TOWARDS DIGITAL TWIN FACTORY

BY FOCUSING ON DIFFERENT SCENARIOS FOR LCA AND LCC APPROACHES

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Towards Digital Twin Factory by focusing on different scenarios for LCA and LCC approaches

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Abstract

In the face of escalating climate challenges and rising energy demands, the construction and manufacturing sectors, jointly responsible for over 36% of global energy use and 39% of carbon emissions, must evolve toward sustainability. This thesis presents a holistic framework integrating Digital Twin (DT) technologies, Building Information Modeling (BIM), Building Energy Modeling (BEM), Life Cycle Assessment (LCA), and Life Cycle Costing (LCC) within an industrial retrofit context. The San Benigno Plastic Factory in Ivrea, Italy, serves as a representative case study of a mid-sized European industrial facility, used to test scalable strategies aligned with Industry 5.0 and EU Green Deal goals.

The research develops a digital twin workflow using Revit, DesignBuilder, One Click LCA, and Dynamo to evaluate retrofit scenarios for wall and glazing components based on energy efficiency, environmental impact, and 40-year economic performance. Three wall scenarios, mineral insulation (Rocksilk), green walls, and cavity walls and three glazing types, double, triple, and BIPV, were modeled. Simulations followed DM 2015 and Climate Zone E regulations.

Results show double and triple-glazed windows reduce energy demand by 12–14%, with triple glazing offering minimal additional savings but higher embodied carbon and cost. Hemp insulation showed the lowest embodied carbon but required costly full replacement at year 40. LCA revealed that material production (A1–A3) contributes over 90% of total emissions. Rocksilk and glazing systems were hotspots. Although Solution 1 (hemp and double glazing) had the lowest emissions (10 kg CO_2e/m^2), Solution 2 (mineral and triple glazing) proved more cost-effective (LCC: €4.73M vs. €5.63M).

Automated workflows with Dynamo reduced modeling time, while shared parameters enabled live feedback loops. Data interoperability challenges such as BIM-to-LCA integration and gbXML export issues were addressed using standardized formats and localized databases. Despite slightly lower energy savings, Solution 2 was identified as the optimal balance of cost and performance.

This research contributes a replicable digital methodology for sustainable industrial retrofits, highlights trade-offs between natural and synthetic materials, and supports Industry 5.0 with data-driven, adaptable decision-making. It offers practical value for designers, policymakers, and researchers committed to decarbonizing industrial buildings.

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CHAPTER 1

INTRODUCTION

Chapter 1: Introduction

Climate neutrality and sustainability are critical challenges of the 21st century, especially for industries such as construction and manufacturing, which account for significant energy consumption and environmental impact globally. These sectors are among the largest contributors to carbon emissions, necessitating transformative approaches to achieve the dual goals of resource efficiency and environmental responsibility. Digital Twin (DT) technologies, Building Information Modeling (BIM), Building Energy Modeling (BEM), and Life Cycle Assessment (LCA) have emerged as essential tools to meet these objectives.

Digital Twins create a virtual representation of physical systems, enabling real-time monitoring, optimization, and decision-making. Coupled with BIM and BEM workflows, they facilitate comprehensive energy performance analysis and operational efficiency, while LCA quantifies environmental impacts across a project's lifecycle. This thesis applies these methodologies to the San Benigno Factory as a case study, demonstrating how digital innovation can drive sustainable industrial practices aligned with Industry 5.0 principles.

1.1 Project Overview: San Benigno Factory

The San Benigno Factory, located in Ivrea, Italy, serves as a focal point for exploring the potential of Digital Twin technologies. This medium-sized industrial facility represents a typical example of European manufacturing operations, providing a valuable context for analyzing sustainability and efficiency improvements. Through this case study, the factory is retrofitted with a comprehensive Digital Twin framework, integrating BIM-to-BEM workflows, LCA, and Life Cycle Cost Analysis (LCCA).

The BIM model of the San Benigno Factory incorporates detailed material properties, operational data, and lifecycle parameters. These inputs are used to simulate energy performance and evaluate the environmental and economic impacts of retrofit scenarios. By adopting advanced simulation tools, the Digital Twin enables real-time monitoring and optimization, aligning with the European Green Deal objectives (European Commission, 2019).

1.2 Research Objectives

In recent years, numerous studies have addressed the topics of Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Building Energy Modeling (BEM), recognizing each as a crucial tool in evaluating the sustainability of building projects. However, most of the existing literature tends to focus on these methodologies separately, analyzing either the environmental impact, the economic feasibility, or the energy performance in isolation.

During the research, It is observed a significant gap: there is a lack of comprehensive studies that integrate LCA, LCC, and BEM within a unified BIM-based workflow. This fragmentation can limit holistic decision-making during the design and planning stages of sustainable buildings.

This thesis aims to fill that gap by proposing a combined approach that connects environmental, economic, and energy performance indicators. By doing so, the research intends to demonstrate how a more integrated methodology can lead to more informed, balanced, and sustainable design decisions.

The primary objectives of this research are:

1. Developing Resilient BIM-to-BEM Workflows: Developing a seamless framework to integrate BIM and BEM for accurate energy simulations.

2. Evaluating Lifecycle Impacts: Applying LCA methodologies to quantify environmental effects, focusing on carbon emissions and energy use.

3. Optimizing Economic Viability**:** Using LCC to assess and compare the cost implications of various energy-efficient retrofits.

4. Advancing Human-Centric Interfaces: Enhancing the Digital Twin environment to improve usability, collaboration, and human-system interaction in alignment with Industry 5.0 principles.

5. Improving Data Interoperability: Addressing integration challenges across BIM, BEM, and LCA platforms for comprehensive analyses.

These objectives address both technical and environmental challenges, ensuring that the methodologies developed are scalable and replicable across other industrial contexts.

1.3 Research Questions:

1. How can a reliable and interoperable BIM-based workflow integrating BEM, LCA, and LCC be developed to enable accurate energy simulations and support Digital Twin applications in industrial retrofit projects?

2. How does the integration of LCA and LCC within a BIM-based workflow influence the evaluation of environmental impacts and economic viability of different retrofit solutions?
3. Is it possible to develop a single BIM model that can reliably support Building Energy Modeling (BEM), Life Cycle Assessment (LCA), and Life Cycle Costing (LCC) without redundant data inputs or model duplication?

1.4 Structure of the Thesis

The thesis is structured into the following chapters:

- **Chapter 1: Introduction** This chapter synthesizes existing research on Digital Twin technologies, BIM-to-BEM integration, LCA, and LCC methodologies, focusing on their role in sustainability.
- **Chapter 2: Methodology** Details the research design, data collection methods, and analytical tools used to create the Digital Twin framework for the San Benigno Factory.
- **Chapter 3: Result** Presents findings from energy simulations, LCA, and LCC, discussing their implications for sustainable practices.
- **Chapter 5: Conclusion and Recommendations** Summarizes key contributions and provides actionable recommendations for implementing Digital Twin technologies in industrial retrofits.
- **Chapter 6: References**

1.5 Literature Review

1.5.1 Introduction to Sustainability in Construction

A significant portion of the global environmental impact is attributed to the manufacturing and construction industries, which use 36% of the world's energy supply and contribute roughly 39% of all carbon emissions (Hollberg et al., 2020). More than one-third of the world's greenhouse gas (GHG) emissions come from these industries, which also produce a lot of waste and deplete raw materials. The European Commission has proposed long-term plans like the Renovation Wave and the Green Deal in response to this unsustainable trend. These plans aim to make the built environment a more resilient and resource-efficient system by 2050 and achieve carbon neutrality (Serrano-Baena et al., 2023).

A life cycle approach that incorporates operational, financial, and environmental performance standards from the very beginning of design to deconstruction is necessary to meet these challenges. Workflows for sustainability assessments now require tools like Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Building Information Modeling (BIM), and Building Energy Modeling (BEM). With accuracy and data-supported clarity, these techniques help designers and stakeholders evaluate environmental effects, project long-term economic costs, and enhance energy performance (Santos et al., 2019).

By integrating building materials, geometrical features, and cost parameters into a central digital environment, the use of building information modeling makes multi-dimensional design coordination easier. BIM's usefulness goes beyond design management to include energy modeling, carbon footprint estimation, and scenario analysis when it is expanded to support environmental simulations, especially through LCA and BEM integration (Bueno & Fabricio, 2018). This change lessens the need for reactive redesigns later on by enabling design teams to make sustainability-driven decisions instantly.

By enabling real-time synchronization between the digital and physical assets, digital twin technologies reinforce this integrated framework even more. Throughout the building lifecycle, this enables responsive environmental optimization, predictive maintenance, and ongoing performance monitoring (Santos et al., 2019). Specifically, the combination of BIM and Digital Twin platforms, aided by Internet of Things (IoT) sensors and sophisticated data analytics, allows stakeholders to manage systems in real time, correcting inefficiencies and enhancing asset resilience (Serrano-Baena et al., 2023).

Despite these developments, robust information modeling protocols and structured data interoperability are still necessary for the successful integration of LCA, BIM, BEM, and Digital Twin technologies. Research has indicated that the absence or inconsistency of semantic information in BIM objects restricts automation and lowers the precision of cost and environmental evaluations. In order to address this, Santos et al. (2019) created a BIM-based framework that is backed by Model View Definitions (MVD) and an Information Delivery Manual (IDM), which formalize the data exchanges necessary for precise LCA and LCC calculations.

By providing plug-in solutions that link BIM platforms with LCA databases and cost estimation tools, One Click LCA, Tally, and Open BIM Quantities are examples of useful developments in operationalizing these integrations. Full automation and standardization are still hampered by differences in database completeness, presumptions in environmental impact categories, and incompatibilities between simulation and design software (Bueno & Fabricio, 2018; Hollberg et al., 2020).

Design teams and facility managers can make more informed decisions by combining these digital approaches into a single assessment system. Because of this convergence, conventional linear processes become data-rich, iterative feedback loops that allow for ongoing optimization of lifecycle costs, emissions, and energy use. Construction and manufacturing are thus moving toward performance-based, predictive, and low-carbon pathways as a result of the digitization of sustainability analysis (Serrano-Baena et al., 2023).

This chapter develops findings from a wide range of peer-reviewed literature and technical sources to examine the development and integration of LCA, BIM, BEM, and Digital Twin technologies. These approaches are examined in detail in each of the ensuing sections, which also highlight their theoretical underpinnings, real-world uses, and functions within sustainable design workflows.

1.5.2 Definition of Industry 5.0 Principles

Industry 5.0 is an emerging industrial paradigm that builds upon the foundation of Industry 4.0 but expands its vision by integrating deeper social and environmental considerations. Unlike Industry 4.0, which emphasized automation, digitization, and efficiency through technologies such as AI, IoT, and cyber-physical systems, Industry 5.0 shifts focus toward aligning industrial progress with human-centric values, environmental sustainability, and systemic resilience.

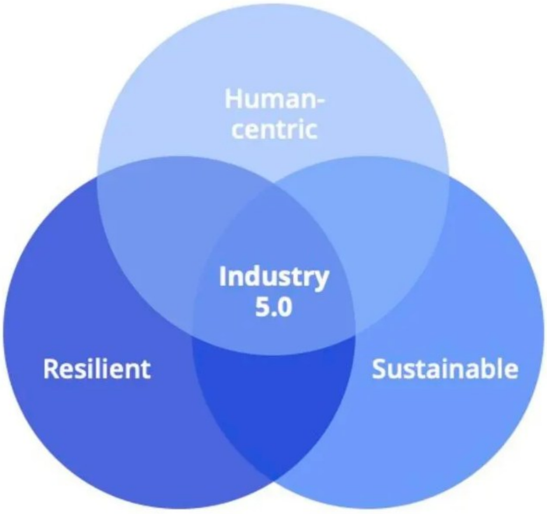


Figure 1 - The Three Pillars of Industry 5.0, European Commission. (2021)

According to the European Commission (2021), Industry 5.0 is characterized by three fundamental principles:

- Human-Centricity

This principle emphasizes the role of human creativity, critical thinking, and well-being in the design and operation of industrial systems. Technologies should complement human capabilities—not replace them—by creating collaborative environments where workers are empowered, valued, and protected.

- Sustainability

Industry 5.0 seeks to ensure that industrial development contributes to the protection and regeneration of natural ecosystems. It promotes the use of circular economy principles, energy efficiency, and reduced carbon emissions to align with global climate and sustainability goals.

- Resilience

The resilience pillar focuses on enhancing the adaptive capacity of industrial systems to cope with unexpected disruptions such as pandemics, economic crises, or geopolitical instabilities.

It encourages diversity in supply chains, redundancy in operations, and digital agility to ensure continuity under stress.

Together, these principles reflect a shift from a purely efficiency-driven model to a value-driven approach, where technological innovation supports broader societal goals including inclusivity, ecological responsibility, and long-term stability.

1.5.3 Building Information Modeling (BIM)

1.5.3.1 BIM Definition:

Building Information Modeling (BIM) refers to a comprehensive digital representation of a building that integrates its geometry, functionality, and individual component behavior into a unified model. This model extends across the entire lifecycle of a building and includes essential data related to construction timelines and production workflows (Eastman, 1999).

BIM is defined as a streamlined process that enhances all phases of a facility's life cycle, from planning and design to construction, operation, and maintenance, through the use of a standardized, machine-readable data model. This model captures and stores all essential information related to a facility, whether new or existing, in a format that can be accessed and utilized by various stakeholders at any stage of the facility's lifespan (Motawa & Almarshad, 2013).

Another definition describes Building Information Modeling (BIM) as an integrated system of policies, processes, and technologies that collectively enable the effective management of essential design and project information in a digital environment throughout the entire life cycle of a building (Succar, 2009).

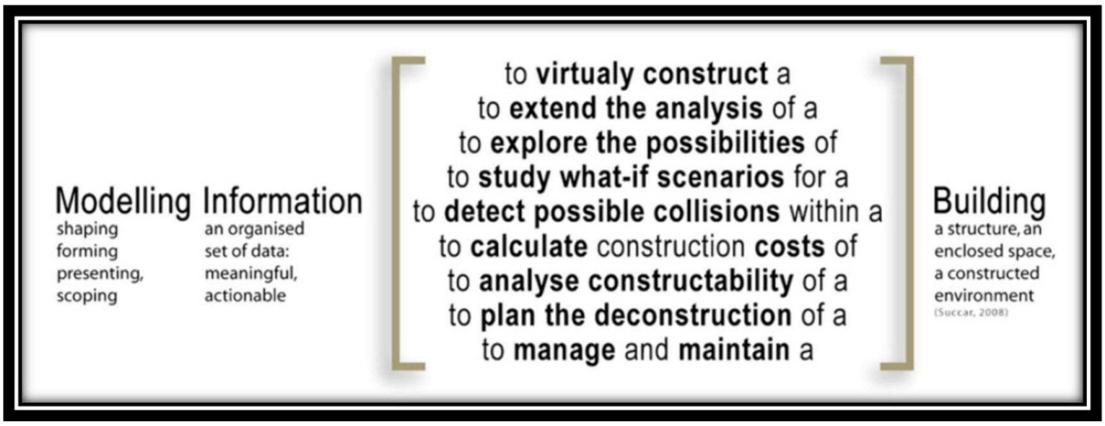


Figure 2 -Some Common Connotations of Multiple BIM Terms (Succar, 2009).

There is a growing emphasis on leveraging the advantages of BIM to enhance the efficiency and effectiveness of a building's operation and maintenance phases throughout its lifecycle (Jordani, 2008).

With the rise of smart building technologies, many facilities are now equipped with intelligent automation systems that utilize a range of sensors to collect extensive real-time data. When this sensor data is integrated with spatial information from a BIM model, it can significantly enhance the evaluation of building system performance and support informed decision-making in facility management and operations (Liu & Akinci, 2009).

1.5.3.2 BIM Dimension:

BIM, often referred to as n-D modeling, has been described by Oraee et al. as both a technological and managerial approach that supports various dimensions of project information throughout the building lifecycle (Oraee et al., n.d.).

Initially, BIM was introduced for its advanced digital parametric modeling features, offering clear advantages over traditional CAD tools. Over time, however, BIM evolved beyond just geometric representation, expanding into an n-D modeling framework. Time became the fourth dimension, cost the fifth, and aspects such as sustainability, energy performance, project lifecycle, safety, and facility management were integrated as the sixth dimension. The seventh dimension is often associated with either sustainability or facility management, while some studies identify accident prevention as the eighth dimension (Alexander, 1996).

According to the voluntary technical standards UNI 11337, which guide digital construction information management in Italy, BIM dimensions can be classified as follows:

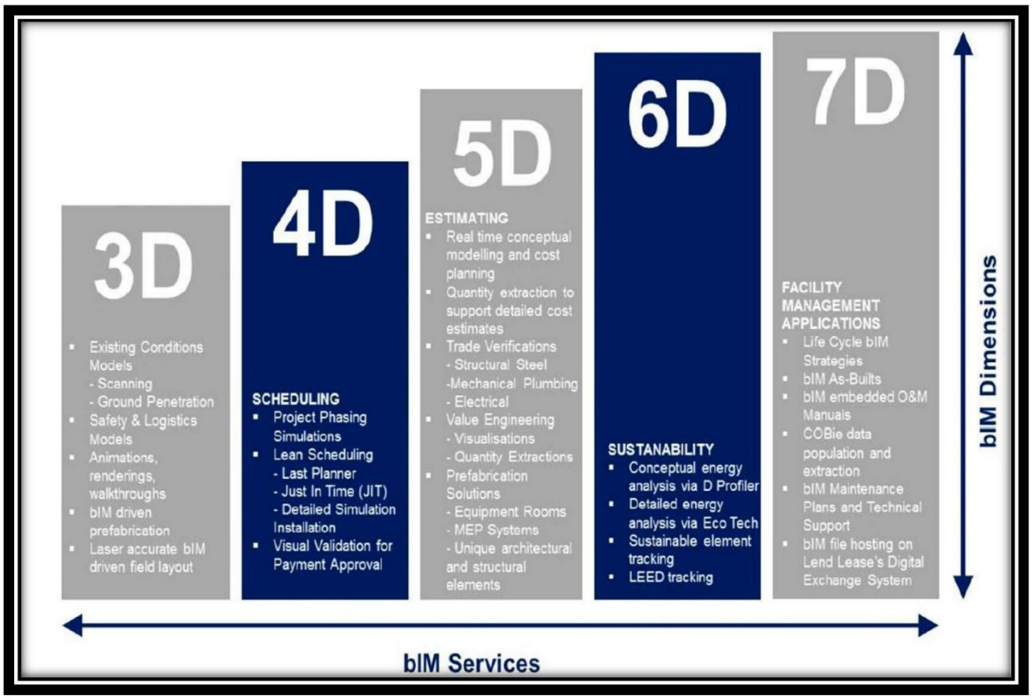


Figure 3 - BIM dimensions (Karimi, 2021.)

3D involves traditional three-dimensional modeling, allowing the visualization of the building throughout its lifecycle and helping to prevent design and execution errors.

4D introduces time management by integrating scheduling into the model, which supports better planning and reduces disruptions during project development and building use.

5D incorporates cost estimation and economic control, enabling comprehensive budget management when combined with 3D and 4D data.

6D focuses on the management and maintenance of the building across its entire lifecycle, improving operational efficiency.

7D addresses sustainability, emphasizing energy performance analysis from the design phase to promote energy-efficient and environmentally responsible buildings. (Karimi, 2021.)

1.5.4 Life Cycle Assessment (LCA)

1.5.4.1 Framework and Importance

Life Cycle Assessment (LCA) is a systematic method for evaluating the environmental impacts of products, processes, or systems throughout their lifecycle. Standards like ISO 14040/14044 and EN 15978 ensure consistency and comparability in LCA studies (Shibata et al., 2023; Gao et al., 2024). The methodology encompasses stages such as raw material extraction, manufacturing, transportation, use, and end-of-life disposal.

LCA provides critical insights into both embodied and operational carbon. For instance, Gao et al. (2024) demonstrated that prefabricated buildings achieve a 9.61% reduction in carbon emissions compared to traditional construction methods, highlighting the importance of material efficiency and sustainable practices.

The process operates under the ISO standards 14040 and 14044 by establishing the fundamental principles which define the assessment procedure across four stages:

- Goal and Scope Definition: The first step establishes the assessment's primary objective. The study's extent and detail get determined by the established assessment goal. The determination of functional unit and system boundaries depends on data quality and availability.
- Life Cycle Inventory (LCI): This phase involves the identification and quantification of all material and energy flows and waste generation and emission production across the functional unit. The data utilized for LCI analysis are either primary data collected

firsthand or secondary data obtained from LCA databases and Environmental Product Declarations.

- Impact Assessment: The assessment evaluates the possible environmental effects through the examination of inventory data.
- Interpretation: The concluding evaluation steps involve the review of previous results to form conclusions which assess the findings against initial study objectives.

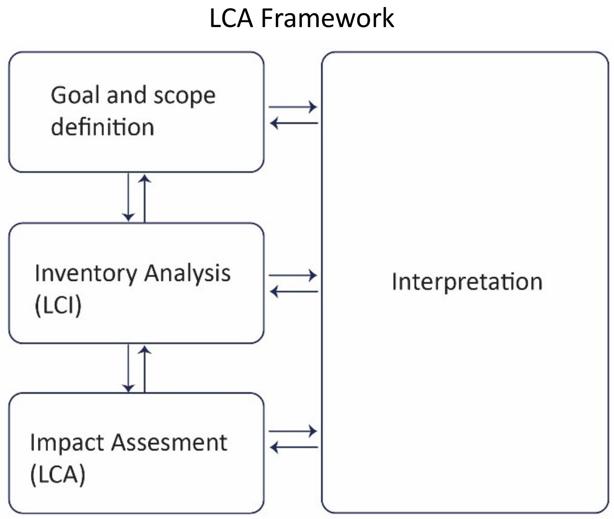


Figure 4 - Diagram of the structure of the LCA based on ISO 14040/14044 - figure was redrawn based on ISO 14040/14044 standards.

The chart below provides a summary of EN 15804, a key standard used for conducting Life Cycle Assessments (LCAs) in the construction industry. It outlines the main environmental impact categories considered in this framework. While EN 15804 is widely used, there are other impact assessment methods available that may include slightly different sets of categories.

Impact Category / Indicator	**Unit**	**Description**
Global warming	kg CO_2-eq	Indicator of potential global warming due to emissions of greenhouse gases to air
Ozone depletion	kg CFC-11-eq	Indicator of emissions to air that cause the destruction of the stratospheric ozone layer
Acidification of soil and water	kg SO_2-eq	Indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides
Eutrophication	kg PO_4^{3-}-eq	Indicator of the enrichment of the aquatic ecosystem with nutritional elements, due to the emission of nitrogen or phosphor containing compounds
Photochemical ozone creation	kg ethene-eq	Indicator of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight

Depletion of abiotic resources – elements	kg Sb-eq	Indicator of the depletion of natural non-fossil resources
Depletion of abiotic resources – fossil fuels	MJ	Indicator of the depletion of natural fossil fuel resources
Human toxicity	1,4-DCB-eq	Impact on humans of toxic substances emitted to the environment (Dutch version of EN15804 only)
Fresh water aquatic ecotoxicity	1,4-DCB-eq	Impact on freshwater organisms of toxic substances emitted to the environment (Dutch version of EN15804 only)
Marine aquatic ecotoxicity	1,4-DCB-eq	Impact on sea water organisms of toxic substances emitted to the environment (Dutch version of EN15804 only)
Terrestrial ecotoxicity	1,4-DCB-eq	Impact on land organisms of toxic substances emitted to the environment (Dutch version of EN15804 only)
Water pollution	m^3	Indicator of the amount of water required to dilute toxic elements emitted into water or soil (French version of EN15804 only)
Air pollution	m^3	Indicator of the amount of air required to dilute toxic elements emitted into air (French version of EN15804 only)

Table 1 - Environmental impacts categories from EN15804 standard - Redraw by authors

1.5.4.2 Life Cycle Stages

Implementing a Life Cycle Assessment (LCA) requires a comprehensive understanding of the various stages in a building's life cycle. This structured approach allows professionals to systematically assess environmental impacts at each phase, enabling stakeholders, particularly architects and engineers, to identify opportunities for reducing environmental burdens and optimizing sustainability across different life cycle phases (Cabeza et al., 2014). By analyzing the environmental consequences of inputs, outputs, and related impacts throughout a building's lifespan, decision-makers can better understand how design choices affect long-term performance.

A core strength of the LCA methodology lies in its phased structure. Recognizing and distinguishing between these life cycle stages enhances the capacity to compare conventional design scenarios with optimized ones. In subsequent chapters, specific stages from this framework will be selected for further analysis, including Business-As-Usual (BAU) comparisons and sustainable design alternatives (Dixit et al., 2012). The structure of these stages is established by the European standard EN 15978:2011, titled *Sustainability of Construction Works – Assessment of Environmental Performance of Buildings – Calculation Method*. This standard, developed by the European Committee for Standardization (CEN), provides a harmonized methodology for assessing environmental performance across a building's full life cycle (EN 15978, 2011).

The life cycle modules, illustrated in Figure , are divided into distinct stages. Modules A1 to A3 (the Product Stage) encompass raw material extraction, transportation to the manufacturing facility, and the actual manufacturing process. These phases involve all flows of materials, products, and energy, including waste processing up to the point of the product's final formation. Notably, this stage focuses exclusively on the building and its components, excluding furnishings and appliances (Chastas et al., 2016).

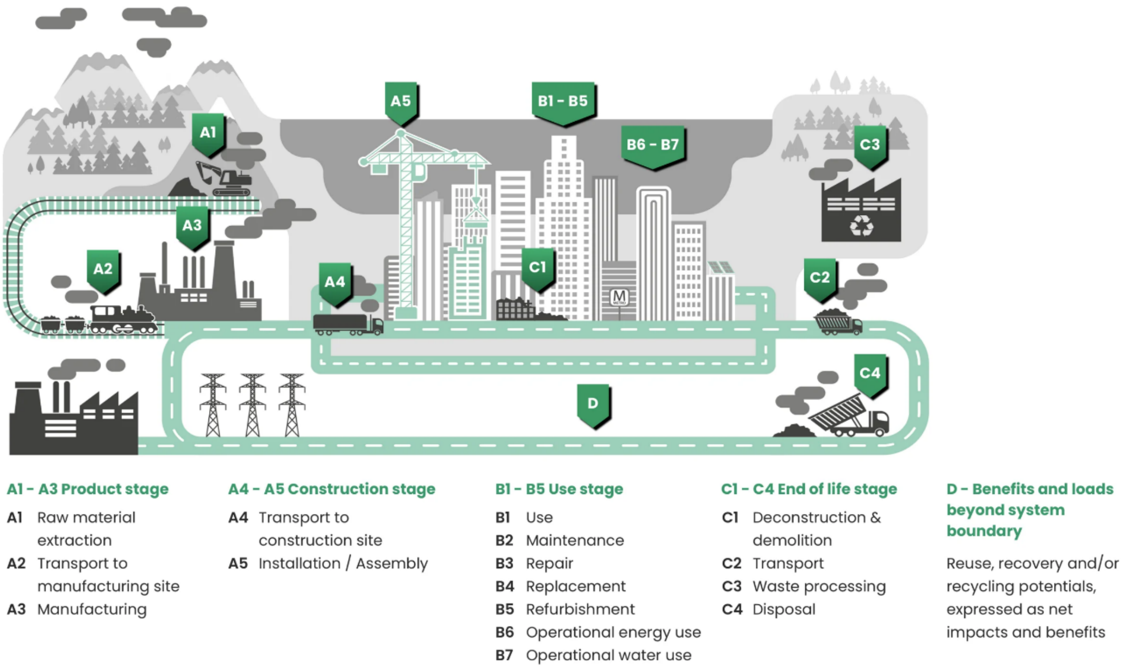


Figure 5 - Schematic classification of life cycle stages according to the EN 15978 standard (One Click LCA, 2023).

Modules A4 and A5 represent the Construction Process Stage, covering transportation to the site and the installation or assembly processes. Environmental impacts at this phase include energy use, transportation emissions, and potential material losses.

Modules B1 to B7 refer to the Use Stage, which spans several decades (typically 60–80 years). This stage accounts for the building's operation, including energy and water consumption (B6 and B7), and interventions such as maintenance, repair, replacement, and refurbishment (B2–B5).

The End-of-Life Stage (C1 to C4) addresses processes like deconstruction, demolition, transportation of waste, processing, and final disposal. Finally, Module D extends beyond the system boundary to account for reuse, recovery, and recycling potentials. This module aligns with circular economy principles and reflects a “cradle-to-cradle” perspective, allowing environmental credits from material recovery to be accounted for after a building’s useful life (Pomponi & Moncaster, 2016).

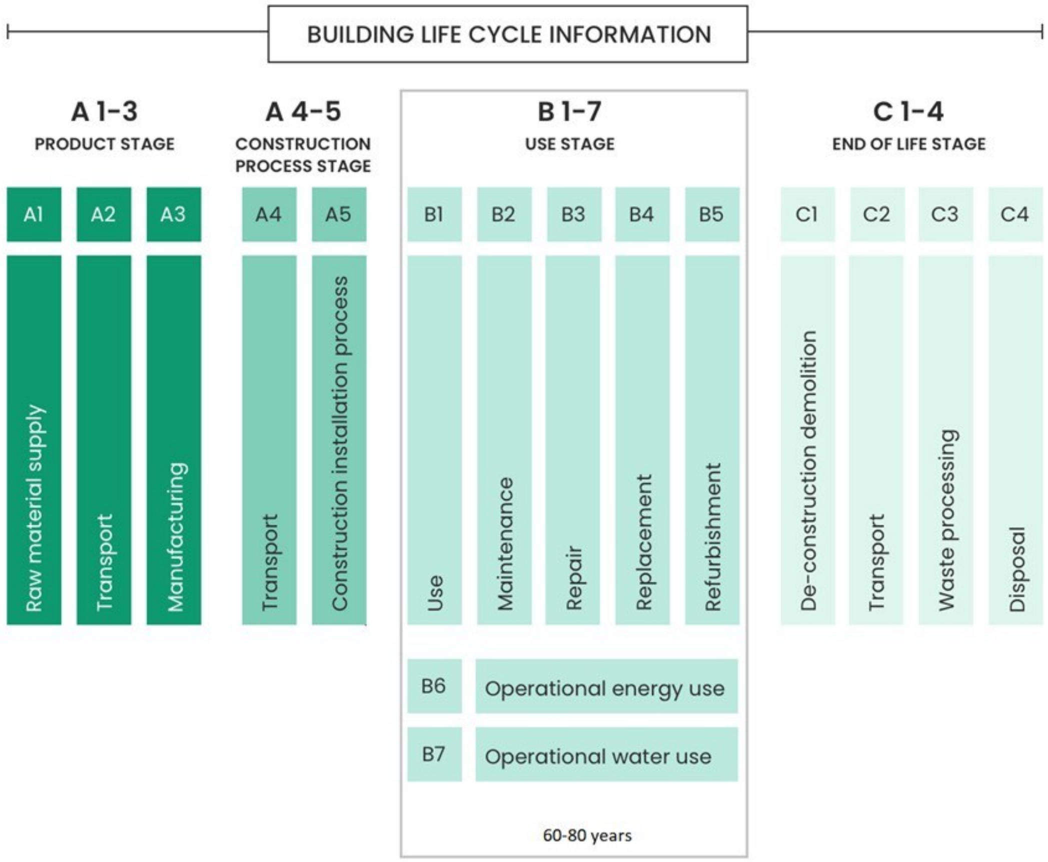


Figure 6 - Visual representation of the life cycle stages of a building, based on EN 15978. (One Click LCA, 2023; Syzygy Consulting, 2023).

1.5.4.3 Life Cycle Boundaries:

- **Cradle-to-Gate** covers only the Product Stage (A1–A3), which includes material extraction and manufacturing but excludes transport to site or construction impacts.
- **Cradle-to-Practical Completion** includes stages A1 to A5, encompassing the full process from material production to construction.
- **Cradle-to-Grave** represents the most complete assessment from A1 to C4, addressing the entire life span from material extraction to demolition and waste treatment.
- **Cradle-to-Cradle** goes a step further by including Module D, reflecting a closed-loop system where post-demolition materials re-enter the product cycle, thus minimizing environmental depletion and maximizing material recovery.

1.5.4.4 Environmental Indicators

Key indicators in LCA include Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential from Land Use and Land-Use Change (GWP–LULUC) which LULUC refers to the climate impact of changes in land use, such as deforestation for raw material extraction (e.g. cutting down forests for timber or mining bauxite for aluminum), converting grasslands into agricultural land for crops used in building materials (e.g. natural insulation), land degradation or changes in soil carbon stocks.

Serrano-Baena et al. (2023) emphasized the importance of using circular materials to reduce embodied energy, achieving significant reductions in GWP, embodied energy, and waste generation.

1.5.4.5 Integration with Digital Tools

Integrating LCA with digital platforms like BIM enables real-time environmental assessments. Xu et al. (2022) highlighted the automation of embodied carbon calculations using BIM-integrated LCA tools, which reduced modeling time by 91.5%. This integration facilitates dynamic sustainability assessments across project phases.

1.5.5 green building Rating systems

1.5.5.1 BREEAM:

BREEAM, which stands for Building Research Establishment Environmental Assessment Method, is the world's first green building rating system, created by the Building Research Establishment in the UK. Launched in 1990, it originally focused on office buildings but has since affected many other systems like LEED, Green Star, and CASBEE. What makes BREEAM special is its flexibility; it considers local building rules and conditions, making it applicable in various countries. It looks at every stage of a building's life—from design and construction to operation and renovation—and offers specific guidelines for different people involved in the process.

So far, over 560,000 certifications have been granted, and that number keeps rising, showing how popular it is. In fact, BREEAM accounts for about 80% of all sustainable building certifications in Europe. While it covers all aspects of sustainability, it particularly focuses on environmental performance in areas like energy, water, waste, and pollution. (55)

1.5.5.2 LEED:

LEED (Leadership in Energy and Environmental Design), which was created by the United States Green Building Council (USGBC), arose in 1998 as a voluntary system for encouraging more sustainable building. LEED might have followed BREEAM, but it quickly became the most widely used green building certification worldwide. As of 2012, there were over 79,000 projects in 135 countries that were using it—and two years later, the number had risen to nearly 150 countries. Today, LEED has operations in over 160 countries and territories.

Its growth has been nothing short of phenomenal: from 2008 to 2016, LEED-certified buildings increased from around 0.15 billion to over 15 billion square feet. What makes LEED so powerful is its holistic approach, it looks at a building from every conceivable angle. Whether it's whether or not to choose a site, how water and energy are used, what materials are used, or the manner in which the indoor environment affects people, LEED encourages wise, performance-based choices.

It also reacts to different sizes and phases of construction, giving direction for new building, interior spaces, continuous operations, and even entire neighborhoods. Basically, LEED gives teams a practical, flexible roadmap to design and operate healthier, greener spaces. (56)

1.5.5.3 CASBEE:

CASBEE (Comprehensive Assessment System for Built Environment Efficiency) launched in 2001 in Japan as a coalition of universities, industry practitioners, and local governments. While still largely tailored to the Japanese context—that explains its relatively lower certification number (around 330 since 2004)—CASBEE stands out in covering the widest array of assessments among the major green building rating systems.

Originally targeted at local projects, CASBEE took its first step toward international use with an inaugural global edition in 2015. The system evaluates a building's entire life cycle, starting from the design stage up to renovation. It offers a range of specialized manuals, including CASBEE for Buildings, Commercial Interiors, and Temporary Construction.

What is unique is that CASBEE does not just look at individual buildings—it also has tools like CASBEE for Urban Development and CASBEE for Cities that enable the analysis of entire groups of buildings or cities. In so doing, CASBEE presents a more integrated and scalable concept of sustainability, although its application outside Japan is still in the process of developing. (57)

1.5.5.4 Green Star NZ:

Green Star NZ, launched in 2007 by the New Zealand Green Building Council (NZGBC), is the youngest of the main green building rating systems and is based on the Australian Green Star model. While it is still establishing itself, it has already made considerable inroads in quite a short time. Among the distinctions is that, unlike other systems, Green Star NZ does not yet have a manual for evaluating building performance after occupancy.

Despite this limitation, the system has shown heartening growth. The number of certified buildings has grown tenfold since 2009, with 125 certifications. Though smaller in scale than overseas systems like LEED or BREEAM, Green Star NZ reflects New Zealand's construction industry's growing commitment to sustainability. (58)

1.5.5.5 Overview of Green Building Certification Systems

BREEAM, LEED, CASBEE, and Green Star NZ each have their respective strengths in their green building rating systems. BREEAM, LEED, and Green Star NZ were all developed by nongovernmental organizations, with the vision of promoting sustainability through industry collaboration. CASBEE stands out with the leading role played by the Japanese government, in collaboration with universities and industry experts. This mix of public and private input enables CASBEE to receive ongoing and precise feedback, positioning it to lead the way in evaluating larger-scale developments, groups of buildings and even whole cities.

While CASBEE has grown quickly since its launch, despite being a late entrant relative to BREEAM and LEED, its reach is still mostly limited to Japan. Meanwhile, Green Star NZ, the youngest among them, has had encouraging growth during the past several years but still remains without a system of assessing building performance in the longer term, which circumscribes its impact in the long term.

Throughout the board, all the systems are continuously developing, with periodic updates designed to remain pertinent and efficient. Nonetheless, BREEAM and LEED are still the most commonly used on an international scale, in large part because of their greater flexibility and global applicability. (59)

For this project, the most suitable certification system was BREEAM. Its flexibility, combined with good European applicability and a strong lifecycle-based approach, makes it especially fitting for the context and aims of this project. It offers the tools and standards needed to analyze the project holistically, from initial design through to operation, while being firmly aligned with regional regulations and sustainability priorities.

While each of the principal green building rating systems was developed within the context of a specific region, BREEAM is distinguished by being extremely flexible to international schemes, with the choice of applying either global or local standards. Its strong entrenchment in the European market, combined with its broad scope and depth, places it particularly well for projects within this region. While LEED is typically defined by an open framework, BREEAM provides a more holistic and context-dependent evaluation and therefore a more suitable fit for project diversity and variable climates.

In terms of assessment categories, BREEAM shares a lot with LEED and Green Star NZ, reflecting the robustness and maturity of its scheme. CASBEE, while innovative in methodology, remains narrower in scope and primarily Japan-focused.

A key strength of BREEAM is the equal weighting of the sustainability factors. While, in common with the other schemes, it prioritizes energy performance in acknowledgement of the high energy intensity of the industry, BREEAM also prioritizes strongly factors such as material impacts, occupant well-being, and site ecology, reflecting a holistic consideration of environmental and human factors.

Methodologically, BREEAM offers a clear and structured methodology through its pre-weighted category system. This provides a consistent framework for evaluating sustainability performance to design teams at all phases of any project, from design to operation. Compared to systems like LEED, which is founded on additive point scoring, and CASBEE, which uses a quality-load ratio that is more complex, BREEAM provides a pragmatic balance between rigor and usability.

Although each of the four rating tools is voluntary in a technical sense, BREEAM is being increasingly integrated into national legislation, procurement policy, and funding requirements, especially within Europe. Its growing international recognition and regional adaptability reaffirm why BREEAM has been chosen for use on this project as the most practical and contextually relevant sustainability tool. (59)

	BREEAM	LEED	CASBEE	Green Star NZ
Country	UK	US	Japan	NZ
Organizations	BRE	USGBC	JSBC	NZGBC
Flexibility	77 countries	160 countries	1 country	1 country
First version	1990	1998	2002	2007
Building adaptations	New Construction . In-Use Refurbish. and Fit-Out Communities	New Construction. Existing Buildings. Operations and Maintenance Comm. Interiors Core and Shell Schools Retail Healthcare Homes. Neighbor. Develop.	Pre-design New Construction . Existing Building and Renovation	Communities Buildings Des and As Built Interiors Performances
Categories	Manageme Health and Well-being Energy Transport Water Material Waste Land Use and Ecology Pollution Innovatio	Integrative Process Location and Transportation Sustainable Site Water Efficiency Energy and Atmosphere Material and Resources Indoor Env. Quality Regional Priority Innovation	Indoor Environment Quality of Service On-site Environment Ener Resource and Materials Off-site Environment	Management Indoor Environment Quality Energy Transport Water Material Land Use and Ecology Emissions Innovation
Assessment method	Pre-weighted categories	Additive credits	BEE ranking char	Pre-weighted categories
Certification levels	Pass ≥ 30 Good ≥ 45 Very Good ≥ 55 Excellent ≥ 70 Outstanding ≥ 85	Certified 40–49 Silver 50–59 Gold 60–79 Platinum ≥ 80	Poor: BEE < 0.5 Fairy Poor: BEE 0.5–1.0 Good: BEE 1–1.5 Very Good: BEE 1.5–3 or BEE ≥ 3 and Q < 50 Excellent: BEE ≥ 3 and Q ≥ 50	Min. Practice (1 star) Average Practice (2) Good Practice (3) Best Practice (4) Austr. Excellence (5) World Leader. (6)

Table 2 - International rating system differences- (59)

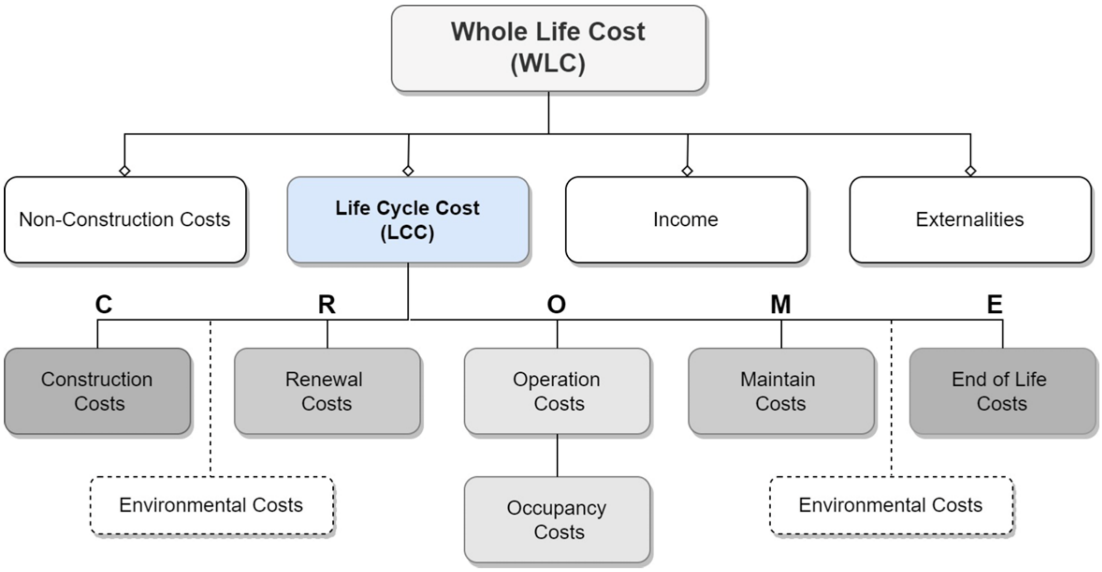
1.5.6 Life Cycle Costing (LCC)

1.5.6.1 Economic Sustainability

Life Cycle Costing (LCC) evaluates the total cost of ownership, encompassing acquisition, operational, maintenance, and disposal costs. Combining LCC with LCA allows decision-makers to balance environmental and economic trade-offs (Santos et al., 2019). Shibata et al. (2023) demonstrated that retrofitting buildings with air-source heat pumps and photovoltaic panels (ASHP + PV) achieved substantial cost savings over their lifecycle.

1.5.6.2 Methodologies and Applications

LCC methodologies use metrics like Net Present Value (NPV) and payback periods to assess cost-effectiveness. These analyses are particularly useful in retrofitting scenarios, where operational energy savings significantly offset higher initial investments (Tam et al., 2022).



1.5.7 Building Energy Modeling (BEM)

Building Energy Modeling (BEM) refers to a simulation approach grounded in physics, designed to estimate a building's energy performance. It utilizes a detailed set of inputs, including building geometry, materials, system configurations (such as HVAC, lighting, and renewables), equipment efficiencies, and operational strategies. Additionally, user behavior data like occupancy schedules, lighting usage, and thermostat settings are incorporated. BEM integrates these inputs with climate data and applies physical equations to evaluate thermal loads, system responses, and overall energy consumption. The simulation typically runs hourly or at finer intervals over a full year and considers complex interactions among building systems, such as how lighting affects heating or cooling demands. (U.S. Department of Energy, 2017).

Figure 8 - Breakdown of Whole Life Cost (WLC) and Life Cycle Cost (LCC) Components, (Madanayake & Othman, 2022)

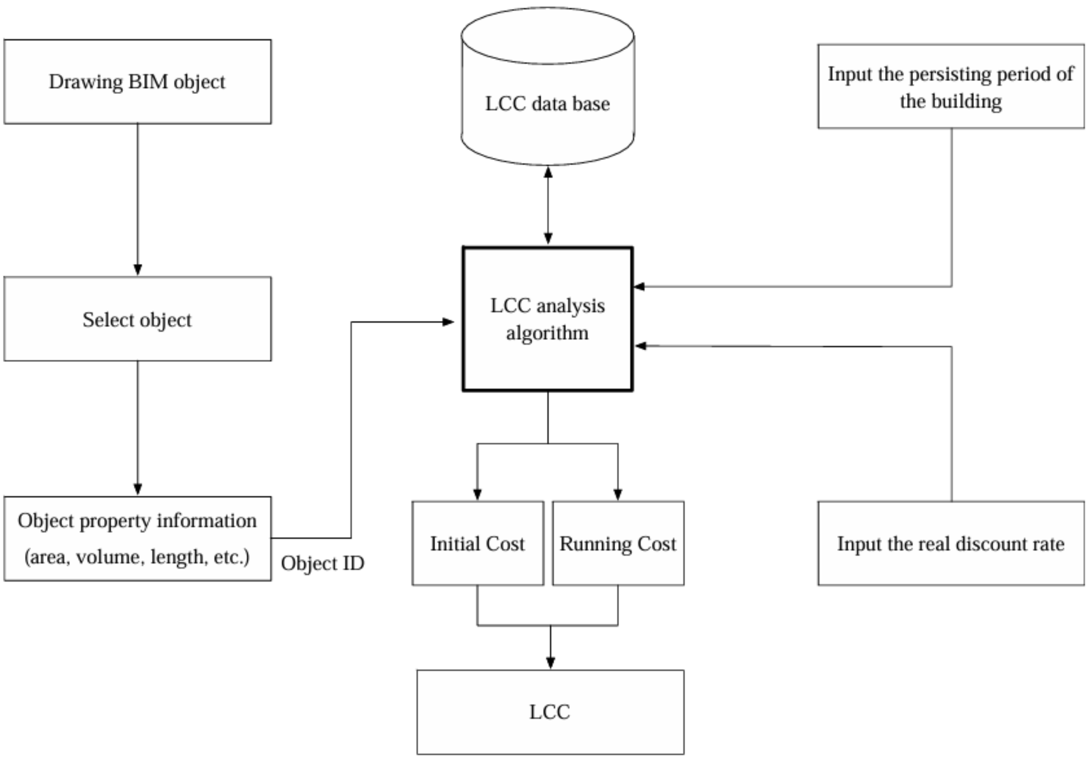


Figure 7 - Workflow of Life Cycle Cost (LCC) Analysis Integrated with BIM (Lee, 2019)

1.5.8 Concept and Definition of Digital Twin

A Digital Twin represents a dynamic and real-time virtual model of a unique entity, which may be a physical object, service, intangible asset, or an integrated system that includes both physical components and associated services (Choudhury et al., 2024).

In order to be recognized as a true Digital Twin, a model must meet several essential criteria. These include fidelity, which ensures the model accurately reflects its physical counterpart;

expansibility, or the ability to integrate additional models; interoperability, which allows for seamless translation and alignment between different modeling standards; and scalability, the capacity to process and assess data across various scales and complexities (Durão et al., 2018).

The term Digital Twin generally refers to a virtual counterpart of a physical asset that exists throughout the asset's lifecycle, with the capability to interpret data, adapt through learning, and make informed decisions in real time. Alternatively, it is also defined as a data-driven simulation model that continuously receives input from real-world sources and can influence or trigger responses in physical systems (Attaran & Celik, 2023).

A Digital Twin (DT) is a highly precise virtual representation of a real-world process, capturing its current condition and its interactions with the surrounding environment. Beyond visualization, it also plays a critical role in predicting the future performance of the product or system it represents (Durão et al., 2018).

In industrial settings, the Digital Twin (DT) concept is applied in diverse ways depending on organizational goals. Some manufacturers emphasize linking virtual models with their physical counterparts to enhance production flexibility. Others leverage DTs to monitor a product's lifecycle in order to improve manufacturing quality, while certain companies adopt the technology primarily to refine product design (Choudhury et al., 2024).

This multifunctionality is further emphasized in the work of Osello et al. (2024), who position the Digital Twin as a key enabler in the transition toward Industry 5.0 and climate-neutral industrial practices. Their study demonstrates how DTs can be developed through a BIM-to-BEM (Building Information Modeling to Building Energy Modeling) workflow, integrating architectural, mechanical, and environmental data for enhanced building performance simulation. The proposed platform combines static and dynamic data with Extended Reality (XR) tools and interoperable file formats (e.g., .ifc, .gbxml), enabling intuitive decision-making, energy forecasting, and automated simulations. This holistic, human-centered approach enhances operational efficiency while directly supporting sustainability and energy transition objectives (Osello et al. (2024)).

1.5.9 Integration of BIM, LCA, and LCC

Integrating BIM with LCA and LCC offers a holistic approach to sustainability. Santos et al. (2019) demonstrated how BIM-based frameworks automate data collection and analysis, enabling early-stage design optimization and lifecycle assessments.

1.5.9.1 BIM–LCA Integration:

Building Information Modeling (BIM)-based Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) processes have become more and more central to the analysis of building sustainability over their whole life cycle. These integrated processes can be classified into three general categories depending on their function in the architectural design process. The first category consists of methods applied in the detailed design phase, where models are properly established and contain detailed geometric and material specifications. During this stage, more reliable environmental and economic evaluations can be made with the use of finer data. The applications within this category often involve direct interfacing with BIM software, employing detailed quantities and material specifications to provide authentic LCA outcomes. The second group consists of tools targeting the early design stage when only concept models exist and project information is limited. Streamlined or parametric LCA methods are applied here to provide quick feedback to support decision-making. These methods prefer to utilize external databases with pre-assembled material compositions or statistical surrogates for estimating impacts. The third category reflects state-of-the-art LCA methods that can operate across the entire design process. They are hierarchical database-driven and with flexible data structures that mature along with the BIM model's maturity. The advantage of such techniques is the continuity whereby the sustainability analysis can develop alongside the project from preliminary concepts to construction-ready drawings [Li et al., 2023].

Since design choices made in the early stages have the biggest impact on the building's life cycle performance, the importance of early-stage evaluation is widely recognized in the literature. Nevertheless, the actual application of LCA is frequently postponed until later stages, when project data is more comprehensive and appropriate for examination. Researchers have suggested simplified life cycle assessment (LCA) methods to close this gap. These methods use external databases and predefined material assemblies to generate assessments more quickly but with greater accuracy. Due to the generalized nature of early-stage data, these techniques are especially helpful for offering statistical estimates or visual guidance, but they typically lack precision (Li et al., 2023).

At the stage of detailed design, software such as Tally, Simapro, and eBalance have seen extensive application because they are capable of linking BIM models and detailed environmental databases such as GaBi, Ecoinvent, and others. These software enable practitioners to estimate a broad assortment of indicators—such as Global Warming Potential (GWP), Acidification Potential (AP), and Primary Energy Demand (PED)—with high accuracy. Additionally, other writers have suggested hybrid methodologies that try to close the gap between low and high Levels of Development. For example, BIMEELCA was made adaptable to different Levels of Development (LOD) so that LCA calculations may develop alongside the design. In the same manner, workflows proposed by Hollberg et al., Rezaei, and Cavalliere are made to accommodate ongoing LCA integration by recalculating impact data as the model is developed in more detail. Notwithstanding all these developments, the majority of these investigations address embodied environmental effects and are confined to certain regional contexts—most frequently Europe. Furthermore, the majority of these methods do not consider the economic performance or operational energy use, which are relevant to whole-system sustainability evaluation.

There is a noticeable trend toward the use of increasingly complex tools that interface directly with intricate digital models as project development advances and the BIM model develops. Accurate, multi-indicator environmental assessments are made possible by applications like Tally, Simapro, and other LCA platforms that link building element specifications in BIM to well-known life cycle inventory (LCI) databases like Ecoinvent and GaBi (Eleftheriadis et al., 2017). These tools are usually used in the detailed design stage, when precise and trustworthy results are made possible by finely defined geometry and material definitions.

However, because of the lower level of geometric and semantic information, it is still difficult to integrate simplified early-stage models with such tools. Adaptive workflows that support several Levels of Development (LOD) during the design process have been developed as a result of this limitation. By progressively enhancing the specificity and level of detail of sustainability assessments, these methods seek to preserve continuity as the model develops. The approach put forth by Röck et al. (2018), who created a BIM-integrated framework by connecting conceptual building elements to a library of environmental data using visual scripting (Dynamo), is a notable illustration of this. Their research showed how embodied impacts can be computed early in the design process and graphically depicted in the BIM model, giving designers insightful input to guide sustainable choices as the design develops.

Despite these developments, operational energy performance, economic assessment, and geographic adaptability outside of Europe are frequently overlooked in favor of embodied carbon—especially in the European context (Li et al., 2023; Hollberg et al., 2018). BIM-LCA tools are frequently created using localized assumptions or fixed datasets, which restricts their applicability to projects in areas with different material markets, regulatory frameworks, and environmental baselines. Furthermore, many tools are restricted to particular stages of the design process and do not have the ability to work iteratively across several project lifecycle stages or adapt to changes in the design (Röck et al., 2018; Eleftheriadis et al., 2017).
Given these drawbacks, this study suggests utilizing One Click LCA, a tool created to close the operational and methodological divide between preliminary estimates and in-depth design evaluations. One Click LCA, in contrast to many traditional tools, can support multi-stage evaluation by using model-derived quantities directly in BIM environments like Grasshopper, Revit, and ArchiCAD. Additionally, it integrates with major international certification schemes such as LEED, BREEAM, and DGNB and offers compatibility with a wide range of environmental and economic indicators (One Click LCA, 2023).

Crucially, One Click LCA makes it possible to use localized and customizable datasets, which improves its suitability for non-European contexts where many other tools are inadequate.

According to Zabalza Bribián et al. (2009), this capability is particularly pertinent to projects that seek comparative or multi-criteria sustainability analysis across various regions or climates. Therefore, One Click LCA was chosen for this study for both strategic and investigative reasons: it meets the practical requirements of flexibility, interoperability, and ongoing feedback while also advancing scholarly discussion by examining its underutilized potential in comprehensive BIM–LCA–LCC workflows.

1.5.9.2 BIM–LCC Integration:

Although Life Cycle Assessment (LCA) is a vital tool for environmental assessment in sustainable building design, it is insufficient on its own to inform well-informed and well-balanced decisions. An equally significant element is life cycle costing (LCC), which assesses a building's total cost of ownership, taking into account not only the initial investment but also the costs associated with operation, maintenance, repair, and disposal over the course of its service life (ISO, 2008). LCC integration into Building Information Modeling (BIM) has become a crucial tactic to support decision-making throughout the building design and operation lifecycle, as sustainability increasingly includes both ecological performance and economic viability.

To make BIM–LCC integration easier, a variety of techniques have been developed. These include using commercial tools and specialized plug-ins, like One Click LCA, which supports both LCA and LCC in a common digital environment, external cost databases connected to BIM objects, and custom workflows created using Revit, Excel, and Dynamo scripting environments (Zanni et al., 2019). For instance, One Click LCA enables users to choose from regionalized datasets and automate cost analyses based on quantities derived from BIM. Although plug-ins can expedite the process, they frequently operate as "black-box" solutions with little control over the LCC methodology being used, transparency, or customization.

One of the main advantages of BIM, according to Barlish and Sullivan (2012), is its ability to increase efficiency and accuracy by facilitating real-time feedback loops. This directly relates to cost assessments: users can test the economic effects of design changes at different stages by dynamically updating cost outputs and connecting quantity take-offs to external cost data. More flexibility is provided in this situation by adaptable BIM–LCC workflows, particularly those that use Revit + Excel + Dynamo. These enable precise control over input variables and assumptions, integration of local or project-based cost libraries, and the definition of user-specific LCC structures.

Many academics contend that completely transparent, user-defined workflows enable a more thorough and context-sensitive cost evaluation, even though commercial tools automate the process. For example, Zanni et al. (2019) point out that a truly BIM-enabled sustainability process needs to align cost data with the project's changing Level of Development (LOD) and take into account both operational and embodied aspects. This adaptability is especially important during the early stages of design, when choices will affect sustainability and cost in the long run.

The main approach for implementing LCC in this thesis is the combination of Revit, Excel, and Dynamo. This strategy is in line with scholarly suggestions for open, flexible, and iterative assessment techniques. It facilitates region-specific customization, allows for dynamic interaction between the BIM model and cost data, and offers a strong basis for evaluating design options in terms of both economic viability and environmental impacts (through life cycle assessment, or LCA) over the course of the building lifecycle.

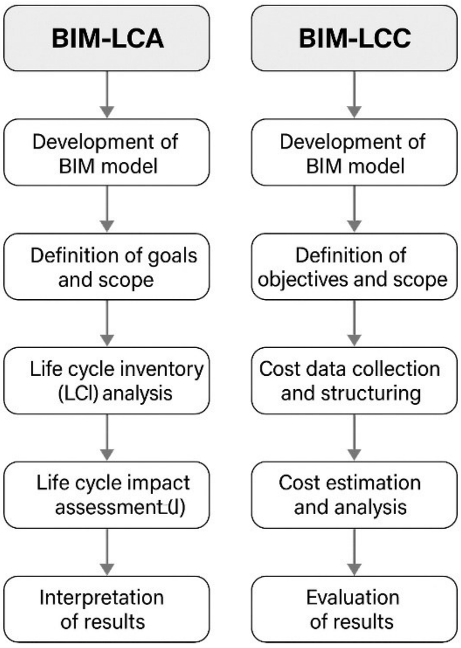


Figure 9-Workflow comparison between BIM–LCA and BIM–LCC integration processes

1.5.9.3 Automation and Efficiency

By increasing productivity, reducing errors, and facilitating ongoing design feedback, automation greatly improves the integration of Building Information Modeling (BIM) with Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). Data extraction, transformation, and linking between BIM environments and external databases or simulation platforms can be done automatically with the help of visual scripting tools like Dynamo and Rhino–Grasshopper. This allows for the dynamic updating of environmental assessments in response to changes made to design elements (Ciccozzi et al., 2023).

Automatic quantity take-offs and their relationship to material-specific impact factors are made easier by structured mapping between life cycle databases and BIM elements. This enhances the traceability of sustainability data across the design phases and eliminates the need for repetitive manual input (Ciccozzi et al., 2023). To help with decision-making, quantities can be extracted from the Revit environment using Dynamo, connected to external Excel-based LCA datasets, and visually reported back into the BIM model. Components with significant environmental impacts can be identified directly within the model view thanks to color-coded feedback in the BIM interface (Röck et al., 2018).

The user can evaluate performance without having to rebuild models or manually export data thanks to the continuous recalculation of environmental indicators based on design parameters. This feedback loop is supported by the use of parametric environments like Grasshopper, particularly in the conceptual and early design phases when options are regularly changed (Hollberg et al., 2020).

Additionally, multi-phase assessment across various Levels of Development (LOD) is supported by BIM-based automation, allowing for increasingly sophisticated LCA and LCC evaluations during the design and planning phase. Without the need for new input structures or repeated modeling, automated material and geometry data extraction guarantees that model updates are reflected in the sustainability metrics (Li et al., 2023).

In addition to streamlining sustainability analysis, these workflows incorporate it straight into the design environment, enabling the real-time assessment of environmental and economic performance in conjunction with other design considerations.

1.5.9.4 Challenges and Opportunities in Integration

1.5.9.4.1 Data Interoperability

Data interoperability is one of the most important technical challenges in integrating Building Information Modeling (BIM) with Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). Different data structures and levels of information granularity are used by the BIM, LCA, and LCC systems. While LCA systems need comprehensive material, energy, and environmental impact data, and LCC depends on cost elements linked to time and usage, BIM environments are mainly focused on geometric modeling and object parameters (Pezeshki et al., 2019). When trying to connect these tools, the disparity in goals and data representation frequently leads to redundant data entry, information loss, or semantic mismatches. The process becomes disjointed, prone to errors, and ineffective in the absence of a strong interoperability framework.

The absence of standardized data schemas and file formats that can capture all pertinent information across domains is one of the main challenges (Xu et al., 2022). A lot of proprietary software platforms have closed data structures, which hinder smooth communication and frequently necessitate manual translation or the creation of scripts for intermediate conversion. When stakeholders from various disciplines try to work together using incompatible digital tools or modeling techniques, this problem is especially noticeable. This could lead to inaccurate cross-platform transfer of important sustainability data, like material quantities, life span, or cost breakdowns (Obrecht & Röck, 2020).

A number of encouraging solutions have surfaced in spite of these obstacles. Green Building XML (gbXML) and Industry Foundation Classes (IFC) are being used more and more to standardize data exchange and improve model compatibility between LCA/LCC engines and BIM tools. The capacity of IFC to support geometry, material properties, and even classification metadata in an open, platform-neutral format has been acknowledged (Pezeshki et al., 2019). Furthermore, there is potential to improve automated data interpretation and lower manual errors through semantic enrichment research, which includes the use of ontologies and linked data technologies (Xu et al., 2022). Common Data

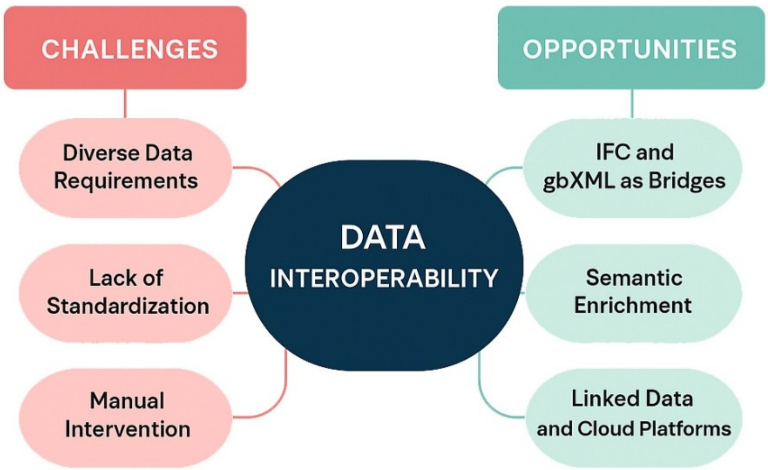


Figure 10-Data Interoperability - Challenges and Strategies

Environments (CDEs) and cloud-based platforms facilitate collaboration by centrally storing all model data, enabling cross-disciplinary coordination and real-time access (Memon et al., 2021).

1.5.9.4.2 Enhancing Adoption

Even though BIM-based sustainability tools are becoming more sophisticated, organizational, procedural, and educational obstacles still prevent integrated BIM–LCA–LCC workflows from being widely used. The lack of knowledge and technical proficiency among professionals in the Architecture, Engineering, and Construction (AEC) sector is a major obstacle (Abdelaal & Guo, 2022). Many practitioners are skeptical and resistant to change because they are not familiar with the features and advantages of these integrated approaches. Furthermore, inconsistent results and doubts regarding the dependability of results arise from the lack of standardized workflows and implementation protocols (Memon et al., 2021). Sustainability integration is a multidisciplinary process that necessitates coordination between architects, engineers, energy modelers, and cost consultants. This makes adoption even more challenging, particularly when fragmented digital environments impede communication (Pezeshki et al., 2019).

Nonetheless, there are encouraging chances to increase uptake. Closing the skills gap and increasing capacity across professional roles can be achieved by funding extensive training programs, workshops, and certification initiatives. (Microsol Resources, 2023). Simultaneously, Concurrently, the creation and distribution of standardized data structures, protocols, and templates can improve interoperability and lessen the need for ad hoc approaches (Memon et al., 2021). Better collaboration, real-time information access, and simpler cross-disciplinary coordination are made possible by the increasing use of cloud-based platforms and shared data environments (Xu et al., 2022). Additionally, proving practical advantages like better sustainability ratings, cost savings, and regulatory compliance can be a strong motivator for institutional and industry-wide adoption (Barlish & Sullivan, 2012). Figure 3 provides a visual summary of these strategic enablers and presents a framework for overcoming opposition and fostering successful implementation.

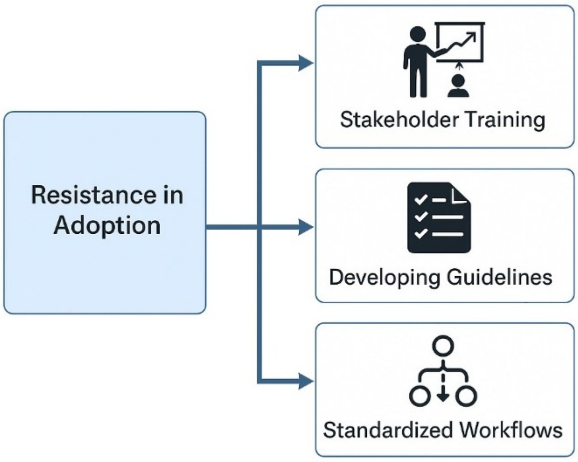


Figure 11-Enhancing Adoption-Challenges and Strategies

1.5.10 BIM-BEM Integration:

The process of transitioning from Building Information Modeling (BIM) to Building Energy Modeling (BEM) involves utilizing digital data from a BIM model to generate a virtual energy simulation of a building, enabling performance analysis and optimization. The types of data that can be transferred from BIM to BEM include:

- Building geometry:

The three-dimensional structure of the building, including components like walls, floors, ceilings, roofs, windows, and doors, can be imported from BIM into BEM software to support accurate spatial modeling.

Thermal properties of building materials:

Information embedded in the BIM model about the thermal performance of materials—such as wall insulation, window glazing, and roofing—can be used in BEM tools to simulate and evaluate energy efficiency.

- Lighting information:

Details about the types, placements, and specifications of lighting fixtures are often included in BIM models. These can be utilized in BEM to calculate lighting loads and predict energy consumption related to artificial lighting.

- HVAC system information:

BIM may contain detailed layouts and specifications of HVAC systems, including the position of heating and cooling units, duct networks, and ventilation components. These elements are crucial in BEM for simulating thermal comfort and energy demands.

- Occupancy and usage information:

Data regarding building occupancy—such as the number of users, their activity patterns, and schedules—can be integrated into BEM models to reflect real-time usage and improve the accuracy of energy consumption forecasts.

- Weather data:

To evaluate energy performance under actual environmental conditions, BEM relies on external data related to local climate, including temperature, solar exposure, and humidity. This information is often sourced from climate databases and applied to the simulation model.

Overall, integrating these data sets from BIM into BEM supports more precise and holistic evaluations of a building's energy behavior, contributing to improved sustainability and informed retrofitting strategies (Ghofranikajani, 2023).

1.5.11 Fundamental Definitions Associated with LOD

According to AIA (American Institute of Architects), LOD outlines the design requirements at each stage. At LOD 100, which is the pre-design stage, the model consists of 2D symbols and the masses to signify an element's existence. At LOD 200, the elements are partially defined by outlining its approximate quantity, size, shape, and location. By LOD 300, the elements are defined with exact dimensions and their relative positions bolstering precision. LOD 350 describes the information about an element precisely and outlines an element's relation and connection with other components. The LOD 400 level outlines the basic information about the construction of various elements. By LOD 500, the model begins representing the real-life functions of elements in a real building. Here are all the levels of development with their definition in detail (United-BIM, 2019).

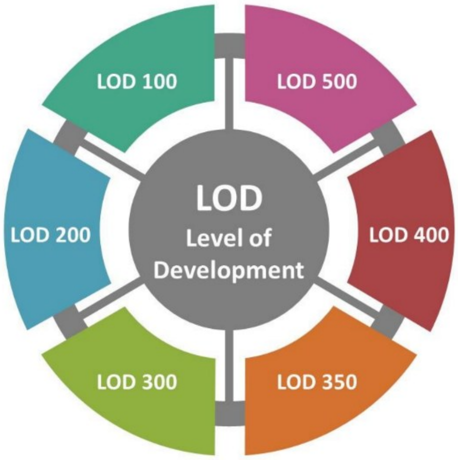


Figure 12 - Graphical representation of BIM Levels of Development (LOD) by (United-BIM, 2019).

LOD 100 The Model Element may be graphically represented in the Model with a symbol or other generic representation. Information related to the Model Element can be derived from other Model Elements. Any information derived from LOD 100 elements must be considered approximate.

LOD 200 The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element. Any information derived from LOD 200 elements must be considered approximate.

LOD 200 The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element. Any information derived from LOD 200 elements must be considered approximate.

LOD 350 The Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the Model Element.

LOD 400 The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element.

LOD 500 The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements. (United-BIM, 2019)

LOD	3D Coordination	4D Scheduling	Cost Estimating	Sustainability / Analysis
100–200	Site & major object	Rough phasing	$/sf concept	Basic LEED strategies
300–350	Detailed coordination	Detailed assembly sequencing	Assembly-level cost	Assembly-specific analysis
400	Fabrication coordination	Fabrication-level scheduling	Purchase pricing	Manufacturer-based sustainability analysis
500	Operational integration	n/a	Record cost	Performance tracking (united-bim.com)

Table 3 - Summary of BIM Levels of Development (LOD) and their relationship to 3D coordination, 4D scheduling, cost estimating, and sustainability analysis. Illustrated by authors.

The American Institute of Architects (AIA) first introduced the concept of Level of Development (LoD) in its 2008 protocol. As illustrated in Figure , each LoD stage describes how detailed and reliable a model element should be at different points in the design and construction process. The term “level of development” was deliberately chosen instead of “level of detail” to highlight an important distinction: a model element might look highly detailed, but unless its information is reliable and usable, it remains essentially generic (Ait Hadda, 2021).

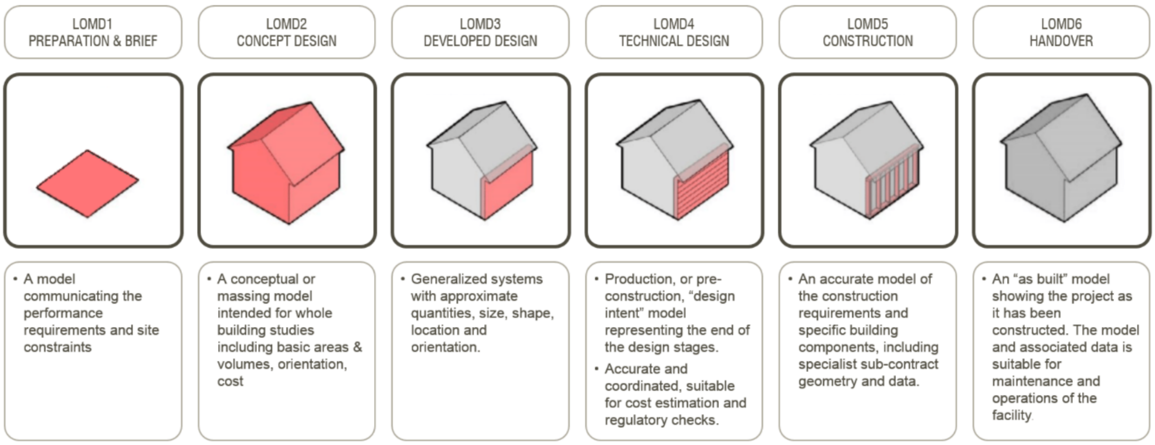


Figure 13 - Stages of Level of Model Definition (LoMD) according to the UK BIM framework, ranging from LOMD1 (Preparation & Brief) to LOMD6 (Handover) by Evolve Consultancy 2014.

Another important international reference comes from British legislation, which distinguishes between Level of Detail (LoD), referring to the graphical aspects of a model, and Level of Information (LoI), referring to its non-graphical data. Together, these two components define what is known as the Level of Model Definition (LoMD), as illustrated in Figure 4. In the UK, the Royal Institute of British Architects (RIBA) follows a well-established, project-driven framework that informs contracts, fee structures, and project phases. Unlike the U.S. system, where LoD is often tied to individual objects, the British standard PAS 1192-2 focuses on the model as a whole, emphasizing its overall level of definition (Pavan. A, 2017).

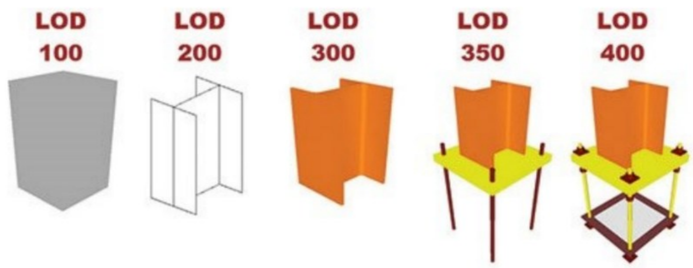


Figure 14 - Visual representation of BIM Levels of Development (LOD) from 100 to 400 by (Pavan. A, 2017).

Various protocols such as those from the AIA, British standards, and other international guidelines, aim to define the appropriate level of detail required in the development of BIM models. However, each country approaches this issue differently, resulting in the absence of a universally adopted system. In response, Italy has chosen to engage with these global standards, particularly those of the U.S. and the U.K., to develop its own national framework (Ait Hadda, 2021).

The first Italian standard to reference the concept of LoD is UNI 11337-4:2017, which allows for flexible use of existing international LoD scales based on the context and project requirements. This flexibility ensures clarity and transparency for all stakeholders involved.

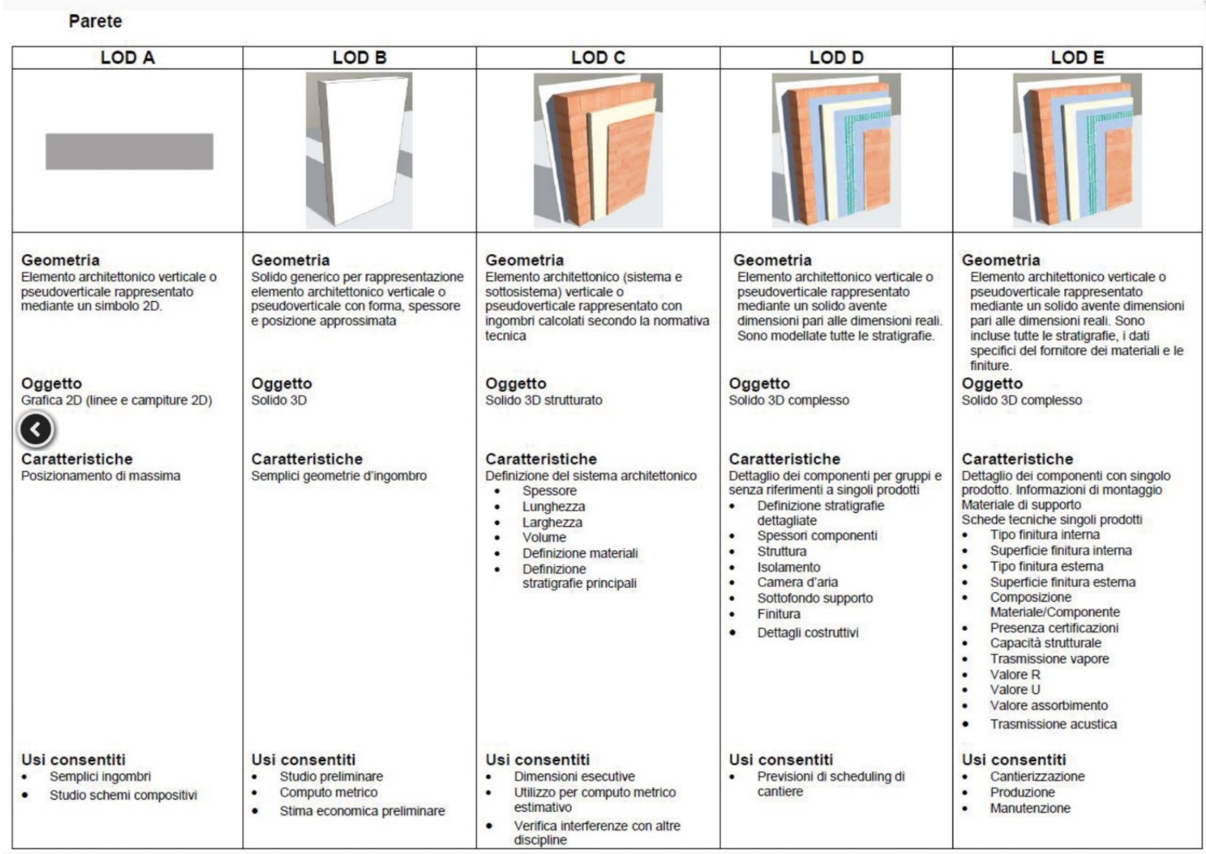
Italy has also introduced specific terminology to distinguish between different aspects of model development:

LOG: Level of development of geometric attributes

LOI: Level of development of information attributes

LOD: Level of development of digital objects

To avoid confusion with U.S. or British systems, Italy uses an alphabetical LoD scale (LOD A, B, C, etc., as shown in Figure 5). While the Italian approach is influenced by both American and British models, it also incorporates unique national considerations that reflect Italy's specific regulatory and design culture (Pavan. A, 2017).



Parete

LOD A	LOD B	LOD C	LOD D	LOD E
Geometria Elemento architettonico verticale o pseudoverticale rappresentato mediante un simbolo 2D.	**Geometria** Solido generico per rappresentazione elemento architettonico verticale o pseudoverticale con forma, spessore e posizione approssimata	**Geometria** Elemento architettonico (sistema e sottosistema) verticale o pseudoverticale rappresentato con ingombri calcolati secondo la normativa tecnica	**Geometria** Elemento architettonico verticale o pseudoverticale rappresentato mediante un solido avente dimensioni pari alle dimensioni reali. Sono modellate tutte le stratigrafie.	**Geometria** Elemento architettonico verticale o pseudoverticale rappresentato mediante un solido avente dimensioni pari alle dimensioni reali. Sono incluse tutte le stratigrafie, i dati specifici del fornitore dei materiali e le finiture.
Oggetto Grafica 2D (linee e campiture 2D)	**Oggetto** Solido 3D	**Oggetto** Solido 3D strutturato	**Oggetto** Solido 3D complesso	**Oggetto** Solido 3D complesso
Caratteristiche Posizionamento di massima	**Caratteristiche** Semplici geometrie d'ingombro	**Caratteristiche** Definizione del sistema architettonico • Spessore • Lunghezza • Larghezza • Volume • Definizione materiali • Definizione stratigrafie principali	**Caratteristiche** Dettaglio dei componenti per gruppi e senza riferimenti a singoli prodotti • Definizione stratigrafie dettagliate • Spessori componenti • Struttura • Isolamento • Camera d'aria • Sottofondo supporto • Finitura • Dettagli costruttivi	**Caratteristiche** Dettaglio dei componenti con singolo prodotto. Informazioni di montaggio Materiale di supporto Schede tecniche singoli prodotti • Tipo finitura interna • Superficie finitura interna • Tipo finitura esterna • Superficie finitura esterna • Composizione Materiale/Componente • Presenza certificazioni • Capacità strutturale • Trasmissione vapore • Valore R • Valore U • Valore assorbimento • Trasmissione acustica
Usi consentiti • Semplici ingombri • Studio schemi compositivi	**Usi consentiti** • Studio preliminare • Computo metrico • Stima economica preliminare	**Usi consentiti** • Dimensioni esecutive • Utilizzo per computo metrico estimativo • Verifica interferenze con altre discipline	**Usi consentiti** • Previsioni di scheduling di cantiere	**Usi consentiti** • Cantierizzazione • Produzione • Manutenzione

Figure 15 - Overview of the Italian BIM classification system using an alphabetical Level of Development (LoD) scale from A to E. by (Pavan. A, 2017).

1.5.11.1 UNI EN 17412-1: 2021:

The UNI EN 17412-1:2021 standard introduces a more refined approach to defining the Level of Information Need, distinguishing itself from traditional uses of LoD. By providing a clearer and more structured framework for information requirements, this standard aims to:

- Enhance information quality, allowing for automatic or semi-automatic comparison between what is required and what is actually provided;
- Support legal and contractual clarity, by reducing ambiguity in interpreting requirements and simplifying compliance checks;
- Increase efficiency and adaptability within BIM processes, ensuring that only the information truly needed is generated—avoiding both overload (e.g., overly detailed models) and gaps (e.g., vague or incomplete requests).

This method helps clarify the specific context in which digital processes operate and improves the overall reliability of project information. The approach aligns closely with the principles of ISO 19650, which emphasizes that the purpose of the information must be clearly defined before deciding what information is required. In this way, UNI EN 17412-1 complements ISO 19650 by providing a practical methodology for specifying the Level of Information Need more precisely (Bolpagni, 2021).

1.5.11.2 Level of Information Need (LOIN):

Information models consist of both geometric representations and various attributes, such as element types, materials, properties, and performance data. Consequently, models can be evaluated based on both their graphical detail and the richness of their information. However, the inconsistency in the definition and interpretation of Levels of Development (LODs) across different countries and standards has highlighted the need for a more unified approach. This led to the development of the concept known as the Level of Information Need (LOIN) in the ISO 19650 standard. LOIN shifts the focus toward the relevance and sufficiency of information, regardless of its form, and emphasizes that only the necessary type, amount, and quality of data should be included in the model (ISO 19650, 2018).

1.5.12 Case Study: San Benigno Plastic Factory

PCMA (Plastic Components and Modules Automotive) is located in the municipality of San Benigno Canavese (TO), along an urban road just a few kilometers from the town center and about 30 minutes from the city of Turin. In 2007, the company was acquired by the Fiat Group, which later became FCA (Fiat Chrysler Automobiles), and in 2021 it became part of the Stellantis Group. Since its early days, the company has specialized in the production of plastic components for the automotive sector. This manufacturing takes place within the facility shown in Figure 6, which covers an area of approximately 25,000 m^2.

Figure 16 – San Benigno Plastic Factory site plan- Google maps

Inside, the building is divided into several areas, each designated for a specific function. This layout is designed to optimize operations and ensure clear separation between the different stages of production.

1.5.12.1 Data Collection:

The company provided three main files for analysis: an AutoCAD (.dwg) file, a Revit (.rvt) model, and a PowerPoint presentation. Among these, the Revit file was primarily used, as it was integrated into the project through a linked Revit model. However, the Revit file presented some technical issues, particularly when attempting to export the model to gbXML format, specifically related to the roof geometry, which caused inconsistencies or incomplete data during the export process.

On the PowerPoint file (.pptx), it is illustrating both the current and proposed future layouts of the facility, following a planned expansion. The layouts show the division of spaces according to their function. It is presented the current configuration (labeled "AS-IS"), and the future layout (labeled "TO-BE") that will result from the spatial reorganization.

1.5.12.2 Factory Elements:

The factory has three types of external wall constructions, each contributing to the overall thermal performance of the building envelope. The primary façade is composed of prefabricated concrete panels with the thickness of 30 cm, which provide a U-value of 1.43 $W/m^2 \cdot K$, While the U-value limit is 0.3 $W/m^2 \cdot K$ (D.M, 2015). Additionally, the building includes four extended sections constructed using 20 cm thick brick masonry walls, with an estimated U-value of 2.00 $W/m^2 \cdot K$, indicating comparatively lower thermal resistance. A third wall type is found in the areas surrounding the roof-level windows, which serve as additional vertical enclosures but differ in construction characteristics from the main façade (UNI/TR 11552, 2021).

The existing glazing throughout the building consists of 9 mm single-glaze windows, with a U_w-value ranging between 5.5 and 6.0 $W/m^2 \cdot K$ While the U-value limit for windows is 1.4 $W/m^2 \cdot K$. These values reflect high thermal transmittance, suggesting a significant potential for heat loss through the glazed surfaces and highlighting the need for potential improvements in terms of energy efficiency (UK Government, 2013).

CHAPTER 2

METHODOLOGY

Chapter 2: Methodology:

This chapter describes the methodological approach adopted to evaluate and improve the performance of a selected building through the integration of Building Information Modeling (BIM), Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Building Energy Modeling (BEM). The process began with the definition of three initial design scenarios, each exploring different strategies for enhancing energy efficiency, environmental sustainability, and cost-effectiveness. Following a initial evaluation, these were merged into two optimized solutions, which were fully developed and analyzed in the BIM environment using Autodesk Revit. Each solution included detailed modeling of geometry, materials, and technical systems. Environmental data such as Global Warming Potential (GWP) and emission factors, were embedded using shared parameters. To assess operational energy performance, the models were exported in gbXML format and simulated in DesignBuilder. LCA was carried out using One Click LCA to quantify the environmental impact of each scenario, while LCC was performed to estimate and compare the total cost of ownership over a 40-year period and replacement costs. This integrated approach enabled a comprehensive evaluation of the environmental and economic balancing considerations between the two retrofit strategies.

2.1 Scenarios

To evaluate and compare the energy and economic performance of various retrofit strategies, a set of envelope scenarios was developed. These were structured to reflect practical retrofit approaches based on material availability, construction feasibility, and thermal performance requirements. The focus was on wall retrofit systems and window glazing configurations, both of which are critical components affecting the building's energy performance.

2.1.1 Climatic Classification and Regulatory Limits

The thermal transmittance values (U-values) proposed in the wall and window retrofit scenarios were defined in compliance with the Italian national energy efficiency regulations, as outlined in DM Requisiti Minimi, Appendice A (2015, updated in 2021). These reference standards specify mandatory maximum U-values for different envelope components depending on the climatic zone of the project location.

According to the climatic zoning provided by Tuttitalia.it, the project site; Ivrea, in the Province of Torino, falls under Climate Zone E. As such, the applicable regulatory maximum U-values for retrofit interventions are:

- **Vertical opaque walls**: U_{max}= 0.30 W/m²K
- **Transparent surfaces (windows, including frame)**: U_{max}=1.40 W/m²K

These limits serve as benchmarks in the scenario modeling phase and are critical for evaluating whether each façade and glazing option complies with national energy performance standards. In all retrofit configurations presented, the calculated or simulated

U-values for walls and windows are assessed against these regulatory thresholds to ensure full compliance.

The retrofit strategies applied to these walls are categorized into the following three scenarios:

2.1.2 Wall Retrofit Scenarios

Three distinct wall configurations were proposed each applied over different existing wall conditions. The wall types used in this factory is mostly prefabricated cement wall with various thickness; Type 1, 300 mm, Type 2, 100 mm representing the main structural wall of the building and Type 3, 200 mm is solid brick masonry.

- **Scenario 1: Adding Insulation to Existing Walls**

This solution involves attaching a ventilated façade system composed of insulation layers (e.g., Rocksilk RainScreen Slabs), aluminum substructure (T-profiles), and terracotta cladding. Fasteners and brackets are included as sub-components. This method is widely adopted for its durability and high thermal resistance, resulting in significantly reduced U-values (as low as 0.105 W/m²K).

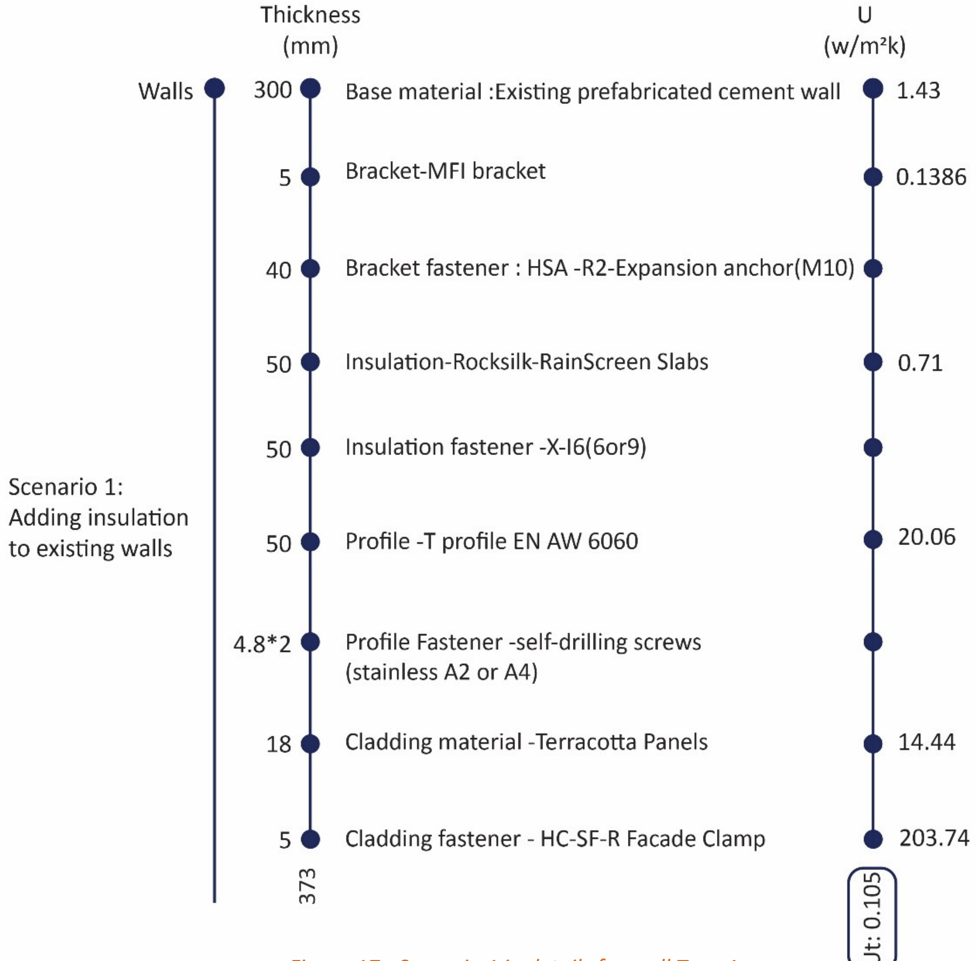


Figure 17 - Scenario 1 in details for wall Type 1.

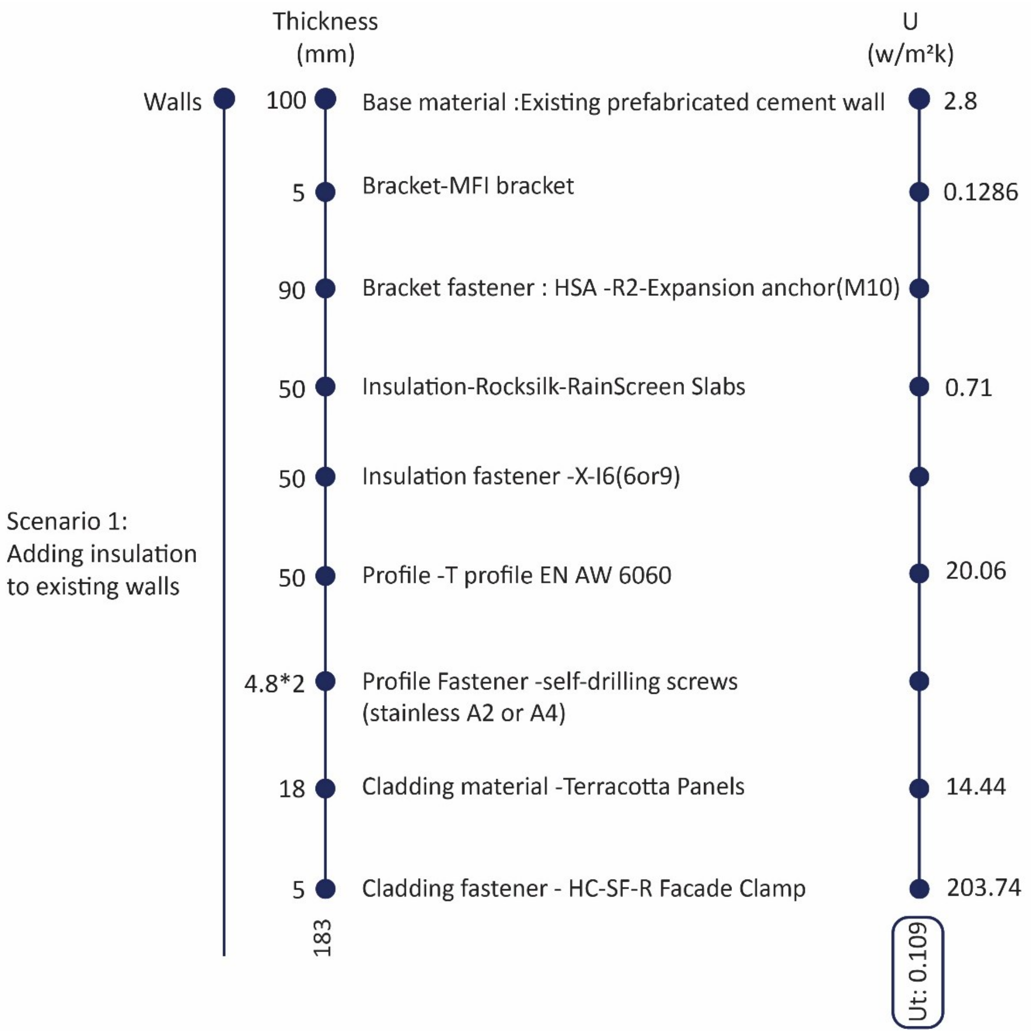


Figure 18 - Scenario 1 in details for wall Type 2.

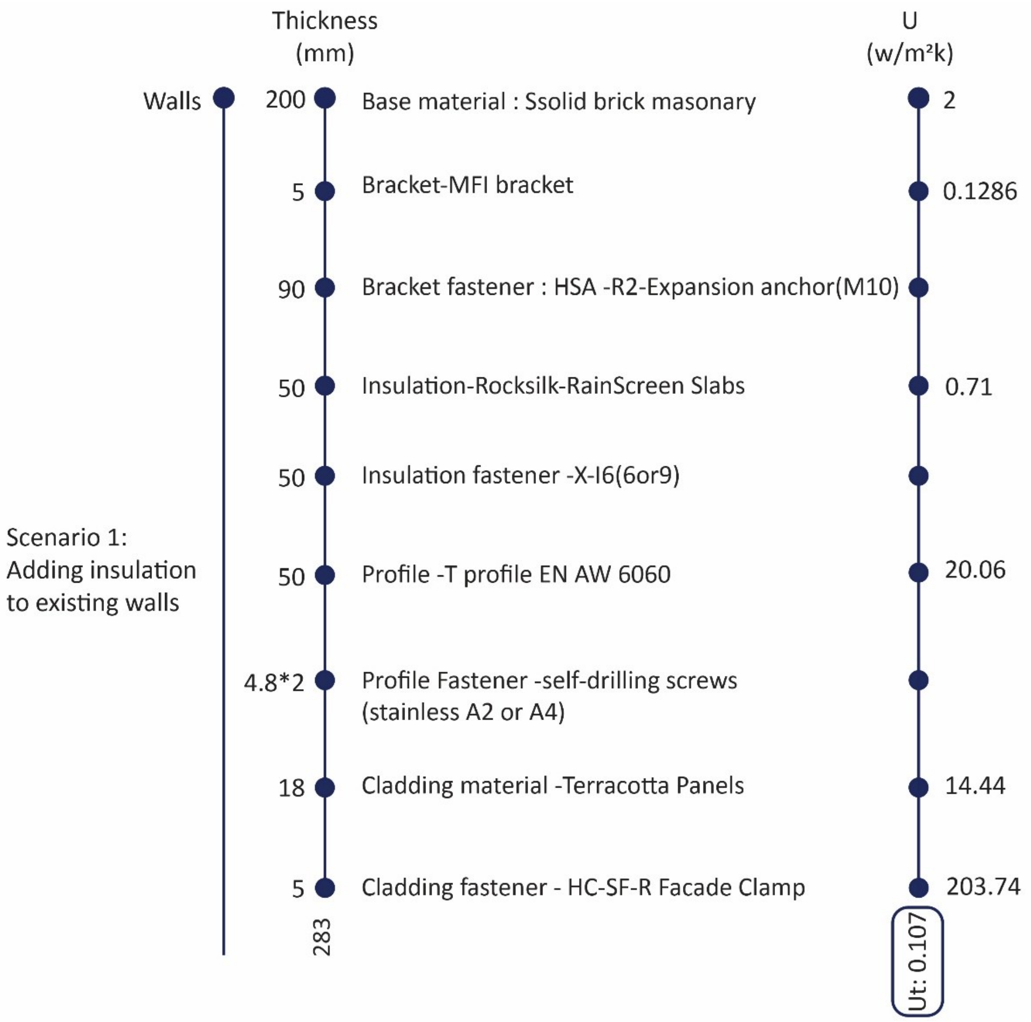


Figure 19 - Scenario 1 in details for wall Type 3.

- **Scenario 2: Using Green Walls on Existing Walls**

In this biophilic approach, green wall systems composed of super soil boxes and vegetation layers (e.g., Planet® systems) are mounted on the existing façade. These systems offer added insulation and thermal buffering while contributing to environmental quality and aesthetic enhancement. U-values in this scenario vary depending on moisture retention and plant density, with typical values around 0.27 W/m²K.

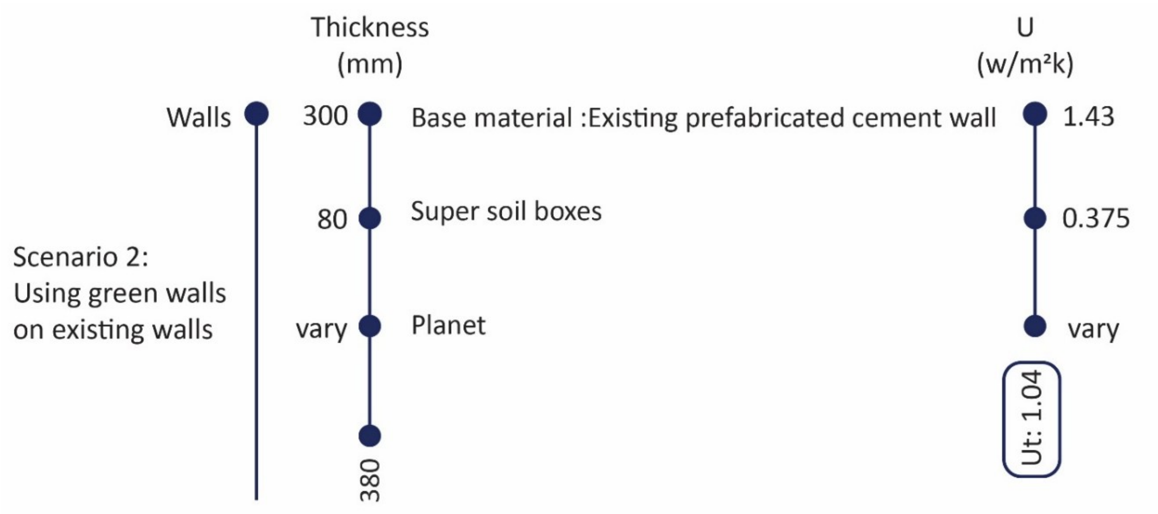


Figure 21 - Scenario 2 in details for wall Type 1. [90]

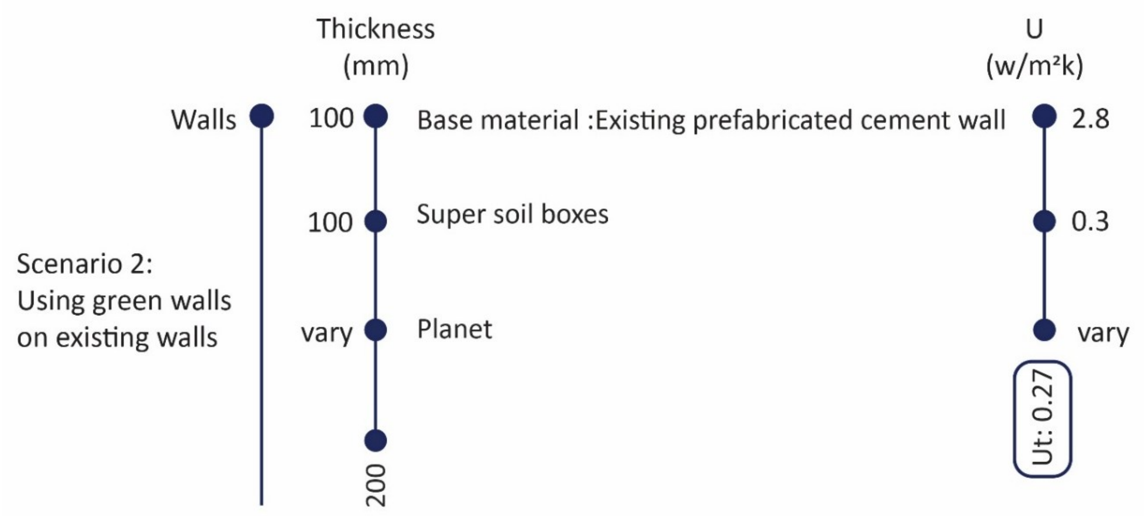


Figure 20 - Scenario 2 in details for wall Type 2. [90]

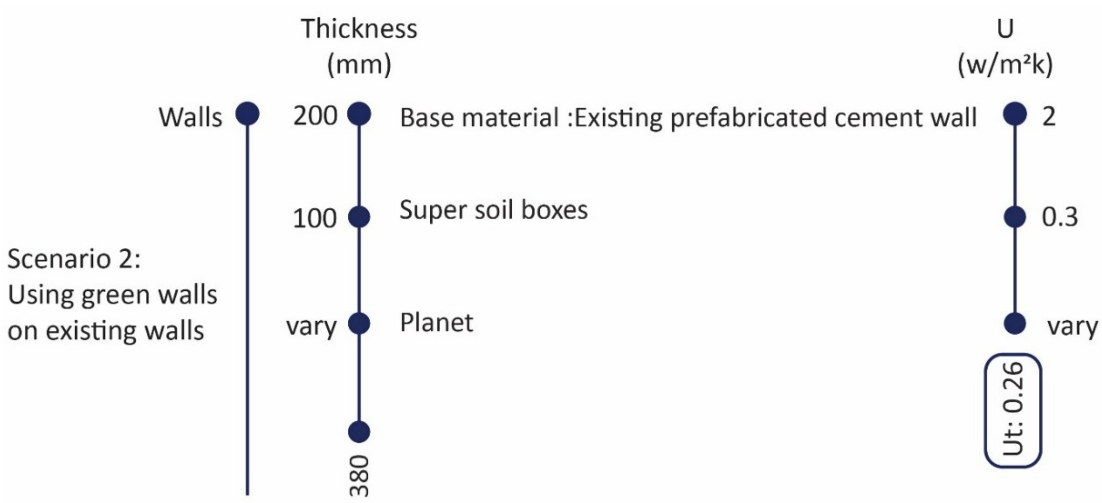


Figure 22 - Scenario 2 in details for wall Type 3. [90]

- **Scenario 3: Using Cavity Walls**

This strategy builds a double-skin wall comprising an air gap and a secondary clay brick layer (Canna Brick). It is a traditional yet effective passive method to reduce heat loss, with resulting U-values ranging from 0.14 to 0.3 W/m²K, depending on wall thickness and materials used.

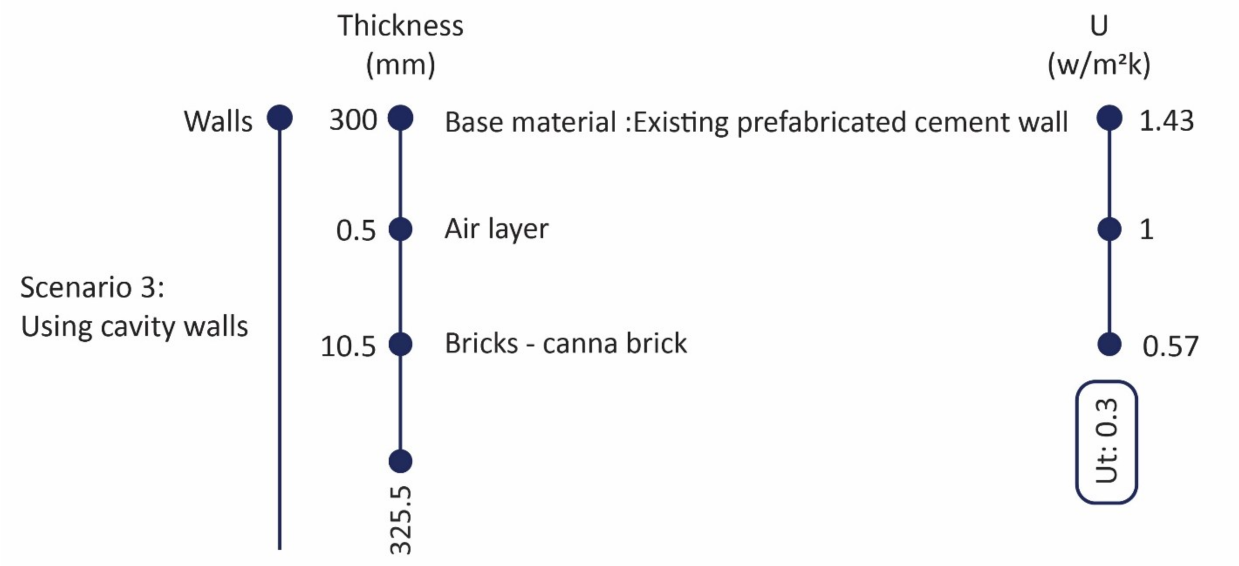


Figure 23 - Scenario 3 in details for wall Type 1. [90]

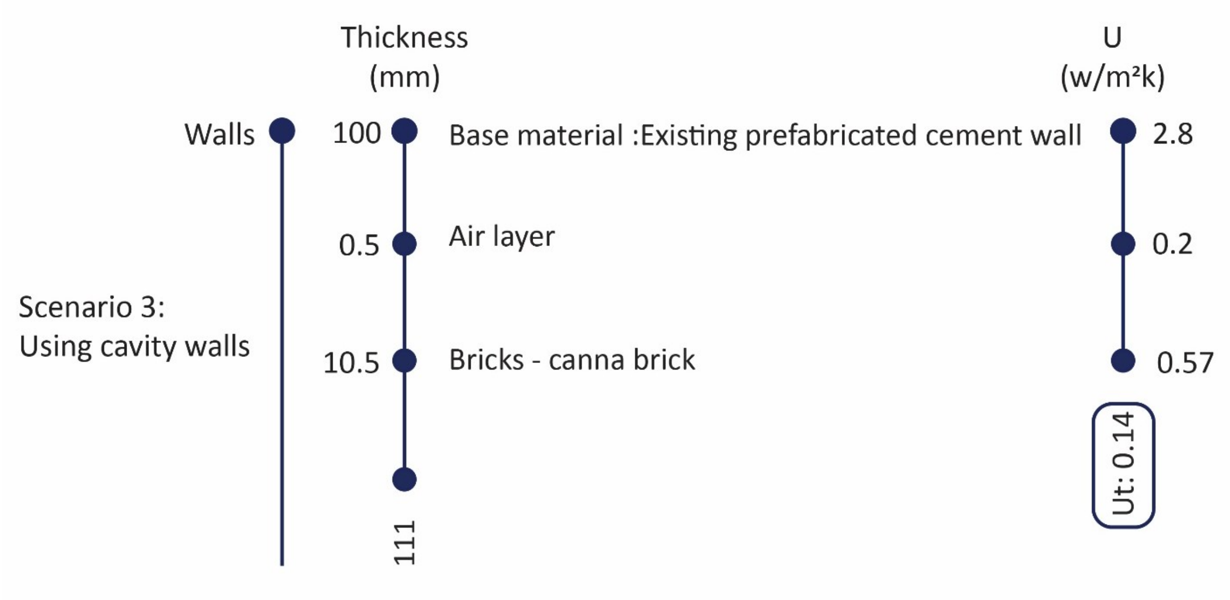


Figure 24 - Scenario 3 in details for wall Type 2. [90]

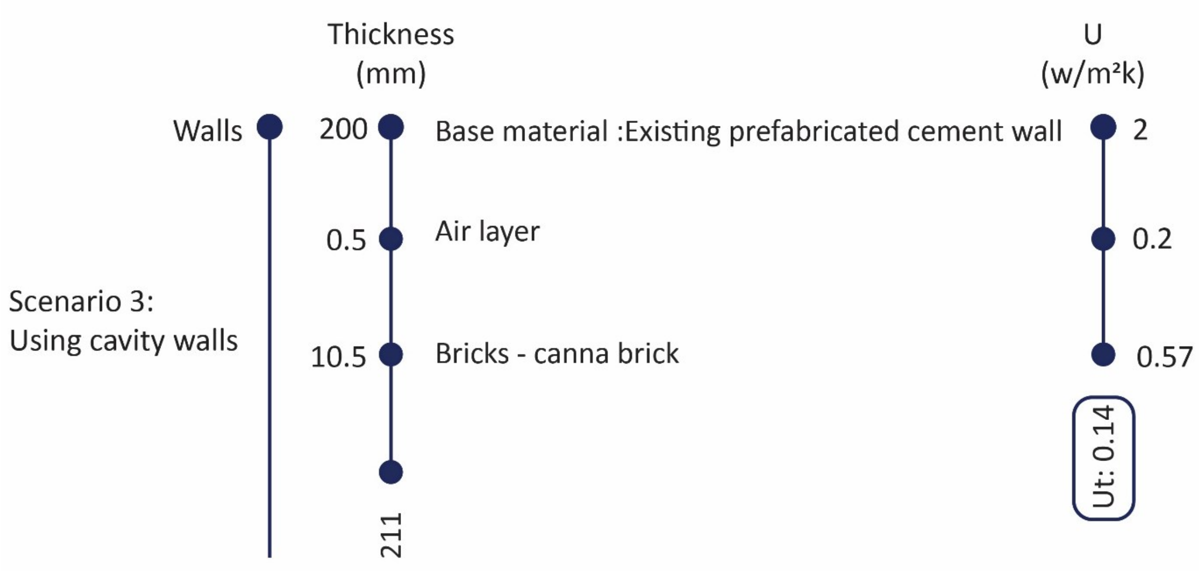


Figure 25 - Scenario 3 in details for wall Type 3. [90]

2.1.3 Glazing Scenarios

Three window types were analyzed to assess their influence on overall thermal performance:

- **Scenario 1: Double-Glazed Windows**

  Featuring 40 mm glass and 56 mm frames, this configuration results in a U-value of 1.3 W/m²K. It represents a common and economically balanced option for standard energy-efficient buildings.

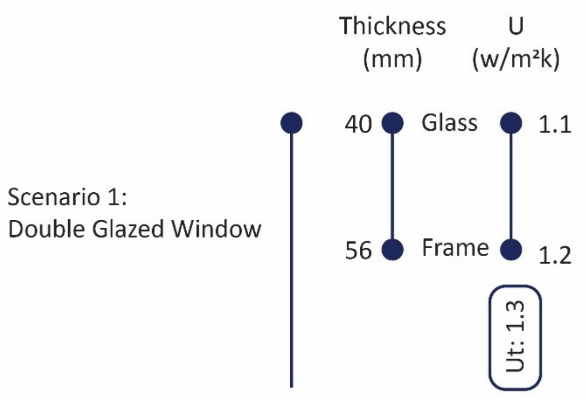


Figure 26 - Scenario 1 in details for window. [94,95]

- **Scenario 2: Triple-Glazed Windows**

Offering enhanced insulation through a 60 mm glazing system and thicker frames, this solution reduces the overall U-value to 1.1 W/m²K, improving energy savings at a slightly higher upfront cost.

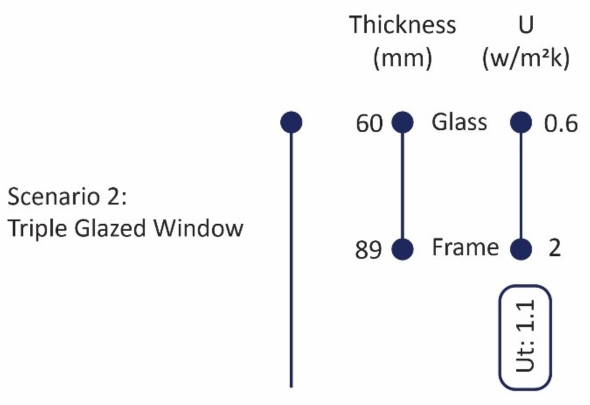


Figure 27 - Scenario 2 in details for window. [96]

- **Scenario 3: BIPV (Building Integrated Photovoltaic) Glass**

This energy-generating glazing integrates photovoltaic technology, delivering energy back to the building. While the U-value is much higher (6 W/m²K) due to single-layer glass (4 mm), it compensates through active energy production and reduced electricity demand.

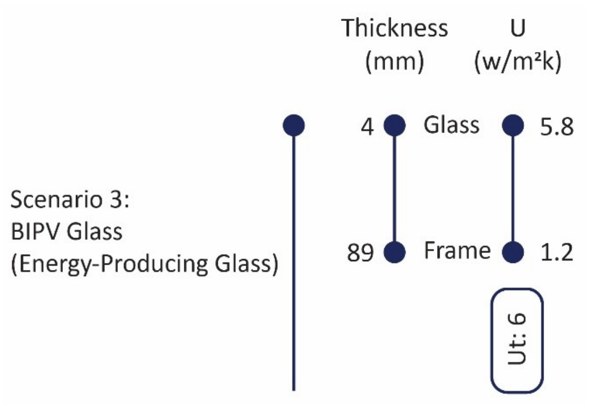


Figure 28 - Scenario 3 in details for window. [97]

2.2 Thermal Transmittance Calculation Method

To evaluate the thermal performance of the proposed envelope systems, the U-value (thermal transmittance) of each wall configuration was calculated by considering all layers of the assembly. For multilayer walls, the overall thermal resistance (R_{tot}) is computed as the sum of the individual resistances of each material layer, including internal and external surface resistances, according to the UNI EN ISO 6946 standard.

The total U-value is then derived from the total thermal resistance using the following relation:

$$U_{tot} = \frac{1}{R_{tot}}$$

Where: U_{tot} is the overall thermal transmittance (W/m²·K)

R_{tot} is the total thermal resistance (m²·K/W)

For multilayer walls, where materials are stacked in series (e.g., plaster + insulation + structural wall + cladding), the total thermal resistance is calculated by summing the resistances of each layer:

$$R_{tot} = R_1 + R_2 + R_3 + \cdots$$

So,

$$\frac{1}{U_{tot}} = \frac{1}{U_1} + \frac{1}{U_2} + \frac{1}{U_3} + \cdots$$

In the context of building envelope analysis, the Uw-value represents the overall thermal transmittance of a complete window system, including both the glazing unit, the frame, and the thermal bridge at the interface between them. The calculation follows the standard defined in UNI EN ISO 10077-1.

The Uw-value is calculated as:

$$U_w = \frac{U_f . A_f + U_g . A_g}{A_f + A_g} + \Psi . L_g$$

Where:

- U_w = Overall U-value of the window (W/m²·K)
- U_f = Thermal transmittance of the frame (W/m²·K)
- U_g = Thermal transmittance of the glazing (W/m²·K)
- A_f = Area of the frame (m²)
- A_g = Area of the glazing (m²)
- Ψ = Linear thermal transmittance of the glass–frame edge (W/m·K)
- L_g = Length of the glass perimeter in contact with the frame (m)

These formulas allowed for accurate assessment of each scenario's compliance with the national thermal transmittance limits defined for Climate Zone E, specifically U ≤ 0.30 W/m²·K for opaque walls and U ≤ 1.40 W/m²·K for transparent components, in accordance with *DM Requisiti Minimi – Appendice A* (2015/2021).

2.3 Selected scenarios

According to the U-value limits for Ivrea established by DM 2015, and based on the predefined wall and window retrofit scenarios, only Wall Scenario 1 (adding insulation) complies with the requirements. For the windows, both Scenario 1 (double glazing) and Scenario 2 (triple glazing) are suitable options. Regarding insulation strategies, two main categories were considered: mineral and natural.

Mineral insulation materials such as rock silk are widely used in construction for their excellent thermal performance, fire resistance, and long-term durability. With thermal conductivity typically around 0.035–0.045 W/m·K, rock silk provides stable performance across varying moisture conditions. However, its production is energy-intensive, resulting in relatively high embodied carbon emissions (Collet & Pretot, 2014). In contrast, natural insulation materials like hemp fiber offer significant environmental benefits due to their renewable origin, lower embodied energy, and biogenic carbon sequestration. Hemp insulation generally achieves thermal conductivities between 0.040 and 0.060 W/m·K and also contributes to indoor air quality and material breathability (Ip & Miller, 2012).

Hemp insulation achieved approximately 10% lower global warming potential than conventional mineral-based insulation, although the life cycle cost (LCC) of hemp was approximately 20% higher (Hult and Karlsmo (2022)). Bio-based insulations like hemp provide better environmental performance across most impact categories, despite slightly higher initial costs. So, hemp insulation is environmentally superior but less economical, while rock silk is cost-effective yet environmentally heavier (Turnholz et al. (2021)). Therefore, selecting insulation materials for retrofit projects depends on project priorities, whether minimizing carbon footprint or optimizing economic performance. According to the thesis case study which is an industrial building, for the matter of safety hemp insulation materials exhibit reliable fire performance and are considered to pose a low risk in building applications. Their fire resistance can be further enhanced when used in combination with plaster finishes, which offer additional protective layers and improve overall safety (Shewalul et al., 2023).

At the end, rock silk was selected as the representative material for mineral insulation, while hemp was used to represent natural insulation.

Since the defined scenarios primarily use mineral insulation (Rocksilk), an additional configuration was developed below to represent Wall Scenario 1 using natural insulation, specifically hemp, as a comparative alternative.

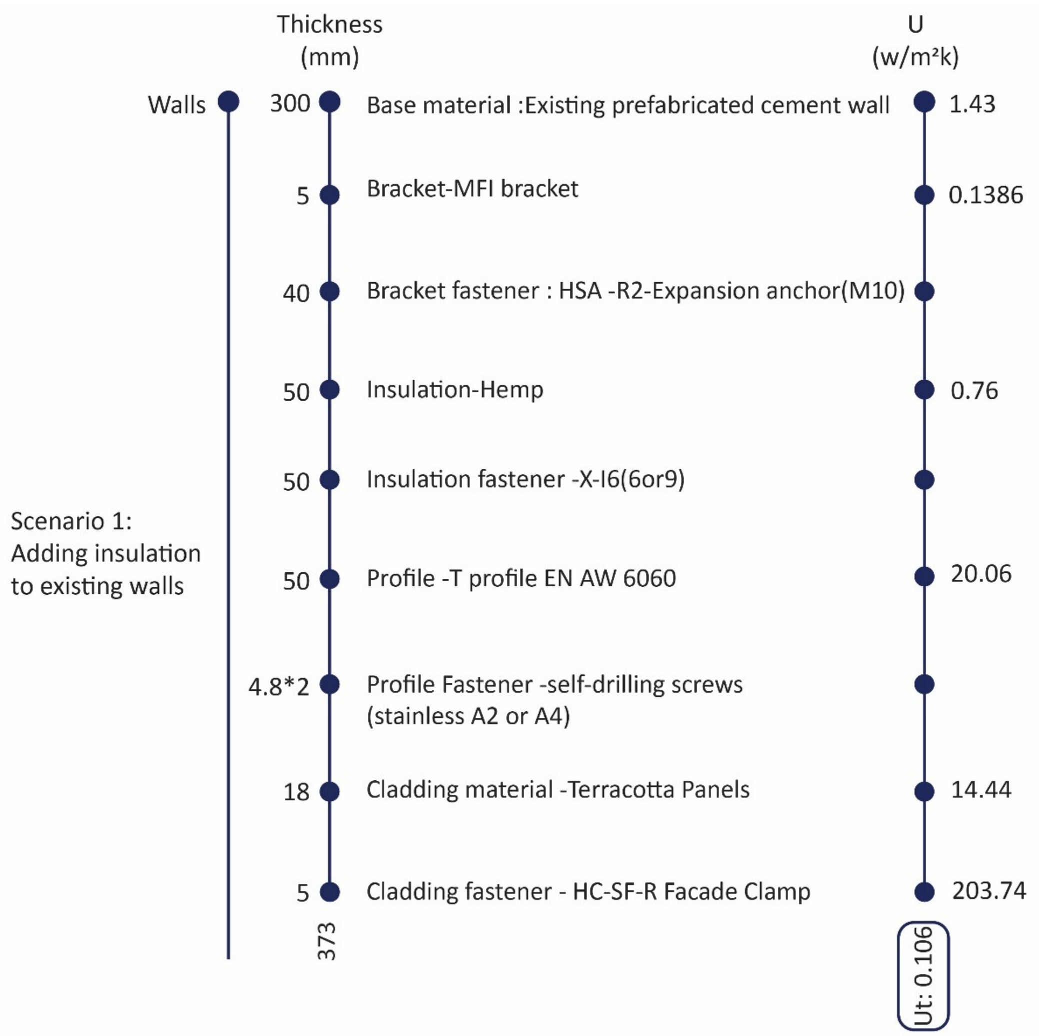


Figure 29 - Scenario 1 in details with hemp insulation for wall Type 1.

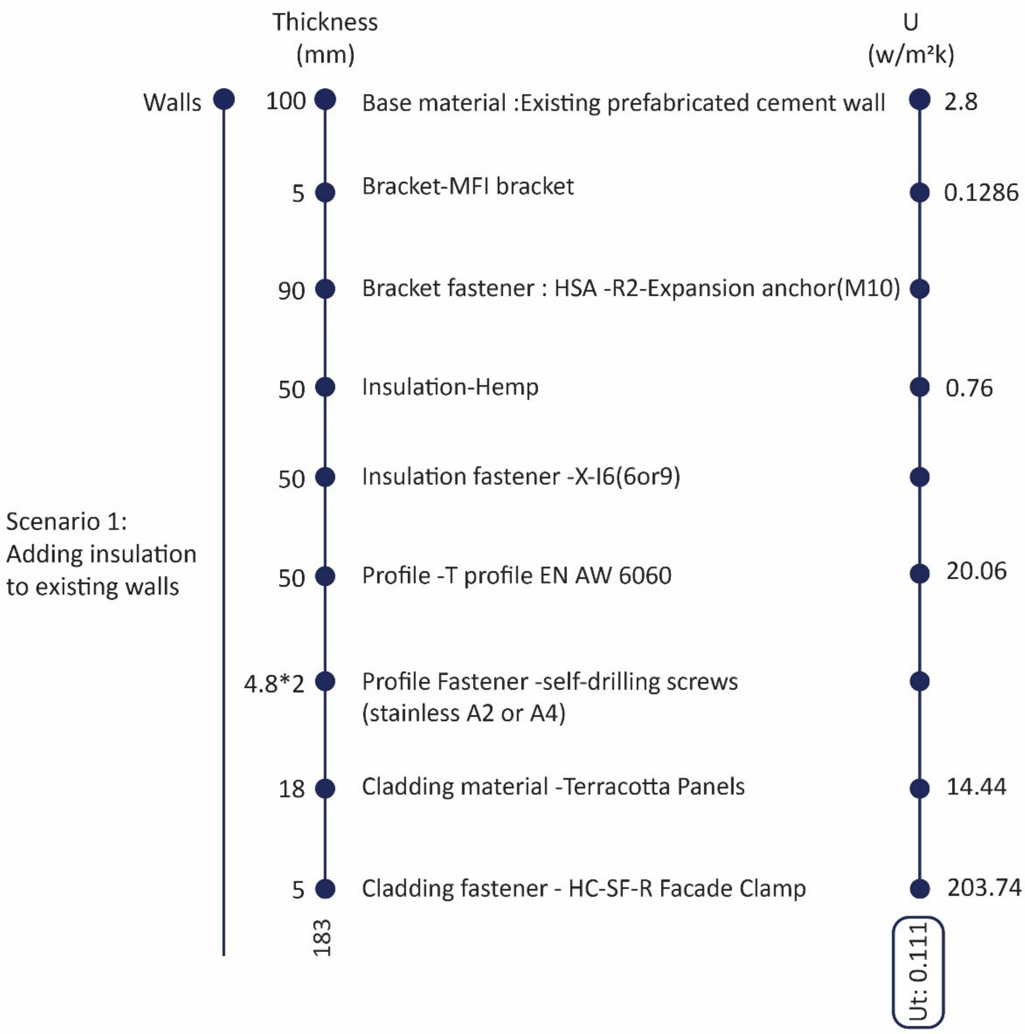


Figure 30 - Scenario 1 in details with hemp insulation for wall Type 2.

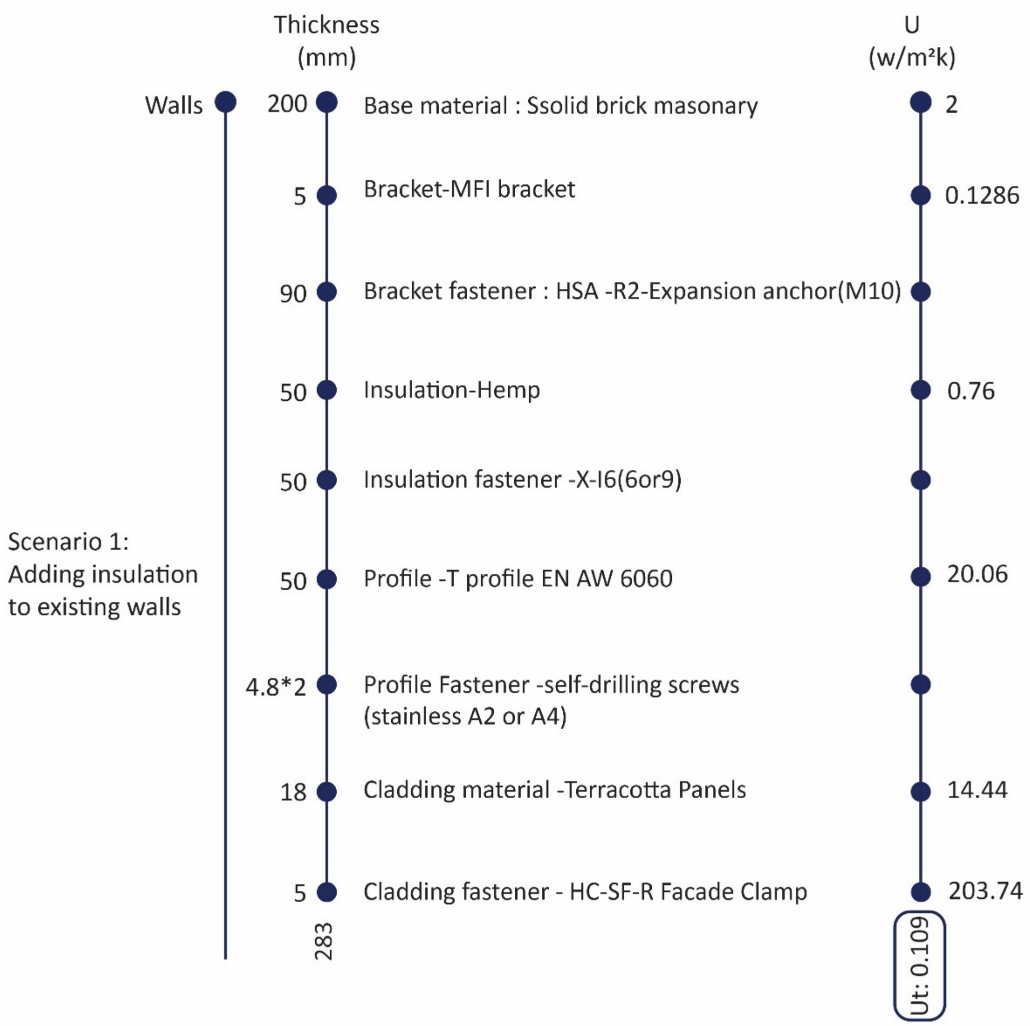


Figure 31 - Scenario 1 in details with hemp insulation for wall Type 3.

2.3 BIM modelling for LCA

2.3.1 Wall

The model has been initiated based on the selected stratigraphy of the insulation layers.

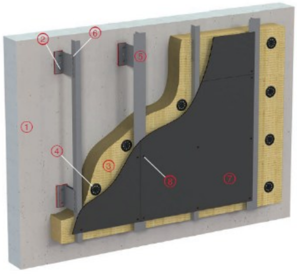


Figure 32 - (MFT Technical Manual, 2020).

1-Linking the Main Model

The primary Revit file was linked using the "Link Revit" function to integrate the main project model into the working environment to work in Revit as a federated model.

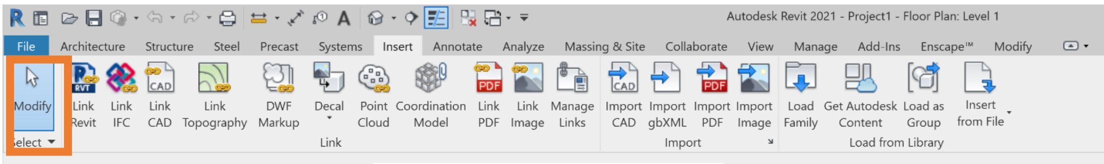


Figure 33 - Linking the Main Model

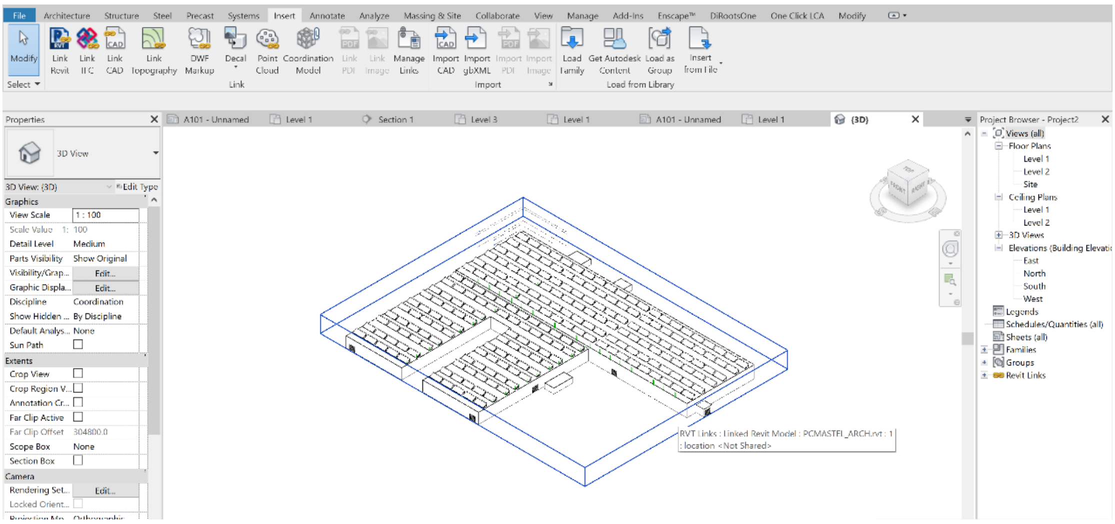


Figure 34 - The base model

2-Adding the Insulation Layer

The insulation layer was modelled as a wall, with thermal properties assigned accordingly to reflect its real-life performance and the dimensions which we found in the manufacturing company. In order to model an insulation wall with the required thickness, the wall type must be edited through the wall properties. This involves duplicating the existing type, renaming it appropriately, and adjusting the layer thickness as needed.

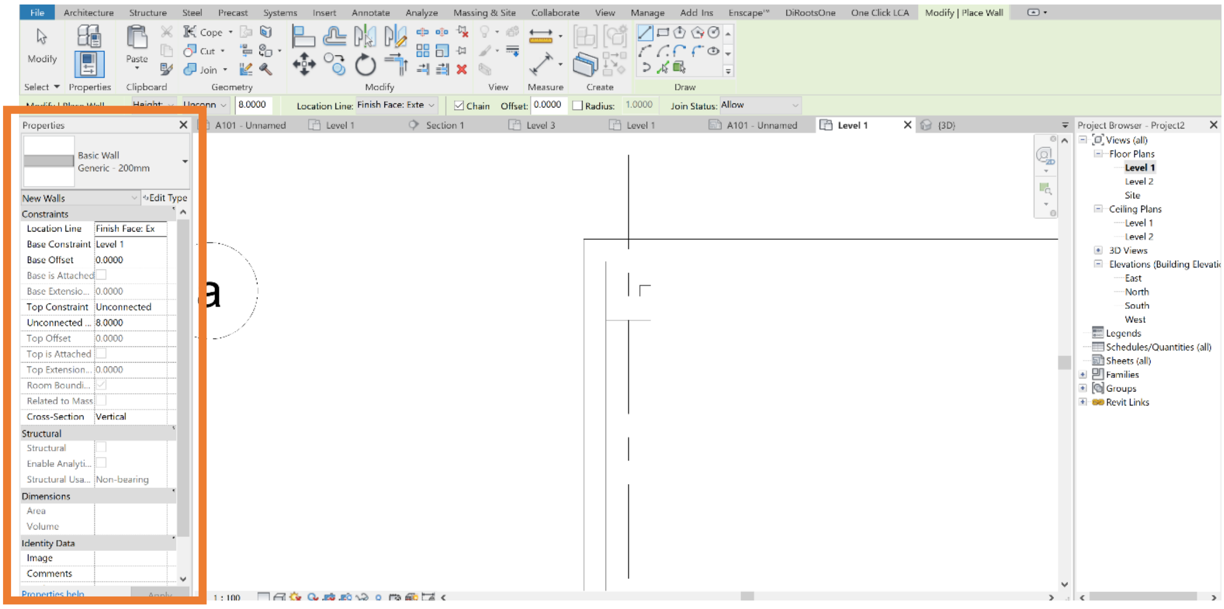


Figure 35 – Editing the properties of the wall

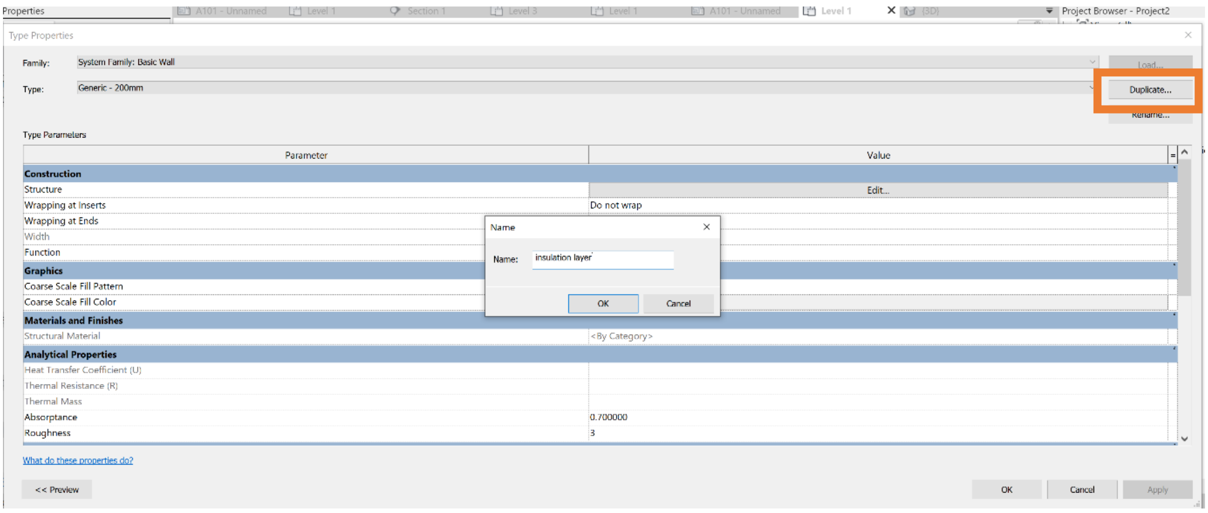


Figure 36 - Getting duplicate from wall and changing the name to Insulation layer

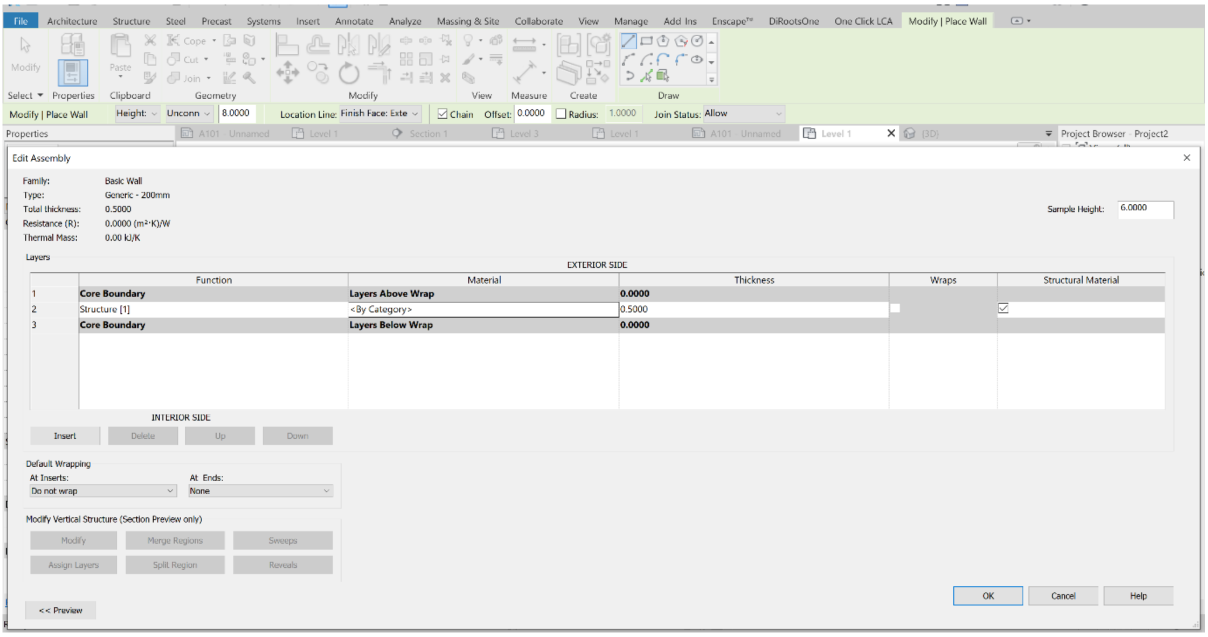


Figure 37 – Changing the thickness of the wall

Given the specified dimensions of the insulation slab, the wall needs to be segmented using the 'Create Parts' tool to ensure accurate layering and detailing.

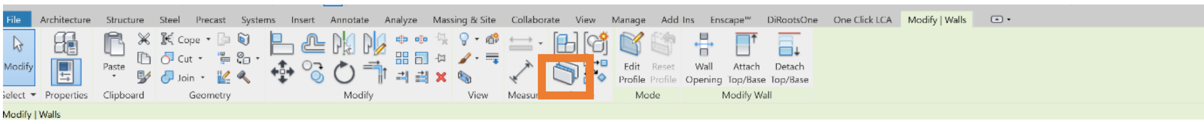


Figure 38 - Create parts of the wall

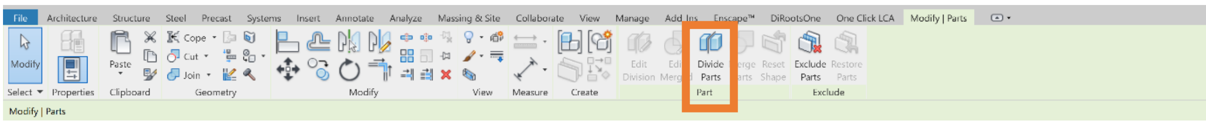


Figure 39 - Divide the part of wall

4-Connecting the Insulation to the structural walls

To attach the insulation layer to the concrete wall, brackets were used as structural connectors. The connections were reinforced with plastic twists, which were specifically selected for their lack of thermal conductivity in order to minimize thermal bridging.

In the initial phase of modeling, the connectors were placed individually, a process that proved to be very time-consuming. To improve efficiency, three different families were later created based on wall height and applied to the corresponding wall types.

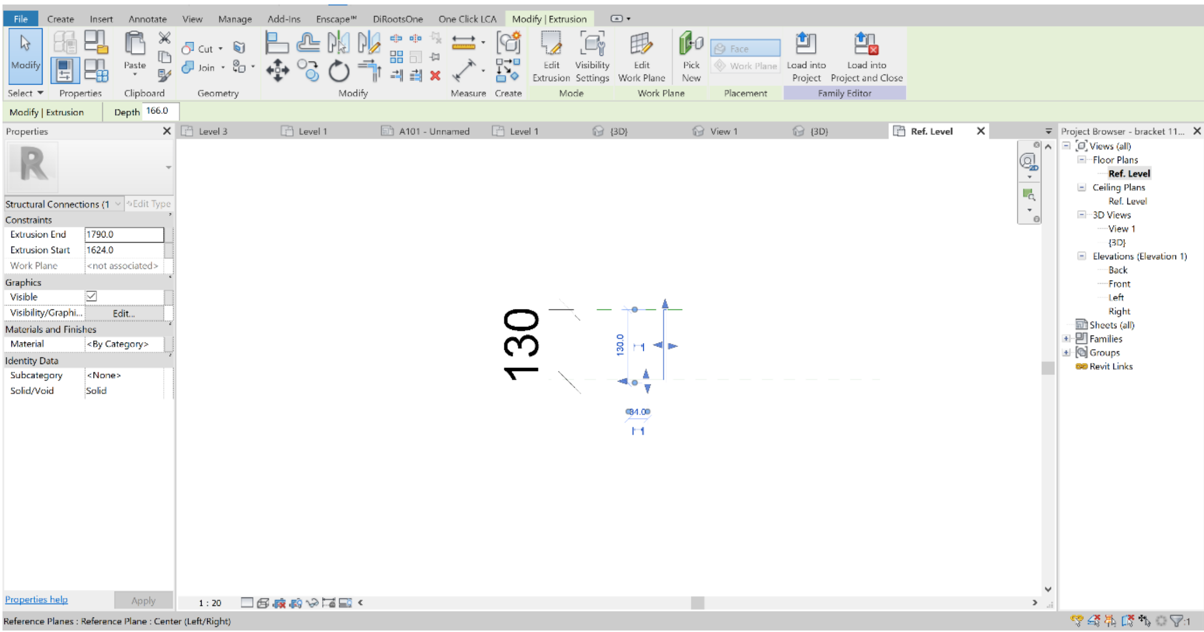


Figure 40 - Creating bracket as a structural connection family

5-Beam Structure for Cladding Support

A beam-based support system was modelled to connect the insulation layer to the cladding, ensuring structural integrity. The process of modelling was model as a wall after that using beam structure on wall and using the studs which we used in the project for the beams. Then, the host wall has to be deleted.

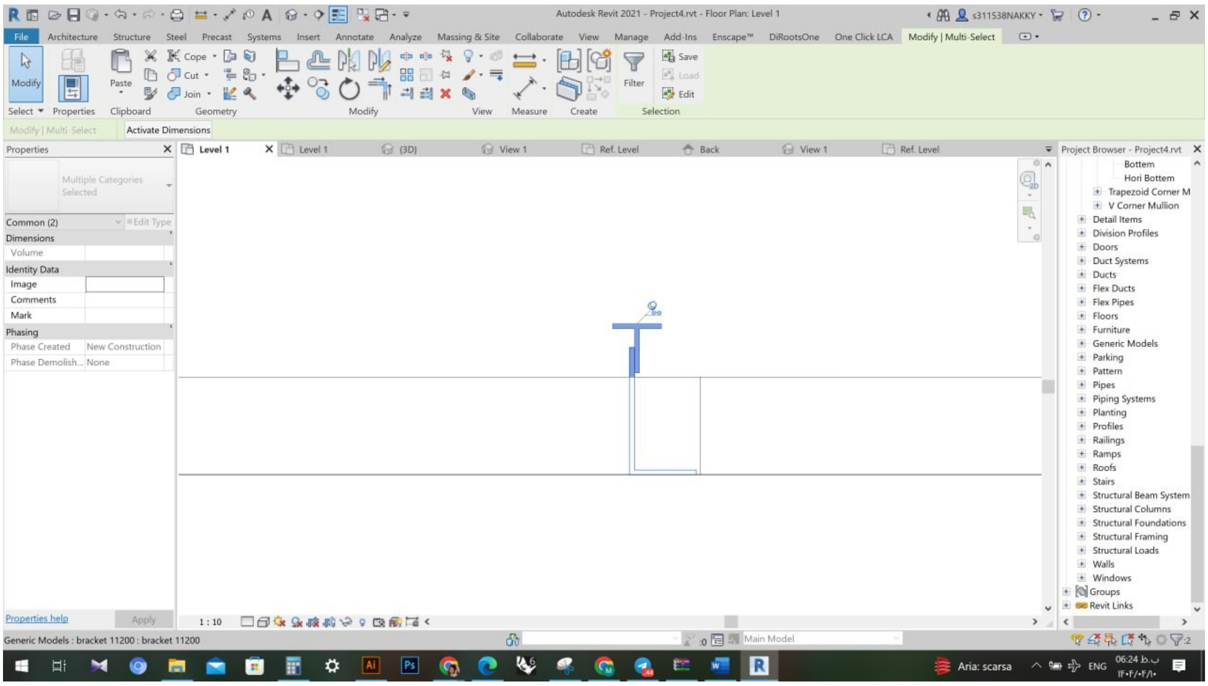


Figure 41 - Connecting T-profile to the brackets

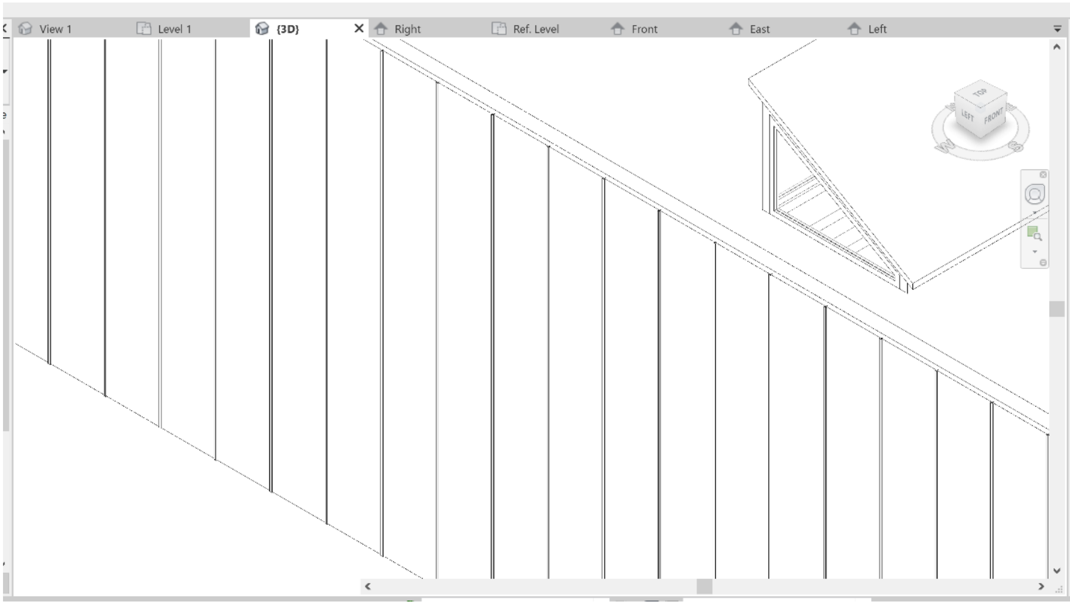


Figure 42 - T-profile as Structural framing

6-Clamping System for Joining

Clamps were implemented to secure the cladding system to the underlying structure, ensuring a stable connection. These clamps modelled as structural connections exactly like the brackets in 3 family types.

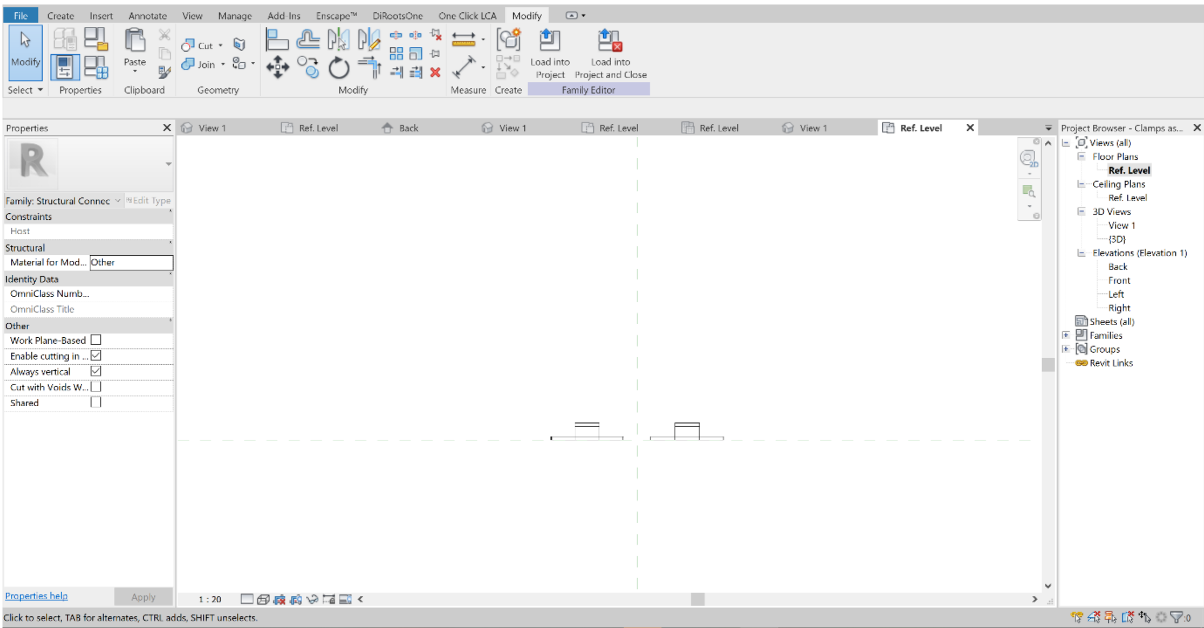


Figure 43 - Bracket as a structural connection family

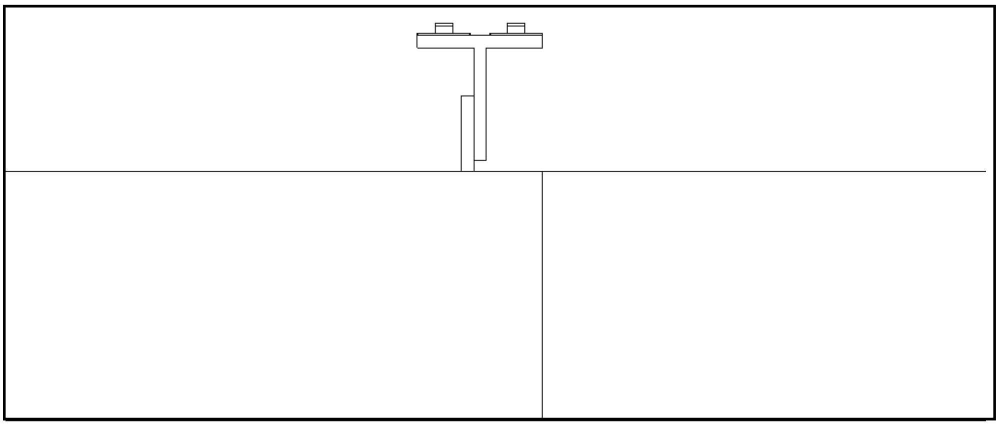


Figure 44 - Connection between T-profile and clamps

7-Final Cladding Layer

The outermost layer consists of cladding tiles, providing both aesthetic and functional protection for the building envelope which is modelled as a wall same as insulation with the cuts in the tile dimensions.

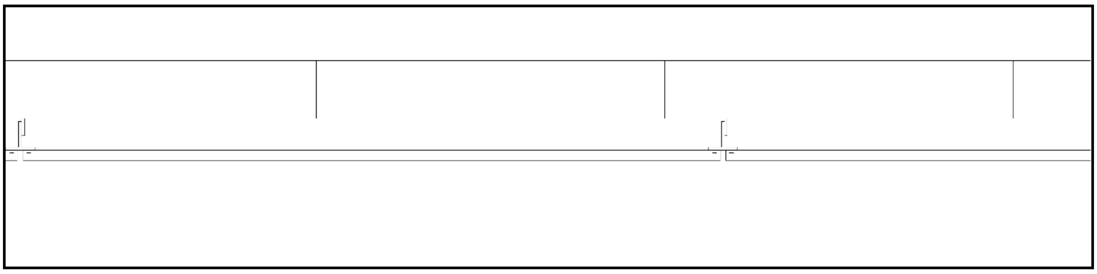


Figure 45 - Connecting cladding to the T-profile by clamps (Plan view)

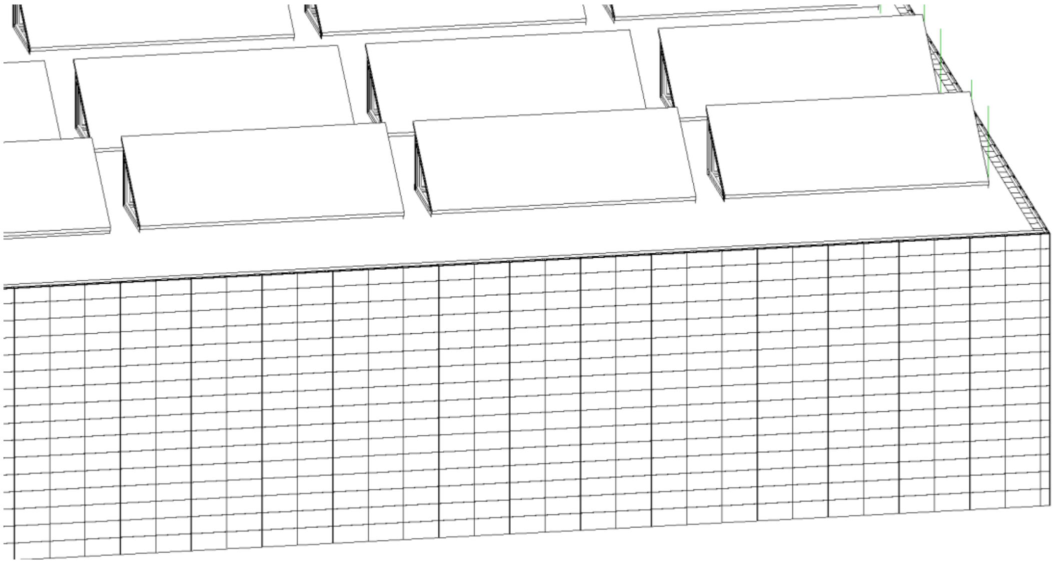


Figure 46 - Connecting cladding to the T-profile by clamps (3D view)

2.3.2 Window

1. Using the Double-Glazing Window Family

The original plan for the windows' BIM modeling process was to use a pre-established double-glazing window family and adjust its parameters to the project's requirements. But this strategy didn't work. It lacked the adaptability necessary to faithfully depict the windows' precise geometry, size, and arrangement. It was also not appropriate for the degree of accuracy required for this project due to its limitations in detailing and wall composition alignment.

2. Using Curtain Wall with Mullions

A curtain wall system with mullions was used as a more appropriate solution to get around these restrictions. More control over the window design was made possible by this method. On this modelling, it is used 3 types of families, one mullion for frame joining to the wall, another mullion for middle frame and a panel for glazing. Additionally, it made it easier to make adjustments during the design process and allowed for better integration with the surrounding wall elements. When it came to depicting the window components in the BIM model, this approach proved to be more precise and flexible.

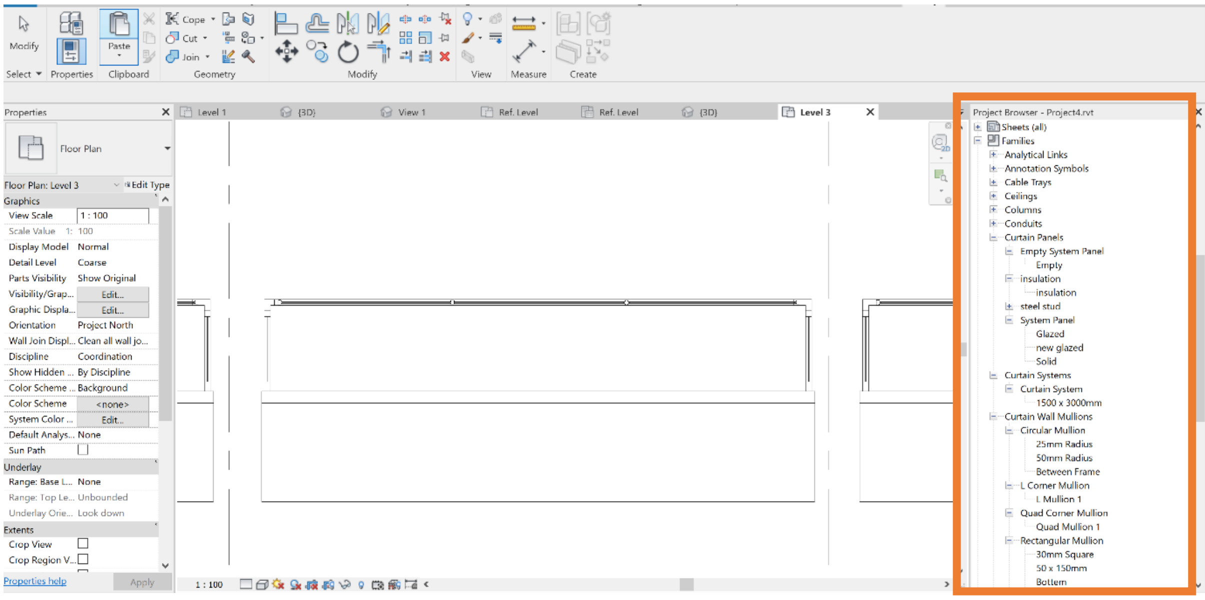


Figure 47 - Window plan with 3 types of the family for curtain wall

2.3.3 Updating the BIM model after LCA issue

After importing the model into One Click LCA, the software was unable to identify the exact count of brackets and clamps because they were all grouped under a single family, rather than as individual components. To resolve this problem, the elements were remodeled using separate families. These new families were then placed into the model using Dynamo to increase modeling speed and efficiency.

To address the issue encountered during the One Click LCA import, a new approach was adopted using Dynamo to optimize and automate the modelling process within Revit. Dynamo, a visual programming extension, was employed to script the placement and arrangement of key architectural components such as brackets, clamps, cladding panels, and insulation slabs using separate families. Instead of manually placing each element, parametric scripts were developed to control geometry placement based on predefined inputs. This not only resolved the component identification issue for LCA analysis but also significantly reduced repetitive actions, enhanced precision, and ensured consistency throughout the BIM model. Two main types of scripts were created: one for standard positioning and another incorporating rotational parameters, which was particularly important for elements like brackets and clamps requiring specific orientations (e.g., 90°, 180°). The execution of these scripts through Dynamo Player allowed users to input custom parameters and generate components directly within the Revit environment, streamlining the workflow, increasing productivity, and enabling efficient design iterations and updates.

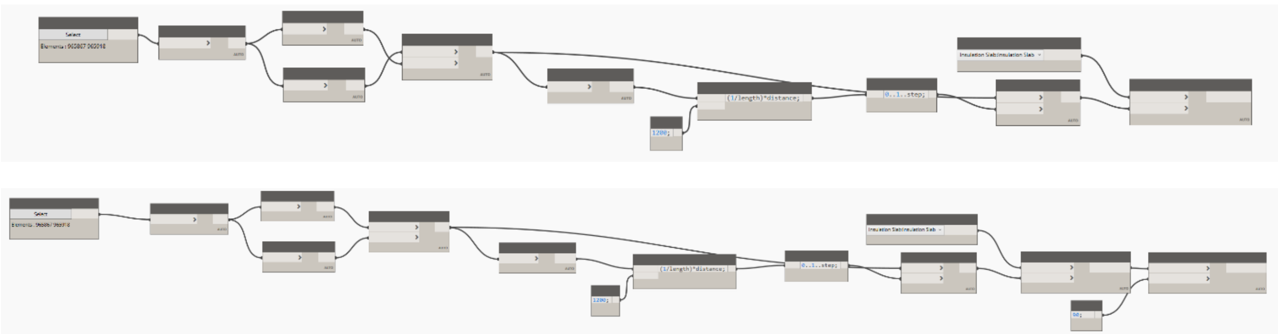


Figure 48 – Dynamo script of for placing bracket and clamps families

2.4 BIM modelling for LCC

The final model used for the LCA analysis was also employed for LCC evaluation. To enable this, cost data for each material, family, and wall system needed to be added as model properties, based on regional pricing. In this study, the costs were assigned according to the official price list of the Piemonte region in Italy (Prezzario Piemonte).

Type	Thickness (mm)	Euro	Per
Bracket-MFI bracket	5	12.31	cad
Bracket fastener-HSA -R2-Expansion anchor(M10)	40	2.9	cad
Insulation - Rocksilk- RainScreen Slabs	100	13.63	m^2
Insulation fastener-X-I6(6or9)	50	0.69	cad
Profile-T profile EN AW 6060	50	16.17	each 1.1 m
Cladding material-Terracotta Panels	18	20.43	m^2
Cladding fastener -HC- SF-R Facade Clamp	5	0.7	cad
Window frame: Aluminium	80	1165.93	m^2
Glass: profile IDEAL 5000	41	22.76	m^2
Hemp Insulation	50	15.55	m^2

Table 4 - List of material's prices based on Prezzario

1. Adding the unit cost of families and materials on Revit

There are two ways for adding the cost, one of them is as a formula in the material takeoff.

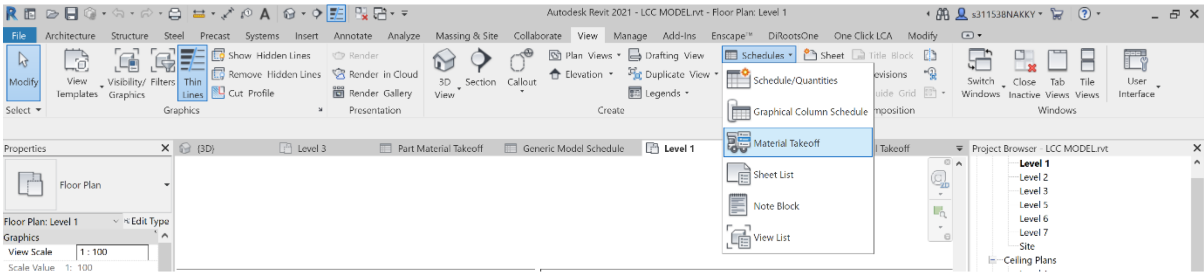


Figure 50 – Select schedule material takeoff

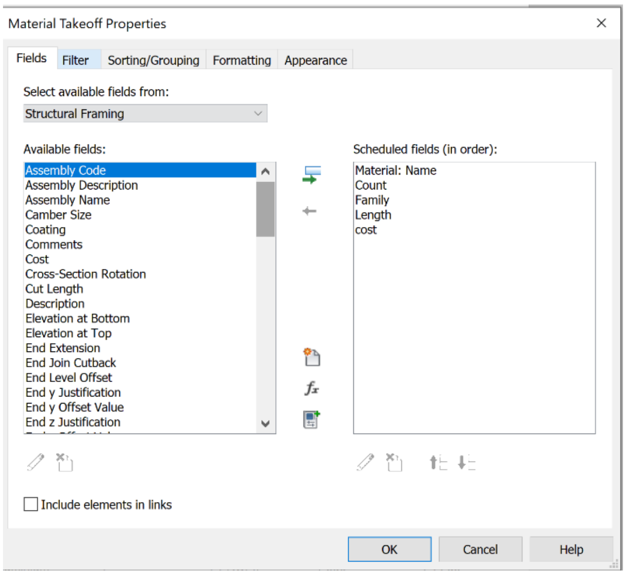


Figure 49 - Material takeoff properties

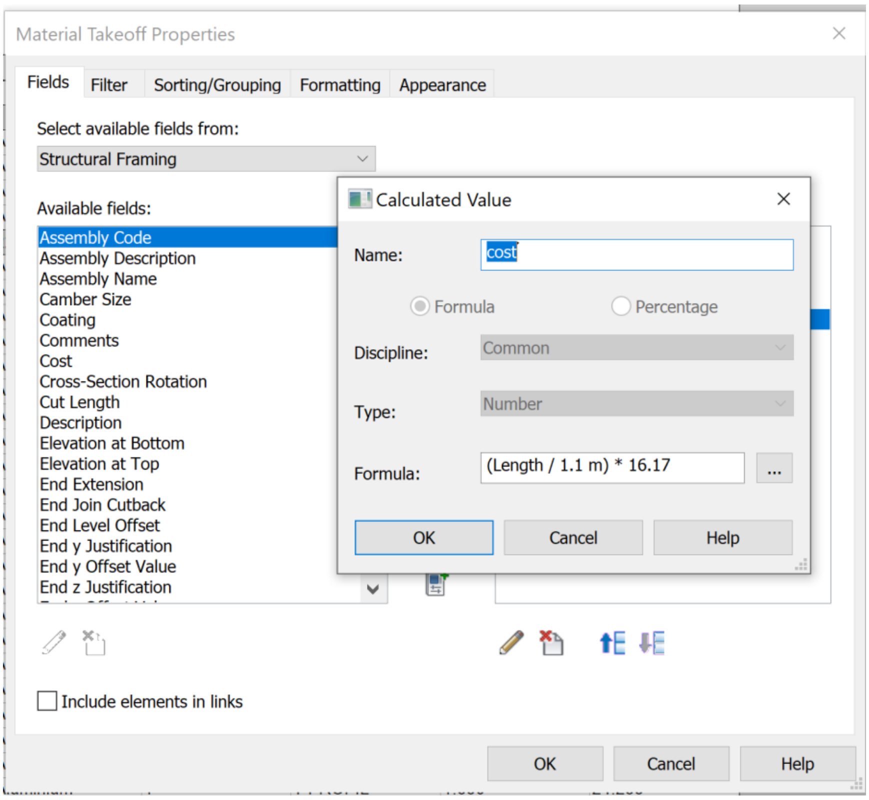


Figure 51 - Writing the formula for the cost

Another way is adding the cost as a property of the material.

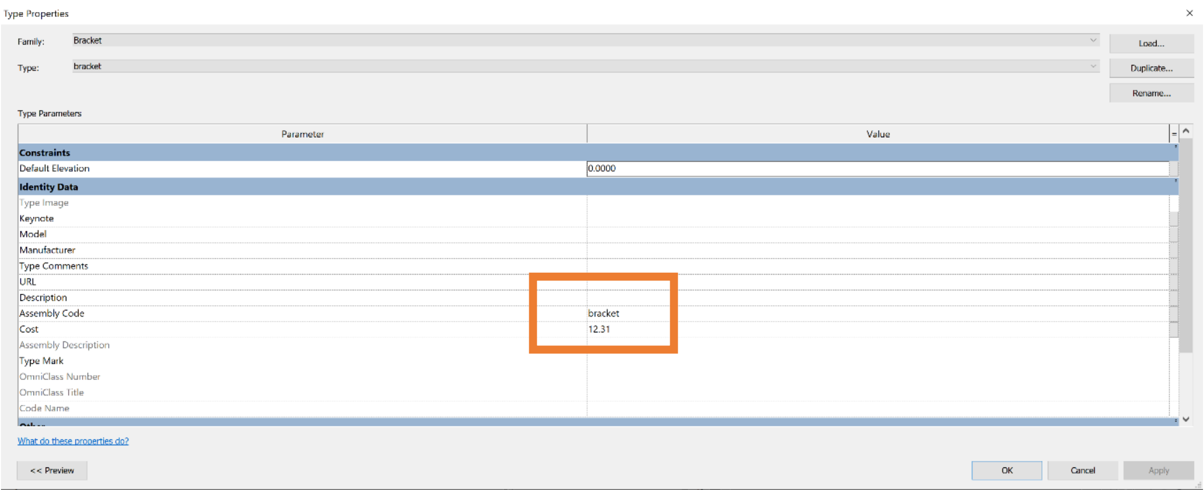


Figure 52 - Cost as a property of the family

In the material takeoff phase, due to the fact that windows were modeled as curtain walls. As a result, the quantities were calculated in square meters (m²), whereas the regional price list (Prezzario) requires the number of window units to be counted individually. To address this, all parts of the curtain wall system, such as mullions and glass panels, had to be converted into an assembly. The material takeoff was then generated based on this assembled unit, allowing accurate quantity extraction aligned with pricing requirements.

<Window Material Takeoff>

A	B	C	D	E
Family and Type	Count	Material: Name	Material: Area	Cost
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	22 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	22 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	22 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	22 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	21 m²	
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double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	21 m²	
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double glazed Pan	1	Glass	21 m²	
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double glazed Pan	1	Glass	22 m²	
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double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	22 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	22 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	22 m²	

Figure 53 - Material takeoff windows

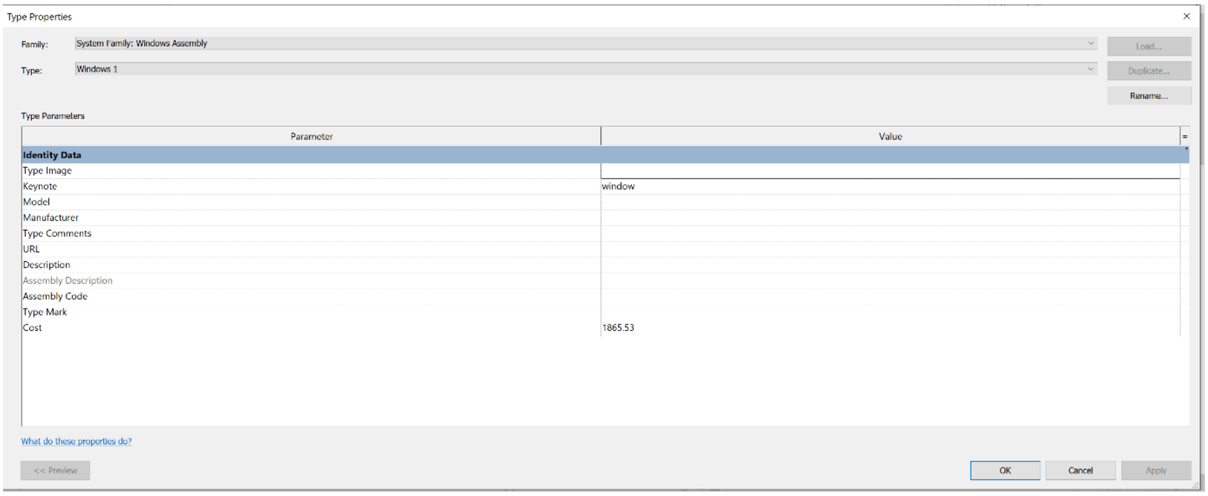


Figure 55 - Cost of each window as assembly

<window Assembly Material Takeoff>

A	B	C	D
Keynote	Count	Cost	Material: Area
window	1	1865.53	64 m²
window	1	1865.53	64 m²
window	1	1865.53	64 m²
window	1	1865.53	64 m²
window	1	1865.53	64 m²
window	1	1865.53	64 m²
window	1	1865.53	64 m²
window	1	1865.53	64 m²
window	1	1865.53	64 m²
window	1	1865.53	64 m²
window	1	1865.53	64 m²
window	1	1865.53	64 m²
window	1	1865.53	59 m²
window	1	1865.53	60 m²
window	1	1865.53	65 m²
window	1	1865.53	65 m²
window	1	1865.53	65 m²
window	1	1865.53	65 m²
window	1	1865.53	65 m²
window	1	1865.53	65 m²
window	1	1865.53	65 m²
window	1	1865.53	65 m²
window	1	1865.53	65 m²
window	1	1865.53	65 m²
window	1	1865.53	65 m²
window	1	1865.53	65 m²
window	1	1865.53	65 m²

Figure 54 - Material takeoff window assembly

After getting material takeoff for all of the materials, it is exported the data from Revit to Excel by DirootsOne. DirootsOne is a plugin which is not free and on this thesis it is used with student account. It is possible to both import excel file and export the Revit schedule. If the data updated in the excel file, DirootsOne automatically update exported and imported data.

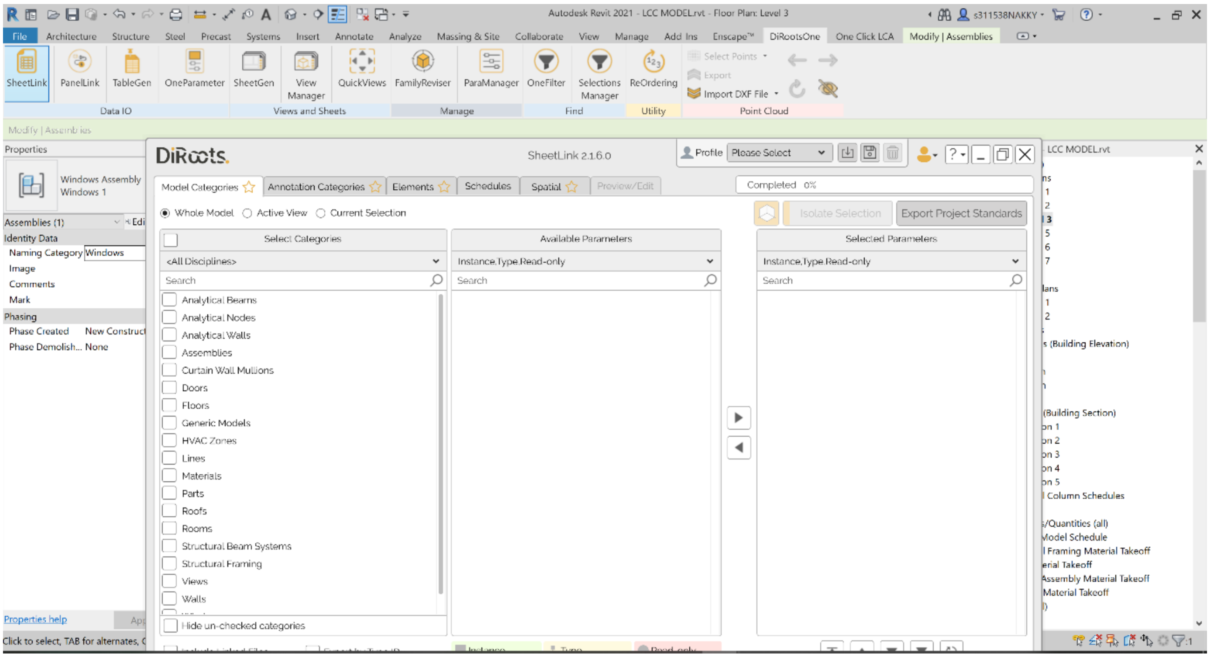


Figure 56 - Exporting Revit schedule by DirootsOne plugin in the sheetlink

2.5 BIM modelling for BEM

The model used before for LCA and LCC analysis was also used for BEM simulation. Regarding BIM to BEM integration, various methods are available for exporting data. In this thesis, the gbXML format was adopted. To enable gbXML export from Revit, it is necessary to define and place *Rooms* within the model, as they serve as the basis for generating energy analysis zones required by simulation software.

It is essential that the Revit model be on the 3D view For getting export of gbxml.

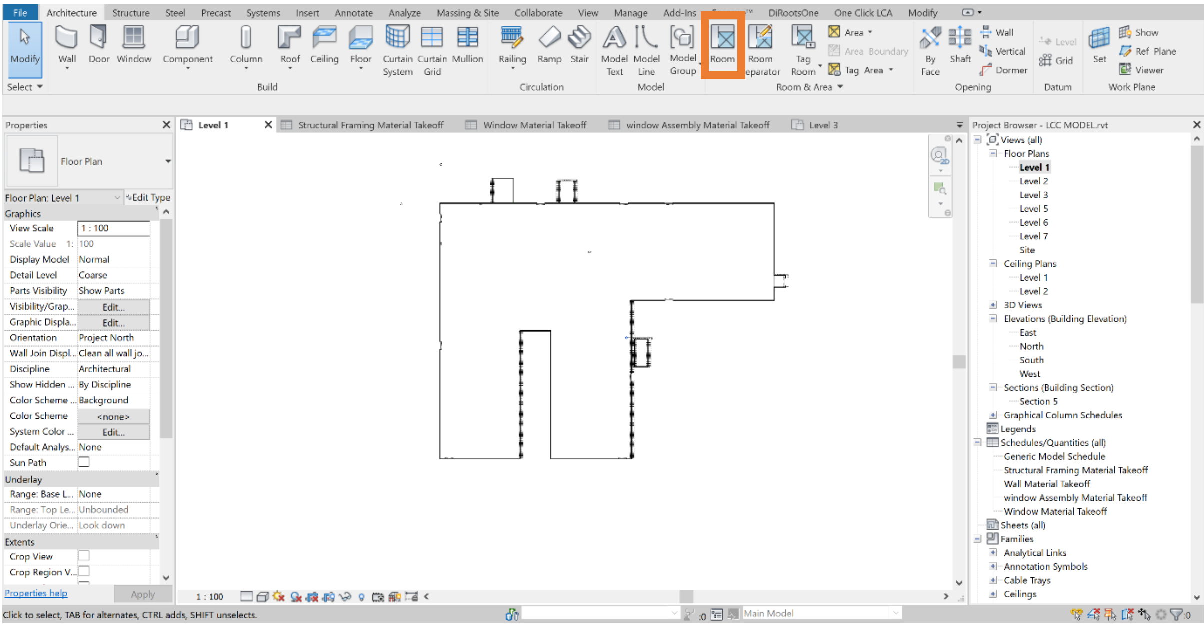


Figure 57 - Creating Rooms

After importing the gbxml file to the Design Builder as BEM tool, it couldn't identify the model because of the complexity of the model for Design Builder due to some reasons such as three attached wall (existing wall, insulation wall and Cladding) and complication of the window assemblies and having too much families. Then the model had to be regenerated using single-layer walls representing the total thickness and overall U-value of the composite construction.

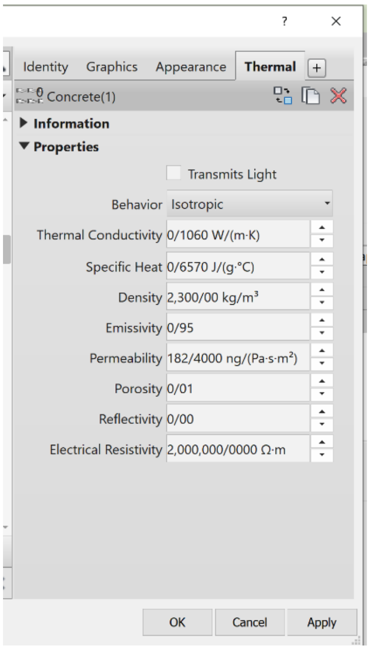


Figure 58 - Setting U-value

Moreover, simplified window families were used in the model, with the overall U-value assigned as a custom property within the family parameters to facilitate accurate energy performance simulations.

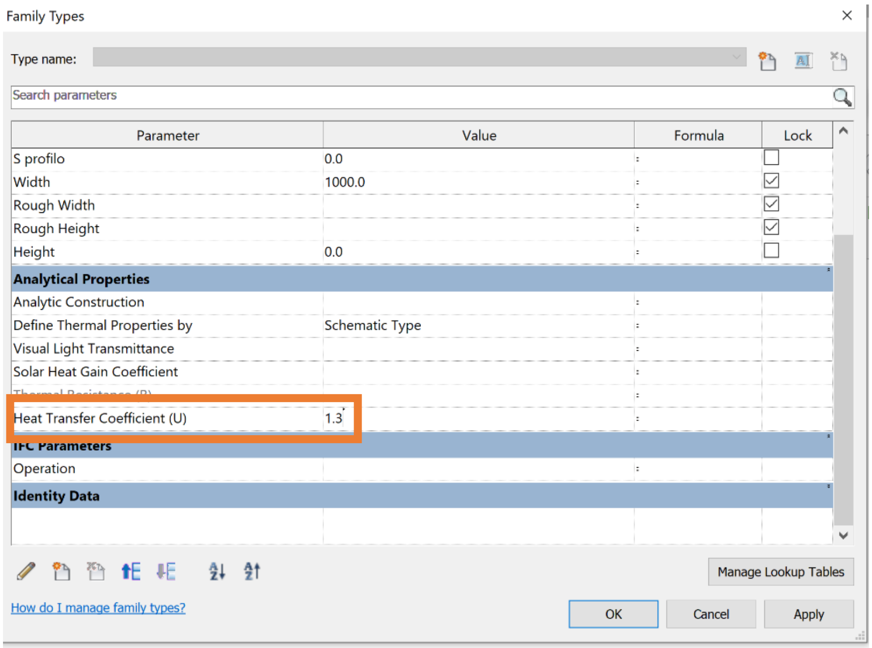


Figure 59 - Adding U value of the window family

As a conclusion of the BIM modelling the workflow is on the below.

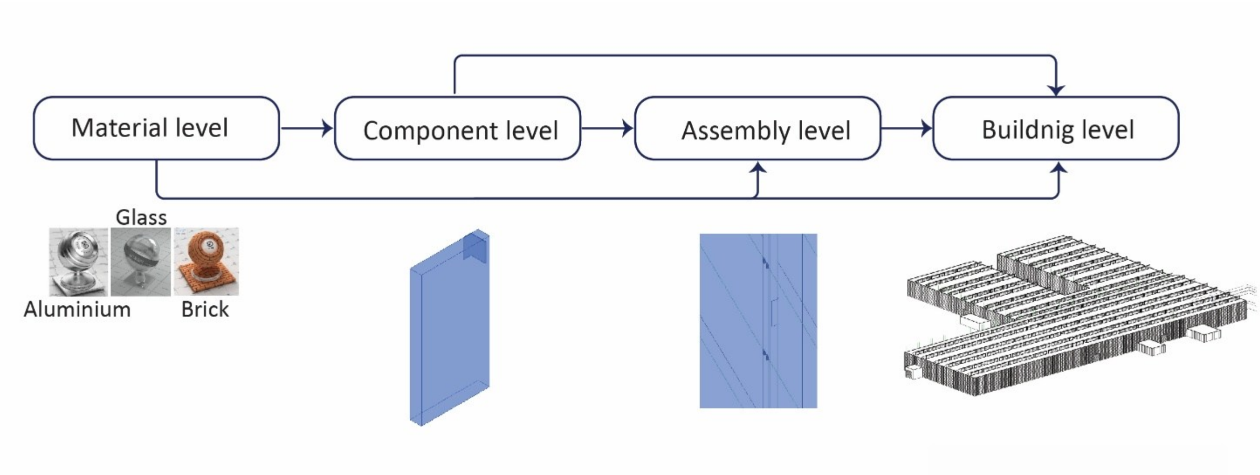


Figure 60 - BIM data preparation framework illustrated by the authors based on Xu et al. (2022)

2.6 Stratigraphy of Selected scenario:

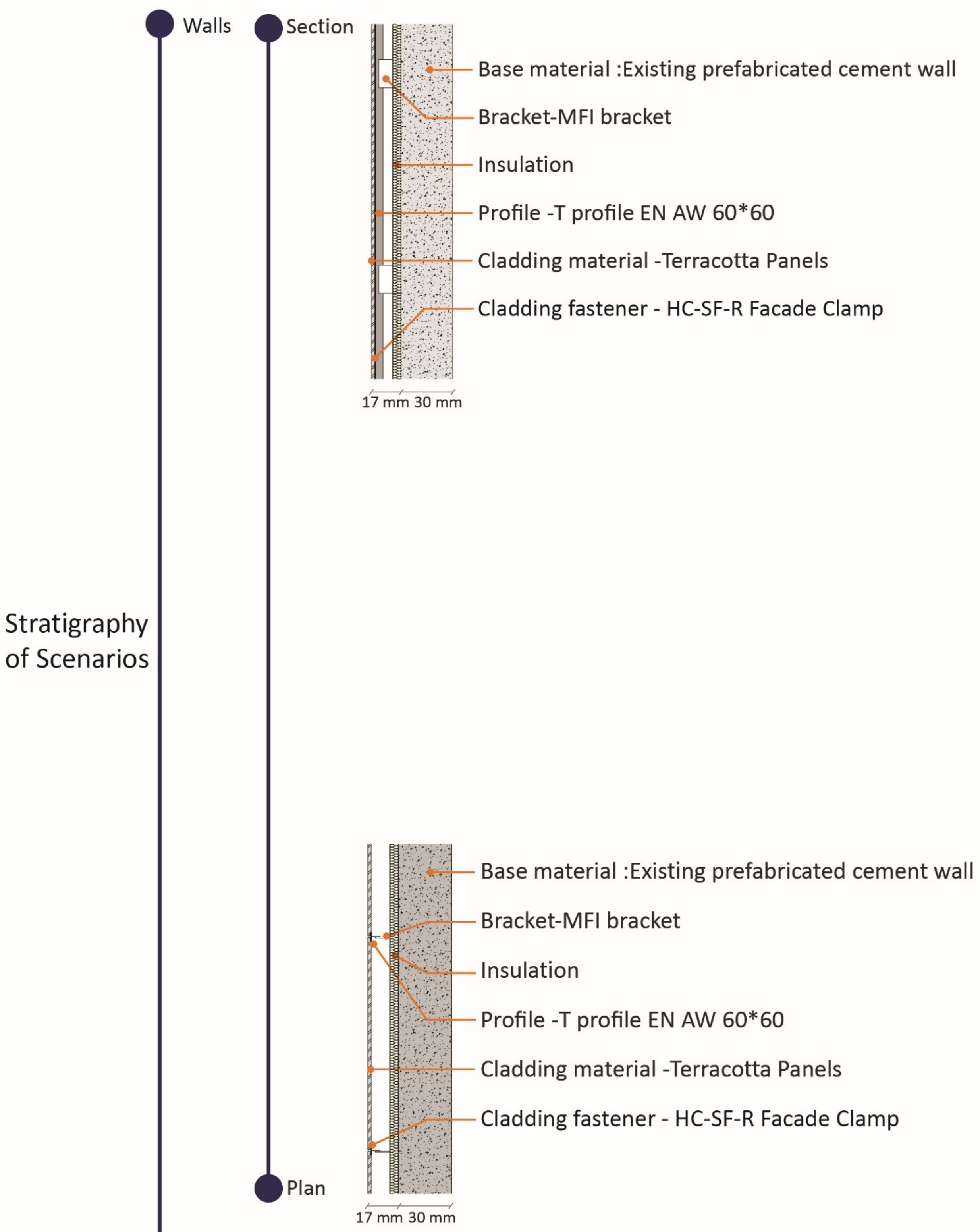


Figure 61 - Stratigraphy of Walls

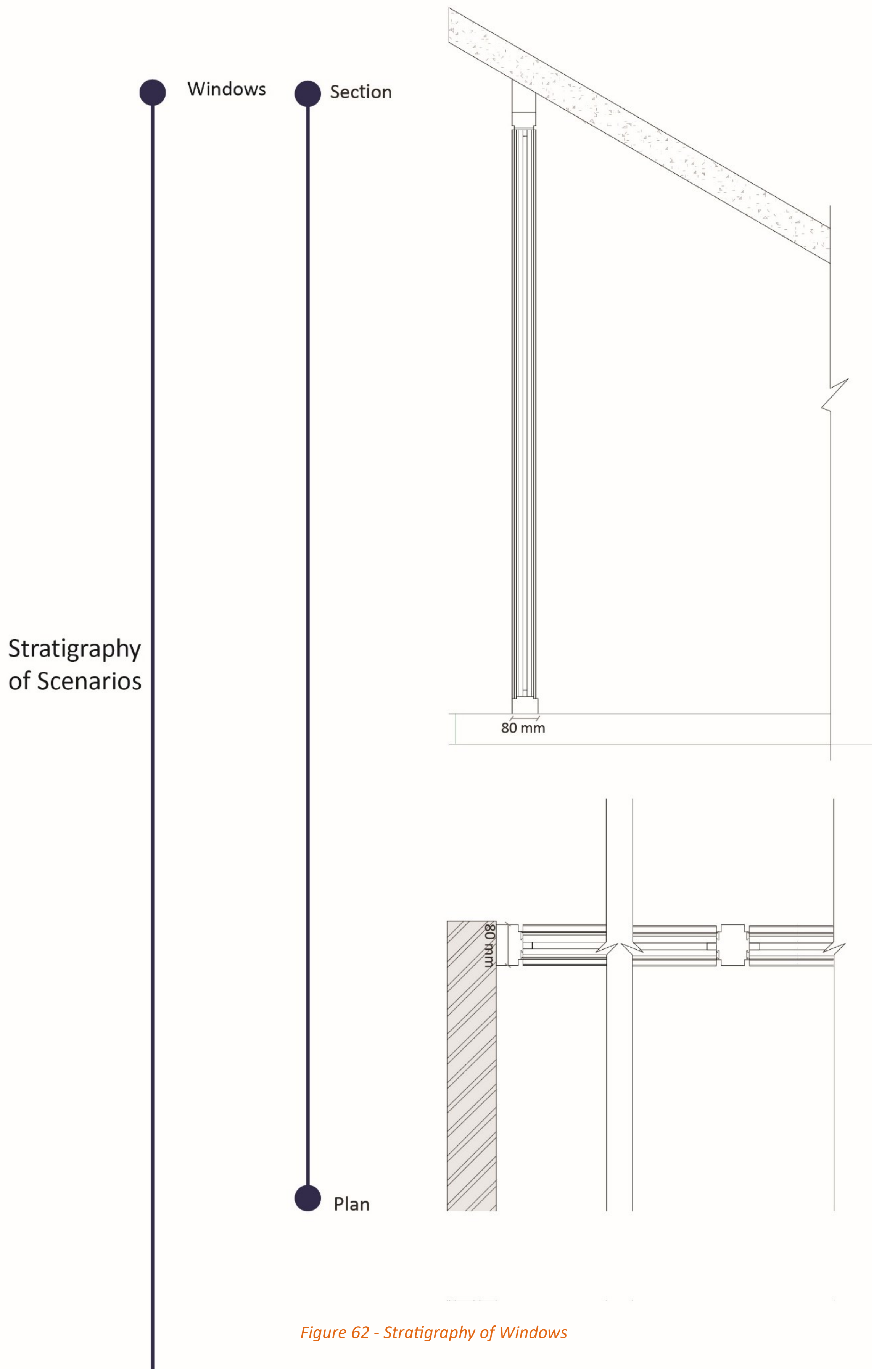


Figure 62 - Stratigraphy of Windows

2.7 Life Cycle Assessment Using One Click LCA

One Click LCA has been chosen as the main software tool for carrying out the Life Cycle Assessment (LCA) based on findings from the literature review and pertinent scholarly sources. This section provides a detailed account of the LCA's implementation for the San Benigno Factory, including the difficulties that occurred during the process.

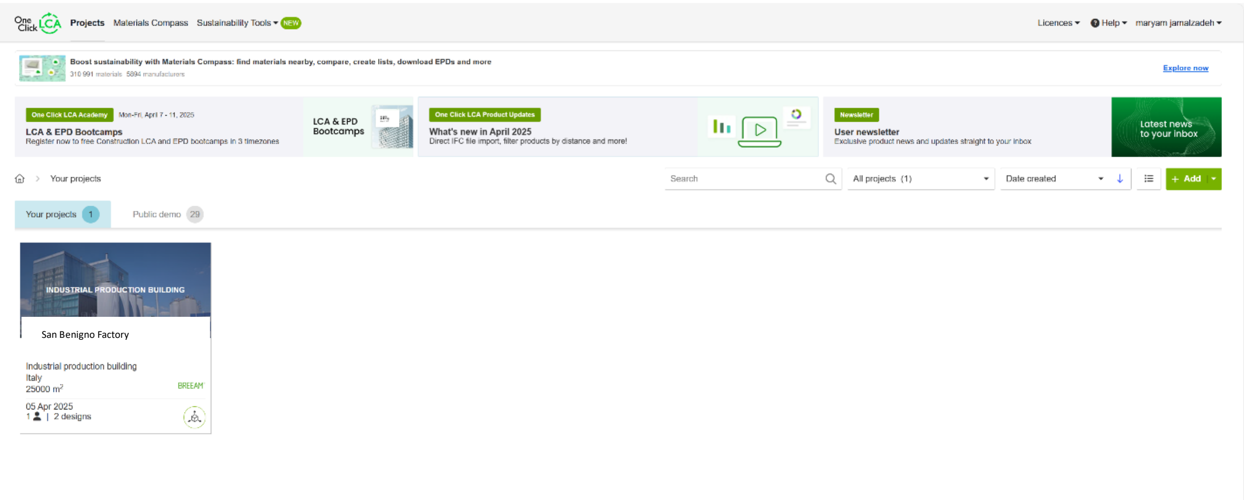


Figure 63 – Adding project to One click LCA

- Building Type: Industrial / Factory building
- Functional Unit: 1 m² of gross floor area (GFA) over a reference study period of 50 years
- System Boundaries: Includes product stage (A1–A3), transport (A4), construction (A5), use stage (B1–B7), and end-of-life (C1–C4)

1. The initial step involved opening the One Click LCA website, creating a student account, and requesting any student leniency that the tool provided.

2. The Second was to create a new project in the platform after acquiring and activating the One Click LCA student license. The software offers a number of trial options based on various certification systems and regional standards after the license key is entered. The "For International: Trial for BREEAM International (14 days)" license was chosen for this study, bringing the project into alignment with the BREEAM environmental assessment method, which is well-known for assessing buildings' sustainability performance globally.

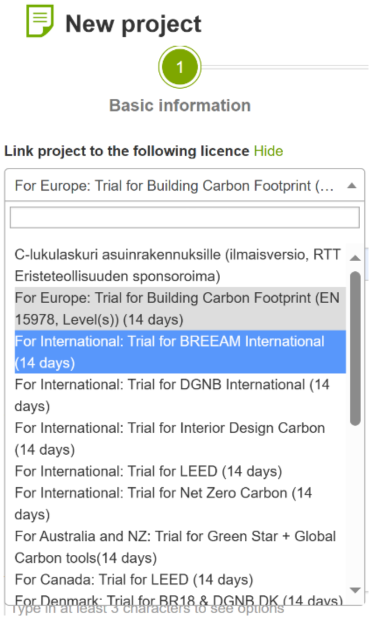


Figure 64 - Initial Project Configuration in One Click LCA: Selection of the BREEAM International Trial License

3. To define the type of construction. This is necessary to guarantee that the evaluation accurately captures the project's unique operational and material features. The typology of "industrial production buildings" was chosen for this study because it aligns with the San Benigno Factory's functional characteristics.

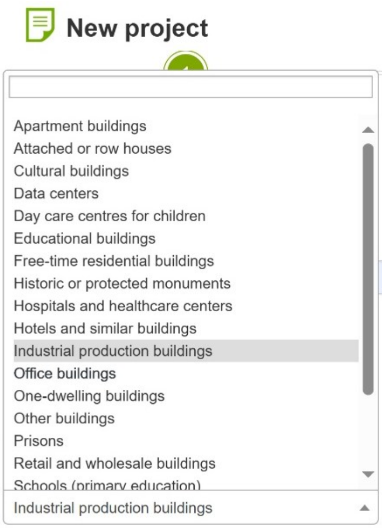


Figure 65 - Selection of Building Typology: 'Industrial Production Buildings'

4. Enter the student license number provided upon the request and location of the project.

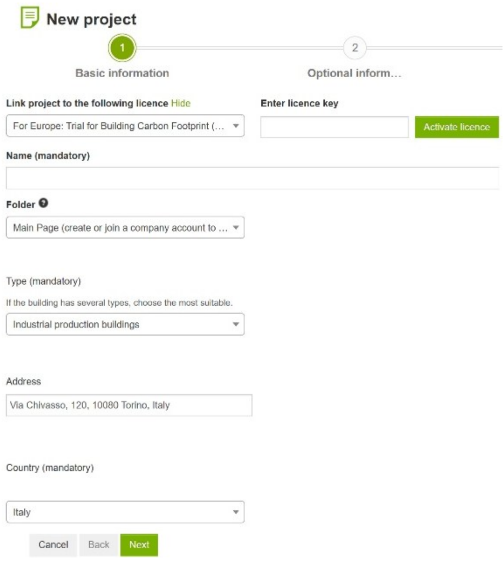


Figure 66 - License Activation and Project Setup in One Click LCA

5. Enter the building's information, then choose the building area and calculation period.

- Enter the building's service life as needed by the client or by legislation; in the context of LCA, this is also the calculation period or reference study period for the analysis.
- Enter the building area. Indicate the gross interior floor area (GIFA) minimum. In order to potentially compare several projects, this will be utilized to present outcomes per m^2.
- Enter the desired assessment plan (BREEAM, LEED, etc.) and the certification being sought.
- Put the desired certification and the assessment plan (BREEAM, LEED, etc.) here. BREEAM was selected.

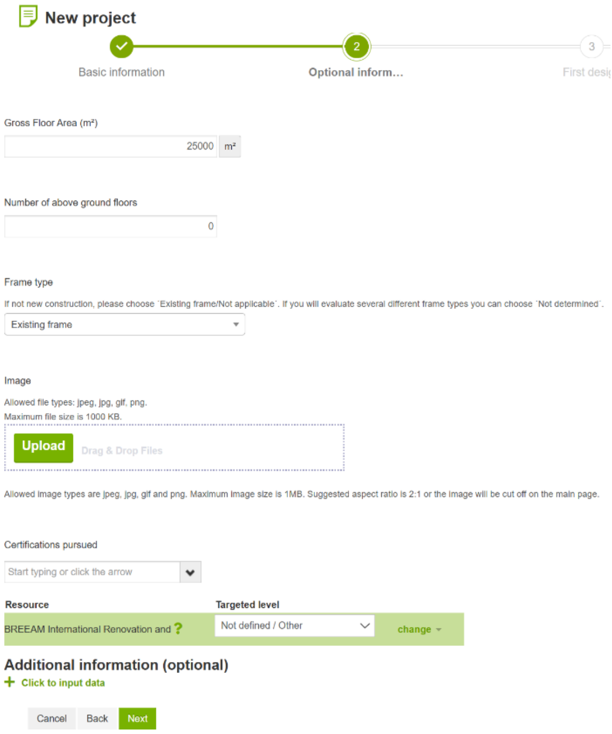


Figure 67 - Adding Optional Project Data to One Click LCA

6. For Design Creation, Select the appropriate computation tool or tools. After that, it may set up the project's basic LCA parameters. Enter the design details through the steps below and then click Next.
   - Stage of construction process (RIBA / AIA stages):

   0 - Strategic Definition: Identify client's Business Case and Strategic Brief and other core project requirements.

   1 - Preparation and Brief: Develop Project Objectives, including Quality Objectives and Project Outcomes, Sustainability Aspirations, Project Budget, other parameters or constraints and develop Initial Project Brief. Undertake Feasibility Studies and review of Site Information.

   2 - Concept Design: Prepare Concept Design, including outline proposals for structural design, building services systems, outline specifications and preliminary Cost Information along with relevant Project Strategies in accordance with Design Program. Agree alterations to brief and issue Final Project Brief.

   3 - Developed Design: Prepare Developed Design, including coordinated and updated proposals for structural design, building services systems, outline specifications, Cost Information and Project Strategies in accordance with Design Program.

   4 - Technical Design: Prepare Technical Design in accordance with Design Responsibility Matrix and Project Strategies to include all architectural, structural and

building services information, specialist subcontractor design and specifications, in accordance with Design Program.

5 - Construction: Offsite manufacturing and onsite Construction in accordance with Construction Program and resolution of Design Queries from site as they arise.

6 - Handover Construction and Close Out: Handover of building and conclusion of Building Contract.

7 - In Use: Undertake In Use services in accordance with Schedule of Services.

Due to the fact that we are changing the component only, so it is chosen the component itself. From these stages, stage 2 - Concept Design was chosen as the stage of the building process for this LCA. Though the San Benigno Factory already exists, the new parts and materials evaluated in this work have not yet been installed.

- Tools using in this design: Carbon footprint for Level(s) – macro-objective 1: Greenhouse gas emissions along a building's life cycle. This calculation tool supports EPDs according to both +A1 and +A2 amendments of the EN15804 standard.

This tool was chosen by default.

- Project type: New construction, whole building, Renovation of an existing building, Expansion of an existing building, Interior design project, Component

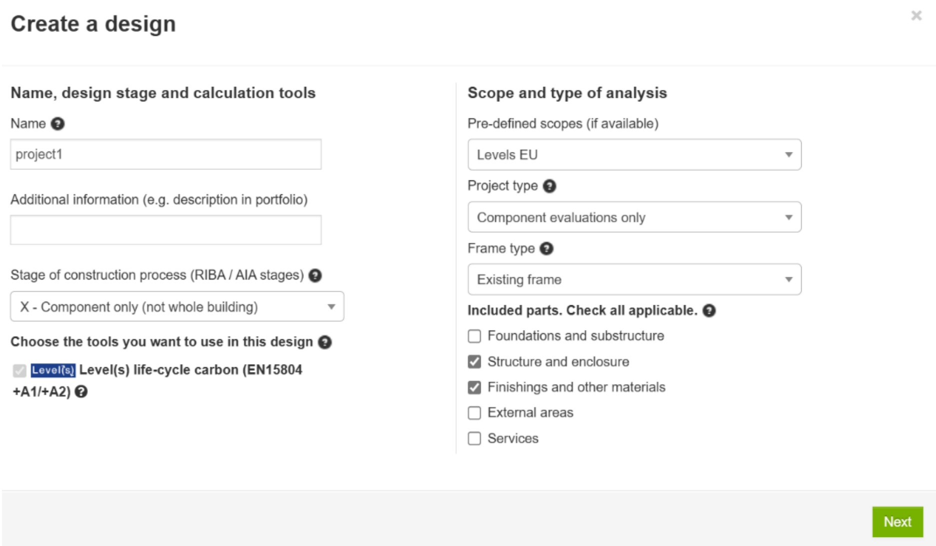


Figure 68 - Developing the Design and Outlining the Analysis's Scope and type

evaluations only, Other type of analysis. "Component evaluations only" was chosen since the emphasis of the evaluation is on windows and supplementary wall components including insulation. So, included parts is consist of "Structure and enclosure" and "Finishings and other materials".

7. LCA parameters: This step is to setup LCA default values for materials calculation in One Click LCA. The parameters include technical service life, European transportation distances, localized manufacturing emissions (v2.1), market scenarios for end-of-life modeling, and district heat-based energy substitution. The environmental impact assessment's precision and regional applicability are improved by these settings.

   - **Service Life <u>(Influences B4-B5 emissions)</u>**

   This establishes the anticipated lifespan of the various materials used in the structure. There are numerous solutions available to you:

   Technical Service Life: What is the lifespan of materials in good condition.

   Commercial Service Life: Materials have a shorter lifespan in environments where interiors are updated more frequently, such as retail stores or hotels.

   Product-Specific Service Life: use Environmental Product Declaration (EPD) data, suitable for DGNB, E+C-, and MPG calculations.

   Options for Service Life by Country: The RICS The default service life is based on the guidelines provided by the Royal Institute of Chartered Surveyors (RICS). The Royal Institute of Chartered Surveyors' (RICS v2) default service life is based on service life values.

   Norway DFØ Default Service Life: Make use of the DFØ standards' service life values.

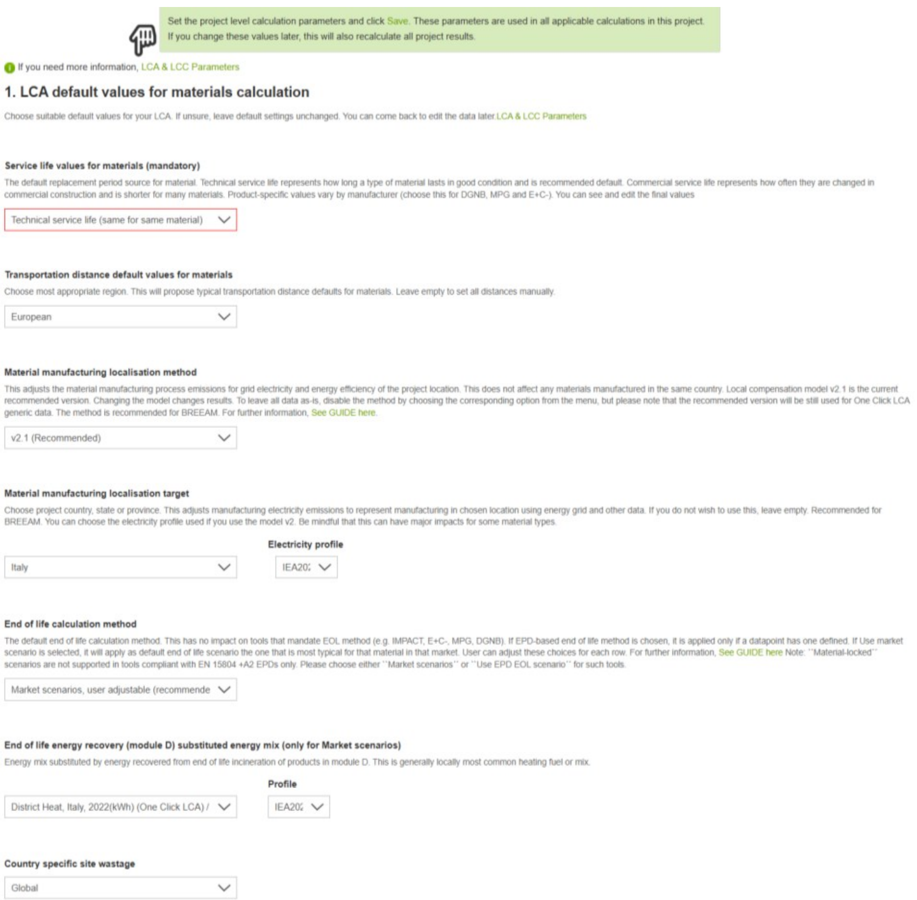


Figure 69 - Configuration of LCA Default Parameters in One Click LCA

It is possible to use One click LCA cloud directly from Revit.

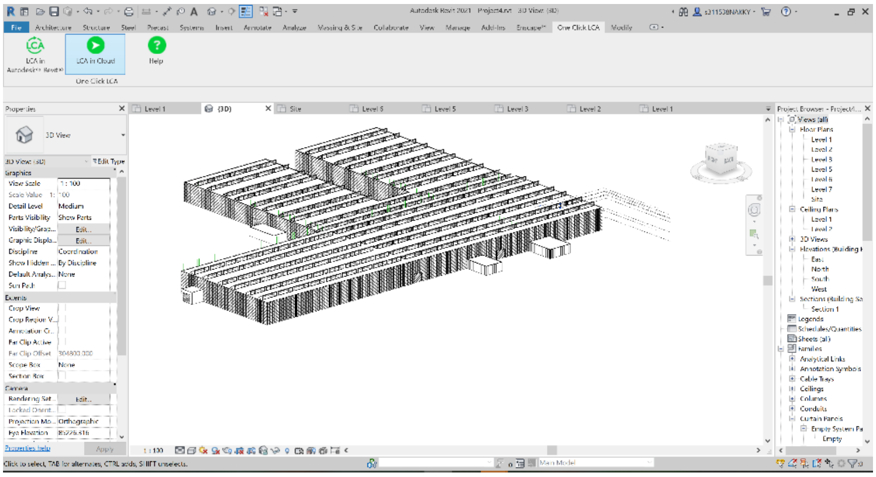


Figure 70 – One click LCA as a plugin on Revit

As it mentioned before, with the first BIM for LCA model, the One click LCA could not identify the model completely. Because it was modeled some building components as a family.

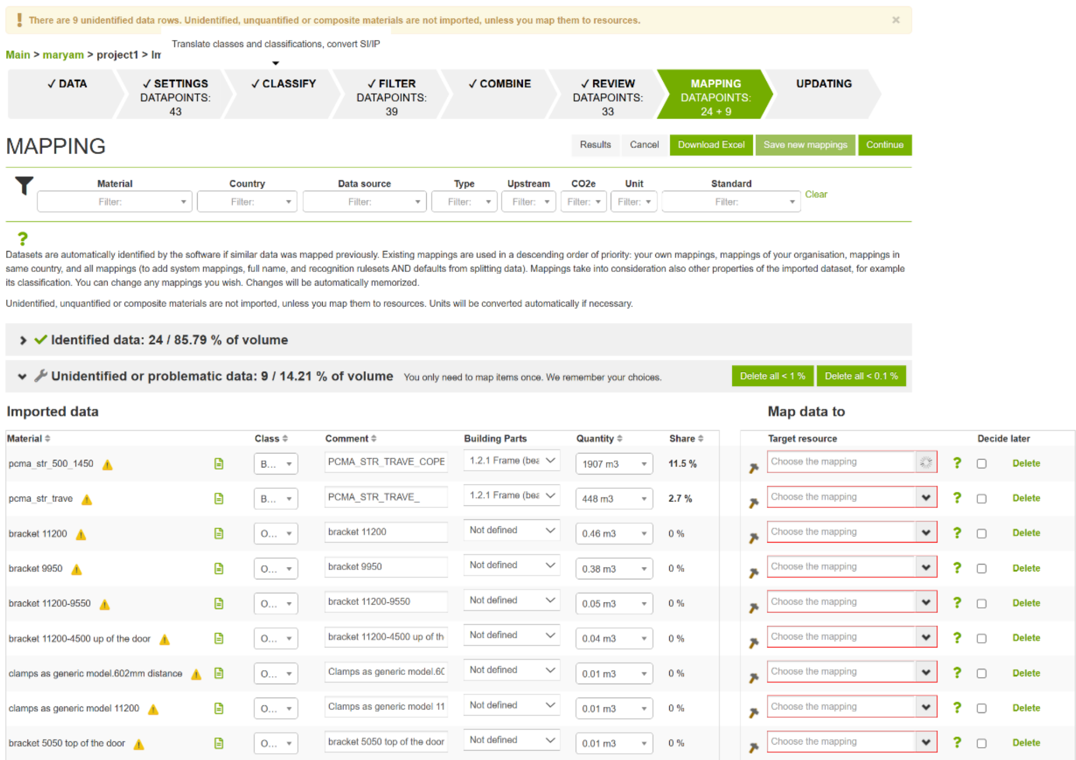
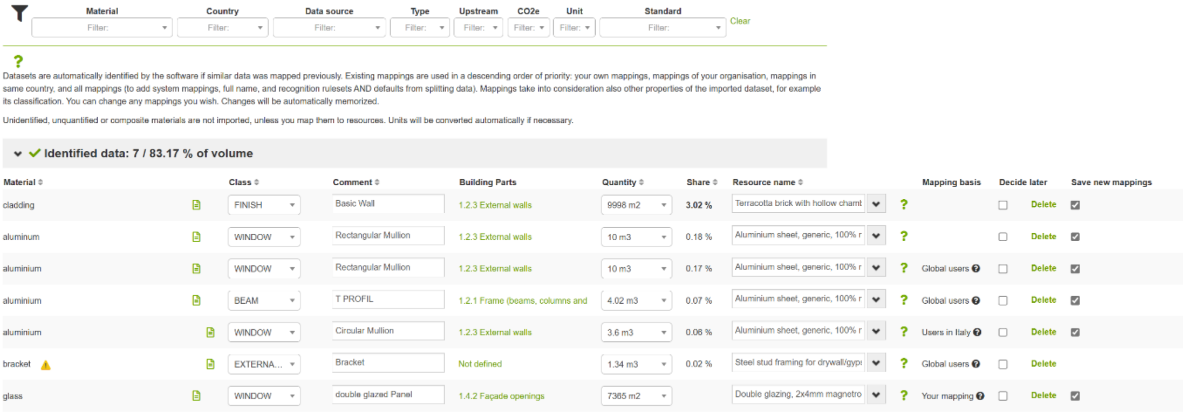


Figure 71 - Problematic data on One click LCA

Then, the BIM model updated as individual families.


Material | Country | Data source | Type | Upstream | CO2e | Unit | Standard
Filter: | Filter: | Filter: | Filter: | Filter: | Filter: | Filter: | Filter: | Clear

?

Datasets are automatically identified by the software if similar data was mapped previously. Existing mappings are used in a descending order of priority: your own mappings, mappings of your organisation, mappings in same country, and all mappings (to add system mappings, full name, and recognition rulesets AND defaults from splitting data). Mappings take into consideration also other properties of the imported dataset, for example its classification. You can change any mappings you wish. Changes will be automatically memorized.

Unidentified, unquantified or composite materials are not imported, unless you map them to resources. Units will be converted automatically if necessary.

Identified data: 7 / 83.17 % of volume

Material	Class	Comment	Building Parts	Quantity	Share	Resource name	Mapping basis	Decide later		Save new mappings
cladding	FINISH	Basic Wall	1.2.3 External walls	9998 m2	3.02 %	Terracotta brick with hollow chamt		☐	Delete	☑
aluminum	WINDOW	Rectangular Mullion	1.2.3 External walls	10 m3	0.18 %	Aluminium sheet, generic, 100% r		☐	Delete	☑
aluminium	WINDOW	Rectangular Mullion	1.2.3 External walls	10 m3	0.17 %	Aluminium sheet, generic, 100% r	Global users	☐	Delete	☑
aluminium	BEAM	T PROFIL	1.2.1 Frame (beams, columns and	4.02 m3	0.07 %	Aluminium sheet, generic, 100% r	Global users	☐	Delete	☑
aluminium	WINDOW	Circular Mullion	1.2.3 External walls	3.6 m3	0.06 %	Aluminium sheet, generic, 100% r	Users in Italy	☐	Delete	☑
bracket	EXTERNA...	Bracket	Not defined	1.34 m3	0.02 %	Steel stud framing for drywall/gyp:	Global users	☐	Delete	
glass	WINDOW	double glazed Panel	1.4.2 Façade openings	7365 m2		Double glazing, 2x4mm magnetro	Your mapping	☐	Delete	☑

Figure 72 – Identified material on One click LCA

After identifying the materials and their exact quantities in One Click LCA, it was necessary to select the appropriate material characteristics from the One Click LCA database, specifically using data sources aligned with the BREEAM standard to ensure consistency and reliability in the environmental impact assessment.

The results were then generated in the form of graphs and Excel files which are GWP Ratio (Global Warming Potential), providing a visual and quantitative representation of the environmental impacts associated with each material and scenario which it has to be returned to the BIM model. In fact, LCA methodologically has to be considered for both removed and added material but on this research it is considered just the added elements.

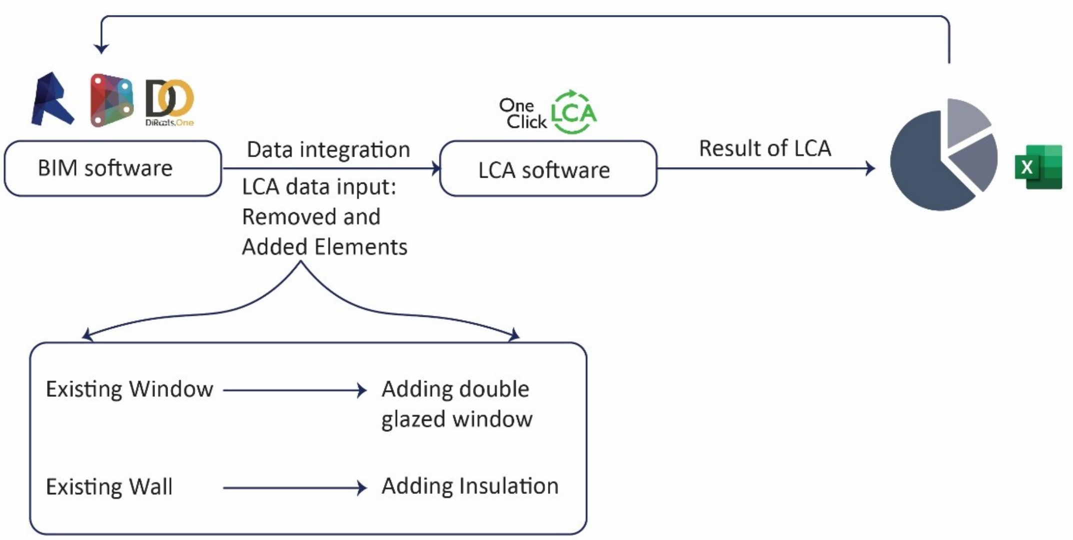


Figure 73 - Methodological Workflow of LCA illustrated by the authors

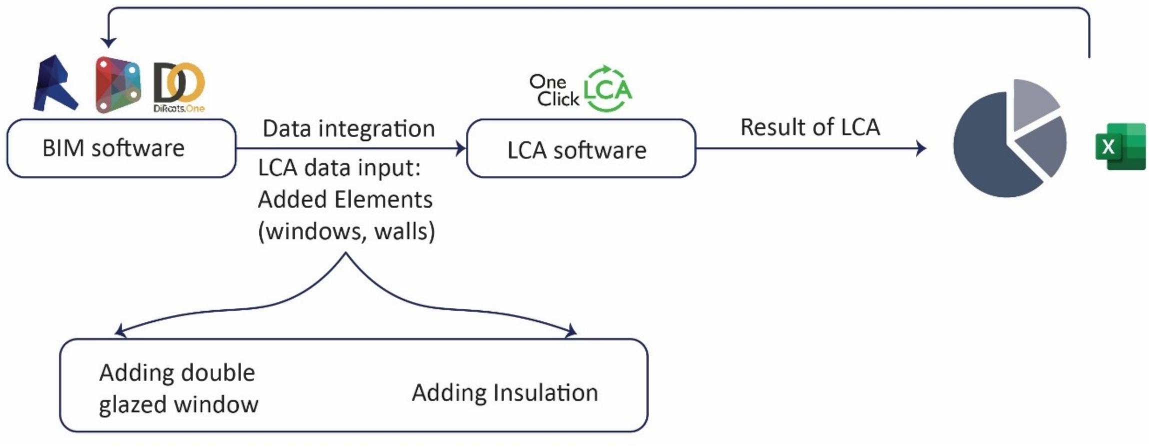


Figure 74 - Technological Workflow of LCA illustrated by the authors

2.8 Life Cycle Cost (LCC) Process:

2.8.1 Data Preparation: As it mentioned before in BIM for LCC, After getting all material takeoff and exporting all schedules from Revit to excel, the process of calculating LCC will be start.

2.8.2 Calculating LCC:

Life Cycle Cost (LCC) analysis is a method for assessing the total economic expenditure of a building or asset over its entire lifespan, from acquisition and construction through operation, maintenance, replacement, and eventual disposal or sale. By incorporating all cost components, LCC provides a more accurate and long-term view of cost-effectiveness than initial capital expenditure alone (Joshi & Kale 2015; WBDG n.d.; ISO 15686-5 2008).

$$Total\ LCC = Initial\ Cost + \text{Operating Costs} + \text{Maintenance Costs} + Present\ Value\ of\ Running\ (Replacement)\ Costs - \text{Residual Value}$$

2.8.2.1 Initial Purchase Price: The initial purchase price includes all initial expenses for the design, construction, and commissioning of a building. These include costs related to materials, labor, site preparation, professional services, and construction equipment. In most cases, the capital cost represents a substantial portion of the total life cycle cost, especially in the early stages of the project. Accurate estimation of these costs is essential for reliable global cost evaluation and comparative analysis across alternative design scenarios (Petrović et al., 2021; Gu et al., 2023).

2.8.2.2 Operating Costs: Operating costs refer to the recurring expenses required to keep the building functional during its use phase. These typically include energy consumption for heating, cooling, lighting, and ventilation, as well as water and other utility services. Over a standard service life of 30 years or more, these costs can become comparable to or even exceed initial investment costs, especially in energy-intensive buildings. Proper estimation of operating costs is therefore essential in comprehensive life cycle evaluations (Petrović et al., 2021; Joshi & Kale, 2015).

2.8.2.3 Maintenance Costs: Maintenance costs include all activities needed to preserve the operational condition of a building, such as cleaning, minor repairs, servicing of equipment, and routine inspections. These interventions help to prevent premature deterioration and extend component lifespans. Over long periods, cumulative maintenance expenditures can be significant, especially for buildings with high-performance systems or specialized materials. Scheduled and preventive maintenance is also a key aspect of strategic asset management (Rosita et al., 2023; ISO 15686-5, 2008).

2.8.2.4 Residual Value: The residual value represents the estimated remaining or recoverable worth of a building or its components at the end of the analysis period. It includes salvage value, resale potential, or material recovery, and is subtracted from the total life cycle cost. Accounting for residual value improves the accuracy of comparative cost assessments, especially when evaluating materials or systems with known secondary market value or recyclability potential (Gu et al., 2023; ISO 15686-5, 2008).

2.8.2.5 Integration into Global Cost Assessment: Life Cycle Costing (LCC) serves as a core component of global cost or whole-life cost assessment frameworks. Its integrative structure enables a complete economic evaluation of design alternatives over a building's entire service life. By systematically including initial costs, operation, maintenance, replacement, and residual values, LCC supports informed decision-making and encourages economically and environmentally sustainable solutions. International standards and best-practice guidelines promote the adoption of LCC methodologies in both public procurement and private-sector development (Joshi & Kale, 2015; WBDG, n.d.; ISO 15686-5, 2008).

2.8.2.6 Replacement Costs: Replacement costs arise when major systems or components reach the end of their useful service life and must be renewed to maintain building performance. Examples include HVAC systems, roofing materials, and facade elements. These costs are typically scheduled at regular intervals based on technical life expectancy and play an important role in long-term financial planning. In multi-decade evaluations, their contribution to LCC can be substantial, particularly in public and institutional buildings (Petrović et al., 2021; MATEC Conferences, 2017).

2.8.2.7 Real Discount Rate Determination

In this study, the real discount rate is calculated to convert future costs to their present value, enabling accurate Life Cycle Cost (LCC) analysis. The formula used is the Fisher equation:

$$r = \frac{1+i}{1+f} - 1$$

Where:

- i is the nominal interest rate
- f is the expected inflation rate

For the Italian context, the nominal interest rate is taken as 3.71%, based on the yield of 10-year Italian government bonds as of April 2025 (YCharts, 2025)

The expected inflation rate is estimated at 1.9%, according to the European Commission's Spring 2025 forecast for Italy (European Commission, 2025).

Substituting these values gives:

$$r = \frac{1+0.0371}{1+0.019} - 1 = 0.0178 \; or \; 1.78\%$$

This 1.78% real discount rate is applied throughout the LCC model, aligning with current Italian macroeconomic conditions and ensuring comparability with other European studies.

2.8.2.8 Repair and Replacement Assumptions

The repair and replacement cycles for the façade components evaluated in this study were determined based on established durability standards and technical literature, including UNI 11156:2006, ISO 15686-5:2017, and the Italian Technical Standards (NTC 2018). These sources provide standardized guidelines for estimating service life and maintenance requirements of building materials, supporting a consistent and evidence-based Life Cycle Costing (LCC) approach (UNI, 2006; ISO, 2017; MIT, 2018). The assumptions adopted for the materials used in this analysis are summarized as follows:

- Rocksilk Insulation (Mineral Wool): According to EN 13162 and manufacturer datasheets, this product exhibits a service life of over 40 years under ventilated and protected façade conditions. Therefore, no replacement is anticipated within the 40-year analysis period (EN 13162, 2012).
- Hemp Insulation: Derived from renewable plant fibers, this bio-based insulation material is estimated to have a service life of approximately 40 years. A single replacement is scheduled at the end of the building life cycle (year 40) to reflect natural degradation and loss of thermal performance over time (ISO, 2017; UNI, 2006).
- Cladding Panels: Typically made from durable composite or metal panels, the cladding is assumed to maintain integrity for at least 40 years with no replacement, based on façade engineering practice and the absence of exposure to aggressive environments (MIT, 2018).
- Brackets and Clamps (Metal Fasteners): Manufactured from stainless or galvanized steel, these load-bearing components are assumed to last the full 40-year lifespan without the need for replacement, unless subject to severe corrosion. This assumption is supported by corrosion protection standards outlined in UNI EN ISO 14713 (ISO 14713, 2009).
- T Profile (Aluminium EN AW 6060): Owing to aluminium’s high corrosion resistance, this component is assumed to require partial replacement (10%) at year 15 due to mechanical fatigue, and complete replacement at year 40, consistent with façade engineering literature and ISO 15686 guidance (ISO, 2017).
- Double Glazed Windows: Standard double glazing units (e.g., IDEAL 5000, U-value 1.1) have an expected lifespan of 20–30 years. This study assumes a full replacement at year 30, aligned with the European Directive on the Energy Performance of

Buildings (Directive 2010/31/EU) and manufacturer performance data (European Parliament, 2010).

- Tripple Glazed Windows: Similarly, high-performance triple glazing is assumed to have a design life of 30 years, with complete replacement scheduled at year 30 to ensure continued energy efficiency and airtightness (European Parliament, 2010).

These assumptions provide a conservative yet realistic framework for evaluating the long-term economic performance of different façade systems in a 40-year Life Cycle Cost (LCC) model.

Component	**Service Life**	**Replacement Schedule**
Rocksilk Insulation	40 years	No replacement
Hemp Insulation	40 years	Replacement at year 40
Cladding	40 years	No replacement
Brackets & Clamps	40 years	No replacement
T Profile (Aluminium)	15 years	10% at year 15, 100% at year 40
Double Window	30 years	Full replacement at year 30
Tripple Window	30 years	Full replacement at year 30

Table 5 - Service life and replacement schedule of selected building components based on durability standards and technical literature (UNI 11156:2006, ISO 15686-5:2017, NTC 2018).

These replacement cycles ensure that the LCC model reflects realistic maintenance and degradation scenarios in line with both Italian standards and European best practices.

2.8.2.9 Present Value (PV) Factor: The Present Value (PV) Factor is derived from the Present Value formula in discounted cash flow analysis, used to convert future costs into today's value using a real discount rate:

$$PV = \frac{1}{(1+r)^n}$$

Where:

- r = real discount rate (in your case, 1.78% or 0.0178)
- n = number of years in the future the cost occurs

Year	Formula	PV Factor (rounded)
15	$\frac{1}{(1+0.0178)^{15}}$	0.726
30	$\frac{1}{(1+0.0178)^{30}}$	0.560
40	$\frac{1}{(1+0.0178)^{40}}$	0.494

Table 6 - Present Value (PV) factors at selected years (15, 30, 40)

Name	Total Count	Total Initial Cost (€)
Rocksilk Insulation	9,774 (m^2)	1,434,456.16
Hemp Insulation	9,774 (m^2)	1,636,521.89
Cladding	9,998 (m^2)	2,198,608.43
Bracket	8343	102702.33
Clamps	17291	34582
T profile	4,826.2 m	127567.24
Double window	224	417878.72
Tripple window	224	489686.4

Table 7 - Initial cost and total count of façade system components used in the LCC analysis

In this research, the Life Cycle Cost (LCC) is calculated by considering the initial cost and the replacement cost, as shown in the formula below.

$$LCC = Initial\ Cost + Present\ Value\ of\ Running\ (Replacement)\ Costs$$

In the following section, this formula is applied step by step to each component included in Solution 1 and 2 considering the initial investment and discounted future replacement costs over a 40-year analysis period

Solution 1:

1. Insulation (Hemp)

- Initial cost: €1,636,521.89
- Replacement at year 40:

$$PV_{40} = 1{,}636{,}521.89 \times 0.494 = 808{,}441.81$$

$$LCC = 1{,}636{,}521.89 + 808{,}441.81 = 2{,}444{,}963.7\ €$$

2. Window (Double)

- Initial cost: €417,878.72
- Replacement at year 30:

$$PV_{30} = 417{,}878.72 \times 0.560 = 234{,}012.08$$

$$LCC = 417{,}878.72 + 234{,}012.08 = 651{,}890.81 \text{ €}$$

3. T Profile

- Initial cost: €127,567.24
- 10% replacement at year 15:

$$0.10 \times 127{,}567.24 = 12{,}756.72$$

$$PV_{15} = 12{,}756.72 \times 0.726 = 9{,}261.38$$

- **100% replacement at year 40**:

$$PV_{40} = 127{,}567.24 \times 0.494 = 63{,}018.21$$

$$LCC = 127{,}567.24 + 9{,}261.38 + 63{,}018.21 = 199{,}846.83 \text{ €}$$

4. Cladding

- Initial cost: €2,198,608.43
- No replacement
- LCC: 2,198,608.43 €

5. Brackets

- Initial cost: €102,702.33
- No replacement
- LCC: 102,702.33 €

6. Clamps

- Initial cost: €34,582.00
- No replacement
- LCC: 34,582.00 €

Total LCC – Solution 1:

$$LCC_{Total} = 2{,}444{,}963.7 + 651{,}890.81 + 199{,}846.83 + 2{,}198{,}608.43 + 102{,}702.33 + 34{,}582 = 5{,}632{,}594.1\ €$$

Solution 2: For T Profile, Cladding, Brackets and Clamps is as Same as Solution 1.

1. Insulation (Rocksilk)

- Initial cost: €1,434,456.16
- No replacement
- LCC: 1,434,456.16 €

2. Window (Tripple)

- Initial cost: €489,686.40
- Replacement at year 30:

$$PV_{30} = 489{,}686.4 \times\ 0.560 = 274{,}224.38$$

$$LCC = 489{,}686.4 + 274{,}224.38 = 763{,}910.78\ €$$

Total LCC – Solution 2:

$$LCC_{Total} = 1{,}434{,}456.16 + 763{,}910.78 + 199{,}846.83 + 2{,}198{,}608.43 + 102{,}702.33 + 34{,}582 = 4{,}734{,}106.53\ €$$

Payback Period Analysis

The Payback Period is a commonly used financial metric in the evaluation of construction and energy efficiency investments. It indicates the amount of time required for an initial investment to be recovered through cumulative savings, such as reductions in energy consumption, maintenance costs, or operational expenses (Fuller & Petersen, 1996; RICS, 2016). The shorter the payback period, the more financially attractive the investment tends to be, particularly when budget constraints or quick returns are prioritized.

Payback Period (PP): This method divides the initial investment by the annual net savings without considering the time value of money. It is straightforward but less accurate for long-term evaluations.

$$PP = \frac{Initial\ Investment}{Annual\ Net\ Savings}$$

$$5 = \frac{4{,}517{,}860.61}{Annual\ Net\ Savings\ (Solution1)}$$

$$5 = \frac{4{,}387{,}602.56}{Annual\ Net\ Savings\ (Solution2)}$$

Annual Net Savings (Solution 1): 903,572.12 €

Annual Net Savings (Solution 2): 877,520.51 €

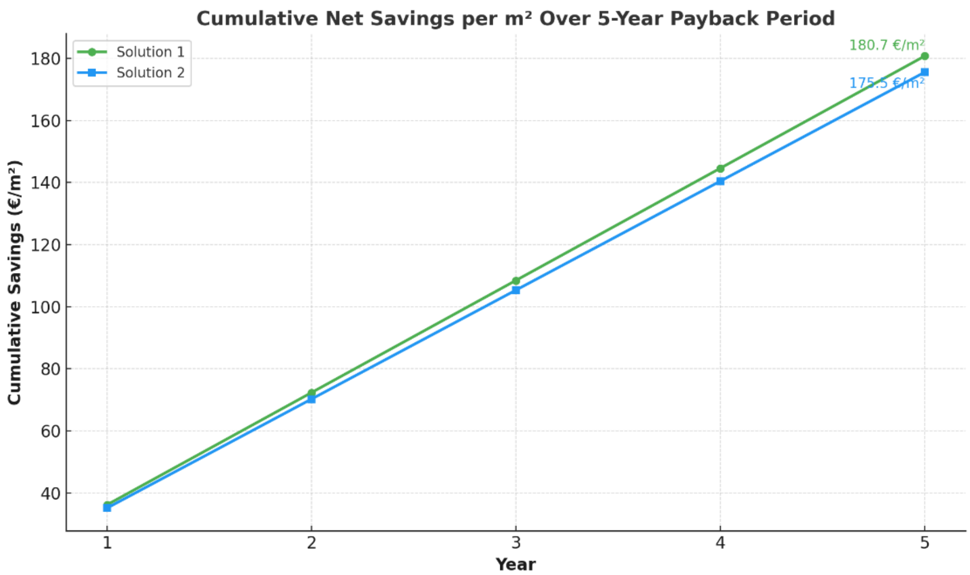


Figure 75 - payback period graph showing the cumulative net savings per square meter over the 5-year period

This clean line graph makes it easy to compare how quickly each solution pays back its investment relative to area (€/m²). Both solutions recover their cost well within the 5-year threshold.

The result of calculating LCC in Excel file will return on BIM with DirootsOne.

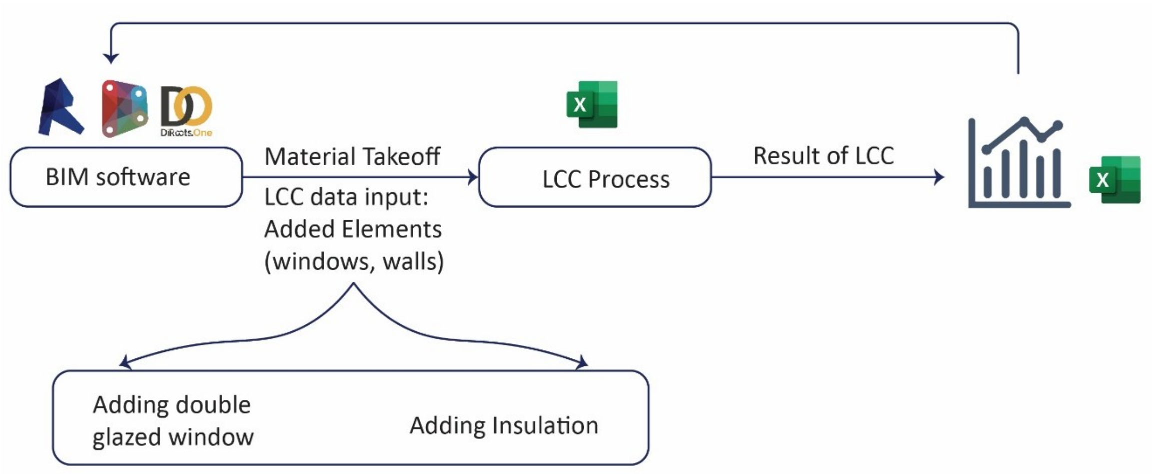


Figure 76 - Technological Workflow of LCC illustrated by the authors

Name	Total Count	LCC (€)
Rocksilk Insulation	9,774 (m^2)	1,434,456.16
Hemp Insulation	9,774 (m^2)	2,444,963.7
Cladding	9,998 (m^2)	2,198,608.43
Bracket	8343	102,702.33
Clamps	17291	34582
T profile	4,826.2 m	199,846.83
Double window	224	651,890.81
Tripple window	224	763,910.78

Table 8 - LCC result

2.9 Building Energy Model (BEM):

For BIM to BEM as previously mentioned, the first model based on LCA and LCC model were used as imported model to Design Builder but the software could not identify because of the complexity of the file.

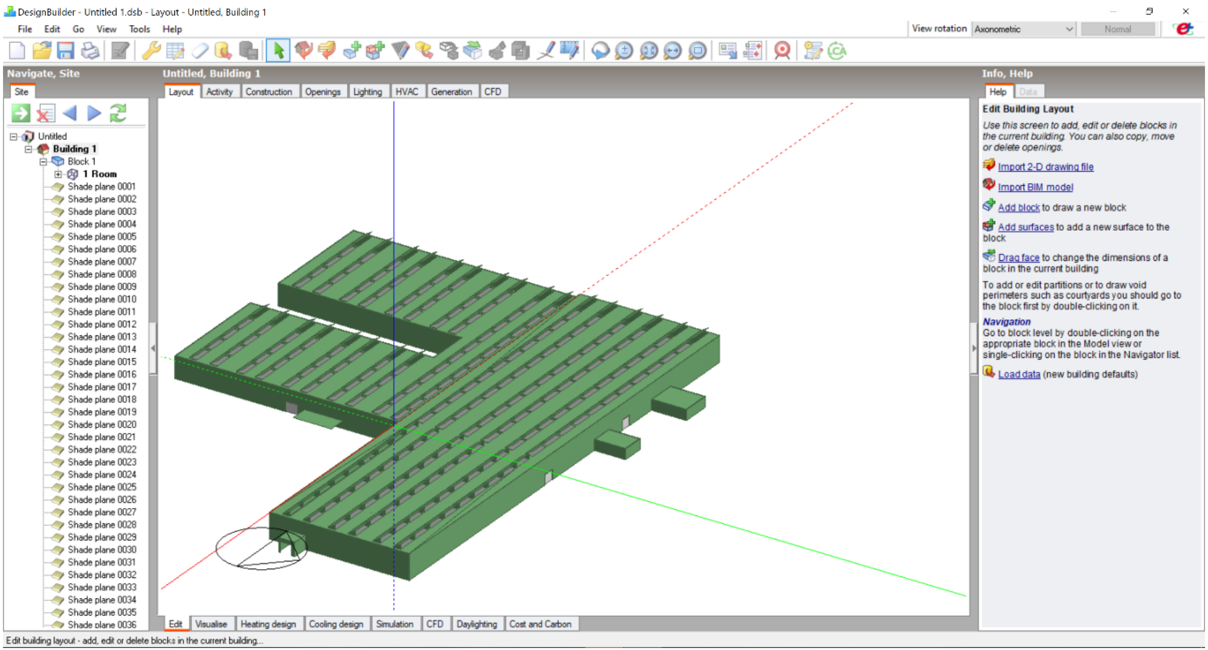


Figure 77 - Problematic gbxml file in Design Builder

So, the model with single wall and simple windows which it is specified thermal properties imported to Design Builder.

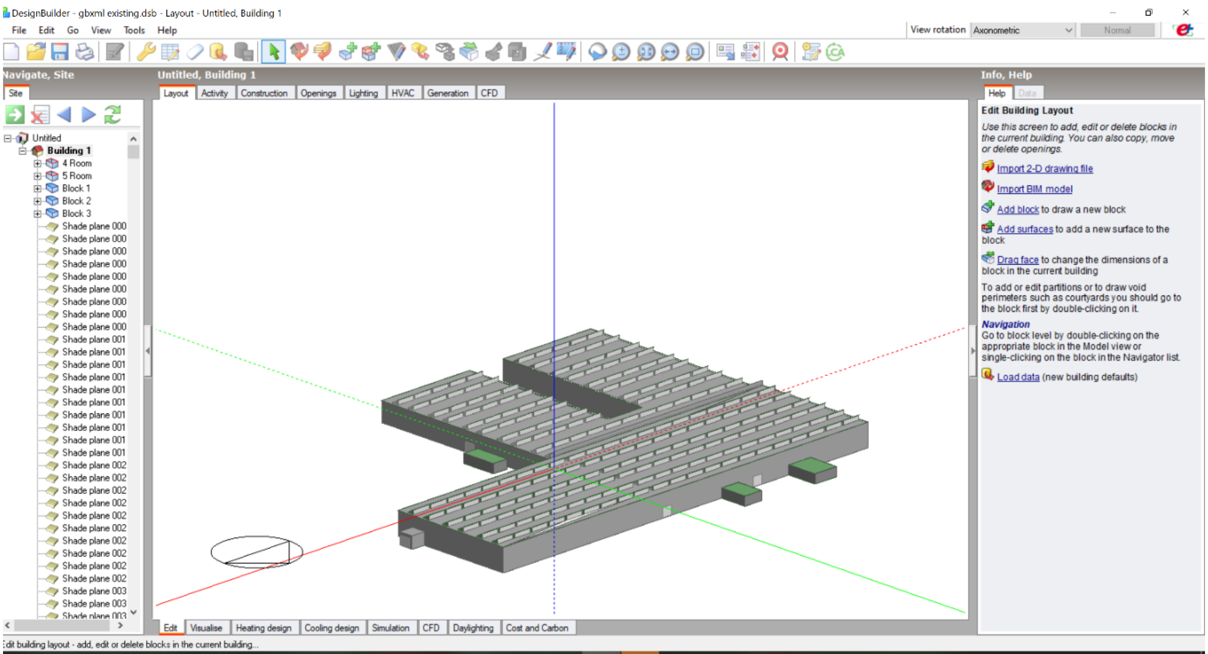


Figure 78 - Identified model

To assess and improve the building's energy performance, the gbXML file was exported from the existing BIM model in Revit and imported into Design Builder. This allowed simulation of the current energy consumption using local climate data (e.g., Torino/Caselle). The same process was repeated with the proposed model, enabling comparison of results to evaluate energy efficiency improvements based on modifications in materials, geometry, or systems.

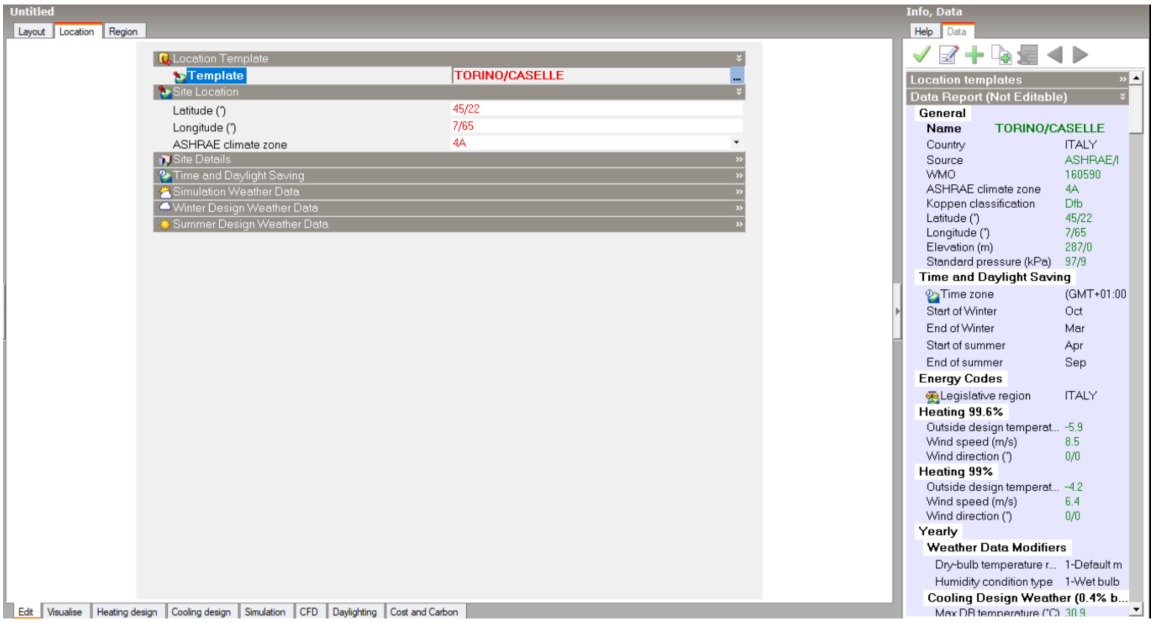


Figure 80 - Defining the location of the project on Design Builder

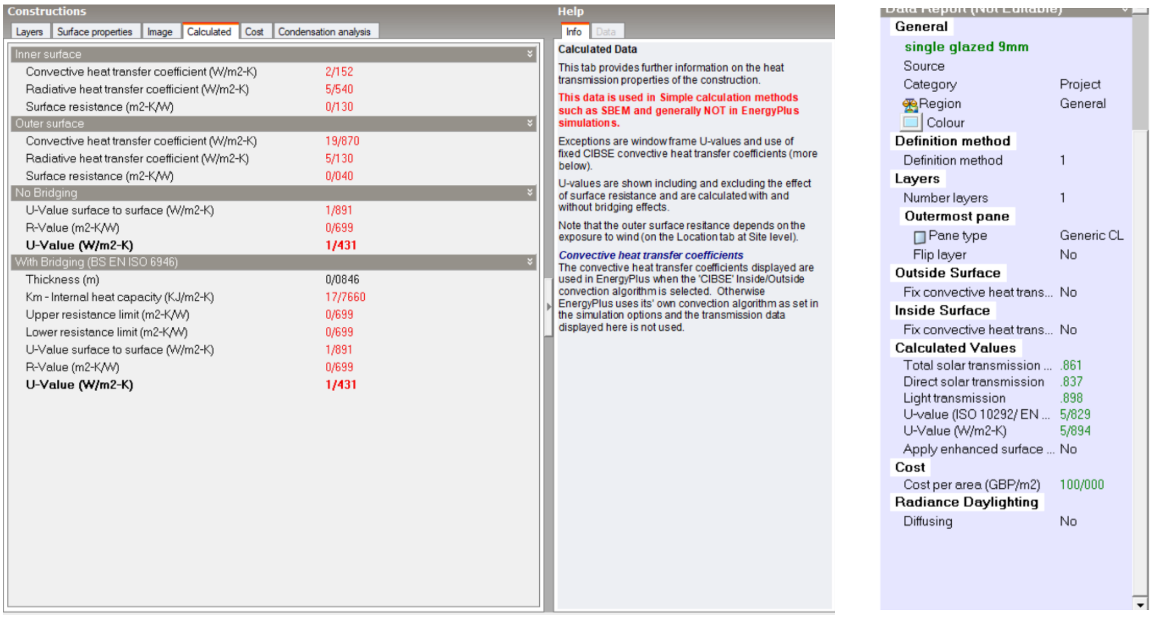


Figure 79 - Adding wall and window's construction detail

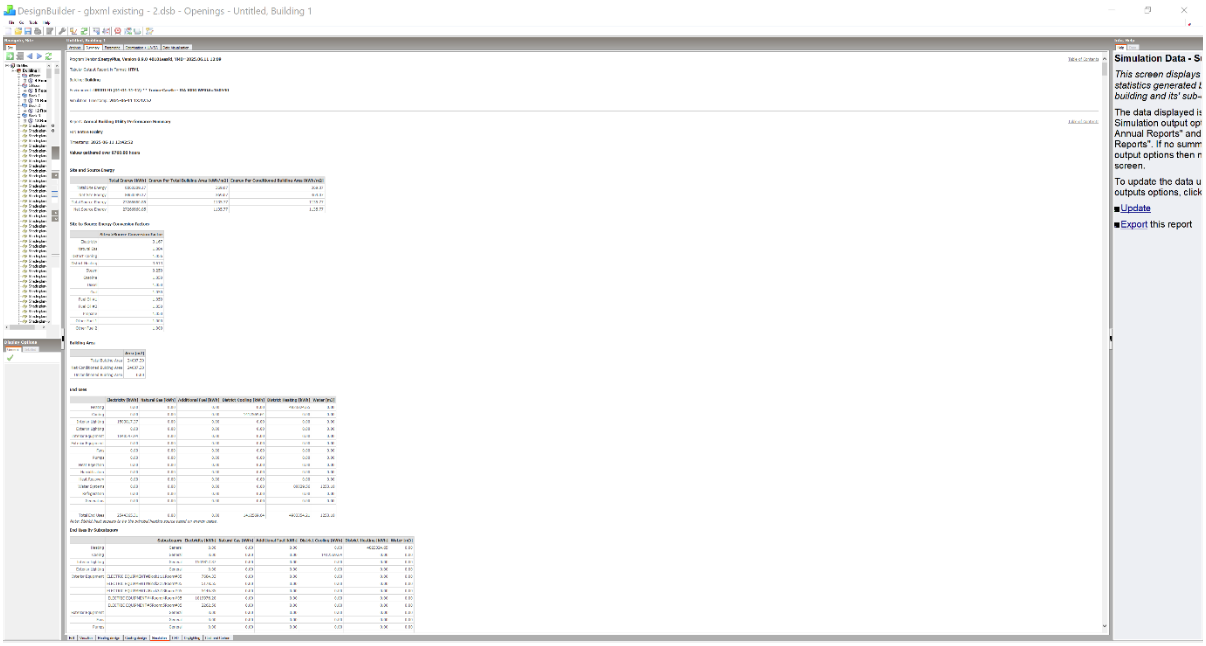
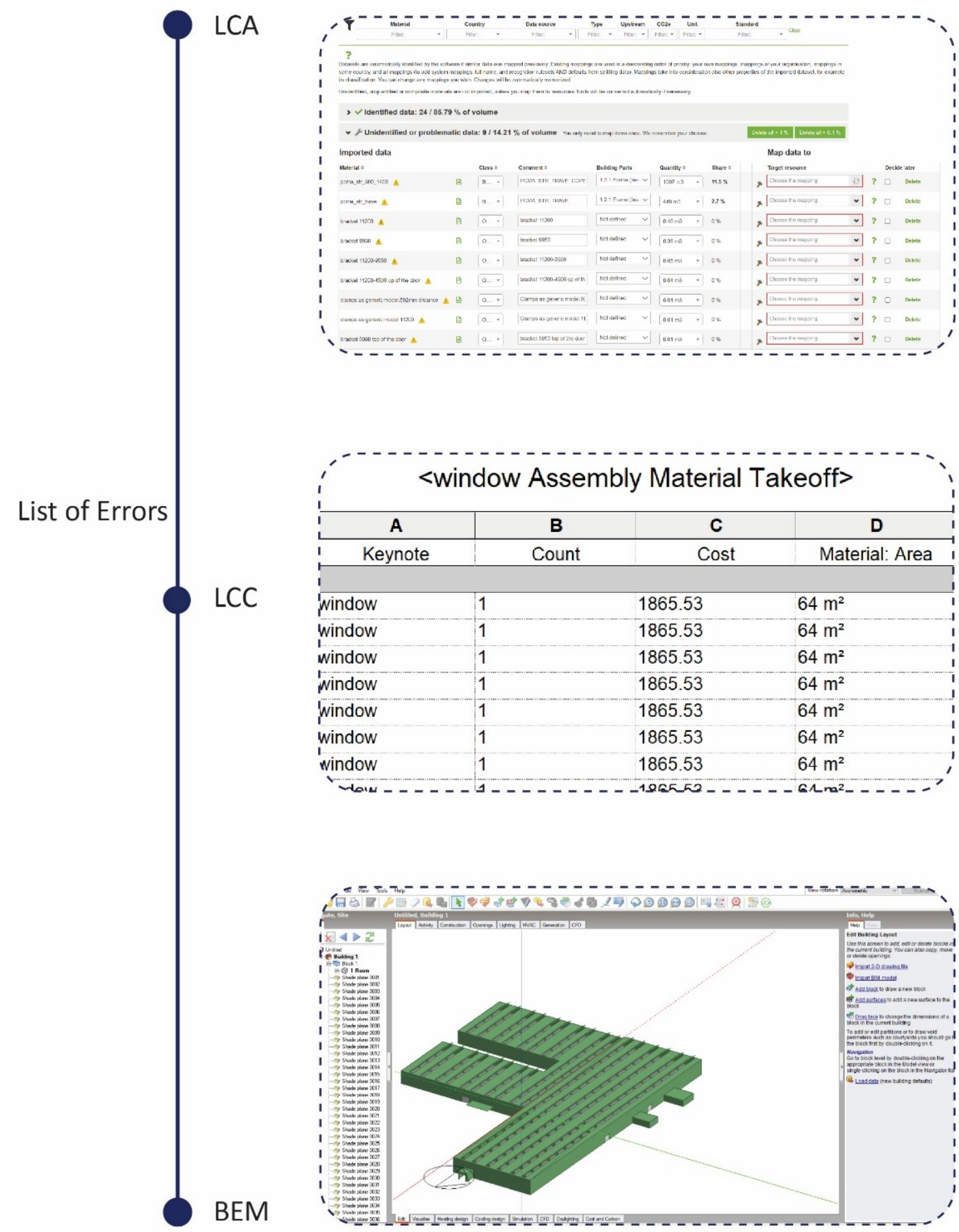


Figure 81 - Simulation Result in Design Builder

The simulation had been done three times for existing situation, Solution 1 and Solution 2 to be comparable the amount of energy consumption. The result of this simulation was graphs and CSV file, then convert the CSV to Excel file which it will return to the Revit by DirootsOne.

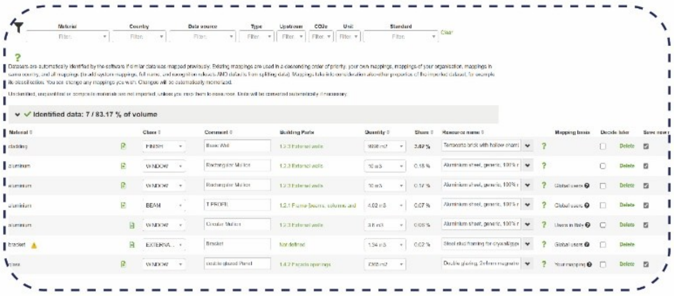
Figure 82 - Technological Workflow of BEM illustrated by the authors

2.10 List of issues from BIM to LCA, LCC and BEM



Resolved Errors

LCA

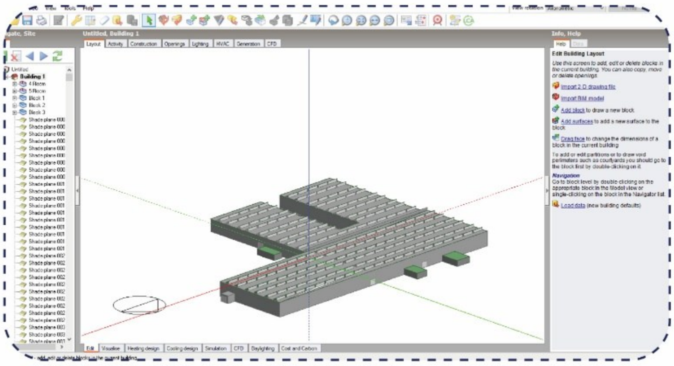


LCC

<Window Material Takeoff>

A	B	C	D	E
Family and Type	Count	Material: Name	Material: Area	Cost
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	22 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	22 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	22 m²	
double glazed Pan	1	Glass	21 m²	
double glazed Pan	1	Glass	21 m²	
ouble glazed Pan	1	Glass	22 m²	

BEM



2.11 Return from LCA, LCC and BEM to BIM

2.11.1 LCA and LCC to BIM

Shared parameters are definitions stored outside of any specific Revit family or project, enabling consistent use across multiple files. Since they're defined in an external shared parameter file, they can be added to various families and projects, yet their values aren't automatically transferred, each instance must be manually filled (Autodesk. (2025)).

These parameters are essential for two key workflows:

- Tagging: Only shared parameters can be referenced in tags.
- Multi-category schedules: To include different types of families in the same schedule, they all must contain a shared parameter—without it, combining multiple categories isn't possible

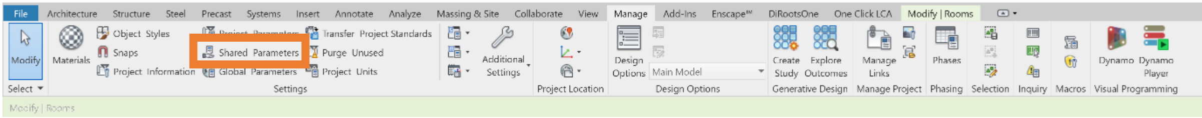


Figure 83 - Shared parameter on Revit

Initially, a shared parameter must be created and subsequently added to the project as a project parameter to enable its use across elements within the BIM environment.

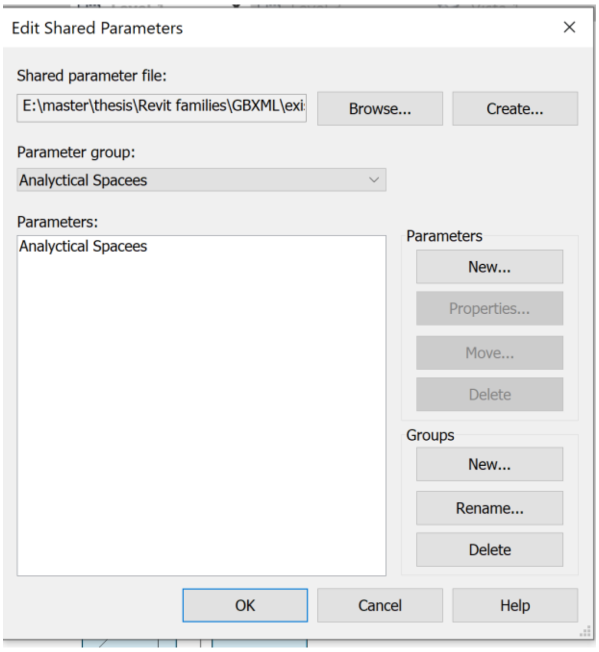


Figure 84 - Creating Shared parameter

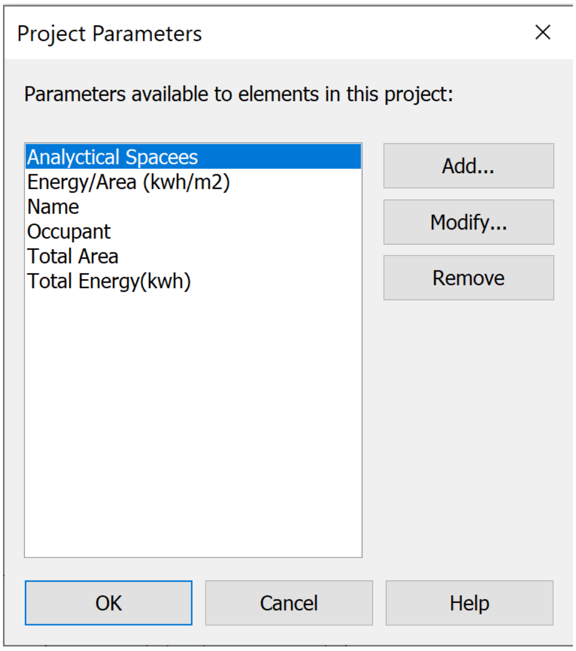


Figure 85 - Adding created shared parameter as project parameter

As outlined above, the Global Warming Potential (GWP) values for the total quantity of each material were obtained from the LCA results exported as an Excel file. These values were then calculated per unit using Dynamo and assigned to each material within the BIM model as shared parameters, enabling a direct link between material quantities and environmental impact. Importing the data by DirootsOne has to be done by TableGen.

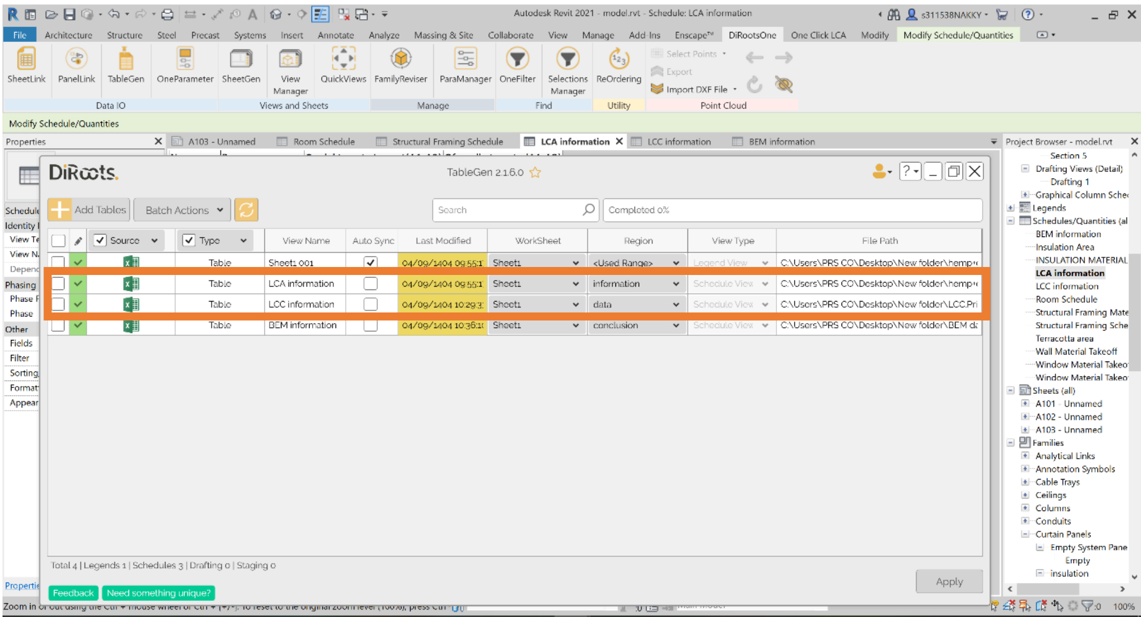


Figure 86 - Importing the LCA data to Revit by DirrotsOne

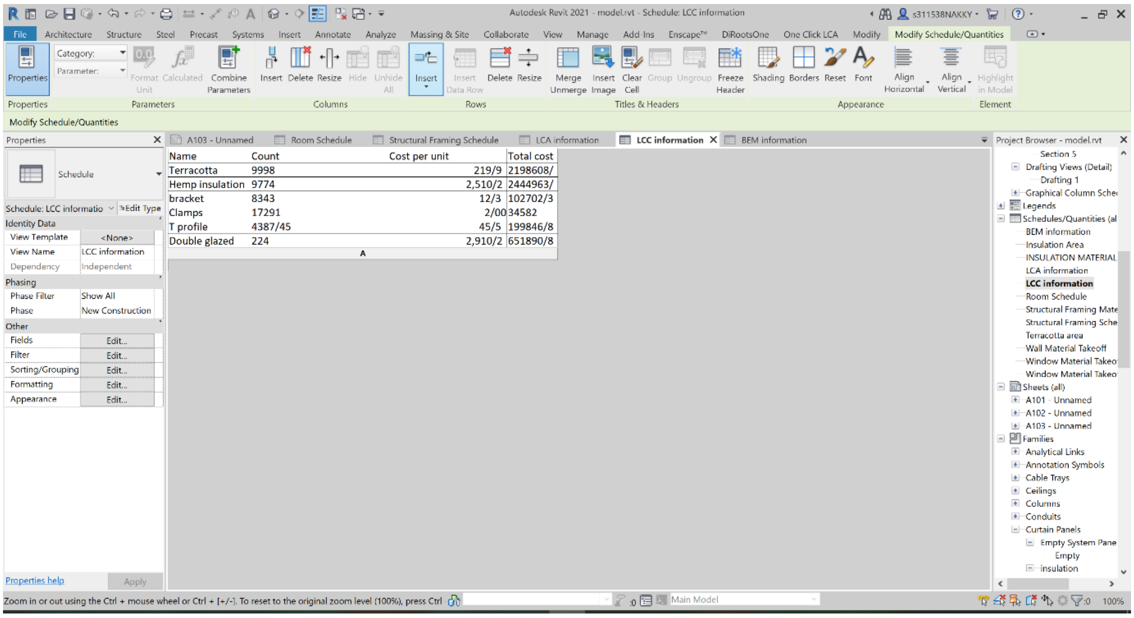


Figure 88 - Imported schedule of LCC information

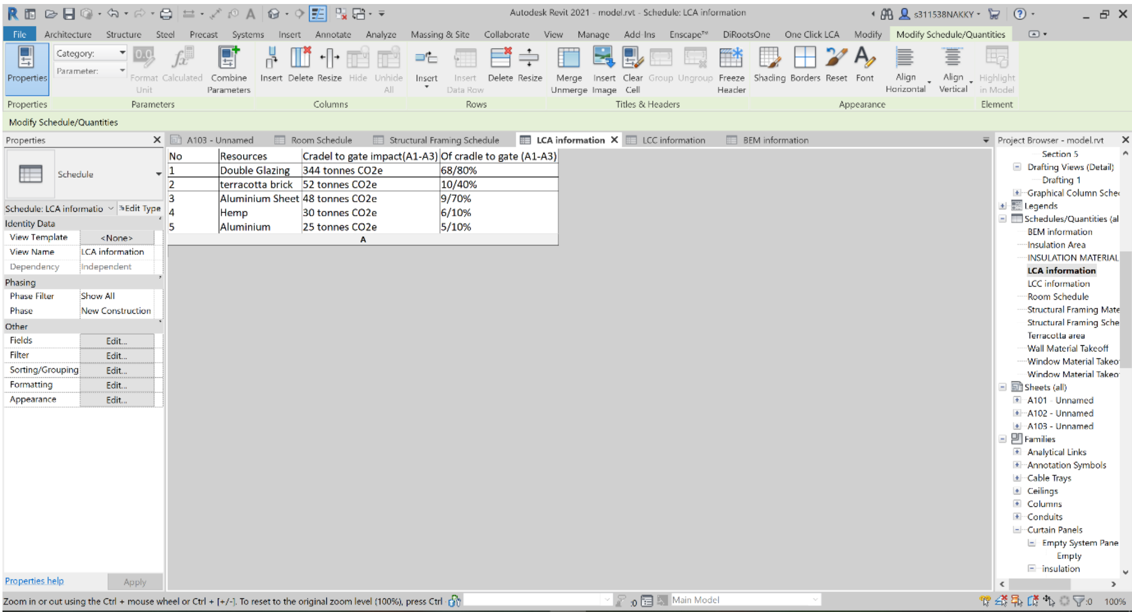


Figure 87 - Imported schedule of LCA information

The total GWP of each material is calculated according to the density for each m^2 as emission factor and assigned it as a shared parameter to the material. On this way, If another thickness is used for the material, it is automatically will calculate the GWP by this Dynamo script.

The figure below outlines a Dynamo script that automates the process of:

1. Collecting wall elements from the BIM model.
2. Extracting thickness information via compound structure layers.

3. Accessing thermal asset data by mapping materials to their thermal properties.
4. Creating a material takeoff schedule to compile thickness, area, and material-related information for LCC and thermal performance analysis.

Since the BIM model for LCA and LCC is the same, the process returning data is the same. For LCC the data is Euro per unit of the material or family.

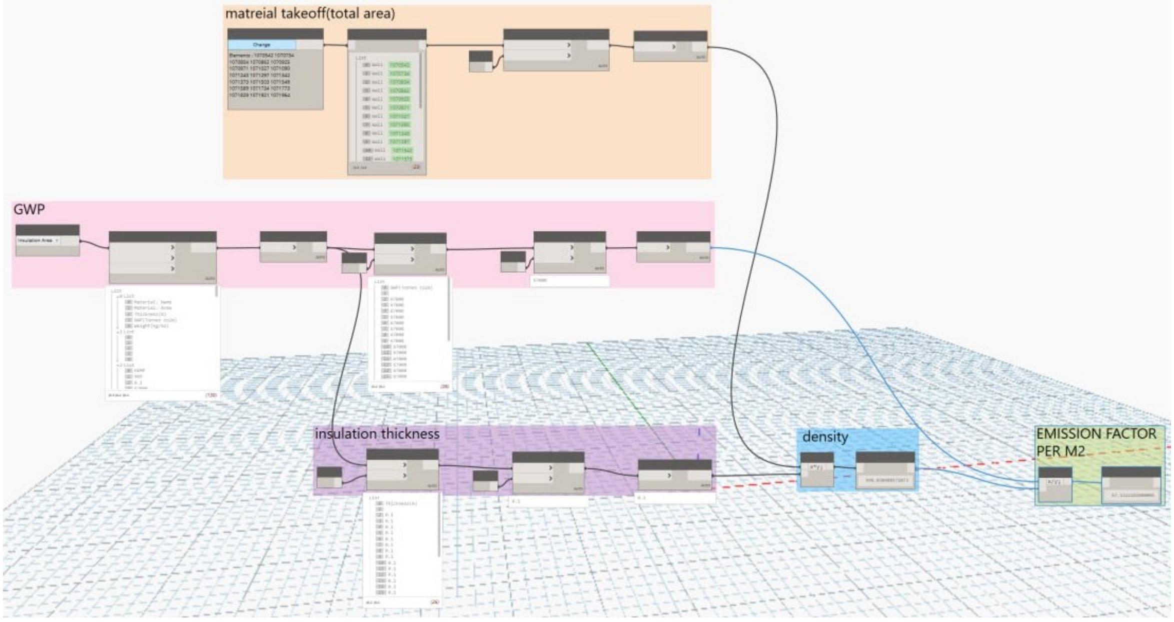


Figure 89 - Dynamo Script Workflow for Extracting Wall Thickness and Thermal Parameters in BIM-This approach is adapted from the BIM-based optimisation framework proposed by Chen et al. (2020)

2.11.3 BEM to BIM

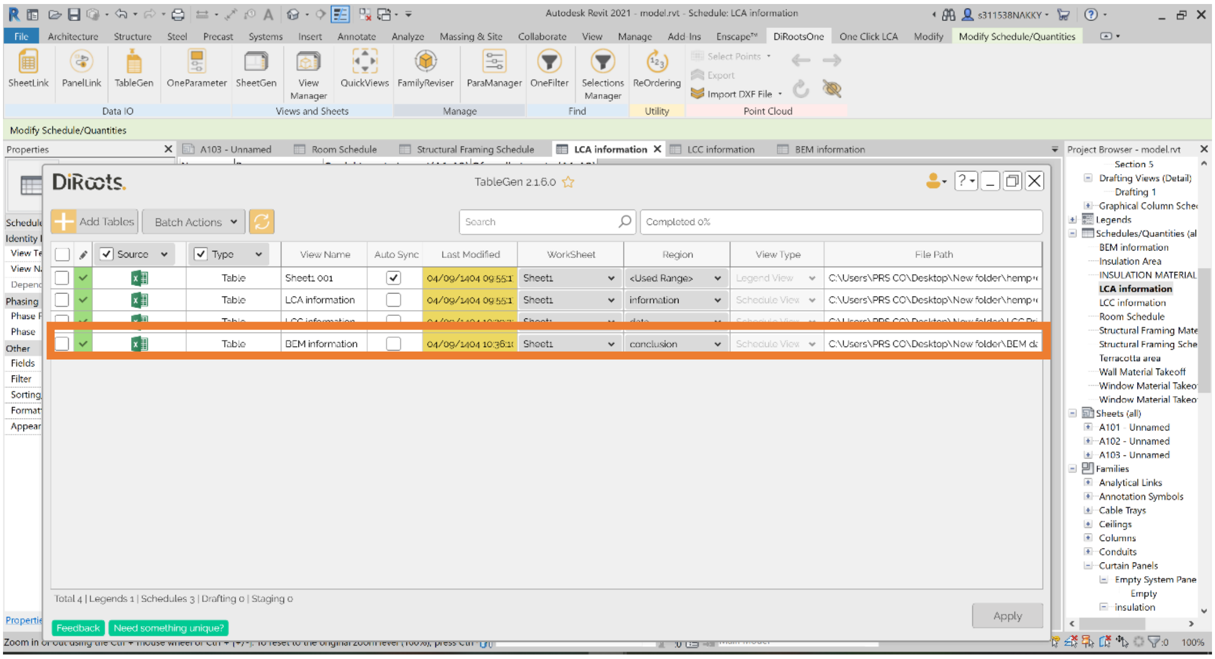


Figure 90 - Importing the BEM data to Revit by DirrotsOne

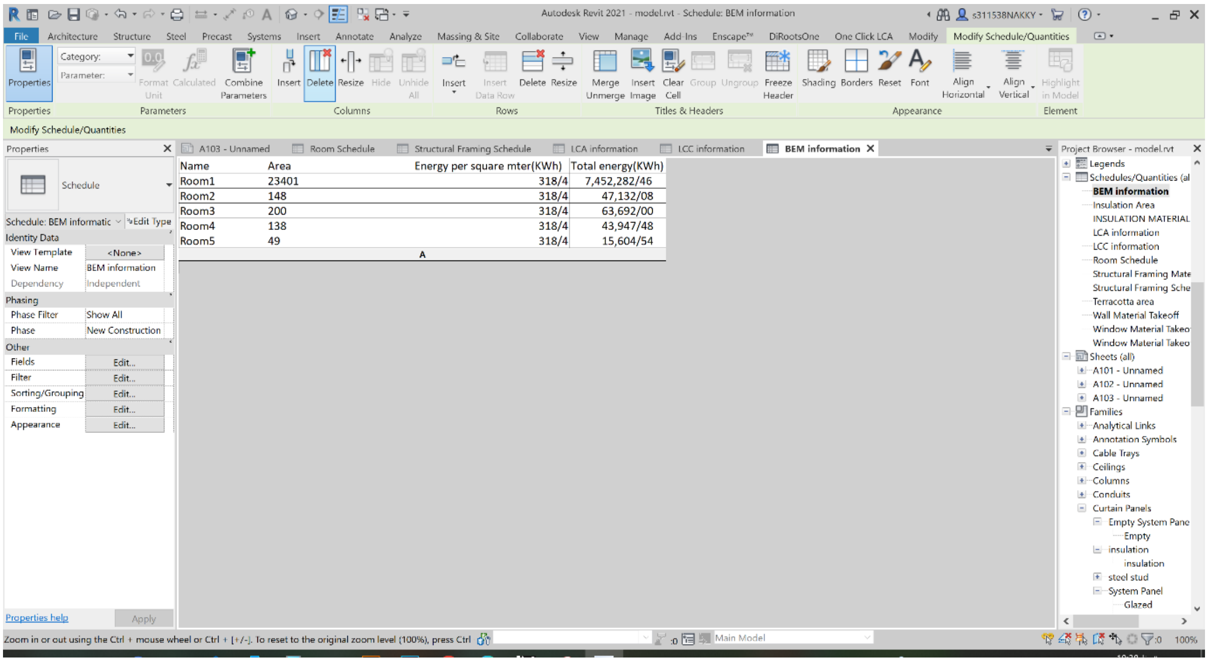


Figure 91 - Imported schedule of BEM information

The result of the simulation from Design Builder is energy consumption per square meter (kwh/m^2) which import to each room as a shared parameter.

If the DirootsOne plugin was not available to use, it would be possible to write Dynamo script for data return between not only BEM but also LCA and LCC to BIM. As it illustrates below, a custom Dynamo script was developed to automate the process of importing the Excel energy data and assigning it to the corresponding Revit room elements. The workflow includes:

- Reading the Excel file path and extracting tabular data.
- Mapping the data fields to the shared parameters.
- Assigning energy values to rooms in Revit based on matching names or indices.

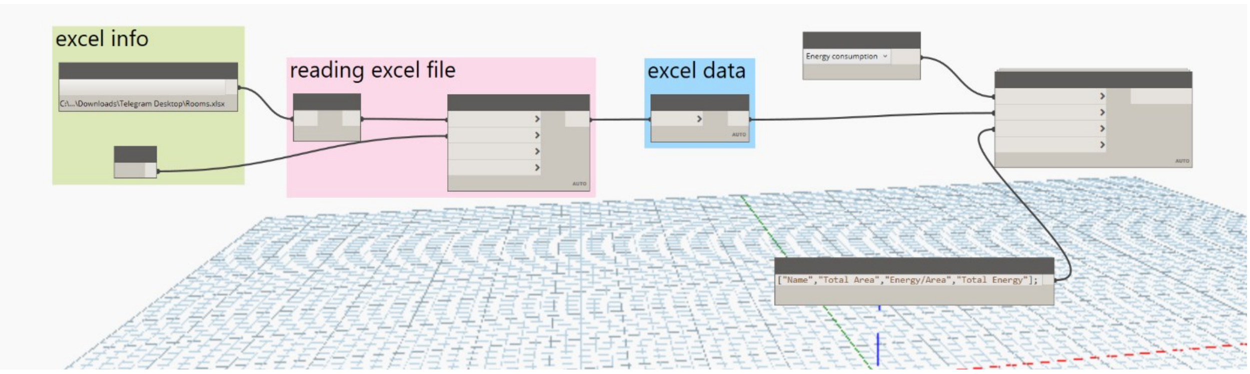
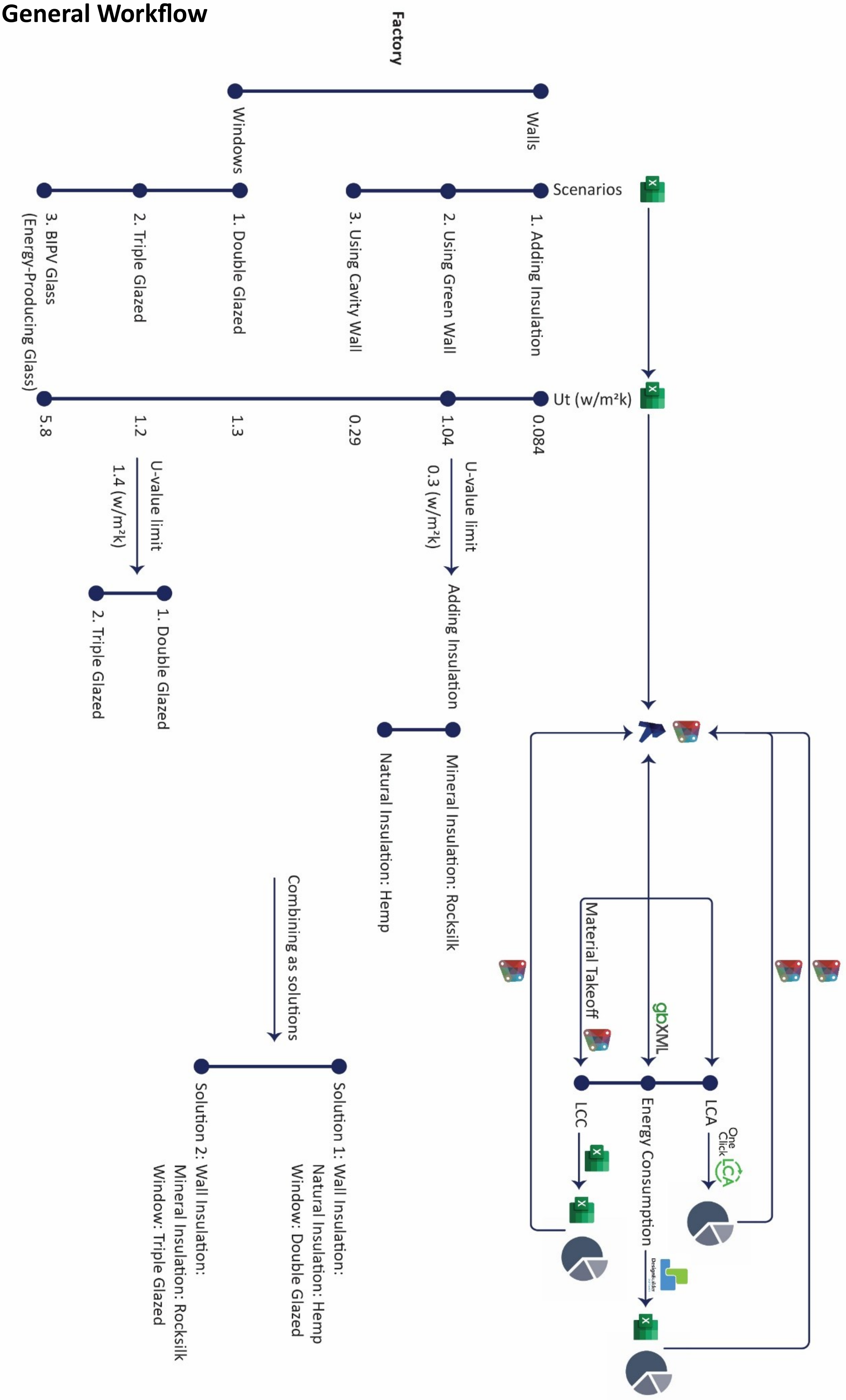


Figure 92 - Dynamo script from BEM to BIM

2.12 General Workflow



2.13 Holistic workflow

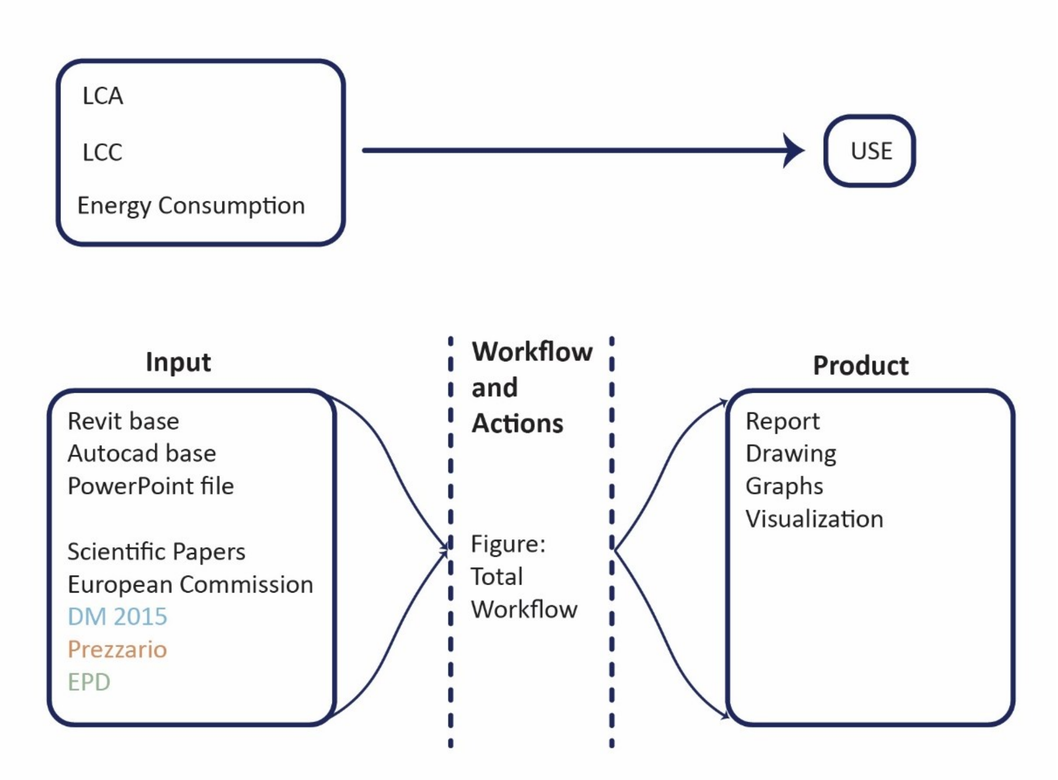
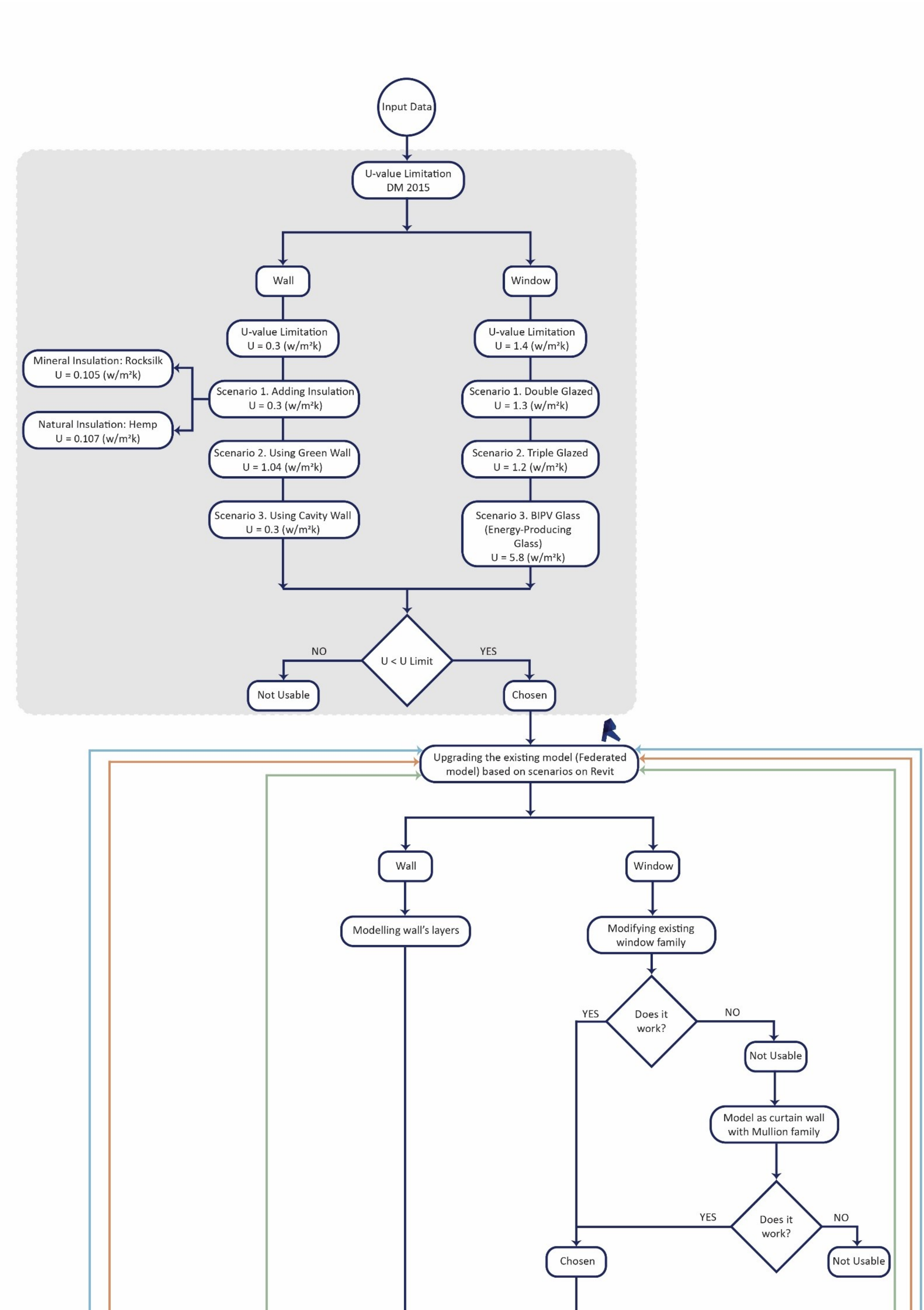
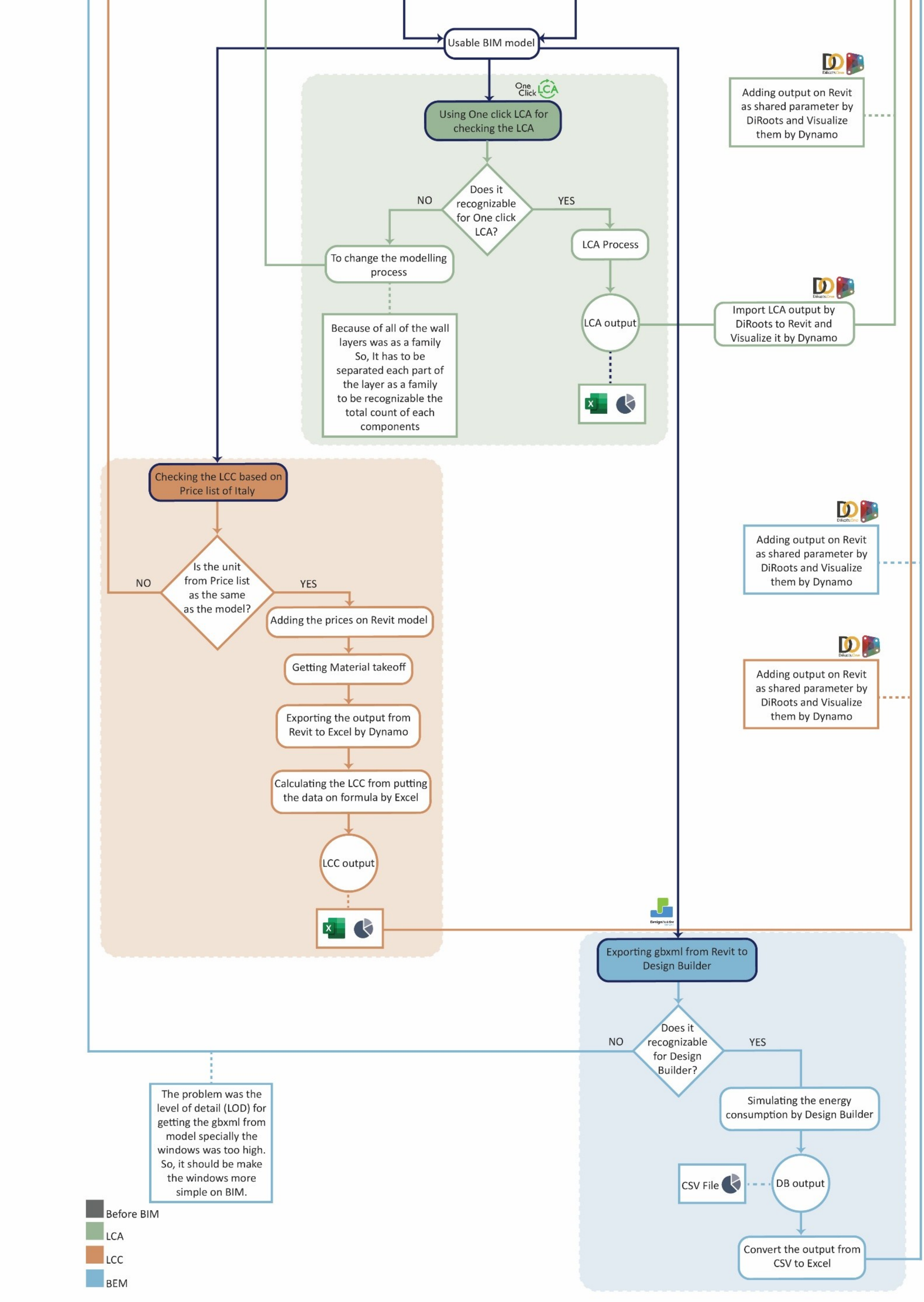


Figure 93 - Workflow overview showing the transformation of BIM and regulatory inputs into reports, visualizations, and performance outputs through LCA, LCC, and energy analysis.

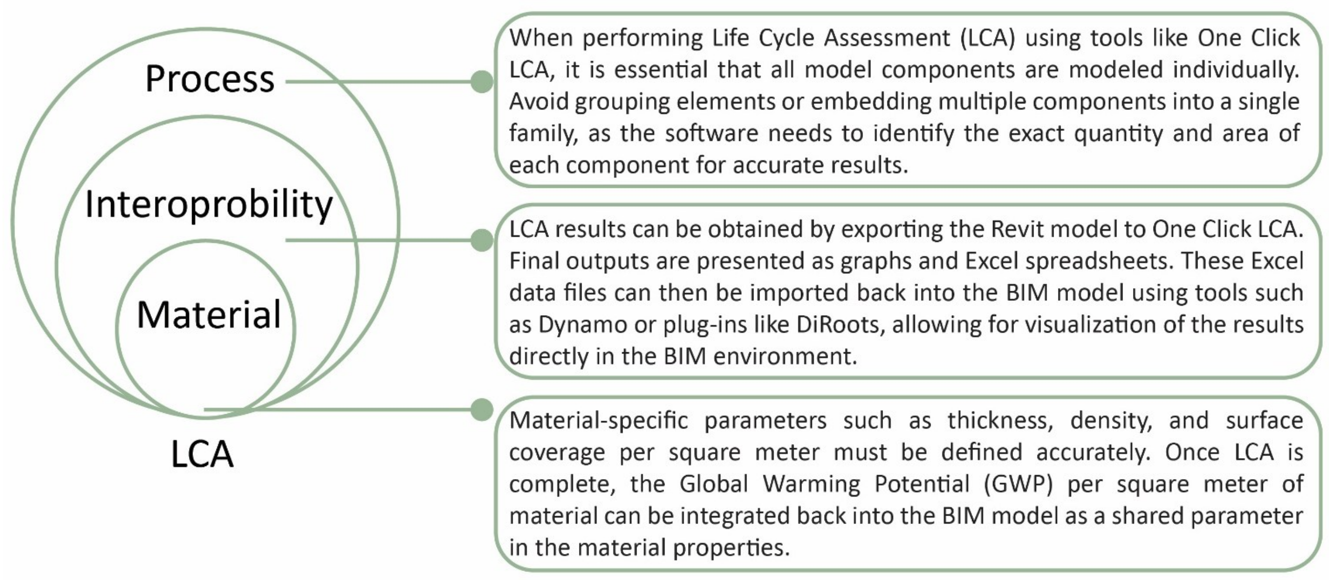
The methodology is based on a cyclical process that transforms foundational design data—originating from DWG, Revit (RVT), and PowerPoint (PPT) files—into measurable outputs through three analytical pathways: BIM to LCA (Life Cycle Assessment), BIM to LCC (Life Cycle Costing), and BIM to BEM (Building Energy Modeling). Each pathway involves specific workflows and tools to extract material quantities, performance data, and spatial configurations needed for simulation and calculation. These actions result in a variety of outputs, including CSV files, Excel spreadsheets, PDFs, and graphical visualizations. However, a crucial part of this cycle is the reintegration of analytical results back into the BIM environment. This is achieved through shared parameters or color-coded visual feedback using Dynamo, allowing the enriched data (e.g., environmental impact, energy consumption, and cost indicators) to be visualized and leveraged directly within the BIM model. This iterative process ensures both design-intelligence continuity and informed decision-making throughout the project's development.

2.13.1 Process Algorithm





Usable BIM model
Using One click LCA for checking the LCA
Does it recognizable for One click LCA?
NO
YES
To change the modelling process
Because of all of the wall layers was as a family So, It has to be separated each part of the layer as a family to be recognizable the total count of each components
LCA Process
LCA output
Adding output on Revit as shared parameter by DiRoots and Visualize them by Dynamo
Import LCA output by DiRoots to Revit and Visualize it by Dynamo
Checking the LCC based on Price list of Italy
Is the unit from Price list as the same as the model?
NO
YES
Adding the prices on Revit model
Getting Material takeoff
Exporting the output from Revit to Excel by Dynamo
Calculating the LCC from putting the data on formula by Excel
LCC output
Adding output on Revit as shared parameter by DiRoots and Visualize them by Dynamo
Adding output on Revit as shared parameter by DiRoots and Visualize them by Dynamo
Exporting gbxml from Revit to Design Builder
Does it recognizable for Design Builder?
NO
YES
Simulating the energy consumption by Design Builder
DB output
CSV File
Convert the output from CSV to Excel
The problem was the level of detail (LOD) for getting the gbxml from model specially the windows was too high. So, it should be make the windows more simple on BIM.
Before BIM
LCA
LCC
BEM



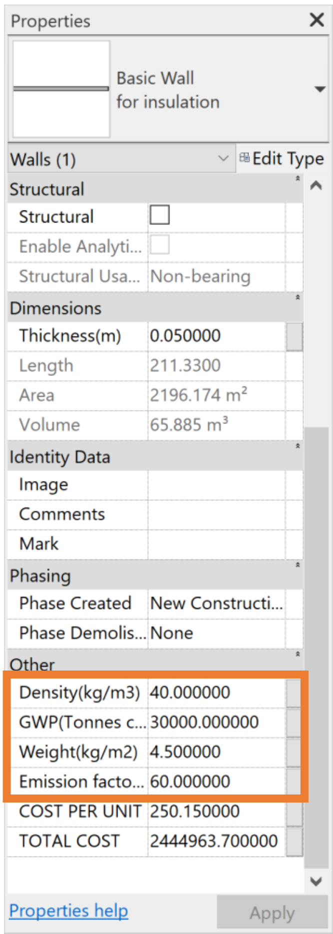
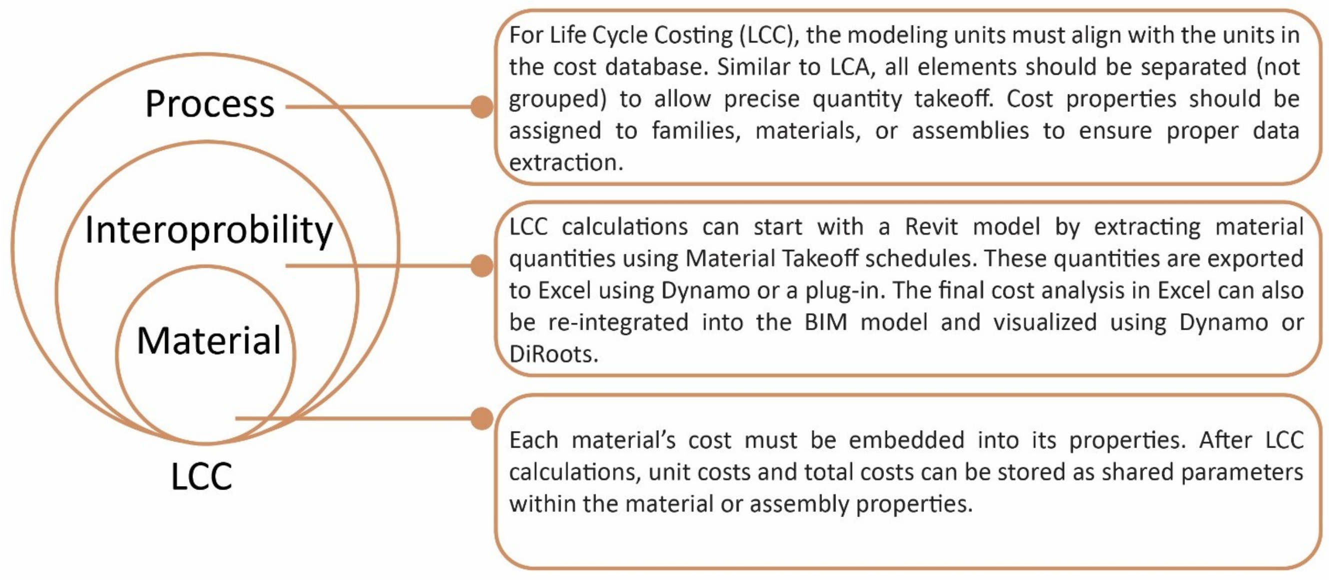


Figure 94 - Shared parameter of GWP on the Revit model



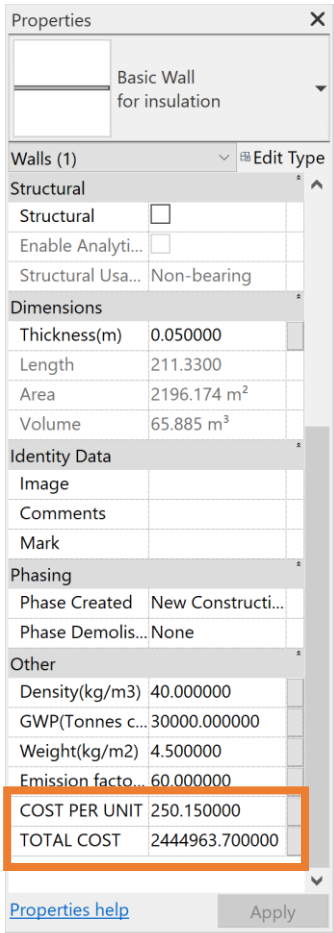
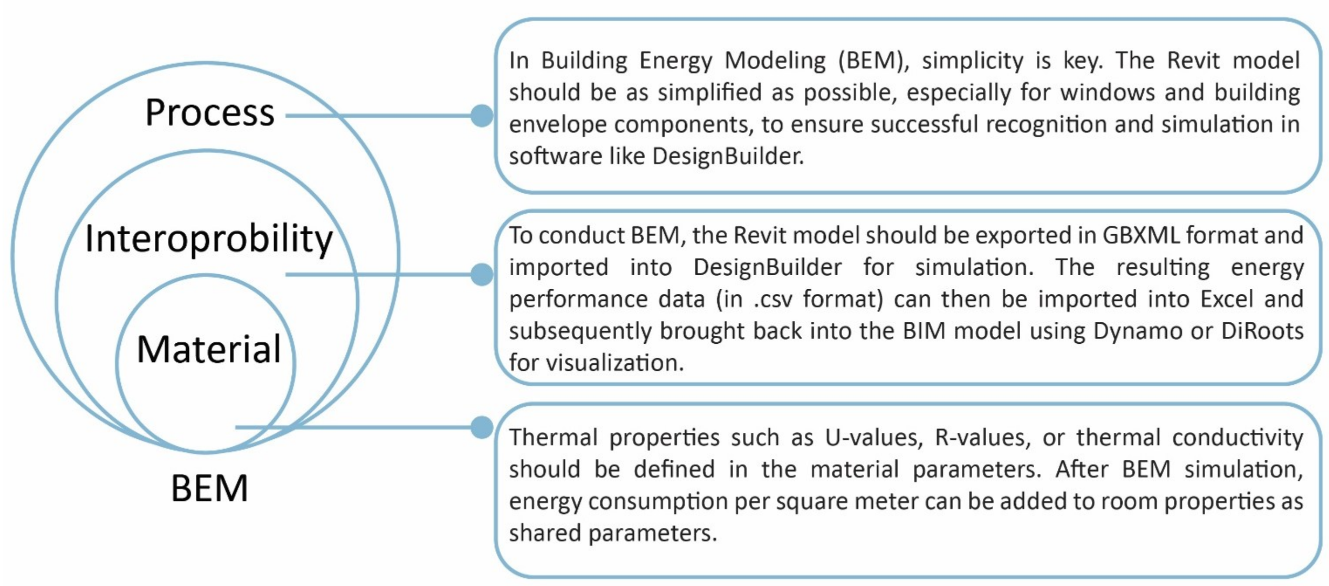


Figure 95 - Shared parameter of LCC on the Revit model



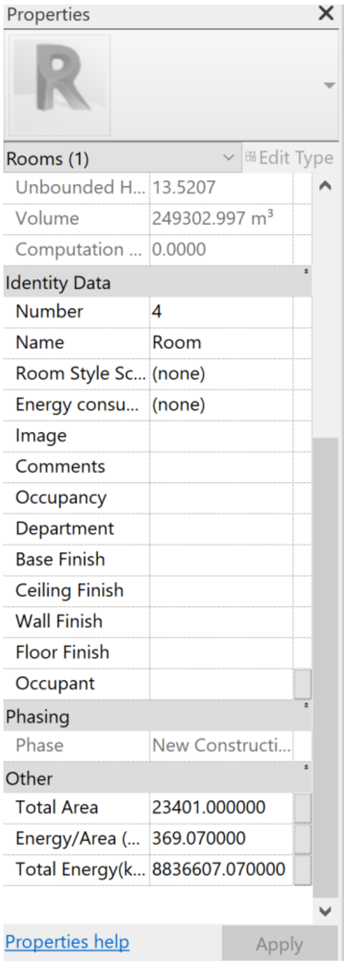


Figure 96 - Shared parameter and rooms of the model

2.14 Model requirements for a BIM based LCA, LCC and BEM

To perform a BIM-based Life Cycle Assessment (LCA), it's essential to structure the model in a way that supports data extraction and analysis. While each BIM software has its own internal organization, this thesis adopts Autodesk Revit due to its hierarchical modeling framework. In Revit, building components are organized across four key levels: Category, Family, Type, and Instance.

A Category represents a broad classification such as walls, glass panels, or structural framing, grouping elements with similar functional roles. Within each category, Families define specific systems or elements (e.g., curtain wall mullions, insulation panels, or brackets). Types further differentiate these families based on geometry or material characteristics (like triple-glazed 0.6×8.7 panels or T-profiles 50×50). Finally, Instances are the individually placed elements in the model, each with a unique identifier and potentially varying properties, essential for accurate LCA and LCC calculations (Ait Hadda, 2021).

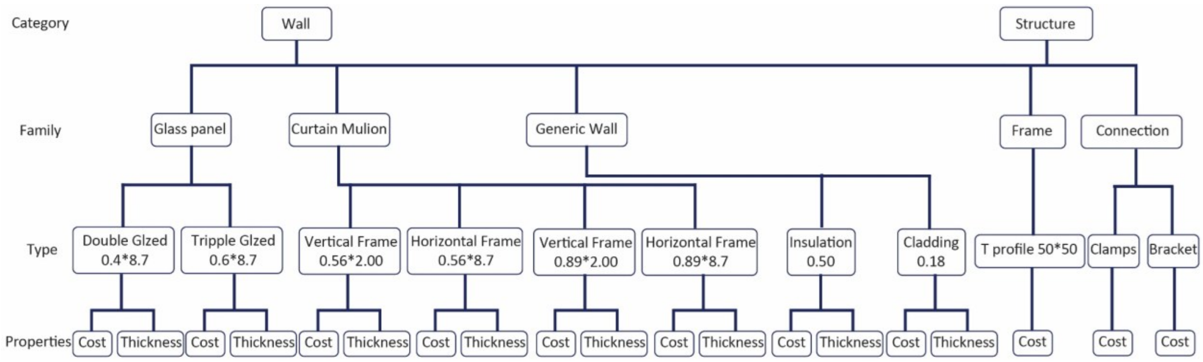


Figure 97 - Revit hierarchy of LCA and LCC - Illustrated by authors

For energy performance analysis, the building model must be structured to accurately represent key envelope elements like walls and windows. In this thesis, Autodesk Revit was used as the modeling environment due to its hierarchical structure, which organizes components by Category, Family, Type, and Instance.

In this setup, walls and windows are the primary categories used for the simulation model. The wall system includes families such as insulation layers and cladding walls, each differentiated by their specific thickness (e.g., 0.05 m and 0.18 m). Windows are defined under the Window Family category, with types specified by dimension, such as 2.1 × 8.7 m. These types are then instantiated throughout the model.

This approach simplifies the model geometry while preserving the key physical characteristics needed for energy simulation, ensuring compatibility with gbXML export workflows and external analysis tools (Ait Hadda, 2021).

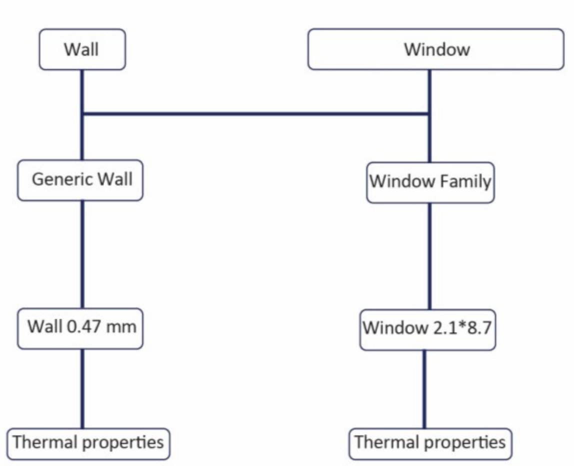


Figure 98 - Revit hierarchy of Energy Consumption - Illustrated by authors

Element	Category	LOD 200 (Conceptual)	LOD 300 (Detailed Design)	LOD 350 (Coordination)	LOD 400 (Fabrication)
Insulation Slab	Generic Model	Volume placeholder	Exact dimensions (1.2×0.6×0.5), thermal properties	Positioned on host wall, reference to material system	Manufacturer spec, fixing method, embodied carbon
Glass Panels	Glass Panel	Generic panel, area estimate	Double/triple glazed, correct size (e.g. 0.6×8.7)	Assembled in curtain wall with mullions	Product info, thickness, U/G-value, installation data
Curtain Mullions	Curtain Mullion	Symbolic vertical/horizontal lines	Frame profiles and real spacing (e.g. 0.89×8.7)	Precise joinery between mullions and panels	Cut lengths, fabrication and fixing details
Cladding Panels	Generic Wall	Simplified façade surface	Panel layout based on module size (e.g. 0.18)	With brackets and clamps coordinated for support	Material spec, supplier, installation guide

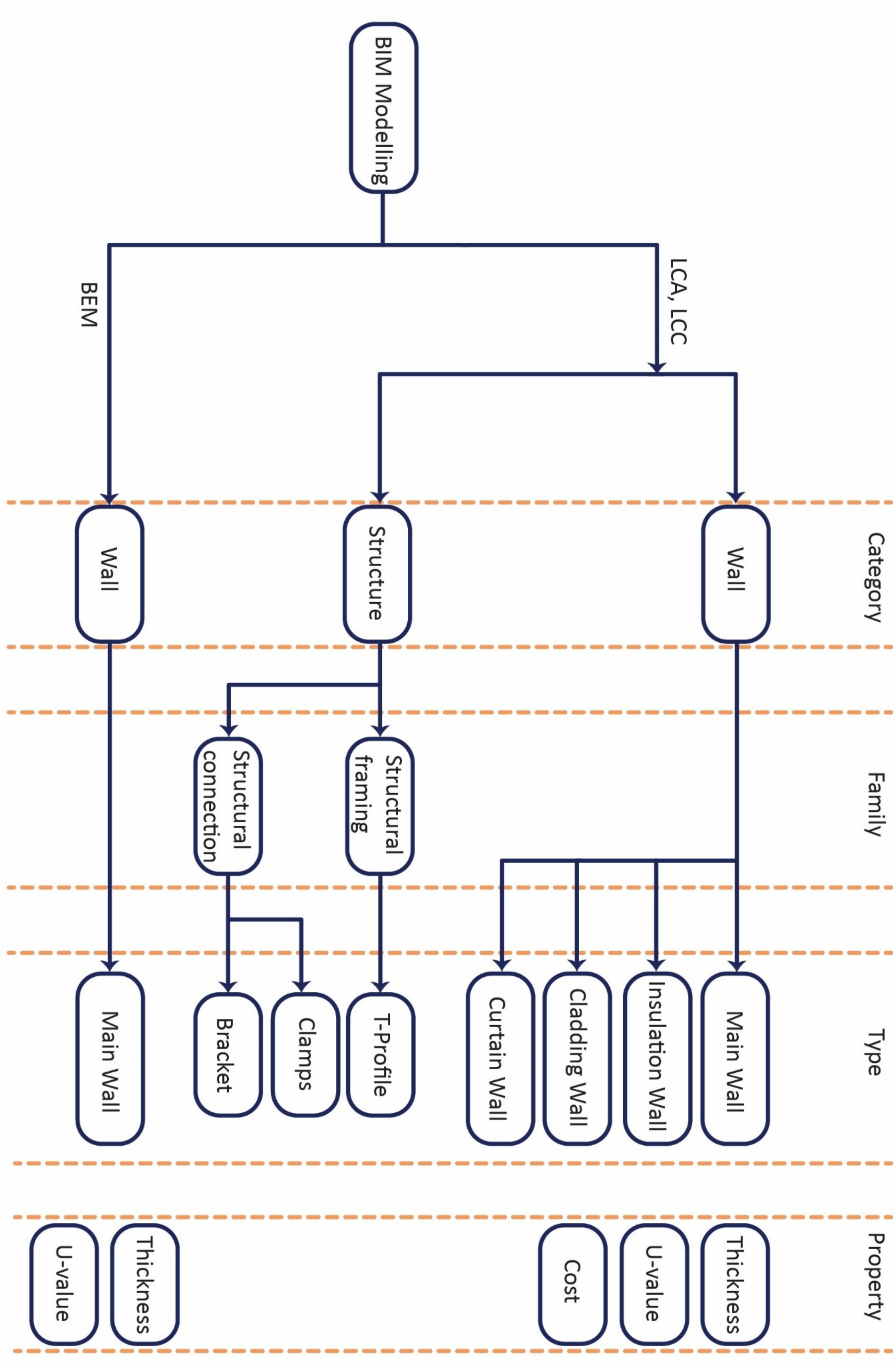
T-Profile 50×50	Structural Framing / Structure	Placeholder profile	Accurate size and material (50×50 mm)	Connected to structure or façade system	Fabrication-ready model with anchor details
Clamps / Brackets	Structural Connection / Generic	Symbolic connectors	Generic size and position	Accurate interface with T-profile and cladding	Detailed geometry with bolt/hole pattern and manufacturer reference

Table 9 - Model requirements for a BIM based LCA/LCC

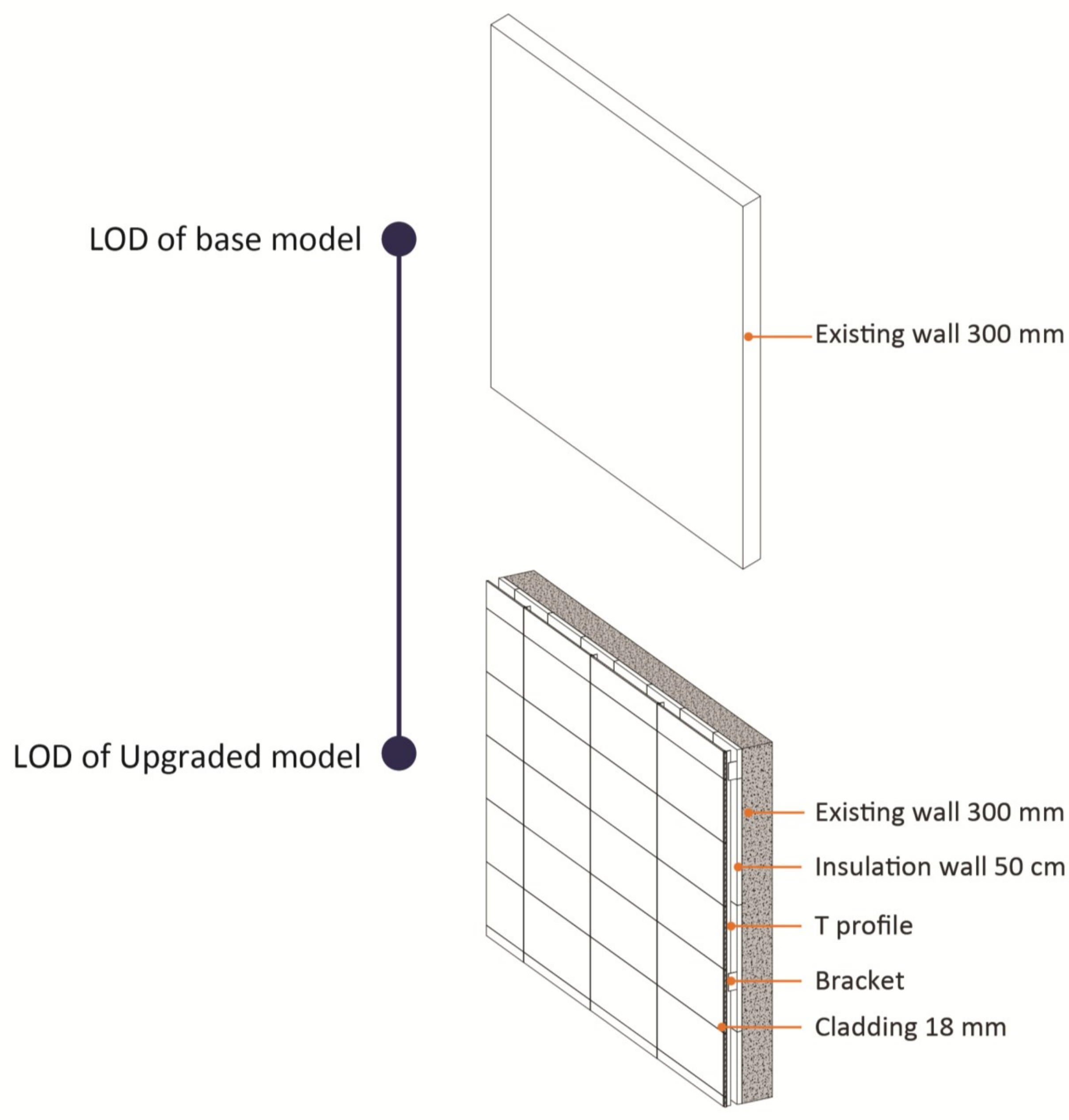
Element	**Category**	**LOD 200 (Conceptual)**	**LOD 300 (Analytical)**	**LOD 350/400 (Optional – For Energy Calibration or Retrofit)**
Insulation Wall	Wall	Basic thickness (e.g., 0.05 m) applied as uniform layer	Accurate material properties (R/U-value), area	Verified U-value, manufacturer, insulation continuity
Cladding Wall	Wall	Placeholder thickness (0.18 m), part of surface area	Included as external layer affecting thermal mass	Cladding type (reflectivity/emissivity), installed conditions
Window	Window	Simple size and location (2.1×8.7 m), no detailing	U-value, SHGC, VT, orientation-specific performance	Specific glass type, frame-to-glass ratio, leakage rate, g-value

Table 10 - Model requirements for a BIM based energy consumption

2.15 BIM Process

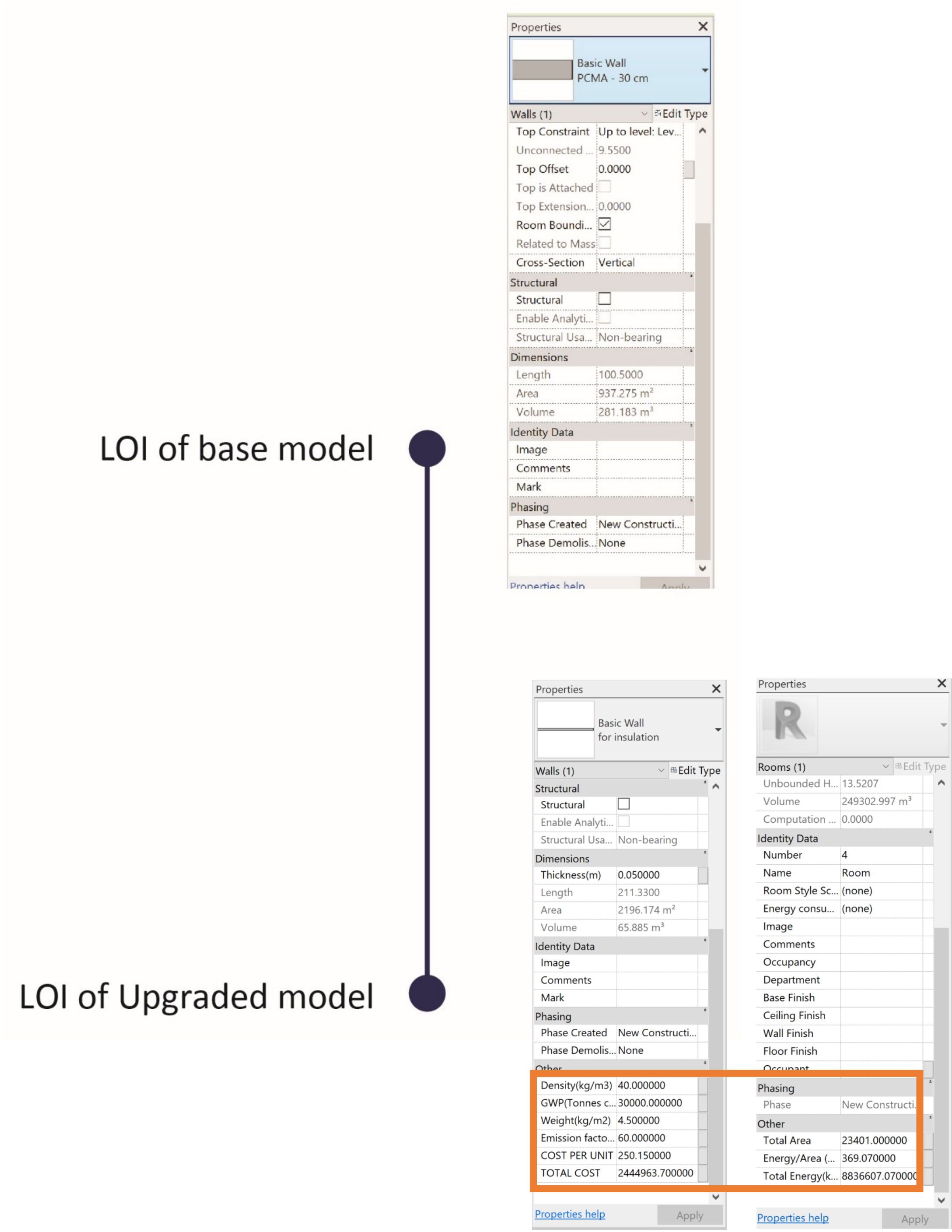


2.16 Level of Geometry (LOG)



2.17 Level of Information (LOI)

Since the Level of Detail (LOD) varies depending on the purpose, a low-LOD base model of the factory was initially used. As the analysis progressed for LCA, LCC, and BEM, the required LOD evolved accordingly. Therefore, additional information was incorporated into the model, and the concept of Level of Information Need (LOIN) was applied to guide the enrichment of the BIM model based on task-specific requirements.



LOIN: LOG upgraded model + LOI upgraded model

2.18 Data Visualization:

2.17.1 Graph Visualization:

For data visualization of LCA, LCC, and BEM results, the *NodeModelChart* package in Dynamo was installed and utilized to generate dynamic and customizable graphical outputs directly within the BIM environment.

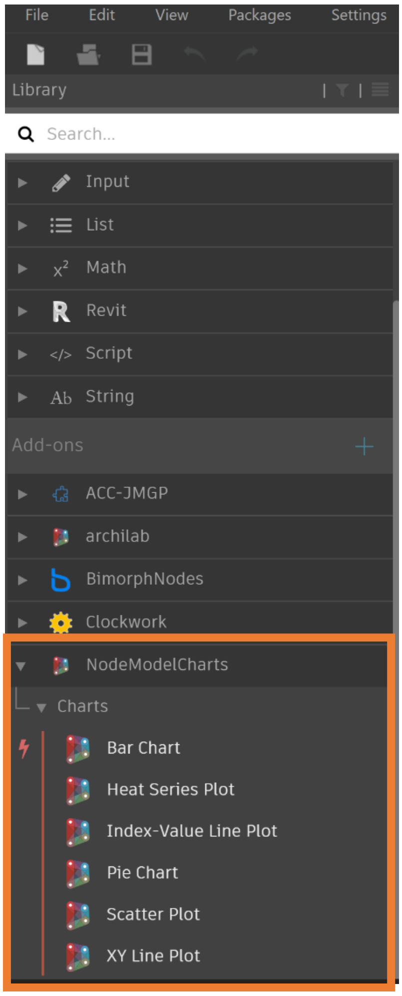


Figure 99 - NodeModelChart *package in Dynamo*

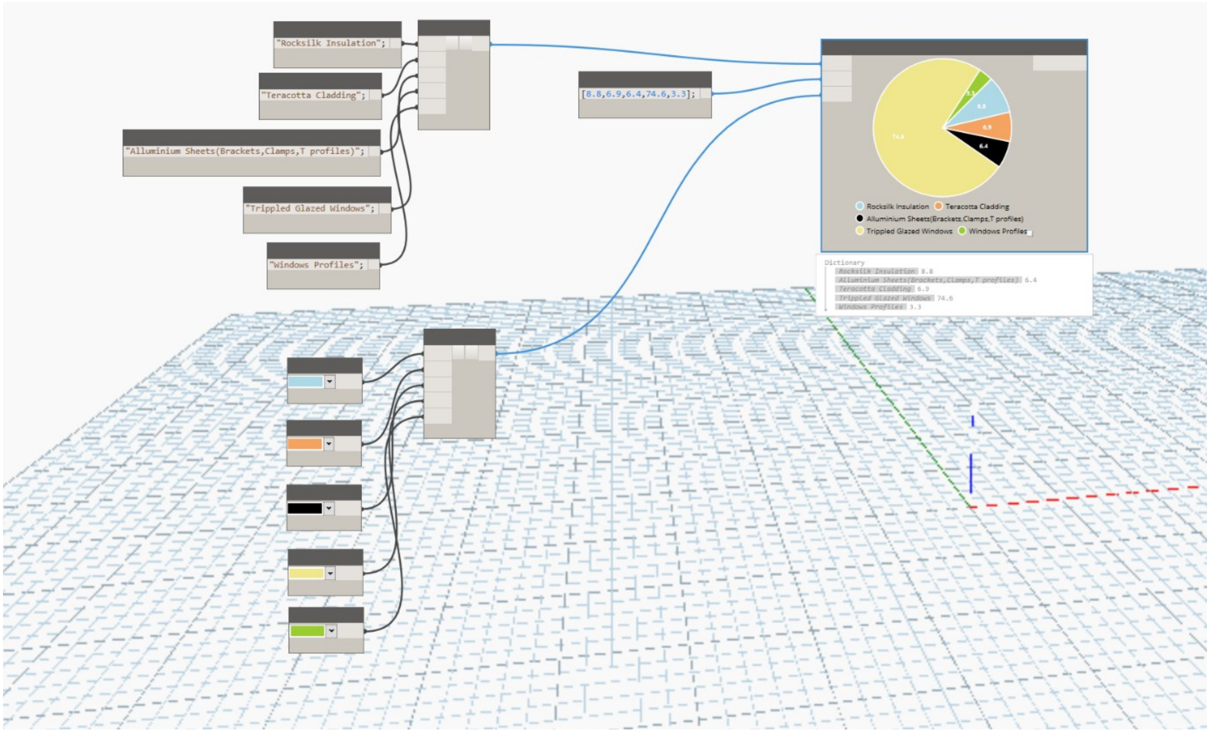


Figure 101 - Visualizing by Dynamo for LCA

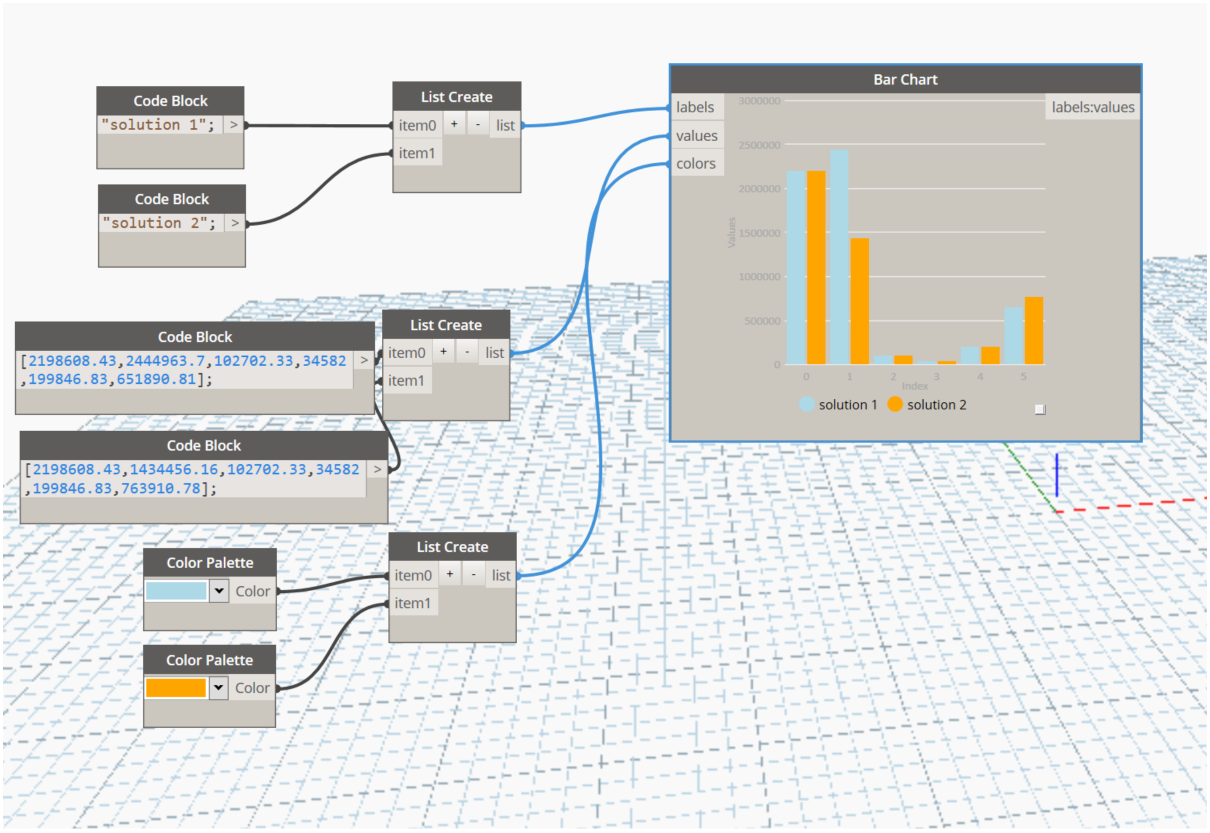


Figure 100 - Visualizing by Dynamo for LCC comparison

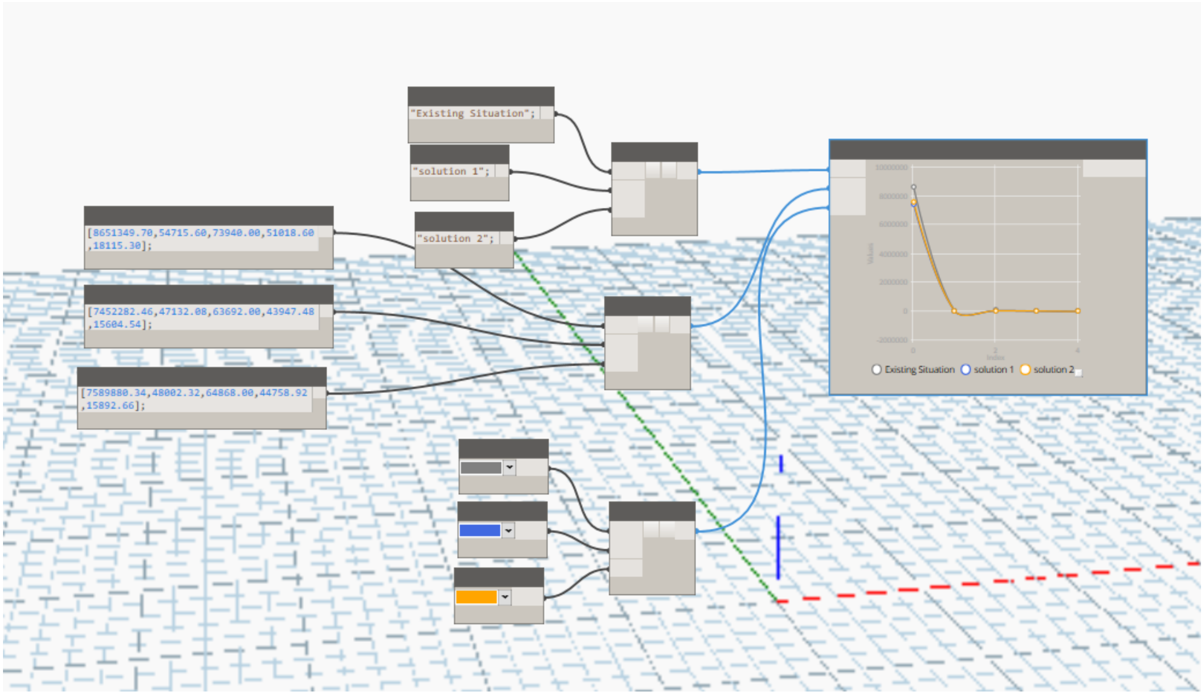


Figure 102 - Visualizing by Dynamo for BEM comparison

2.18.2 Graph Visualization:

By utilizing the created shared parameters, it is possible to apply color schemes through the *Visibility/Graphics* settings under the *Filters* tab in Revit. This allows each shared parameter to be visually represented in selected views, enhancing clarity and communication of data-driven results.

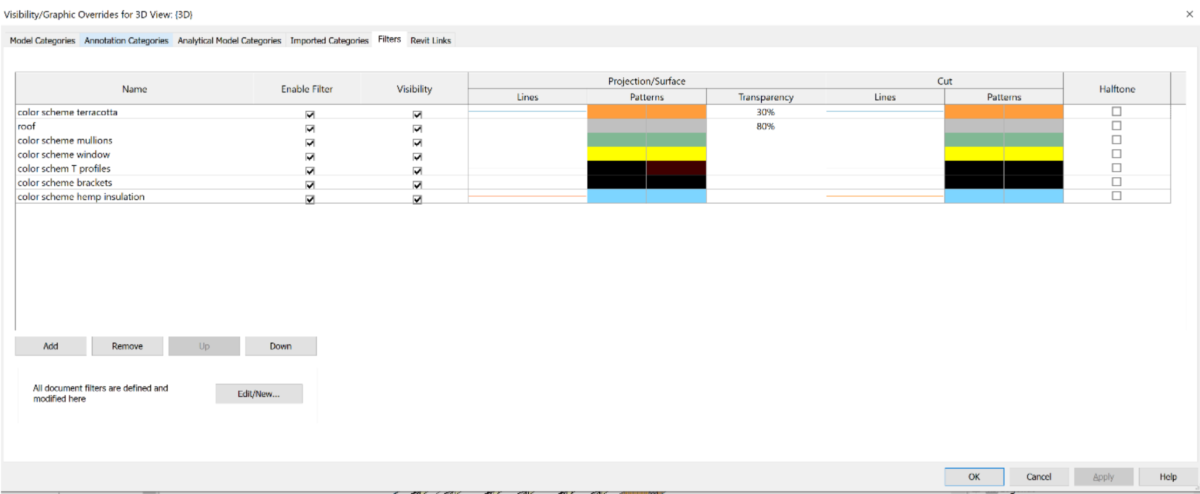


Figure 103 - Visibility/Graphics for visualization

CHAPTER 3

RESULT

Chapter 3: Result:

3.1 LCA Result:

This result was generated using One Click LCA, assessing the full life-cycle environmental impact of the material, from raw material extraction to end-of-life (stages A1–A4, B4–B5, and C1–C4). The total cradle-to-grave Global Warming Potential (GWP) is 15kg CO_2 equivalent per m^2, placing it well within Class A according to the standard impact scale.

Class A indicates a very low carbon footprint (<370 kg CO_2e/m^2), highlighting this material's excellent environmental performance. Such a rating is beneficial for sustainable building certifications (like LEED, BREEAM, or Level(s)) and aligns with the goals of reducing embodied carbon in construction.

This result demonstrates that the material is a highly sustainable choice for low-carbon building design.

Most contributing materials (Global warming potential (incl. +A2)) — Compare data (1)

No.	Resource	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)	Sustainable alternatives	
1.	Triple glazing, 48 mm, LT 73.1%, RLE 16.9%, SF 0.62, 30 kg/m2 ?	564 tonnes CO_2e	74.6 %	Show sustainable alternatives	Add to compare
2.	Rock mineral wool insulation, unfaced, L=0.035 W/mK, R=2.86 m2k/W, 100 mm, 5 kg/m2, 50 kg/m3, Lambda=0.035 W/(m.K) ?	67 tonnes CO_2e	8.8 %	Show sustainable alternatives	Add to compare
3.	Terracotta brick with hollow chambers, for facade application, 24 mm thickness, 150-300 mm height, up to 1200 mm lenght, 31 kg/m2, 2200 kg/m3 ?	52 tonnes CO_2e	6.9 %	Show sustainable alternatives	Add to compare
4.	Aluminium sheet, generic, 100% recycled content, average European aluminium manufacturing technology ?	48 tonnes CO_2e	6.4 %	Show sustainable alternatives	Add to compare
5.	Aluminium sheet, generic, 100% recycled content, average world technology ?	25 tonnes CO_2e	3.3 %	Show sustainable alternatives	Add to compare

Figure 105 - Result of LCA by One click LCA

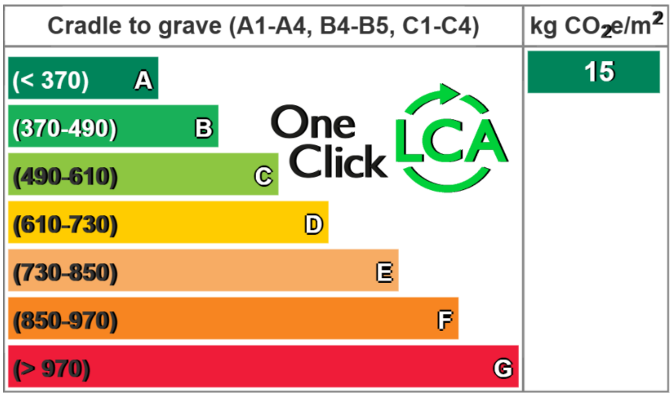


Figure 104 - One Click LCA assessment: Cradle-to-grave carbon footprint of 23 kg CO_2e/m^2, classified as sustainability Class A (excellent performance).

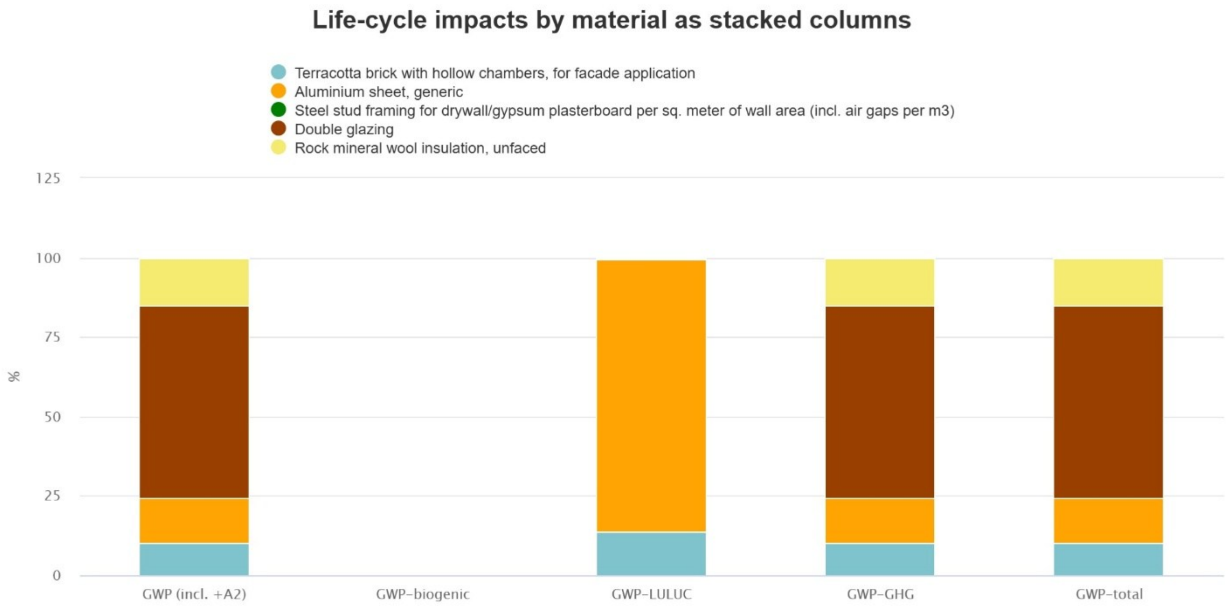


Figure 106 - Stacked column chart showing life-cycle GWP impacts by material.

This stacked column chart visualizes the life-cycle global warming potential (GWP) impacts of different construction materials, expressed in percentages across four GWP categories:

- GWP (incl. A2) – includes transportation impacts
- GWP-biogenic – accounting for biogenic carbon flows
- GWP-LULUC – land use and land-use change impacts
- GWP-total – overall climate change impact

The materials analyzed include:

- Terracotta bricks
- Aluminium sheets
- Steel stud framing
- Double glazing
- Rock mineral wool insulation

The data reveals that double glazing and rock mineral wool insulation are the largest contributors to total GWP. Together, they account for approximately 85–90% of the impact in the GWP (incl. A2), GWP-GHG, and GWP-total categories. Notably, aluminium contributes significantly in the GWP-LULUC category, underlining its high environmental burden related to land use.

The relatively minor contributions of terracotta bricks and steel studs suggest these may be lower-impact options, although the overall carbon footprint still depends on assembly, transport, and end-of-life treatment.

This analysis is useful for identifying hotspots in the environmental performance of building envelope assemblies and supports data-driven material substitution for reducing embodied carbon in construction.

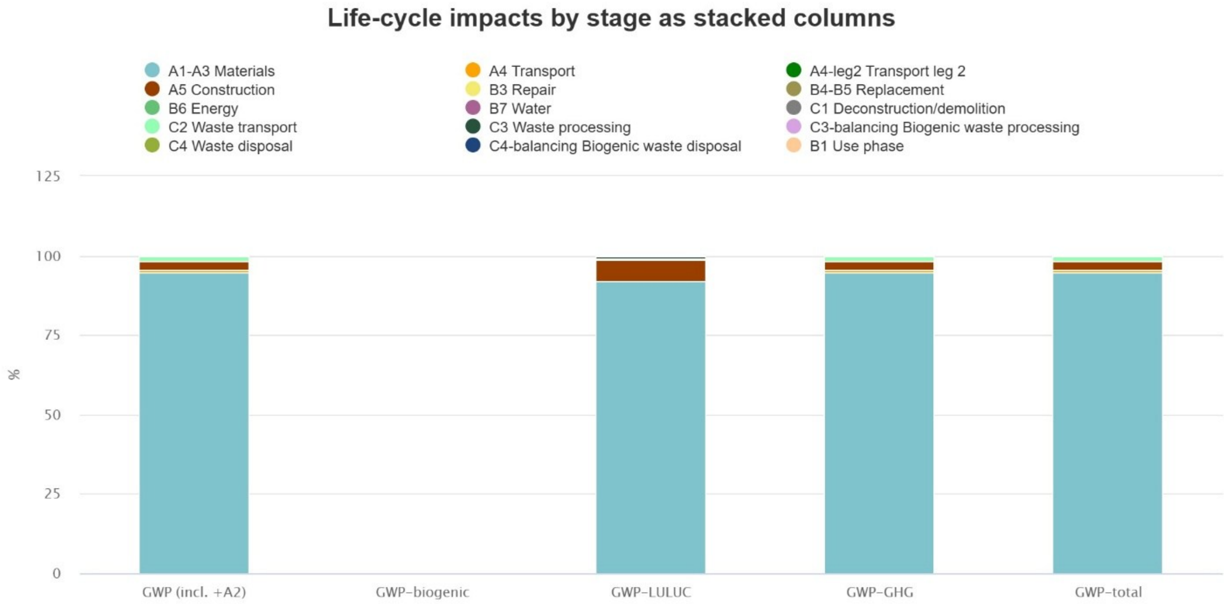


Figure 107 - Stacked column chart showing life-cycle GWP contributions by stage. A1–A3

This chart presents the life-cycle global warming potential (GWP) impacts distributed across the different life-cycle stages, using stacked columns for four impact categories. Each colored segment represents a specific life-cycle stage, such as:

- A1–A3 Materials (light blue): product manufacturing stages
- A4 Transport, A5 Construction, B6 Energy, C2 Waste Transport, C4 Waste Disposal, and others in minor roles

The results clearly show that A1–A3 (Materials) is the dominant contributor, accounting for over 90% of total GWP across all categories. This indicates that the environmental impact of the materials used in the construction phase far outweighs impacts from transportation, installation, energy use, or end-of-life processes.

The construction (A5) and energy use (B6) stages have minor but non-negligible impacts, while waste-related phases (C2, C4) contribute minimally.

This data underscores the importance of material selection in sustainable design and highlights the need to prioritize low-carbon materials during the early design phase to significantly reduce the embodied carbon of a building.

Figure 105 illustrates a comparative Life Cycle Assessment (LCA) of multiple design scenarios for walls and windows, highlighting their associated embodied carbon emissions in tonnes of CO_2 equivalent (CO_2e), as evaluated by One Click LCA.

Wall Design Scenarios:

1. Adding Insulation:
    - Mineral insulation (Rocksilk): 67 tonnes CO_2e
    - Natural insulation (Hemp): 30 tonnes CO_2e → Hemp offers a significantly lower environmental impact, making it a more sustainable insulation choice.
2. Using Green Wall
3. Using Cavity Wall

Window Design Scenarios:

1. Double Glazed: 344 tonnes CO_2e
2. Triple Glazed: 564 tonnes CO_2e
3. BIPV (Building-Integrated Photovoltaic) Glass

The results indicate that natural insulation (hemp) and double-glazed windows have the lowest embodied carbon among the options assessed. In contrast, mineral insulation and triple glazing, while potentially offering better thermal performance, result in significantly higher embodied emissions.

These insights support a balanced design strategy that considers both operational efficiency and embodied carbon, especially important in sustainable and low-carbon building design.

Result of CO_2e for each material which shows that natural insulation (hemp) and double glazing as the lowest-carbon options, with 30 and 344 tonnes CO_2e respectively.

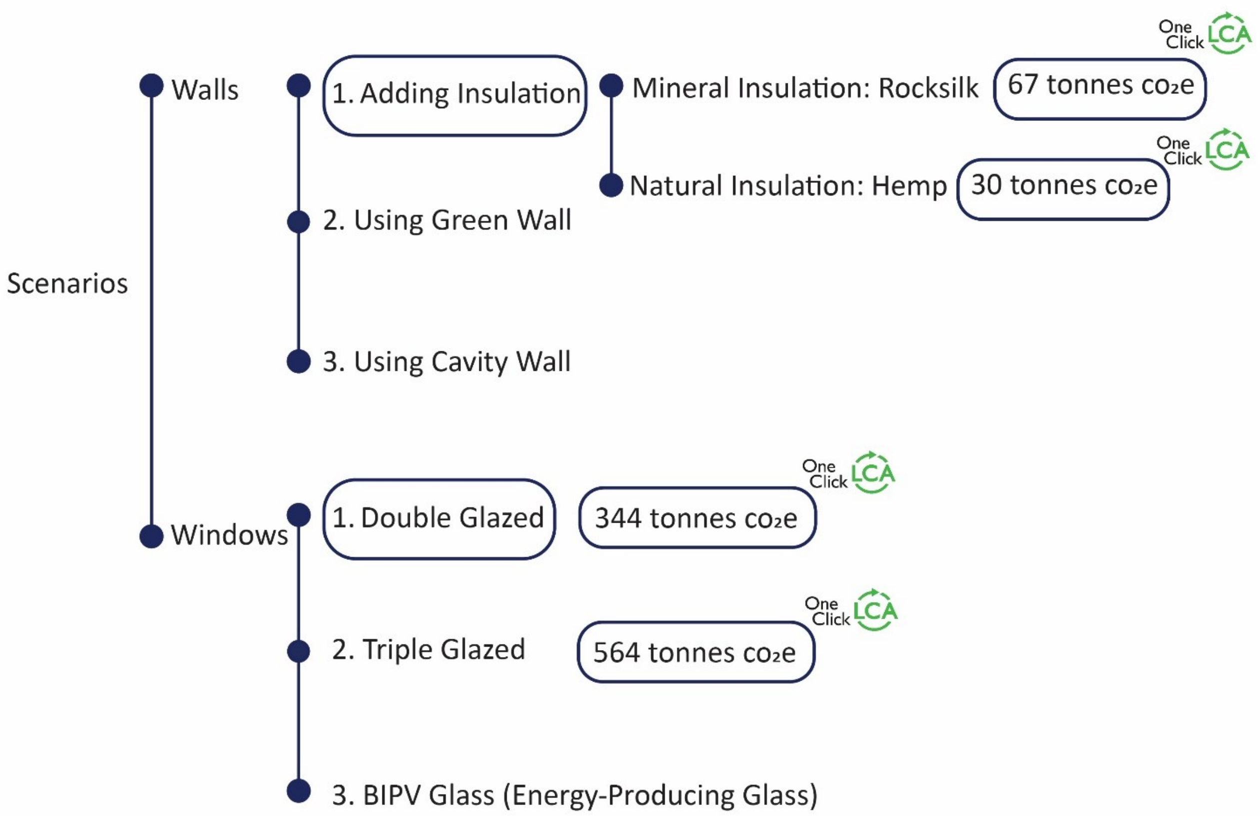


Figure 108 - One Click LCA assessment of wall and window design scenarios shows the tonnes CO_2e

3.2 LCC Result

Based on the results of the Life Cycle Cost (LCC) analysis, Solution 2, which includes rocksilk insulation and tripple glazed windows, is found to be more cost-effective over the 40-year analysis period compared to Solution 1, which uses hemp insulation and double glazed windows. Although tripple glazed windows are more expensive upfront than double glazed ones, the decisive factor influencing the outcome is the insulation material.

Initially, one might expect Solution 1 to be cheaper due to the lower cost of double glazing. However, the hemp insulation not only has a higher initial cost than rocksilk, but it also requires a full replacement at year 40, as its service life does not exceed the analysis period. In contrast, rocksilk insulation is both less expensive and more durable, requiring no replacement within the 40-year lifespan, as supported by technical standards and product datasheets.

This replacement cost of hemp insulation, discounted to present value, adds over €800,000 to Solution 1's total LCC, making it the more expensive option overall. Therefore, Solution 2 emerges as the better-performing solution in economic terms, and this outcome highlights the critical importance of accounting for long-term durability and maintenance when selecting building materials.

This was an important and somewhat unexpected result of the analysis; initially, the cost advantage of using hemp insulation was assumed, but the necessity of its full replacement changed the outcome significantly.

Figure 109 presents a simplified Life Cycle Assessment (LCA) comparison between two alternative building envelope configurations in terms of their embodied carbon emissions:

- Solution 1 combines natural insulation (hemp) with double-glazed windows, resulting in an embodied carbon impact of 10 kg CO_2e/m^2.
- Solution 2 uses mineral insulation (Rocksilk) along with triple-glazed windows, producing a higher impact of 15 kg CO_2e/m^2.

The results suggest that Solution 1 is environmentally preferable, largely due to the use of bio-based insulation materials (like hemp), which tend to have lower embodied carbon and sometimes even carbon-negative properties during growth. On the other hand, mineral wool and triple glazing, although often better in thermal performance, come with higher embodied emissions due to more intensive manufacturing processes

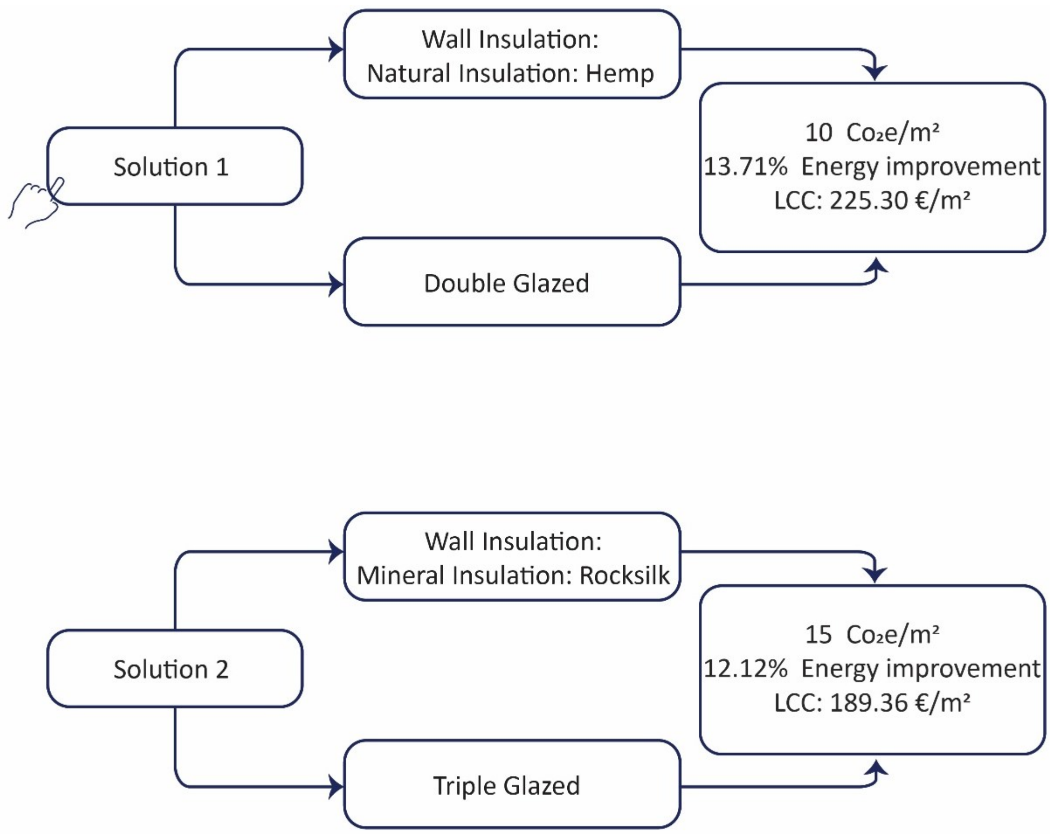


Figure 109 - Comparison of two building envelope solutions using LCA, LCC and energy simulation results: Solution 1 compared to Solution 2

3.3 BEM Result

As shown in the figure, the existing building has an annual energy consumption of 369.07 kWh/m²·year. After implementing the façade retrofit design alternatives, both solutions significantly reduce energy demand:

- Solution 1, which includes hemp insulation and double-glazed windows, reduces consumption to 318.46 kWh/m²·year, achieving an absolute improvement of 50.61 kWh/m²·year which is 13.71%.
- Solution 2, featuring rocksilk insulation and triple-glazed windows, results in 324.34 kWh/m²·year, corresponding to a savings of 44.73 kWh/m²·year which is 12.12 %.

Although Solution 1 provides slightly greater energy savings, Solution 2 may be more attractive from a financial standpoint, as shown in the LCC and payback analyses. Both solutions, however, demonstrate a substantial performance improvement over the existing envelope, confirming the effectiveness of the BIM-integrated design approach for energy efficiency decision-making.

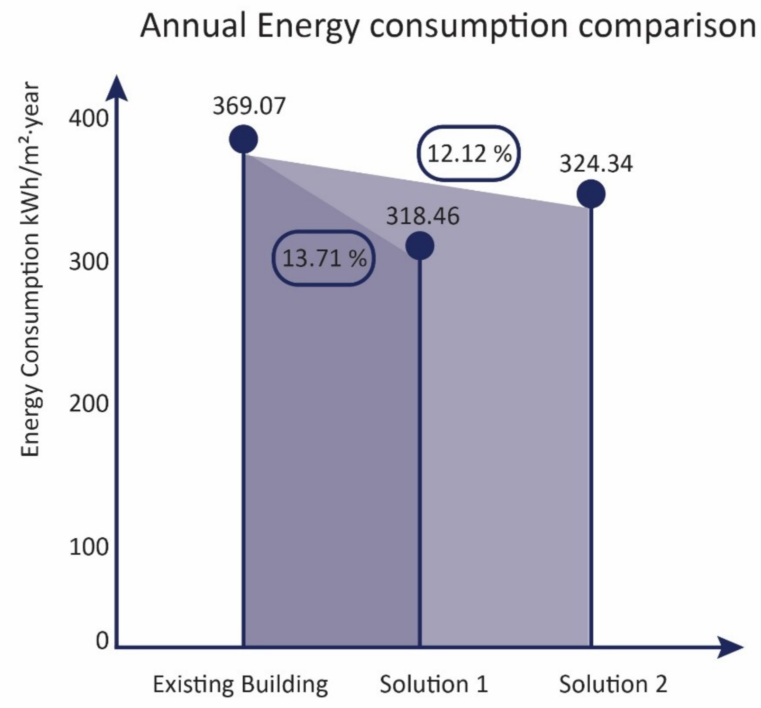


Figure 110 - Annual energy consumption comparison

3.4 Visualization:

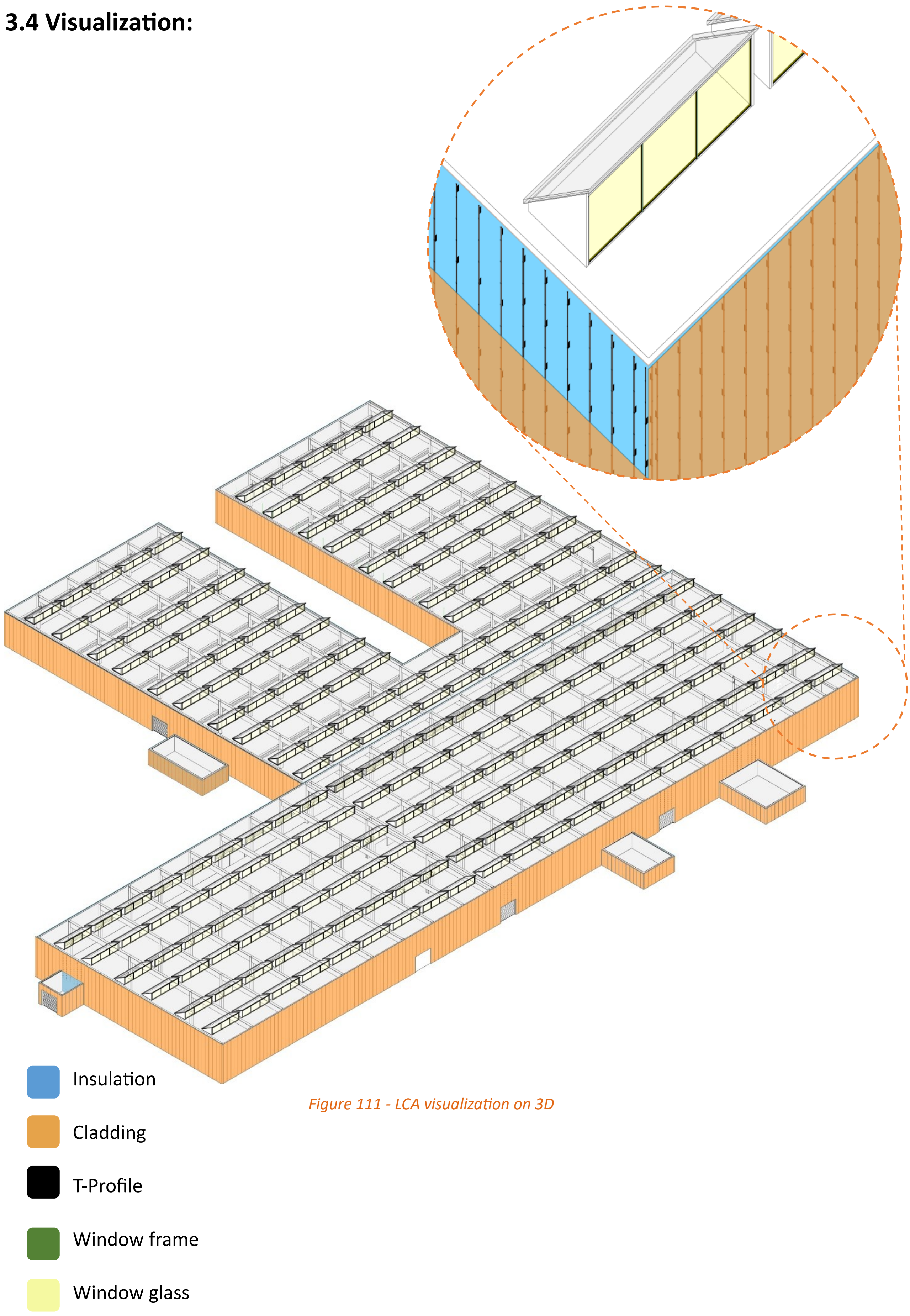


Figure 111 - LCA visualization on 3D

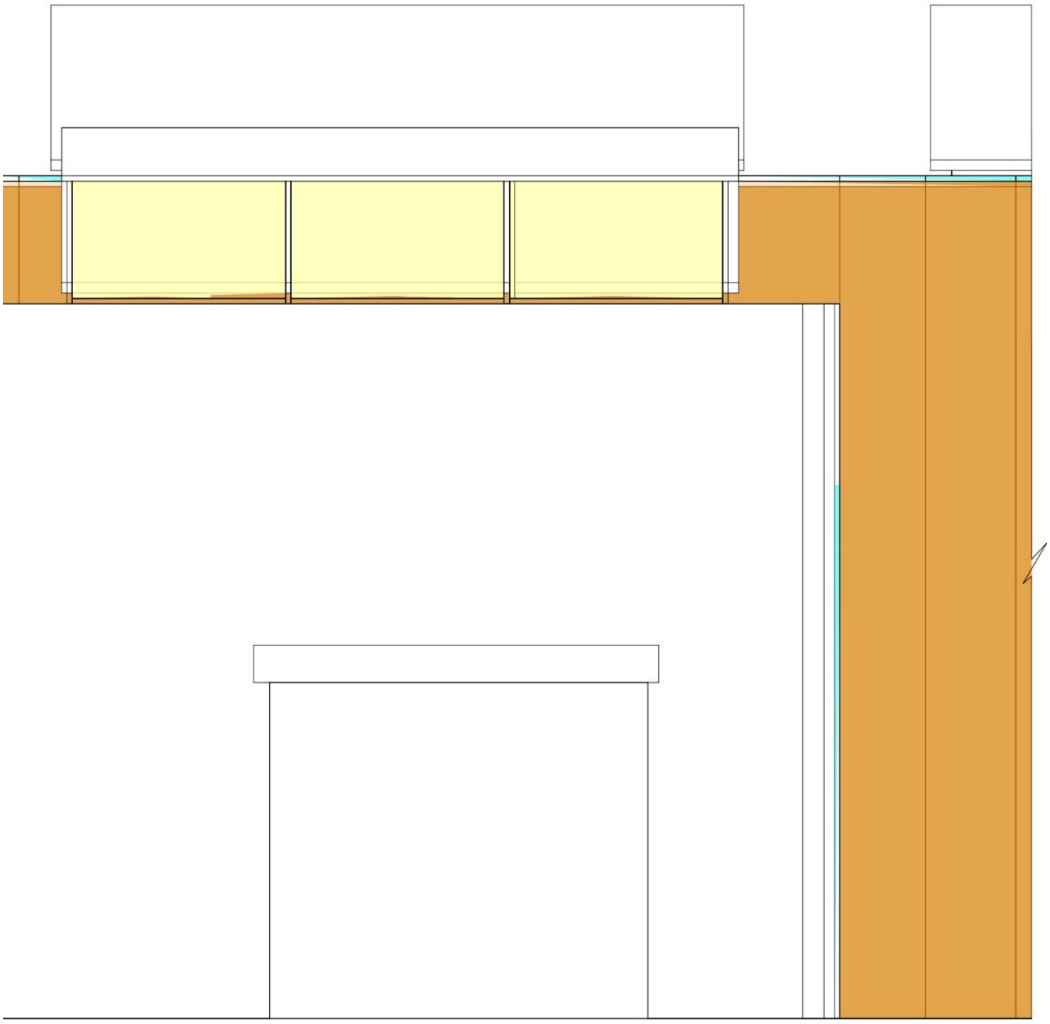


Figure 112 - LCC Visualization on Section

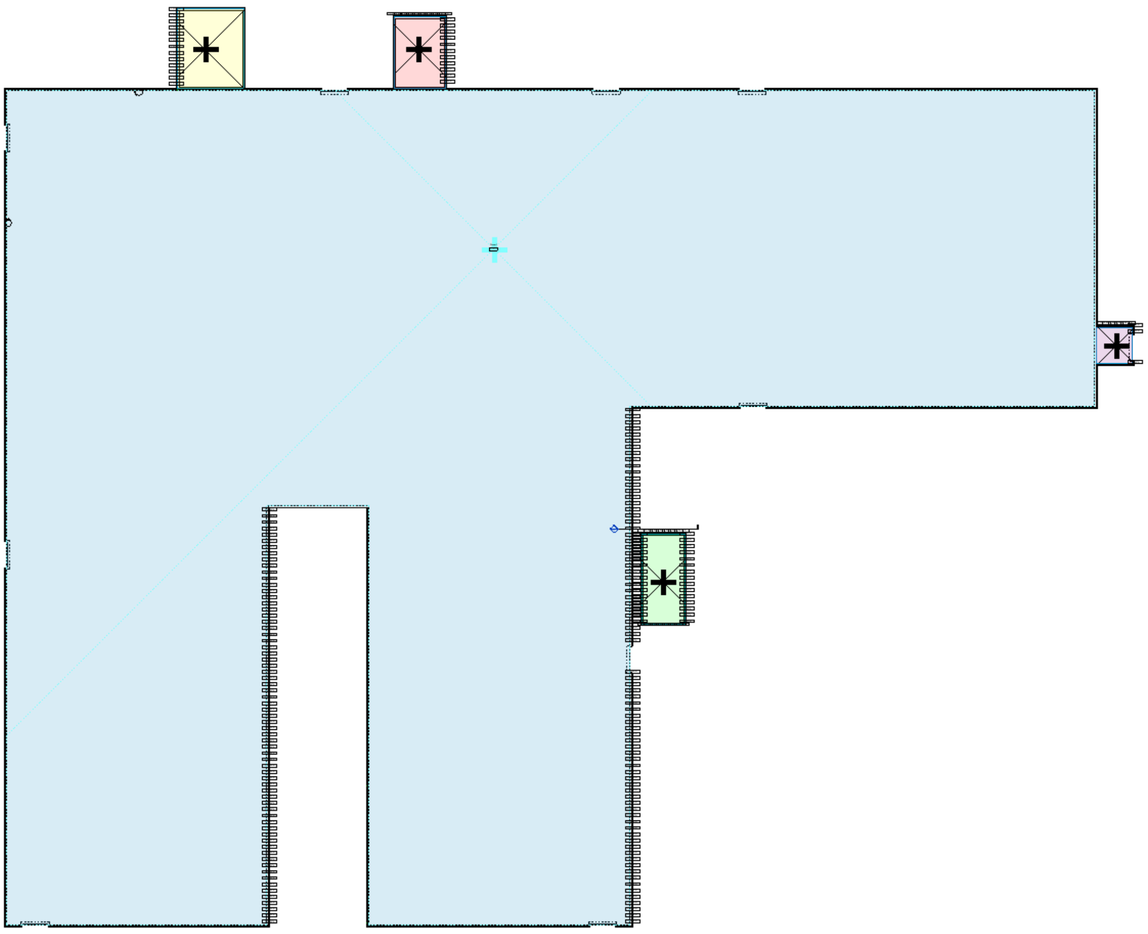
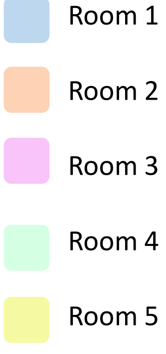


Figure 113 - BEM Visualization on the Plan



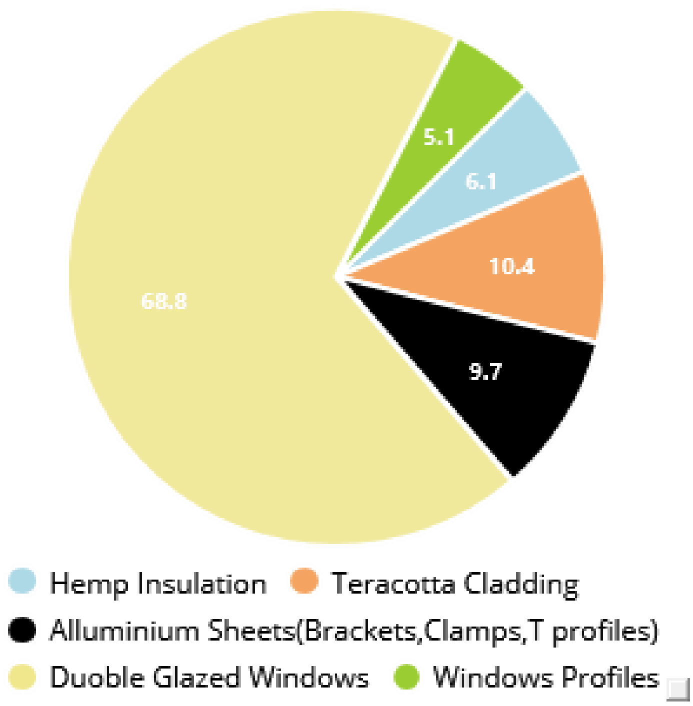


Figure 115 - LCA solution 1

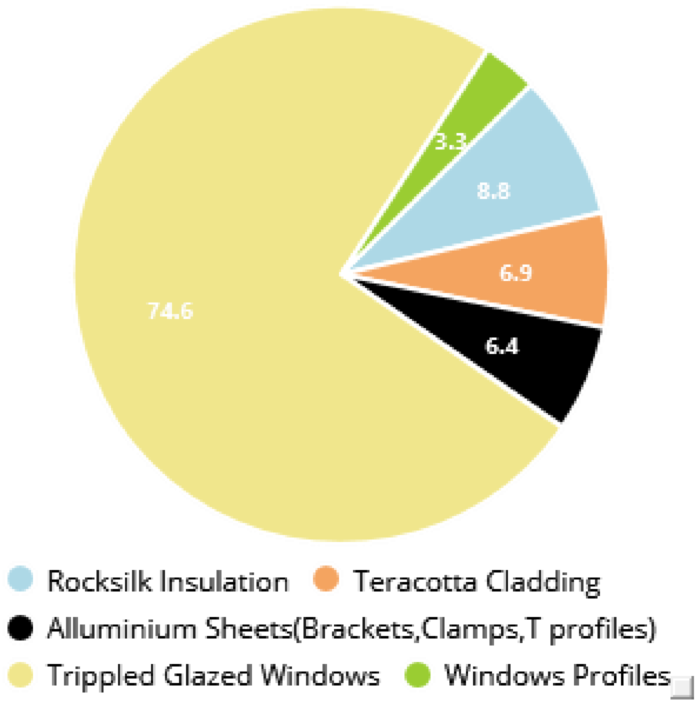


Figure 114 - LCA Solution 2

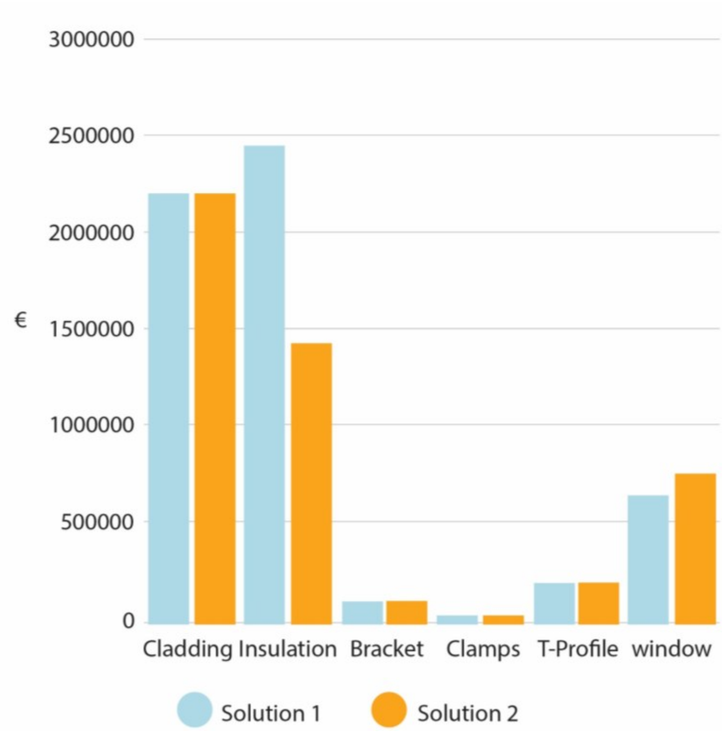


Figure 116 - LCC comparison between solution 1 and solution 2

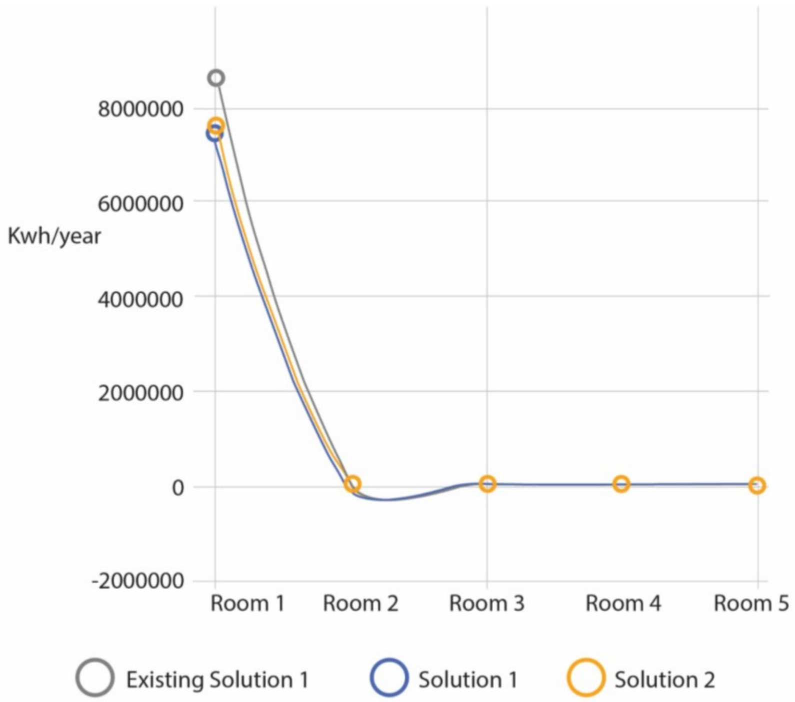


Figure 117 - BEM comparison between solution 1 and solution 2

CHAPTER 4

CONCLUSION

Chapter 4: Conclusion

In response to the urgent need for sustainable solutions in the construction and manufacturing sectors—industries collectively responsible for over 36% of global energy consumption and 39% of CO_2 emissions—this thesis developed an integrated and replicable Digital Twin (DT) framework. By incorporating Building Information Modeling (BIM), Building Energy Modeling (BEM), Life Cycle Assessment (LCA), and Life Cycle Costing (LCC), the study proposed a comprehensive methodology for evaluating and optimizing industrial retrofit strategies. Through the case study of the San Benigno Plastic Factory in Ivrea, Italy, the research addressed current limitations in fragmented sustainability assessments and demonstrated a scalable approach aligned with Industry 5.0 and the European Green Deal.

The primary contribution of this research lies in the development of a reliable and interoperable BIM-based workflow that integrates BEM, LCA, and LCC. Utilizing tools such as Revit, DesignBuilder, One Click LCA, Revit plugins (Diroots) and Dynamo, the methodology enabled accurate energy simulations, environmental impact assessments, and long-term cost evaluations within a single digital environment. Despite some challenges in data interoperability, such as issues with gbXML exports, the research successfully minimized model duplication through standardized data structures and formats for LCA and LCC model.

By applying this integrated methodology to various retrofit scenarios involving wall systems (adding insulation, green walls, cavity walls) and glazing types (double, triple, and BIPV), the study provided a detailed analysis of the Compromises between environmental impact and economic viability. Life Cycle Assessment revealed that material production phases (A1–A3) were responsible for over 90% of total embodied carbon emissions, with insulation materials and glazing systems emerging as environmental hotspots. While hemp insulation and double glazing (Solution 1) yielded the lowest emissions at 10 kg CO_2e/m^2, mineral insulation and triple glazing (Solution 2) offered a more favorable life cycle cost (€4.73M vs. €5.63M). These findings underscore the importance of integrating LCA and LCC into early design stages to make balanced and informed decisions.

Furthermore, the thesis addressed the question of whether a single BIM model can reliably support BEM, LCA, and LCC without redundant data inputs. The results indicate that while a single BIM model can effectively support LCA and LCC analyses, a separate model is required for BEM. This is due to limitations in gbXML export and DesignBuilder, which only recognize single-layer wall assemblies, whereas the retrofit scenarios involve additional insulation layers. As a result, BEM simulations must be conducted using a modified model that reflects these layered configurations. Dynamo scripts and Revit plugins (Diroots) enabled data extraction and transformation across platforms, facilitating optimized interoperability. This demonstrates the potential for reducing fragmentation in sustainability assessments and advancing the practicality of integrated digital workflows.

Lastly, while the research did not directly implement human-centric adaptations within the factory context, it aligns with Industry 5.0 principles by indirectly supporting human-oriented decision-making. Through scenario analysis combining LCA and LCC, the framework facilitates more transparent and accessible evaluations, enabling designers, engineers, and policymakers to make informed, balanced choices. The use of live feedback mechanisms and interoperable tools further enhances the usability of the Digital Twin environment, laying the groundwork for more collaborative and user-aware applications in future implementations.

4.1 Future Research Directions

Future research should explore the integration of Digital Twin and dynamic LCA (Life Cycle Assessment) frameworks to overcome the limitations of current static approaches. Traditional LCA practices often overlook the temporal variations in building performance, leading to incomplete sustainability insights. Combining Digital Twin technology with dynamic LCA can offer real-time, context-sensitive data for more accurate and adaptive assessments. As Fnais et al. (2022) and Strelets et al. (2023) suggest, this integration enables continuous monitoring and simulation throughout the building's life cycle, facilitating proactive decision-making. Further research could specifically investigate applications in industrial contexts, such as enhancing the sustainability of factory elements like the roof, floor, and interior components, aligned with the vision of a Digital Twin Factory.

In parallel, there is a pressing need to develop automated tools for conducting LCA and LCC (Life Cycle Costing) within BIM (Building Information Modeling) environments. Manual data handling remains a significant barrier due to its time-consuming and error-prone nature. As Memon et al. (2021) argue, future work should focus on automating data pipelines that can extract material, geometry, and cost data directly from BIM models, enhancing scalability and reliability. Tools such as gbXML can play a key role in converting Building Energy Models (BEM) back into BIM-compatible formats, allowing a smoother, bidirectional exchange of data. The integration of middleware platforms and real-time plug-ins, as highlighted by Obrecht and Röck (2020), can further support sustainability assessments during the early design and operational stages.

Finally, improving user-centric interfaces is essential for making these tools accessible to a broader range of stakeholders, including architects, engineers, and clients. Current sustainability tools often require specialized expertise, which limits their widespread adoption in day-to-day design workflows. Xu et al. (2022) emphasize the need for intuitive, visually engaging dashboards and streamlined input-output processes to enhance usability. Additionally, future research should investigate how using the full LCC formula in this thesis—considering variables like inflation, discount rates, and operational costs—could affect outcome accuracy. Exploring the impact of accounting for both newly added and pre-existing materials in LCA calculations could also offer a more comprehensive understanding of embodied environmental impacts, leading to more effective sustainability strategies in future projects.

CHAPTER 5

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