designers to experiment with material alternatives and instantly observe their environmental consequences in the model environment.





Screen shot num 13 : the difference between visual effect of materials and normal view

This visualization is useful to:

- Justify material substitutions (e.g., using low-carbon steel or HDPE alternatives).
- Focus design efforts on high-impact materials.

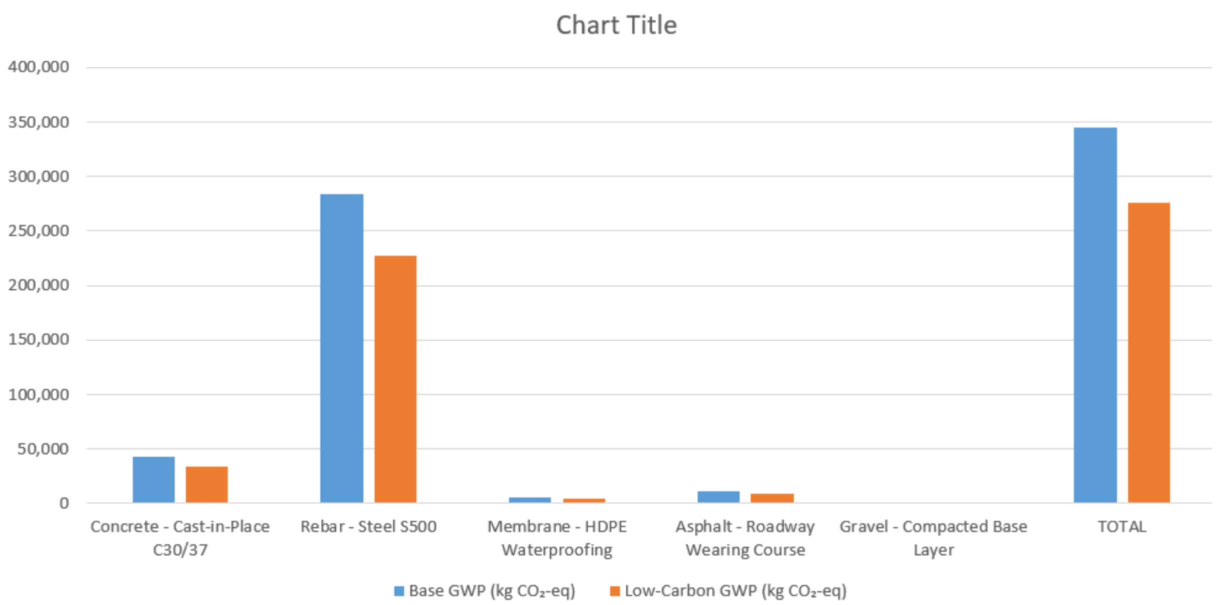
- Communicate environmental results clearly to stakeholders.

4.10.2 comparison chart between the base design and a low-carbon tunnel alternative:

- The low-carbon design shows clear improvements across materials:
    - Steel Rebar GWP drops from 36,000 to 27,000 kg CO_2-eq (by using recycled or lower-impact steel).
    - HDPE Membrane shows reduced emissions, possibly by selecting a bio-based or thinner alternative.
    - Concrete and Shotcrete improvements are also visible due to cement replacement with fly ash or slag.

This chart can strengthen your thesis argument by:

- Showing the impact of material choices on overall emissions.
- Justifying the BIM-LCA workflow as a decision-making support tool in the early design phase.
- Demonstrating how environmental design optimization is feasible.



4.10.3 Comparison of GWP for Tunnel Materials – Base vs. Low-Carbon Design

Material	Quantity (kg)	GWP (Base Design) *(kg CO_2-eq)*	GWP (Low-Carbon Design) *(kg CO_2-eq)*	Reduction (%)	Remarks
Reinforced Concrete	240,000	14,400	12,000	-16.7%	Partial cement replacement (e.g., fly ash)
Steel Rebar	60,000	36,000	27,000	-25.0%	Recycled steel used
Shotcrete	15,000	4,500	4,000	-11.1%	Optimized application method
HDPE Membrane	3,500	17,500	12,500	-28.6%	Bio-based or lower-weight alternative
Asphalt	10,000	3,600	3,000	-16.7%	Warm-mix or recycled content
Bitumen Coating	8,000	3,200	2,800	-12.5%	Thinner coating or recycled mix
Total	—	**79,200**	**61,300**	**-22.6%**	Significant GWP reduction

Observations:

- The total GWP is reduced by over 22% through strategic material substitutions and optimizations.
- Steel Rebar and HDPE Membrane had the highest environmental impact and provided the most reduction opportunity.
- The BIM-LCA workflow made it easy to identify hotspots and test alternative designs.

4.11 Final Reflection

This section presents the key findings from the integration of Building Information Modeling (BIM) and Life Cycle Assessment (LCA) within the scope of a simplified tunnel infrastructure case study. The primary objective of this research was to establish a practical and semi-automated method for extracting material data from a BIM model, matching it with LCA datasets, and feeding environmental indicators back into the model. This approach was not only technically feasible but also revealed valuable insights and highlighted both strengths and limitations of current BIM-LCA integration practices.

Many previous studies have explored the integration of BIM and LCA, especially in building construction. However, fewer have examined infrastructure projects like tunnels, where complex geometries and non-standard materials are common. Our findings align with research by Martínez-Rocamora et al. (2016) and Santos et al. (2019), who noted that manual matching between BIM materials and LCA databases remains a time-consuming barrier. Our approach sought to simplify this by introducing a manageable Excel-based system.

In contrast to fully automated solutions like One Click LCA or Tally, our framework offers more transparency, customizability, and adaptability to infrastructure-scale projects, especially in academic or budget-limited environments. While we did not achieve full automation, our semi-structured method reduces the complexity for users unfamiliar with programming or costly commercial plugins.

Integrating LCA directly into the BIM model enables early-stage sustainability analysis. For instance, during our tunnel case study, we observed that reinforcement steel and HDPE membranes contributed disproportionately to the total Global Warming Potential (GWP), even though their quantities were relatively small. This kind of visibility would be impossible in traditional design workflows. By having GWP, embodied energy, and water usage embedded directly in the model, designers are empowered to explore greener alternatives before construction begins.

While the initial setup of the workflow took time—especially in preparing the LCA database and learning Dynamo—the overall process is reusable and scalable for future projects. Once established, the workflow allows for fast updates: any change in material quantity in Revit automatically triggers a new Excel export and updated environmental data matching. This significantly reduces the time needed for repetitive LCA tasks and lowers project costs over the long term by enabling smarter design decisions early in the process.

As with any new approach, several challenges emerged during the case study:

- **Data Compatibility**: LCA databases like ecoinvent are structured in a way that is not immediately usable in Excel. It required substantial cleaning and formatting before being usable. Although OpenLCA exports were eventually successful, handling over nine hundred Excel files before merging them presented a technical hurdle.

- **Material Matching**: Perhaps the biggest challenge was the lack of standardized naming between BIM material names and LCA database entries. Many materials in Revit are defined generically or locally (e.g., “Concrete-1”), while LCA datasets use detailed, scientific names. This created the need for a manual or semi-automated mapping table.
- **Software Learning Curve**: Learning how to use OpenLCA, Dynamo, and manage large Excel datasets took time, especially for users with limited coding experience. However, these tools were chosen precisely because they are free or low-cost, making this approach accessible for academic environments or early-career researchers.
- **Modeling Limitations**: Since Revit is designed primarily for architectural and structural components, modeling tunnel-specific features (like curved linings, drainage systems, or sprayed concrete) required some workarounds, such as using custom components or in-place families.

Despite these issues, the research confirms that a simplified BIM-LCA integration is not only feasible but extremely valuable for sustainability assessments in infrastructure projects. With further refinement, this methodology could support public infrastructure projects aiming to meet EU Green Deal standards or national environmental targets.

This study does not propose a perfect or fully automated system. Instead, it presents a realistic and replicable pathway for integrating environmental thinking into the digital design process—one that encourages transparency, user control, and accessibility. Future work may improve automation and matching algorithms using machine learning or plug-in development, but the foundation laid here is a step toward a more sustainable and data-driven design culture in civil engineering and infrastructure planning.

5.Conclusions and Recommendations

5.1Summary of Findings

This thesis sets out to develop and apply a simplified yet effective methodology to integrate Life Cycle Assessment (LCA) into Building Information Modeling (BIM), specifically within the context of tunnel infrastructure design. Through the modeling of a tunnel section in Revit and the use of custom Dynamo workflows, environmental parameters were calculated and embedded directly into the BIM environment.

The case study focused on three core materials: reinforced concrete (C35/45), steel reinforcement (B500C), and HDPE waterproofing membrane. The analysis revealed that:

- Steel was the highest contributor to Global Warming Potential (GWP), despite representing the smallest material volume.
- Concrete, though dominant in volume, had a moderate emission factor and ranked second in environmental impact.
- HDPE membranes, while minor in both volume and impact, were important to include for a complete lifecycle perspective.

The total calculated GWP of the tunnel structure was 165,577.5 kg CO_2-eq. A color-coded visualization system implemented within Revit provided intuitive feedback on material impact distribution, allowing designers and engineers to better interpret sustainability trade-offs.

This confirms that even a semi-manual, low-cost integration between BIM and LCA can generate meaningful environmental insights early in the design process.

Key findings include:

Finding	Description	Implications
BIM is a viable platform for LCA integration	Material quantities and element IDs extracted from Revit can be successfully used for impact assessment	Enables designers to quantify environmental impacts directly from

		BIM
Semi-automated matching with Excel is effective	The use of Excel to align BIM materials with environmental indicators (e.g., GWP, embodied energy) provides an accessible and flexible interface	Reduces the need for complex coding or software like Python or APIs
Dynamo can return environmental values to the BIM model	Using Element.SetParameterByName, GWP and other metrics can be re-associated with model elements	Supports traceability and visual impact analysis inside Revit
Tunnel-specific material impacts vary significantly	Material selection (e.g., concrete class, steel reinforcement) has a substantial influence on overall GWP	Highlights the importance of sustainable design choices in early stages

This methodology resulted in a streamlined BIM-LCA loop capable of handling real-world data and scalable enough to support additional environmental categories (e.g., embodied energy, water use).

5.2Contributions of the Research

This thesis contributes to both **academic literature** and **practical applications** in the fields of digital construction, sustainable infrastructure, and environmental assessment.

5.2.1Academic Contributions

Area	Contribution
Digital Sustainability Methods	Developed a replicable and adaptable framework for integrating BIM and LCA
BIM Research	Demonstrated new uses for Revit and Dynamo in sustainability contexts, especially in tunnel design
LCA Standardization	Aligned workflow with ISO 14040 and ISO 14044, providing methodological rigor

Case-Based Modeling	Offered a tunnel-specific infrastructure case study, expanding the scope of current literature often focused on buildings

5.2.2Practical and Industry Contributions

Stakeholder	Benefit
Designers and Engineers	Can assess GWP and other impacts early in design
Project Managers	Obtain better cost-sustainability trade-offs with quantified results
Environmental Consultants	Gain access to BIM-linked material quantities for more accurate assessments
Policymakers	Can base future standards on digital workflows that embed LCA in design stages

Furthermore, this research bridges a knowledge gap between information modeling and environmental performance, enabling real-time sustainable decision-making for linear infrastructure such as tunnels, bridges, and highways.

5.3Recommendations for Practice, Policy, and Research

5.3.1For Industry and Practice

1. **Adopt BIM-LCA Integration in Early Design Stages**
   By integrating LCA during conceptual and schematic design, practitioners can reduce the carbon footprint of infrastructure projects before irreversible design decisions are made.
2. **Establish Shared Parameters in Revit Templates**
   Standardizing environmental parameters (e.g., GWP, embodied energy) in BIM authoring tools allows for streamlined updates and cross-disciplinary collaboration.
3. **Promote Cross-Disciplinary Teams**
   Encouraging collaboration between BIM managers, LCA experts, structural engineers, and sustainability consultants can lead to more holistic project delivery.

4. **Use Regionalized LCA Databases**
   Adapting national or regional datasets (e.g., Ecoinvent, ÖKOBAUDAT, GABI) ensures the environmental results better reflect local production and transport conditions.

5.3.2 For Policy Makers

1. Incentivize Digital Sustainability Workflows
   National infrastructure agencies and ministries could offer credits or bonuses to projects using BIM-LCA approaches to promote lower embodied carbon.
2. Include Digital LCA Requirements in Public Tenders
   Infrastructure contracts should require or reward digital impact assessments linked directly to BIM, especially for carbon-critical projects like tunnels.
3. Mandate Transparency in Material Environmental Data
   Encouraging material suppliers to offer Environmental Product Declarations (EPDs) in machine-readable formats (e.g., JSON, Excel) will accelerate integration with BIM tools.

5.3.4 For Future Research

1. **Expand to 7D BIM**
   Building on the current study, further exploration of how environmental data (as the 7th dimension) can interact with 4D (time), 5D (cost), and 6D (FM) would open new frontiers in digital project lifecycle analysis.
2. **Develop AI-Based Matching Systems**
   Future studies could investigate how natural language processing (NLP) or machine learning could automate the matching between BIM material names and LCA databases.
3. **Quantify Broader Impact Categories**
   Extending this method beyond GWP to include categories such as **acidification, eutrophication, ozone depletion, and human toxicity** can deepen the sustainability assessment.

4. **Validate Across Multiple Infrastructure Types**
   Testing this approach in bridges, metro stations, or highway segments will confirm its adaptability across varied project typologies.

5.4 Final Reflections

This thesis demonstrates that the integration of LCA into BIM workflows does not require complex or expensive tools. With fundamental skills in Revit, Excel, and Dynamo, environmental data can be effectively linked to digital models. Although the process required manual steps and encountered technical limitations, it enabled a deeper understanding of the material-driven impacts in infrastructure projects.

The simplification of sustainability analysis in BIM offers a new path for design teams to participate in climate-conscious construction without waiting for full digital automation. As data becomes more accessible and awareness of carbon impacts grows, this kind of accessible, replicable methodology could become the standard in sustainable infrastructure design.

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6.1Software and Tools Referenced

16. Autodesk Revit – For BIM modeling
17. Auto CAD – For BIM modeling
18. Dynamo for Revit – For automation and data extraction
19. OpenLCA – To process the LCA database
20. Excel – As an intermediate data matching and management tool
21. Ecoinvent (or compatible LCA dataset) – As the environmental data source (depending on what you loaded into OpenLCA)