Univerza *v Ljubljani*
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FABRIZIA DELLA PENNA

TOWARDS A GREEN DIGITAL TWIN FOR LIFE CYCLE ANALYSIS OF BUILDING'S RENOVATION

KORAKI K ZELENEMU DIGITALNEMU DVOJČKU ZA ANALIZO ŽIVLJENJSKEGA CIKLA PRI PRENOVAH STAVB

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Supervisor:
Assist. Prof. Luka Pajek, PhD

Co-supervisor:
Assoc. Prof. Lavinia Chiara Tagliabue, PhD

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Avtor: **Fabrizia Della Penna**

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Izvleček:

Magistrsko delo predstavlja spremenjeni pristop k trajnostnim gradbenim praksam. Osredotoča se na dve ključni področji: izboljšanje interoperabilnosti med programoma Autodesk Revit in One Click LCA ter izvajanje dinamične analize življenjskega cikla (DLCA). Na področju interoperabilnosti študija poenostavlja izmenjavo podatkov med načrtovalskimi orodji in orodji za analizo okoljskega vpliva, kar bistveno izboljša prepoznavanje materialov in avtomatizira procese. Standardno poimenovanje in inovativna orodja, kot so skripte Dynamo, omogočajo povezave med okoljskimi deklaracijami izdelkov (EPD) in modelom v realnem času in zagotavljajo posodobljene informacije. Čeprav je v modelu nekaj ročnih sprememb še vedno potrebnih, so prednosti v natančnosti in učinkovitosti znatne. Poleg tega delo raziskuje DLCA prek teoretičnega okvira za integracijo zelenih digitalnih dvojčkov. Ponuja celosten vpogled v vplive gradbenih materialov skozi celoten njihov življenjski cikel, vključno z nadzorom učinkov v zaprtih prostorih prek sledenja sredstev z uporabo RFID in omrežij LoRa. Študija poudarja tudi pomembnost standardiziranega zbiranja podatkov za gradbene komponente, kar zagotavlja kakovost podatkov in omogoča njihov trajni nadzor. Poleg tega magistrsko delo poudarja pomembnost upoštevanja razvijajočih se energetskih virov pri analizah življenjskega cikla. Dokazuje, kako lahko upoštevanje morebitnih sprememb v energetski mešanici vpliva na rezultate analize življenjskega cikla. V raziskavi je uporaba predstavljenih konceptov prikazana na primeru študije Casa del Capitano, obnovljene zgodovinske stavbe v Veroni, kar ilustrira izvedljivost uvedbe inovativnih pristopov v realnih scenarijih.

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BIBLIOGRAPHIC– DOKUMENTALISTIC INFORMATION AND ABSTRACT

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Author: **Fabrizia Della Penna**

Supervisor: **Assist. Prof. Luka Pajek, PhD**

Cosupervisor: **Assoc. Prof. Lavinia Chiara Tagliabue, PhD**

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Abstract:

This thesis presents a transformative approach to sustainable construction practices. It focuses on two core aspects: enhancing interoperability between Autodesk Revit and One Click LCA and implementing Dynamic Life Cycle Assessment (DLCA) analysis. In the interoperability domain, the study streamlines data exchange between design and LCA tools, significantly improving material recognition and automating processes. Standardized naming conventions and innovative tools like Dynamo scripts facilitate real-time links between Environmental Product Declarations (EPDs) and the model, ensuring up-to-date information. While some manual intervention remains necessary, the benefits in precision and efficiency are substantial. Furthermore, this work explores DLCA through a theoretical framework for the integration of Green Digital Twins. It provides a holistic view of building material impacts throughout their lifecycle, including indoor performance monitoring via RFID-based asset tracking and LoRa networks. The study also emphasizes the significance of standardized data collection for building components, ensuring data quality and enabling ongoing monitoring. Additionally, the thesis underscores the need to consider evolving energy sources in LCA studies. It demonstrates how accounting for potential shifts in the energy mix can impact LCA analysis results. This research culminates in applying these concepts to the case study of Casa del Capitano, a rehabilitated historical building in Verona, illustrating the feasibility of implementing these innovative approaches in real-world scenarios.

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LIST OF ACRONYMS AND ABBREVIATIONS

ADP	Automatic Data Processing
AEC	Architecture, Engineering, and Construction
AI	Artificial Intelligence
ASTM	American Society for Testing and Materials
BEP	BIM Execution Plan
BIM	Building Information Modeling
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
CAD	Computer-Aided Design
CFC	Chlorofluorocarbon
CHP	Combined Heat and Power
CO	Carbon Monoxide
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)
DLCA	Dynamic Lifecycle Assessment
DLT	Distributed Ledger Technology
DT	Digital Twin
EN	European Standard
EPD	Environmental Product Declaration
EU	European Union
GBC	Green Building Council
GBCA	Green Building Council of Australia
GBCSA	Green Building Council of South Africa
GBRS	Green Building Rating Systems
GHG	Greenhouse Gas
GPI	General Programme Instructions
GW	Gigawatt
GWP	Global Warming Potential
IEA	International Energy Agency
IFC	Industry Foundation Class
ILFI	International Living Future Institute
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
IWBI	International WELL Building Institute
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory

LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LEED	Leadership in Energy and Environmental Design
LPWAN	Low Power Wide Area Network
MJ	Megajoule
ML	Machine Learning
NASA	National Aeronautics and Space Administration
NECP	National Energy and Climate Plan
PCR	Product Category Rules
PEF	Product Environmental Footprint
PO	Program Operator
PV	Photovoltaic
REP	Renewable Energy Potential
RFID	Radio-Frequency Identification
SETAC	Society of Environmental Toxicology and Chemistry
USGBC	U.S. Green Building Council
UV	Ultraviolet
VOC	Volatile Organic Compound
WELL	Water and Energy for Life

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1 INTRODUCTION

1.1 Global Warming, Climate Change, and Europe 2030–2050

One of the most controversial and broadly discussed topics of the last decades is, without any doubt, climate change. This phenomenon describes long-term changes in temperature and weather patterns that are mainly brought about by human activity, such as burning fossil fuels and deforestation. Understanding of climate change and its potential consequences has been built upon extensive scientific research and observations. An authoritative source on the subject, the Intergovernmental Panel on Climate Change (IPCC), has offered thorough analyses of the causes and effects of climate change. Concerns about climate change include rising global temperatures, rising sea levels, extreme weather events, and ecosystem disturbances. These changes pose significant risks to human health, food security, water resources, and economic stability. To reduce the severity of climate change's effects, immediate action must be taken to cut greenhouse gas emissions, adapt to the changing environment, and switch to sustainable activities (Romero et al., 2023). Especially in recent years, due to the increase in population and the shift of human habits to a consumeristic way of life in all the more developed countries, the emissions are rising even more and reaching worrying levels that we have never seen before, as shown in Figure 1 (NASA, 2022).

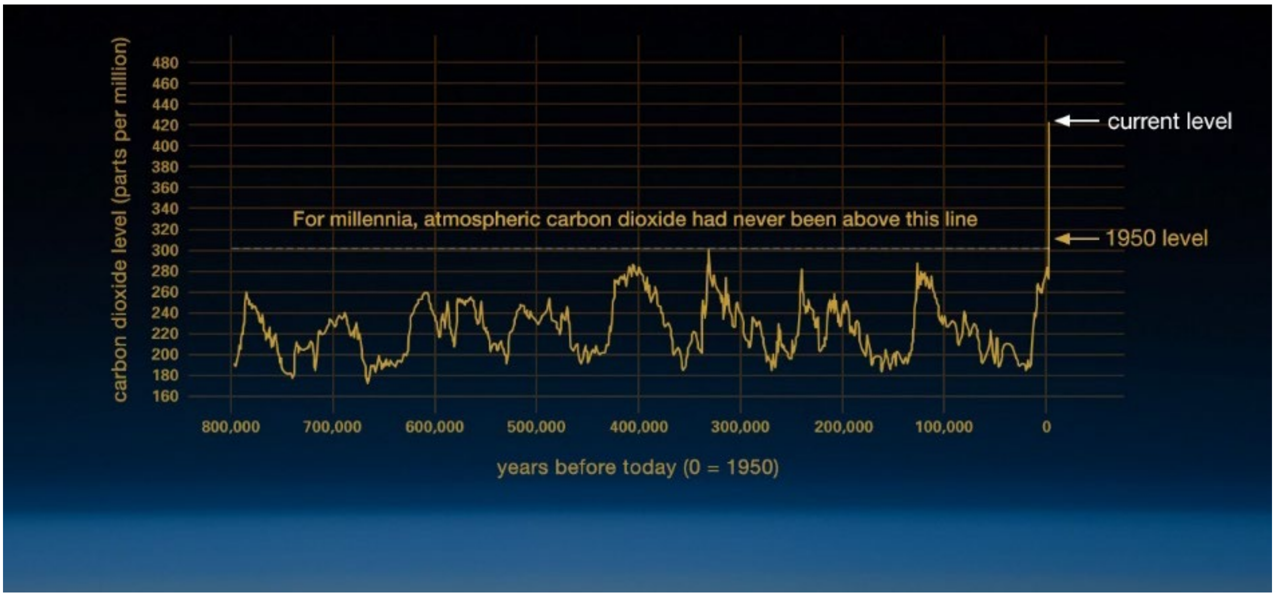


Figure 1 - Carbon dioxide emissions through history (https://climate.nasa.gov/evidence/)

For this reason, all the world's politicians are trying to take action and promote new rules to fight this trend. In Europe, two significant resolutions have been adopted to address this challenge: the Europe 2030 and 2050 resolutions. (EU, 2019) The Europe 2030 resolution sets ambitious targets for reducing greenhouse gas emissions by 55% compared to 1990 levels, increasing the share of renewable energy to 32%, and improving energy efficiency by 32.5%. Based on this, the Europe 2050 resolution aims for Europe to become the world's first climate-neutral continent. It targets net-zero greenhouse gas emissions by 2050 through comprehensive strategies that integrate various sectors and prioritize sustainability. These resolutions (Figure 2) highlight

Europe's commitment to combatting climate change and transitioning to a sustainable future and go under the name of the European Green Deal (EU, 2019).

Figure 2 - European Green Deal Infographic (https://euinasean.eu/eu-green-deal/)

1.2 Building sector and carbon emissions

While essential for societal development, the construction industry significantly contributes to environmental pollution. Construction activities generate various forms of pollution, including air pollution, water pollution, and waste generation. These pollutants arise from material extraction, manufacturing, transportation, on-site construction, and demolition. Air pollution from construction sites is mainly caused by dust, particulate matter, and emissions from machinery and vehicles. Water pollution can occur due to inadequate sediment control measures, improper disposal of construction waste, and the release of chemicals into water bodies. Construction waste, including packaging materials, excess materials, and demolition debris, contributes to landfill accumulation (GhaffarianHoseini, 2018).

The AEC (Architecture, Engineering and Construction) industry plays a significant role in global carbon emissions, accounting for approximately 39% of the total. Within this sector, operational emissions, which include energy use during the lifetime of buildings, have been a primary focus for emissions reduction efforts, constituting 28% of the total emissions. However, with operational emissions showing signs of improvement, attention is shifting towards embodied emissions, which account for 11% and arise from material production and construction processes. The growing importance of embodied emissions is attributed to advancements in operational efficiency: producing new, environmentally-friendly materials tends to be more resource-intensive. To address this issue, it is crucial to evaluate the materials used in construction carefully. Life Cycle Assessments (LCA) and Environmental Product Declarations (EPDs) are essential tools in assessing the environmental impact of materials throughout their life cycle. These tools are evolving in the market and gaining importance as they provide valuable information for making informed decisions about sustainable construction practices (One Click LCA Academy, 2023a).

1.3 Existing buildings and refurbishment

Our society is aware of the ecological impact of our construction, but, at the same time, these new structures are necessary for adjusting to the new needs of an increasing population. For this reason, an alternative approach to the endless construction of new buildings is recognizing the limitations and embracing the concept of energy efficiency in renovating existing structures, particularly historical buildings. This perspective requires proactive management of cities' historical heritage to optimize their energy and environmental performance. Especially in Europe, where the cities are usually composed of a very typical and different historical centre depending on the region, with a significant cultural value, this perspective has gained even more importance, because not only is a good choice under the energy saving point of view but can preserve the peculiar characteristic of the buildings. It is becoming fundamental not to deny the potential for sustainable development in old buildings and to encourage it, aiming to revive the allure of old urban centres and promote professional practices that are increasingly capable and tailored to the unique historical aspects of each building (World Business Council for Sustainable Development, 2007).

In this regard, the 5R (i.e., Refurbish, Reduce, Replace, Reuse, Require) rule, shown in Figure 3 provides a valuable framework for improving the sector's sustainability practices (One Click LCA Academy, 2023b). The first of these Rs, refurbishment, emerges as a primary principle with the potential to reduce emissions and positively transform the industry's environmental footprint. By recognizing the inherent value and potential within already-built environments, refurbishment minimizes the need for resource-intensive new construction. This approach aligns with the broader principles of circular economy, which emphasize optimizing the use of existing resources rather than depleting them. Building new structures entails various carbon-intensive processes, such as manufacturing construction materials, transportation, and on-site construction activities. In contrast, refurbishing structures often require fewer raw materials and mitigates the associated emissions by reusing and repurposing existing components. Refurbishment reduces the carbon footprint of new construction, harnessing the existing infrastructure. Moreover, older buildings often lack modern insulation, energy-efficient systems, and sustainable design elements. Through thoughtful renovation and retrofitting, these structures can be upgraded to meet higher environmental standards, reducing energy consumption and dependence on fossil fuels. Enhancing energy efficiency contributes to emission reductions and has economic advantages by lowering operational costs for building owners and occupants. The refurbishment also fosters the preservation of cultural heritage and community identity. Many older structures hold historical and architectural significance, representing the community's collective memory and cultural heritage. Refurbishing these buildings ensures their continued existence, maintaining a tangible link to the past while meeting society's present and future needs. This preservation and adaptive reuse of existing structures promote sustainable development and foster a sense of place and identity.

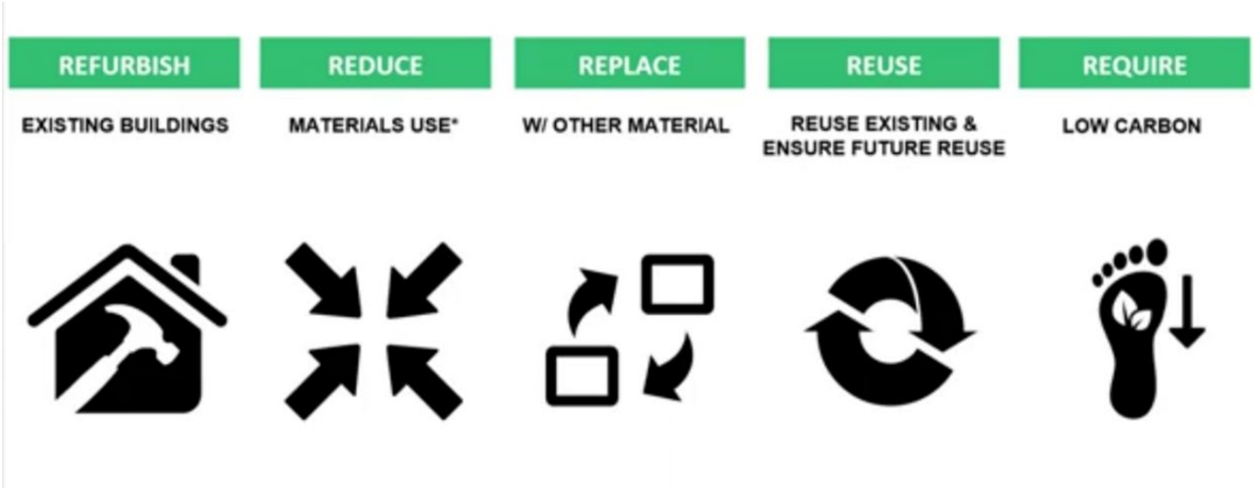


Figure 3 - 5 Rs (One Click LCA Academy)

Nevertheless, in this case, we cannot just focus on the energy performance of the building during its use, but the careful selection of environmentally conscious materials holds great significance. Embracing sustainable materials not only helps reduce the ecological footprint but also promotes resource efficiency. Opting for eco-friendly alternatives involves considering factors such as the materials' origins, manufacturing processes, energy consumption, recyclability, and overall environmental impact. By prioritizing durability and long-lasting materials, the need for frequent replacements can be minimized, consequently reducing waste generation. Embracing sustainable materials paves the way for a more resilient and environmentally friendly approach to building rehabilitation (Qualharini et al., 2019).

1.4 Knowledge gap and goals of this dissertation

This thesis aims to perform a systematic literature review and address several questions regarding integrating Building Information Modelling (BIM) with Life Cycle Assessment (LCA) tools to improve the seamless collaboration of these tools. The key questions this thesis seeks to answer are as follows:

1- BIM and LCA Interoperability:

- How effective is integrating BIM and LCA tools for assessing the environmental impact of construction projects, including building rehabilitation, to enhance sustainability in construction practices?
- What are the main strengths and weaknesses in integrating BIM and LCA tools, and how can the process be optimized for effortless data exchange and automation?

2- Transformation into a Green Digital Twin:

- Which methodologies and technologies facilitate real-time monitoring of building materials throughout their lifecycle, enabling the implementation of a Green Digital Twin concept and contributing to a comprehensive understanding of their environmental impact?
- Is it possible to transform the BIM-LCA model into a dynamic digital twin and how might the consideration of dynamic data, such as shifts in energy mix, influence the accuracy and reliability of LCA results, and what strategies can be employed to integrate this aspect effectively?

Therefore, this work explores the potential of integrating BIM with LCA tools to support environmentally-conscious decision-making, promote sustainable practices in the construction industry, and open the way for a more sustainable future.

The dissertation is divided into four main sections: the first contains the theoretical background, explaining the main concepts, such as BIM, LCA and Green Digital Twins, supported by a careful literature review of the last research conducted in these ambits. After this theoretical introduction, the workflow and methods used in the thesis are explained, referring to the practical programmes and tools used. Besides, the section explains the methodologies developed and the expected results. Furthermore, in the next part the methodology was applied to a real case study, "Casa del Capitano", to expose potential strengths, weaknesses, and outcomes. In conclusion, the results and all the paths taken are discussed, including the problems and solutions found during the process.

2 THEORETICAL BACKGROUND

The subsequent sections provide an elaborate and comprehensive literature review, investigating and explaining the core concepts. This thorough examination is enhanced by incorporating cutting-edge research and studies, ensuring a comprehensive understanding of the subject matter.

2.1 Life cycle assessment

Life Cycle Assessment (LCA) is a widely used methodology for assessing the environmental impacts of a product, process, or service throughout its entire life cycle, from raw material extraction to final disposal (Fnais et al., 2022). It provides a systematic approach to quantify and evaluate the environmental burdens associated with different stages of a product's life, including resource extraction, manufacturing, use, and end-of-life processes. To assess the overall environmental performance, LCA considers various environmental indicators such as energy consumption, greenhouse gas emissions, water usage, and waste generation. By considering the complete life cycle, LCA enables decision-makers to identify areas of improvement and make informed choices to reduce the environmental impact of products and systems. The use of LCA in assessing environmental impacts has been applied to diverse sectors, including building and construction, agriculture, energy systems, transportation, and waste management, among others. Its widespread adoption and standardization in research and industry, such as the guidelines set by the International Organization for Standardization (ISO 14040:2006 and ISO 14044:2006) and the guidelines provided by the Society of Environmental Toxicology and Chemistry (SETAC, 1993), have contributed to a more comprehensive understanding of the environmental implications of various products and systems.

2.1.1 LCA of construction materials

LCA is a crucial tool for lowering the overall environmental impact of buildings and offers insights into the upstream and downstream trade-offs related to environmental pressures, human health and wellbeing, and the use of natural resources. By offering essential data on the environmental performance of buildings, LCA can help policymaking (Fnais et al., 2022).

The application of LCA in the construction industry offers several benefits and opportunities. Firstly, it helps achieve certification credits, such as green building certifications, by providing a comprehensive analysis of the environmental impacts of a building throughout its life cycle. Secondly, LCA assists decision-making processes by enabling comparisons between different designs or materials, considering their life cycle impacts. It promotes carbon awareness, enhancing transparency and understanding of the environmental consequences associated with construction activities. Moreover, LCA can be utilized to regulate and assess the life cycle or material impacts of projects, guiding sustainable practices and mitigating environmental harm. LCA also plays a role in awarding competition prizes based on the environmental performance of designs or projects. Lastly, it can support the building and planning permission process by evaluating the environmental aspects of proposed constructions. Overall, integrating LCA into construction practices fosters sustainability and responsible resource management (One Click LCA Academy, 2023b).

According to ISO14040 (International Organization for Standardization (ISO), 2006), the LCA process typically begins with a goal and scope definition, where the objectives and boundaries of the assessment are established. This includes specifying the functional unit, system boundaries, and impact categories to be considered. The next phase involves data collection, where relevant information on materials, energy consumption, and transportation is gathered. After this, the inventory analysis is conducted, where the collected data is organized and quantified in terms of the inputs and outputs associated with the building works. Once the analysis is complete, the impact assessment phase begins. It is possible to use various impact assessment methods to assess the environmental impacts across multiple categories, including climate change, resource depletion, and human health. These impact assessment methods convert the inventory data into environmental indicators, allowing for a comprehensive evaluation of the building's sustainability performance. Finally, interpreting results is crucial for understanding the findings of the LCA study. This allows stakeholders to identify areas of improvement, prioritize sustainable design choices, and make informed decisions during the construction process.

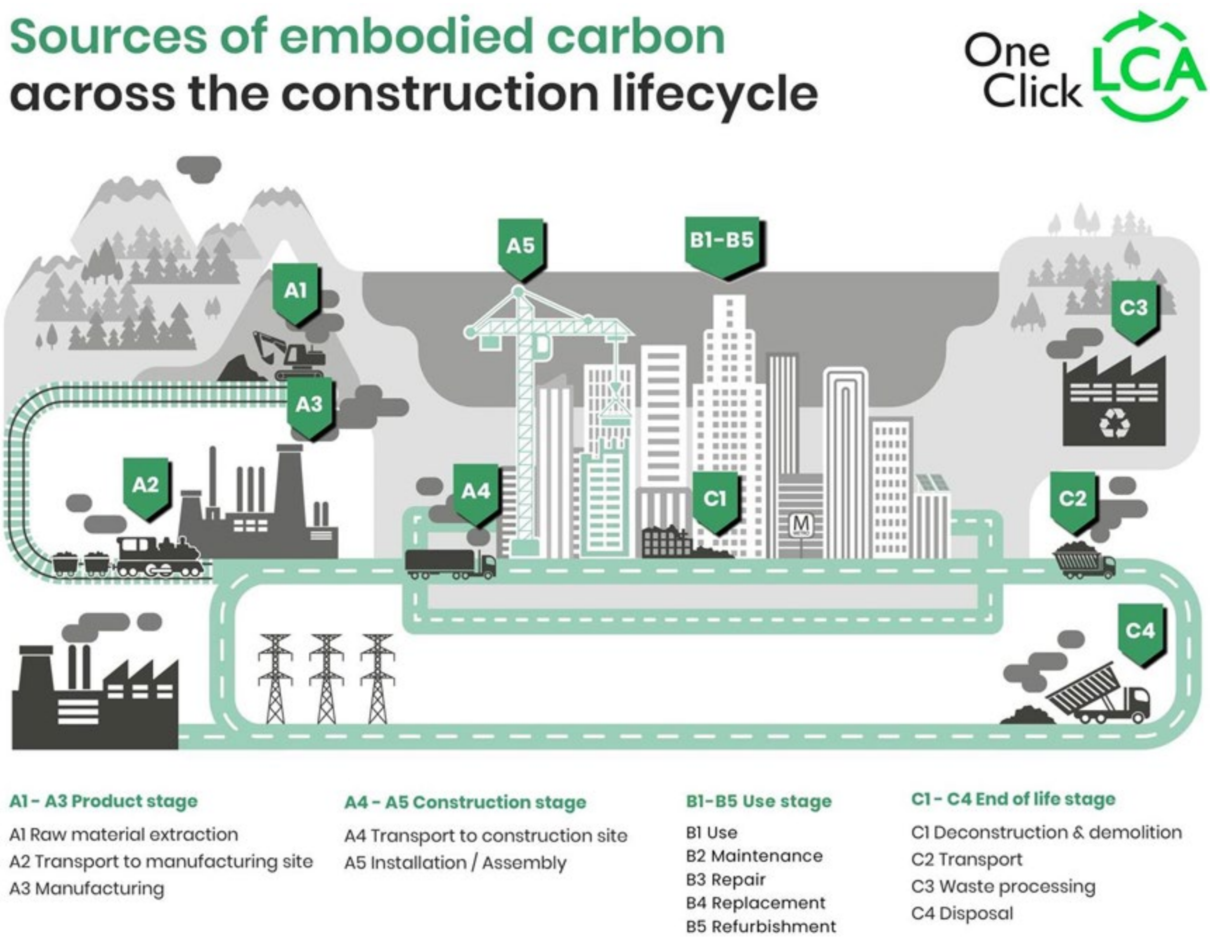


Figure 4 - Embodied carbon sources divided by phases (One Click LCA Academy)

The life cycle of a building, analysed through LCA, consists of several distinct phases encompassing its entire lifespan, as seen in Figure 4 (One Click LCA Academy, 2023b).

These phases typically include:

1. Extraction and transportation of raw materials: This stage entails the extraction and transportation of raw materials, including steel, concrete, and insulation, that will be utilized to build the building.

2. Manufacturing and construction: During this stage, raw materials are turned into building components and processed to create the finished structure.

3. Use and operation: This phase covers the building's lifespan in use, including energy use, maintenance tasks, and any repairs or upgrades that may be required.

4. End of life: The building is demolished, dismantled, or renovated after its useful life. Waste management, material recycling, and safe disposal of any hazardous items are all part of this phase.

These phases are divided into categories indicated by a letter and a number, to categorize and recognize them easily. From A1 to A3, we have the Product Stage, consisting of three stages, where the emission values are sourced directly from EPDs:

▪A1: Raw material extraction/supply;

▪A2: Transport to manufacturing site;

▪A3: Manufacturing.

Stages A4 to A5, related to the Construction Process, include all impacts and aspects related to any fluxes and losses during production, transport, waste processing and the disposal of lost products and materials.

▪A4 stage includes environmental impacts from the transport to the construction site;

▪A5 stage includes the environmental impact of the installation/assembly of the building;

Neither of these life-cycle stages is mandatory in EPDs, so they are often calculated separately.

The Use Stage phases (B1-B7) are not mandatory in some cases and could be challenging to estimate as not all have existing methodologies which allow them to be assessed accurately. They are divided into:

▪B1 impacts include the use or application of installed products (for ex. refrigerants);

▪B2 impacts include maintenance;

▪B3 impacts include repair;

▪B4 impacts include replacement;

▪B5 impacts include refurbishment (often grouped with B4);

▪B6 impacts include operational energy usage (heating, ventilating, cooling, services);

▪B7 impacts include operational water use.

C1 to C4, End of life stages are emissions which happen after and during the building or asset is demolished. The emissions of these stages depend heavily on how materials are handled during this phase. Under the old standard EN15804-A1, C1-C4 data was not mandatory in EPDs. The majority of them did not have data on these stages. However, under the new EN15804:A2 end of life data will become mandatory. End-of-life stages are:

▪C1 emissions include those related to demolition and deconstruction;

▪C2 emissions include the transport of the materials to the waste reprocessing centre or disposal;

▪C3 emissions include waste processing;

▪C4 emissions include waste disposal.

Benefits and loads beyond the system boundary are treated in Stage D, as it includes the reuse, recovery and or recycling potentials. These are expressed as net impacts and benefits. Stage D is often an additional module not included in the totals of the life cycle assessment. Module D allows supplementary information beyond the building lifecycle to be considered and is consistent with a Cradle-to-Cradle approach (One Click LCA Academy, 2023b). All these phases are schematized in the following Figure 5.

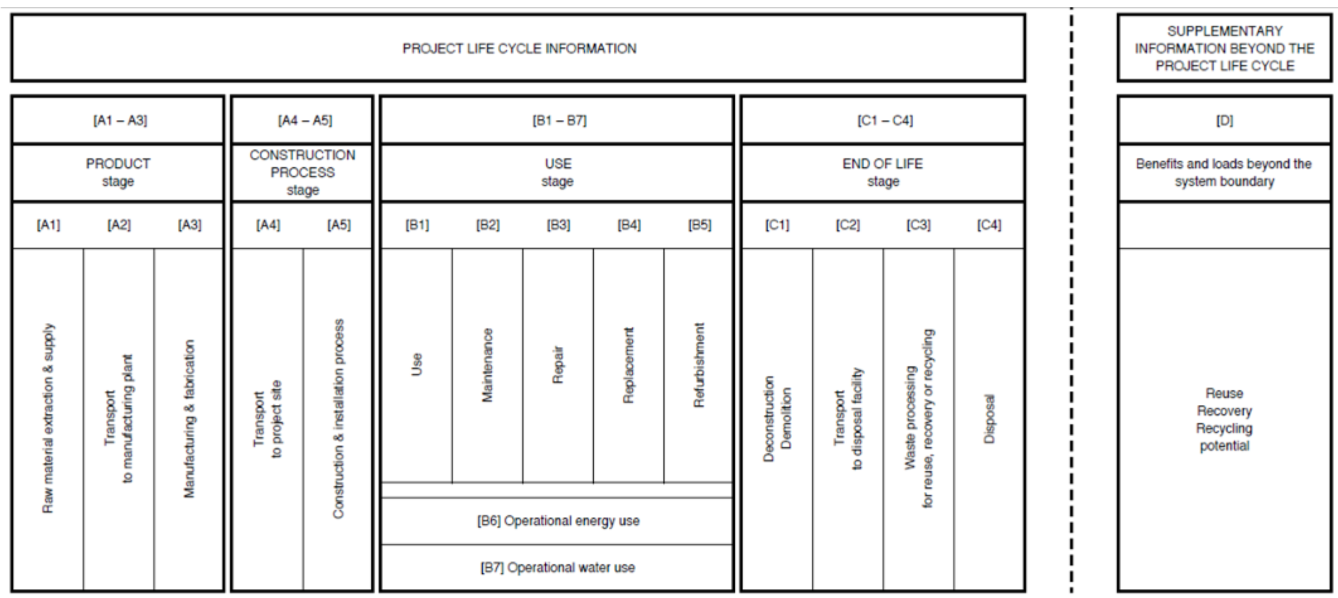


Figure 5 – A to D stages (One Click LCA Academy)

2.1.2 EPD of materials

An Environmental Product Declaration (EPD) is a standardized, independently verified summary of the environmental impact of a product throughout its lifecycle, from raw material extraction to manufacturing, use, and disposal, done through LCA. The EPD includes information about energy consumption, greenhouse gas emissions, resource depletion, and other environmental indicators. It can be compared to a nutrition label of food, as in Figure 6. Their importance comes from comparing different products to assist purchasers and users in making informed choices.

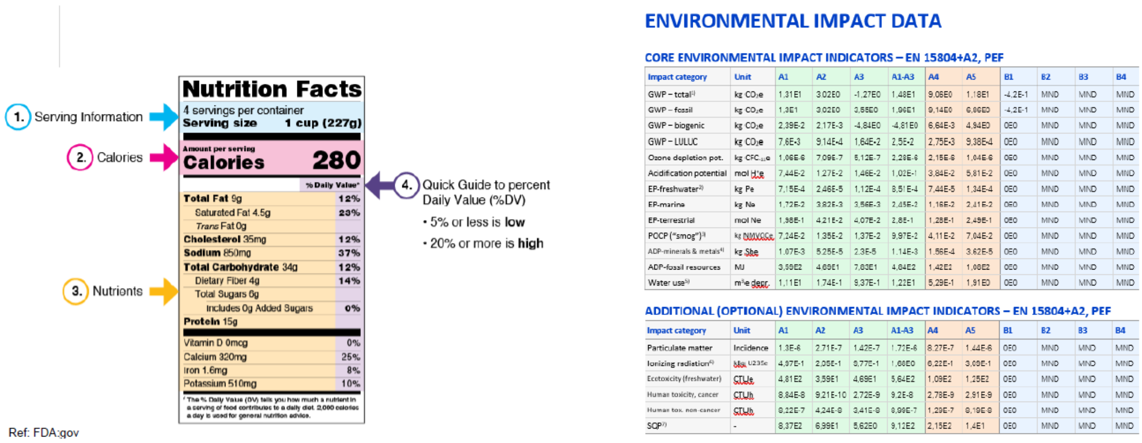


Figure 6 – Comparison between Nutrition label of food and EPD of construction materials (One Click LCA Academy)

EPDs were first developed with comparability in mind, but their primary use was to determine scores for various certification programs, such as the Leadership in Energy and Environmental Design (LEED) rating. However, new initiatives from various governments and LEED support the concept of EPD comparability. As a result, producers and users can benefit from comparing EPD and industry-average outcomes. Construction materials stakeholders are encouraged by the present trend of EPD comparison to consider a robust approach for a reliable and consistent evaluation of various materials. According to several types of research, inconsistencies in the LCA methodology, poorly defined functional units, impact categories, and cut-off rules make EPD approaches problematic. Additionally, a survey analysis revealed that the top worries of LCA practitioners when adopting EPD results are comparability and methodological difficulties. For this reason, Product Category Rules (PCRs) for various construction materials in a specific geographical context have been created and utilized to provide a framework for calculating the potential environmental consequences of construction materials (AzariJafari et al., 2021).

According to ISO 14040:2006, product category rules (PCRs) establish the standards for a particular product category and specify the criteria to be met when developing an environmental product declaration (EPD) for a product. These rules may also be used for the LCA of any product falling within the category. With the help of this set of guidelines, it will be possible to compare products fairly and present LCA results that have been independently confirmed. The Program Operator (PO) is the platform through which EPDs are made available to the public. POs play a crucial role in developing General Programme Instructions (GPI) and Product Category Rules (PCR), which provide the guidelines and requirements for creating EPDs. They are responsible for accrediting independent verifiers who assess and verify the accuracy and compliance of the EPDs. Furthermore, POs maintain a public library or database where stakeholders can access and review all registered EPDs (AzariJafari et al., 2021). Unfortunately, any PO is often an unregulated term with no prequalification procedure or oversight and is free to develop PCRs. As a result of this lack of restrictions, there are more and more overlapping PCRs with inconsistencies between similar products using different rules for their EPDs, such as different LCA methodologies or reporting. To ensure consistency in the quality and information types required by PCRs, a European Standard EN 15804 has been created, and updated to EN 15804 +A2 in 2020 (Gelowitz & McArthur, 2017).

These changes bring the EPDs closer to the "Product Environmental Footprint (PEF)" standard set by the European Commission. The PEF is a new approach and standard that the EU has introduced. It will direct organizations to conduct more accurate environmental measures and seek to level the playing field for all EU country members. This implies that there has to be a closer alignment between the building industries of all EU states following the hierarchy shown in Figure 7.

Figure 7 – Structure of accounting principles and standards (One Click LCA Academy)

In summary, to ensure clarity and adherence to established standards, the publication of an Environmental Product Declaration (EPD) requires compliance with the General Programme Instructions (GPI) and Product Category Rules (PCR). These guidelines outline the requirements and methodologies for conducting a comprehensive Life Cycle Assessment (LCA) of construction materials. Additionally, the verification of EPDs must be carried out by independent third-party entities approved by the Program Operator (PO). This rigorous process guarantees the credibility and reliability of the EPD information, enabling stakeholders to make informed decisions based on transparent and comparable environmental performance data. Figure 8 shows the six steps to create an EPD, considering all the rules and standards to ensure it is valuable and reliable.

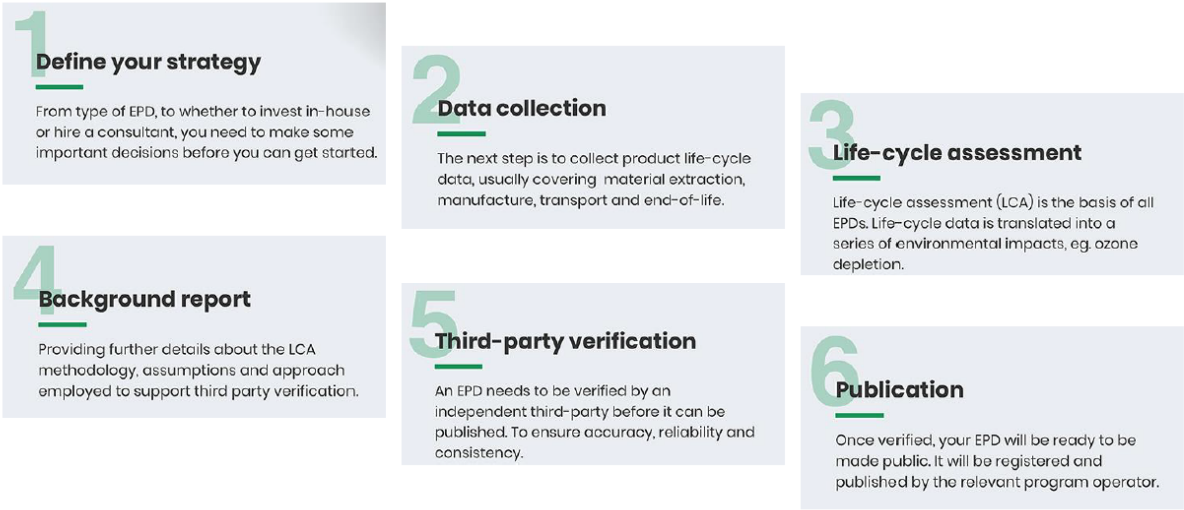


Figure 8 – Steps to create EPD (One Click LCA Academy)

2.1.3 Certifications

Since the 1990s, Green Building Rating Systems (GBRSs) have been created to analyse the environmental performance of buildings using similar assessment methodologies that address factors such as energy consumption, indoor environmental quality, water efficiency, waste management, and material use. Integrating Life Cycle Assessment (LCA) and Environmental Product Declarations (EPDs) into major sustainability certifications, such as LEED (LEED Rating System | U.S. Green Building Council), WELL (WELL - International WELL Building Institute | IWBI), DGNB (German Sustainable Building Council | DGNB GmbH) and Levels (Level(s)), has driven sustainable development. These certifications allocate points based on LCA and EPD criteria, providing a framework to evaluate and reward environmentally conscious practices. Including some of the most renowned, we have LEED, which focuses on energy efficiency, water conservation, indoor environmental quality, and material selection. The WELL Building Standard prioritizes occupant health and well-being through factors like air quality, lighting, and thermal comfort. The Levels certification system evaluates building performance in energy, water, waste, and materials. In all of them, LCA serves as a tool to assess a building's environmental impact throughout its life cycle, considering energy consumption, emissions, resource depletion, and waste generation (Abdelaal et al., 2022). EPDs offer standardized information about a product's environmental performance, facilitating the selection of low-impact materials. Schemes like LEED, BREEAM (BREEAM - BRE Group), and DGNB give credits for specifying products with accompanying EPDs. This is easier and more cost-efficient when compared with achieving other credit requirements. These certifications are crucial in driving sustainable building practices, transforming markets, engaging stakeholders, and promoting informed decision-making. By integrating LCA and EPDs, these certifications enhance environmental performance assessment, support continuous improvement, and contribute to developing more sustainable built environments. Table 1 shows the most common Certification Systems, with their characteristics and the correlation with LCA procedure and the presence of materials with EPDs.

Table 1 - Certification Comparison

Certification	Foundation/Organization	Country	Main Focus	LCA Linked	EPD Credits	Assessment Methodology
LEED (LEED Rating System | U.S. Green Building Council)	U.S. Green Building Council (USGBC)	USA	Energy efficiency and sustainability	Yes	Yes	Utilizes a credit-based scoring system and specific categories
WELL (WELL - International WELL Building Institute | IWBI)	International WELL Building Institute (IWBI)	USA	Occupant well-being and health	No	No	Focuses on indoor environmental quality and people
Living Building Challenge (Living Building Challenge Basics - International Living Future Institute)	International Living Future Institute (ILFI)	USA	Net-zero energy, healthy materials	Yes	Yes	Requires annual performance results and rigorous standards
Green Star (GBCSA)	Green Building Council of Australia (GBCA)	Australia	Sustainability and environmental performance	No	Yes	Utilizes a rating system based on various criteria
BREEAM (BREEAM - BRE Group)	Building Research Establishment (BRE)	UK	Environmental sustainability and performance	Yes	Yes	Evaluates multiple aspects of building performance
DGNB (German Sustainable Building Council | DGNB GmbH)	German Sustainable Building Council	Germany	Sustainability and environmental impact	Yes	No	Focuses on a holistic approach to building assessment
Protocollo Itaca and Green Building Council Italia (GBC Italia)	Green Building Council Italia (GBC Italia)	Italy	Sustainability and energy efficiency	Yes	No	Evaluates buildings based on environmental and energy criteria

In this work will be used the Level(s) certification to assess different indicators of LCA analysis. Level(s) is not included in the table because it is a framework adopted by the European Commission and not a separate certification by itself. It provides a common language and indicators for assessing the sustainable performance of buildings throughout their life cycle. It was developed to fulfil this need and provide an easy, accessible, and consistent way for European construction specialists to gauge, report, and share the environmental performance of their buildings. Level(s) adopt a fully life-cycle-based perspective, which is its most significant strength. By considering a building's performance throughout its entire life cycle, from conception to demolition or refurbishment, it ensures decisions are made with a focus on long-term sustainability. It encourages the implementation of circular economy principles, emphasizing the need for sustainable practices from inception to end-of-life. Level(s) offers a cost-free framework with a concise set of indicators encompassing the fundamental aspects of a building's sustainability. By providing clear priorities for building performance and standardized criteria for new and refurbished constructions, it establishes a universal language collaboratively crafted with the building sector. This common approach facilitates seamless communication among stakeholders across Europe (European Commission, 2021). The categories analysed by the Level(s) certification, in compliance with EN 15978, in this case, are the ones listed in Table 2:

Table 2 – Specific Level(s) parameters

Environmental effect	Symbol	Unit	Description
Global Warming Potential	GWP_{100}	$(kgCO_{2eq})$	Measures the increase of the concentration of greenhouse gas in the atmosphere
Biogenic Carbon Storage		$(kgCO_{2eq}$ bio)	Carbon that is stored in biological materials, such as plants or soil. Bio-based products can contribute to reducing the levels of carbon dioxide in the atmosphere
Ozone Depletion	ODP	$(kgCFC_{11eq})$	Depletion of the stratospheric ozone layer increases the sun's UV-A and UV-B radiation, impacting fauna and flora
Acidification	AP	$(kgSO_{2eq})$	Measures the rate of water acidification, increasing the occurrence of "acid rain"
Eutrophication	EP	(gO_{2eq}/t)	Increase of plants in delicate ecosystems caused by unbalanced amounts of nutrients
Formation of Ozone Lower Atmosphere	POCP	$(gC_2H_{4\,eq}/t)$	Impact the generation of toxic smog and causing damage to the respiratory system
Abiotic Depletion Potential (ADP-elements) For non-fossil resources		$(kgSb_{eq})$	Over-extraction of minerals and other non-living, non-renewable materials can lead to the exhaustion of natural resources
Abiotic Depletion Potential (ADP-fossil fuels) For fossil resources		MJ	Removal of abiotic resources from the earth, or the depletion of non-living natural resources

2.2 BIM and LCA

2.2.1 BIM

BIM, which stands for Building Information Modelling, is a digital technology and methodology used in the architecture, engineering, and construction (AEC) industry. It involves creating and managing a comprehensive virtual representation of a building or infrastructure project. At its core, BIM is a collaborative process that allows various project stakeholders, such as architects, engineers, contractors, and facility managers, to work together in a coordinated manner using a shared digital model. This model contains information about the physical and functional characteristics of the project, including geometry, spatial relationships, materials, quantities, and performance data. BIM goes beyond traditional 2D drawings by incorporating 3D modelling and intelligent data attributes. Through specialized software, BIM enables the creation of a parametric model, where changes made to one aspect of the model automatically update other related elements. BIM's dynamic and interconnected nature enhances communication, coordination, and decision-making throughout the project lifecycle.

The benefits of BIM include improved visualization and simulation capabilities, enhanced coordination and clash detection, better project cost estimation and scheduling, and the ability to perform various analyses, such as energy performance simulations and structural analysis. BIM also supports facilities management, as the model can be utilized for asset management, maintenance planning, and renovation projects. By centralizing project information and facilitating collaboration, BIM streamlines workflows, reduces errors and rework, and improves overall project efficiency. It provides a platform for integrated project delivery and supports sustainable design and construction practices.

Due to various factors, BIM is experiencing a growing trend in adoption and significance within the construction industry This rise in prominence has resulted in increasingly stringent legal requirements regarding the obligatory utilization of BIM technology, as well as the establishment of standards governing its implementation. Consequently, there is a substantial demand for professionals capable of effectively engaging with this innovative approach, leading to numerous new domains where BIM can be applied (Obrecht et al., 2020).

2.2.2 Using BIM tools in LCA

Integrating BIM and LCA delivers both challenges and opportunities for improving sustainability outcomes in the built environment. LCA analysis can be enhanced in several ways utilizing BIM technology, which provides a comprehensive digital representation of a building's design, construction, and operation. Firstly, BIM enables the collecting and management of accurate and detailed information about building materials, components, and systems. This information can be utilized to perform more precise LCA calculations, considering the environmental impacts of resource extraction, manufacturing, transportation, and end-of-life scenarios. Secondly, BIM facilitates the visualization and simulation of building performance, allowing designers and stakeholders to assess the environmental implications of design alternatives. This helps identify opportunities for optimizing energy efficiency, reducing material waste, and minimizing the overall environmental footprint during the life cycle of the building. Furthermore, BIM provides a collaborative platform for interdisciplinary teams to exchange data and knowledge, promoting better decision-making and communication. By integrating LCA data into the BIM model, project stakeholders can have a holistic understanding of the environmental consequences of design choices and make informed decisions prioritising sustainability (Obrecht et al., 2020). However, integrating BIM and LCA also presents challenges, including the need for standardized data formats, interoperability between software platforms, and the accurate allocation of environmental impacts to individual building elements within the BIM model. In conclusion, integrating BIM and LCA offers significant potential for improving sustainability in the built environment. BIM technology provides valuable support for LCA analysis by enabling accurate data management, performance visualization, and interdisciplinary collaboration. Overcoming the challenges associated with this integration can lead to more informed decision-making, optimized design solutions, and, ultimately, more sustainable buildings (Safari & AzariJafari, 2021). Integrating BIM and LCA in the context of sustainable construction practices has led to the development of various software applications. These applications play a crucial role in seamlessly incorporating environmental considerations into the design and construction processes. Prominent BIM tools such as Autodesk Revit, ArchiCAD, and Bentley MicroStation are widely used to create and manage digital building models. These BIM platforms facilitate the storing and retrieving relevant data required for LCA calculations, thereby establishing a foundation for comprehensive environmental analysis. Dedicated LCA software tools are employed to perform detailed life cycle assessments and evaluate the environmental impacts of building materials, energy consumption, and other factors. Examples of popular LCA software applications include SimaPro, GaBi, and OpenLCA, Figure 9.

Figure 9 – More Common LCA Analysis Tools (Google Images)

These tools offer specialized functionalities and databases that support accurate and standardized LCA calculations, allowing professionals to quantify and assess the environmental performance of various design options. Moreover, specific plugins or extensions have been developed to bridge the gap between BIM and LCA software. These plugins, such as Tally or OneClickLCA, facilitate the seamless data exchange between BIM models and LCA calculations. By integrating these plugins into existing BIM software, practitioners can streamline the integration process, enabling more efficient and effective analysis of sustainability measures. The availability and utilization of these software applications contribute significantly to the advancement and practical implementation of BIM-LCA integration. They enhance the accessibility, accuracy, and timeliness of sustainability assessments, empowering professionals to make informed decisions and optimize environmental performance throughout the entire construction lifecycle. As the field of sustainable construction continues to evolve, these software applications play a vital role in supporting research, innovation, and the adoption of environmentally conscious practices.

2.2.3 One Click LCA

This thesis will focus on the One Click LCA plugin in Revit. This plugin allows the easy and almost automatic passage of data and quantities from the Revit model to the OneClickLCA platform online, which allows one to perform LCA analysis quickly and clearly.

One Click LCA offers a range of features that contribute to its effectiveness in supporting sustainable construction practices. Firstly, the software provides comprehensive tools for each phase of the project, encompassing strategic planning, design, and construction. This ensures that sustainability considerations are integrated throughout the entire project lifecycle. Additionally, One Click LCA boasts a vast global database comprising over 100,000 data sets and 40 certifications. This extensive collection of information enables users to access accurate and up-to-date data, facilitating informed decision-making regarding materials, energy consumption, and environmental impacts. The software's user-friendly interface and seamless integrations with commonly used tools enhance usability and ease of implementation. This allows professionals to easily incorporate this tool into their existing workflows without significant disruptions or additional learning curves. Furthermore, a dedicated customer support team and a comprehensive help centre with an extensive library of over 200 articles can assist users, ensuring efficient and effective software utilization. It provides advanced indicators and reports tailored to the specific needs of architects, engineers, and green building consultants. These features enable detailed analysis of sustainability metrics, aiding in evaluating and optimising environmental performance. One Click LCA also goes beyond conventional capabilities by allowing the analysis of non-standard materials and facilitating the integration of elements from existing buildings for reuse. This flexibility ensures that various design choices and resource management strategies can be accurately assessed and evaluated. Moreover, the software accounts for the significant end-of-life processes associated with each material subtype, further enhancing the accuracy and reliability of environmental assessments and meeting the new law requirements about these data. Additionally, EPDs generated by One Click LCA consider the reduced greenhouse gas emissions from the utilization of renewable energy sources, while energy mixes are calculated based on consumption data. Overall, the comprehensive features offered by One Click LCA empower professionals to analyze and address sustainability aspects in construction projects effectively. The software's extensive database, ease of use, advanced reporting capabilities, and consideration of non-standard materials and end-of-life processes contribute to its value as a powerful tool for promoting sustainable practices in the construction industry (One Click LCA Academy, 2023b).

In sections 3.1, 3.2 and 3.3 the interaction between the BIM modelling software, Revit, and this LCA tool will be analyzed. It will explain potential problems which may occur in real-case scenarios and how it could be possible to solve them, focusing on the flow of data from the model to the plugin inside Revit and the online platform.

2.3 Green digital twins

2.3.1 Digital Twins

A Digital Twin (DT) refers to a virtual representation of a physical object, such as a building or infrastructure, created by collecting and integrating data from various sources throughout its lifecycle. It is not just a static 3D model or a visualization tool; it is a dynamic entity that continuously updates itself to reflect the current state and behaviour of the physical counterpart. It mimics the physical object's characteristics, properties, and behaviour, enabling real-time monitoring, analysis of performance, and simulation of various scenarios. Digital twins are used in various industries, including manufacturing, healthcare, transportation, and construction. In the construction industry, digital twins are applied to model, simulate, and analyse buildings, infrastructure, and construction projects. They can aid in the design phase, allowing architects and engineers to visualize and test different design options. Digital twins help monitor and manage the project's progress during the construction phase, detect potential issues, and optimize resource allocation. In the operational phase, digital twins provide real-time insights into the performance, maintenance needs, and energy efficiency of the physical asset. The implementation of digital twins in the construction industry is seen as a transformative solution to the challenges faced by the sector. The construction industry is one of the least digitized sectors, but the potential of digital twin technology cannot be understated. By 2030, the volume of construction output is expected to grow by 85% to $15.5 trillion, and full-scale digitalization is predicted to lead to significant cost savings. Digital twin technology can potentially improve safety, efficiency, and sustainability in the construction industry. It can be utilized to test and optimize new ideas and assets before launching them, reducing costs and improving outcomes. Additionally, digital twins provide a platform for augmented and virtual reality views, enabling intuitive, data-rich, and accurate management processes. Digital twins have expanded beyond their original intended purpose of manufacturing and engine design. New technologies such as Artificial Intelligence (AI), Machine Learning (ML), and predictive analytics have further enhanced the capabilities of digital twins. However, there are challenges in building functional digital twins: understanding the best technology options available, acquiring cutting-edge expertise, and addressing data-related issues are areas companies must navigate. Despite these challenges, digital twins have garnered significant interest in academia, with research on the topic skyrocketing. BIM is considered the most efficient path to creating accurate and high-value digital twins. The use of digital twins in the industry is a growing trend, although the number of actual digital twins in operation is still relatively low. Despite the challenges, digital transformation within the construction industry is inevitable. The trend in research and growing confidence in digital twins suggests that efforts should be focused on investing in technology that can generate tangible results. Investment in digital twins is being carried out by companies such as Autodesk, with digital twin technology being used in architecture, engineering, and construction (Saback et al., 2023).

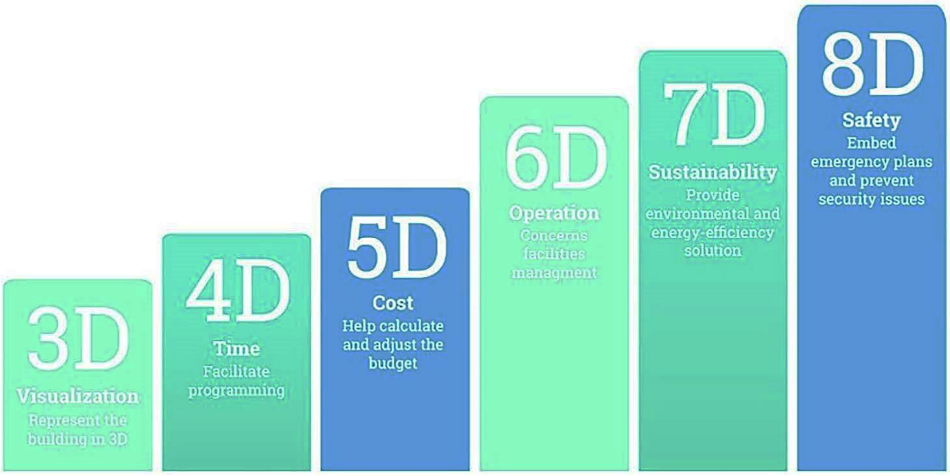


Figure 10 – BIM 3D to 7D (Daniotti et al., 2022)

The evolution from BIM to digital twin in the construction environment involves a shift in the level of detail and data integration (Figure 10). Initially, BIM was used to create 3D models of a building or infrastructure, providing a holistic view of its design and construction phases. However, BIM did not encompass the operational and maintenance aspects of the physical object. Digital twin, on the other hand, incorporates not only design and construction data but also real-time data collected through various sensors and Internet of Things (IoT) devices. This integration allows monitoring and analysis of the object's performance throughout its operational phase. The development of digital twin technology can revolutionize the construction industry by enabling better decision-making, reducing operational costs, improving the quality of construction projects, and enhancing the overall lifecycle management of buildings and infrastructure (Daniotti et al., 2022).

2.3.2 Digital Twins and LCA

The data collected by the sensors and information from the building's digital model constitute a cognitive layer that can also enhance the LCA process and improve the sustainability of building renovation strategies. The digital twin (DT) enables the comparison of actual building behaviour with the ideal model represented in the BIM. Any deviations can be identified, and components requiring intervention or replacement can be pinpointed. For example, increased energy consumption over time may indicate problems with the building envelope or insulation. The cognitive system can suggest replacement options based on cost, energy consumption, or overall LCA impact. The choice of alternative components is informed by an LCA database, which provides up-to-date information on the environmental impact of different technological solutions. The disposal options for replaced components are also factored into the LCA calculation. RFID (Radio-Frequency Identification) tracking technology and blockchain can be utilized to track component disposal and validate their reuse as second-hand materials. Predictive maintenance procedures can be implemented to maintain optimal building performance by detecting deteriorated components before their useful life expires. Integrating green building assessment and LCA evaluation within the DT enhances the sustainability evaluation throughout the building's life cycle. The BIM-based workflow automates the assessment process, utilizing machine-readable EPDs to generate BIM parameters. Artificial intelligence algorithms can recommend different materials and products, and simulations can compare their LCA values. The LCA calculation considers embedded carbon, energy performance, disposal phase, and recyclability of components. This cognitive DT approach offers benefits such as cost-effectiveness, energy savings, and reduced environmental impact for building owners. It can also help public administrations improve their building stock and calculate the environmental benefits of different technological choices (Lavinia Chiara Tagliabue et al., 2023).

BIM and DT act as virtual representations of structures and construction sites, but their scope and purpose differ. Fundamentally, DT is used to track and optimize resource utilization, whereas BIM is used to design and plan. According to the information they collect and offer, each has varying importance at each life cycle stage.

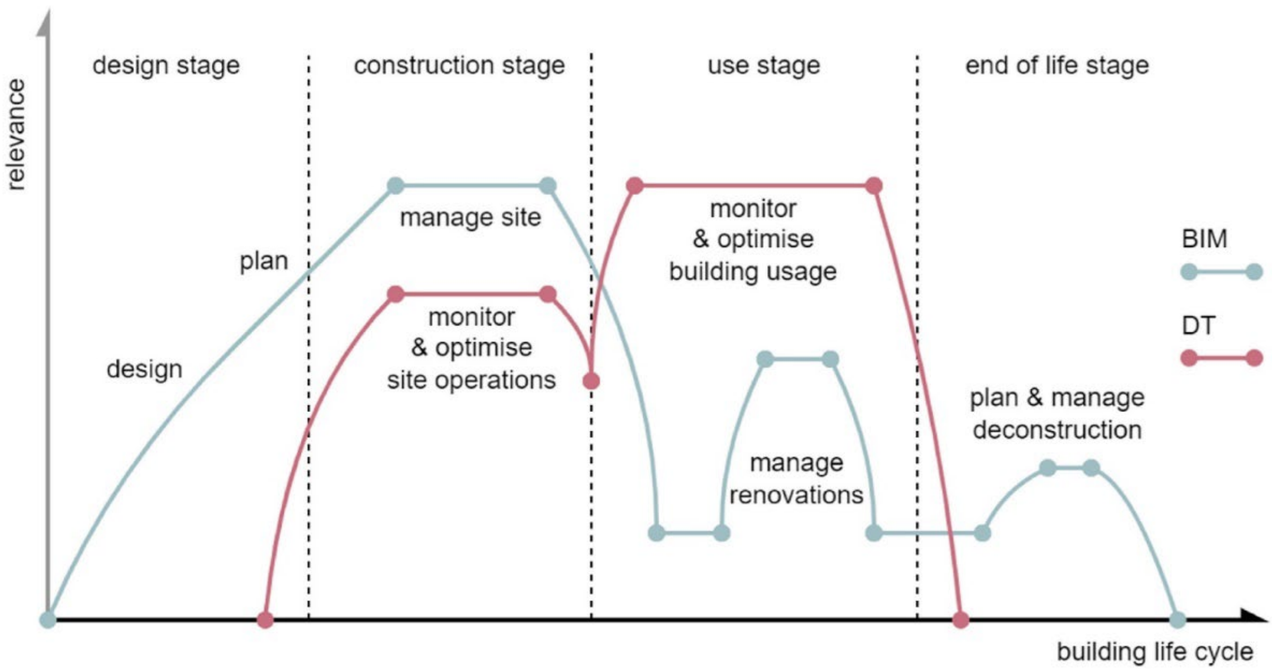


Figure 11 – Use of BIM and DT in the various phases of the project (Boje et al., 2023)

Figure 11 and Figure 12 synthesize as BIM and DT play distinct roles in gathering and utilizing data during the product stage of LCA, with BIM focusing on object-level data integration and DT potentially enabling advanced monitoring and management of product-level information.

According to (Boje et al., 2023), the roles and responsibilities of BIM can be summarized as follows:

- Design: BIM is used to represent the building in 3D, capture architectural features, associate components and materials, and support design processes. It enables accurate quantity take-offs and facilitates sustainability assessments through LCA calculations.
- Plan: 4D BIM defines construction planning, task sequences, phases, and resource allocation. It provides temporal information for lean processes, reducing costs, increasing efficiency, and improving social and environmental impact scores.
- Manage: BIM acts as a reference for construction site managers, guiding material deliveries, task executions, and impacting costs. It can also aid in managing future renovations and eventual deconstruction and demolition processes.
- Gather data (static): BIM accumulates building data throughout its lifecycle, serving as a valuable source of information for various domains.

The roles and responsibilities of the DT can be summarized as follows:

- Monitor: Using sensors, the DT captures real-time data of its physical twin, i.e. a product, construction site, or building. It monitors traffic, weather conditions, working conditions, resource usage, indoor air quality, and occupancy rates. This monitoring enhances socio-economic and environmental scores.
- Validate: The DT captures and stores real-time data about construction and building use, complementing the planned assumptions in BIM. It validates or disconfirms the as-planned assumptions and provides insights into the actual performance of the building.
- Optimize: The DT leverages monitored data and artificial intelligence capabilities to optimize the use of its physical twin. It can predict energy and water usage, plan construction and renovation tasks, and analyze occupancy behaviour, leading to improved resource allocation through optimization techniques.
- Gather data (dynamic): The DT generates valuable insights through accumulated sensed data and experiences of the building across its life cycle. This dynamic data contributes significant value to informed decision-making processes.

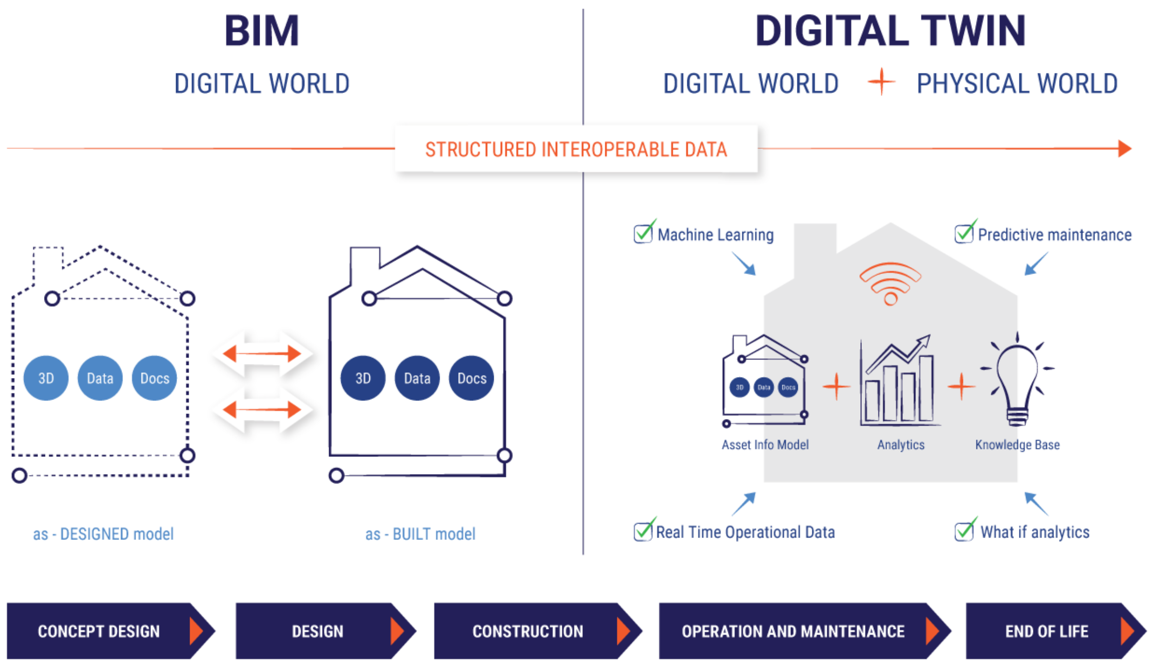


Figure 12 – Differences between BIM and DT (Cobuilder.com)

Table 3 presents the main differences between BIM and Digital Twins in various LCA phases, such as manufacturing, transportation, and beyond. Each technology contributes to better decision-making, real-time monitoring, and overall lifecycle management, ensuring that sustainable practices are effectively integrated at every stage. In detail, these are the roles across different phases:

Table 3 - Use of BIM and DT in the various phases of the project

Stage	BIM Role	DT Role
A1-A3	Used for object-level data gathering, including environmental data for raw materials manufactured on-site. Social data on working conditions can also be considered.	Does not have a role in this stage.
A4	Used to plan site deliveries and estimate costs. Delivery distances are planned, and costs are evaluated.	Tracks and optimizes deliveries, providing real-time data on what was delivered and when. Delivery distances to the site are validated, and costs are re-estimated based on actual events.
A5	Responsible for site planning, management, and regular updates on change management, health and safety measures, deliveries, and costs.	Monitors, validates and optimizes the construction progress, equipment use, working conditions, and their impacts on emissions and human health.

B1	Serves as a repository of as-built data for the building, used as a reference for various applications.	Monitors the indoor environment, including indoor air quality and working conditions, to estimate their impacts on human health and social factors.
B2-B5	Used for design, planning, and management during maintenance, repair, replacement, and refurbishment activities. Old BIM models can be re-used for renovations and changes are monitored and updated.	Monitors and validates renovation progress, working conditions, and factors in noise, comfort, and pollution from new materials.
B6-B7	Serves as a repository of as-built data and is used to create simulations and predictions on energy and water use.	Monitors, validates, and optimizes the energy and water use of the building in real-time, providing data for accurate environmental impact and cost assessments.
C1-C2	Helps plan and manage deconstruction works, simulating costs and efforts for restoration or reuse of components.	Monitors deconstruction site progress, working conditions, emissions of machinery, and social impacts on workers and local communities.
C3-C4	BIM does not play a role in waste processing and disposal.	BIM and DT do not play a role in waste processing and disposal.
D	Provides information on the status and quality of each element/material during its lifecycle.	Record information about the building's components to assist in decision-making for reuse, recovery, and recycling potential.

2.3.3 Static and dynamic LCA

Life cycle assessment is predominantly utilized statically for evaluating the environmental impacts of buildings. The most common approach to LCA is the Static Life Cycle Assessment, which provides a snapshot of a building or infrastructure's environmental impacts at a specific time. It assumes a static situation, where the impacts of material production and use remain constant over time. However, numerous aspects of energy renovation exhibit temporal variations. For this reason, in the last years, another type of approach has gained attention: the Dynamic LCA (DLCA), which takes into account the temporal aspects and changes in building performance and parameters over the project's life cycle. DLCA considers variables such as occupants' behaviour, energy evolution, material degradation, technological advancements, and changes in the electricity mix. By capturing these dynamic variables, DLCA provides a more accurate assessment of the environmental impacts and allows for better decision-making in sustainable building renovations (Van de moortel et al., 2022).

Even though BIM has revolutionized modelling tools in the built environment, enabling automation and serving as a primary information source for conducting automated and semi-automated LCA, it has limitations. For example, in terms of its scope and its inability to account for dynamic changes that occur throughout the life cycle of built assets, such as repairs, shifting energy demands, or changes in the electricity grid. To address these limitations, the DT is complementary to BIM and essential for conducting comprehensive DLCA. BIM serves as a valuable source of static information at the building level, encompassing materials and construction processes. In contrast, the DT can account for dynamic aspects like energy use, indoor air quality, and human health and safety. The DT provides real-time feedback on physical parameters, enabling smarter and more timely actions to mitigate adverse impacts such as energy loss or poor air quality. It serves as a tool to monitor and validate the actual conditions surrounding buildings, facilitating dynamic re-evaluation of environmental impacts, costs, and social aspects. A more comprehensive and dynamic LCA analysis can be achieved by combining BIM and DT, offering valuable insights for informed decision-making processes (Boje et al., 2023).

Moreover, the predominant focus has been on utilizing BIM for new constructions, while existing buildings have largely been overlooked despite their greater relevance to sustainability issues. However, it is becoming increasingly evident that a dynamic approach is more suitable for assessing the sustainability of existing buildings. Unlike new constructions, existing buildings have a complex history and ongoing operational performance that requires real-time analysis and adaptation. The limitations of static BIM-based tools in capturing and considering the dynamic changes in building operations have prompted the exploration of automated, real-time approaches for sustainability assessments. By shifting to a dynamic framework, we can better account for the fluctuating performance of existing buildings, enabling us to identify and address sustainability challenges more effectively. This shift acknowledges the need to overcome obstacles such as the absence of BIM models and the difficulties in obtaining accurate and up-to-date data. By embracing an automated, dynamic, and real-time approach, we can bridge the gap in assessing the sustainability of existing buildings and develop comprehensive frameworks that consider their unique characteristics and performance fluctuations (Schweigkofler et al., 2022).

2.3.4 State of the art

Various assessment models and dynamic variables were experimented with to enhance the temporal resolution of DLCA for buildings. These variables play a crucial role in capturing the time-dependent nature of environmental impacts and improving the accuracy of LCA results. One key aspect is the incorporation of dynamic variables within assessment models. These models, such as system dynamics, agent-based modelling, and discrete-event simulation, provide a framework to represent the complex interactions and feedback loops present in building systems. By considering dynamic variables, including occupancy patterns and climate conditions, the models can more accurately depict the real-world performance of buildings. Types of variables that could be taken into account are (Figure 13):

- Occupancy dynamics: by integrating these dynamic variables into assessment models, researchers can account for the impact of human behaviour on energy use, indoor environmental quality, and overall life cycle performance.
- Climate dynamics: studies are exploring methods to incorporate long-term weather data, climate change projections, and climate-sensitive parameters. By accounting for climate variations, such as seasonal fluctuations and extreme weather events, dynamic LCA models can accurately assess a building's energy demand for heating and cooling and anticipate the impacts of climate change on its performance.
- Maintenance and retrofitting activities: the timing and frequency of maintenance interventions, material replacements, and system upgrades significantly impact a building's operational energy use, durability, and environmental impacts over time. Dynamic variables related to maintenance schedules and retrofitting actions can be incorporated into assessment models to capture the temporal aspects of these activities and improve the accuracy of LCA results.
- Technological advancements and changes in energy systems: integrating evolving energy generation technologies, energy storage systems, and smart building controls into assessment models. By incorporating dynamic variables associated with emerging technologies, researchers can evaluate the environmental benefits and drawbacks of adopting innovative solutions within a building's life cycle (Su et al., 2021).

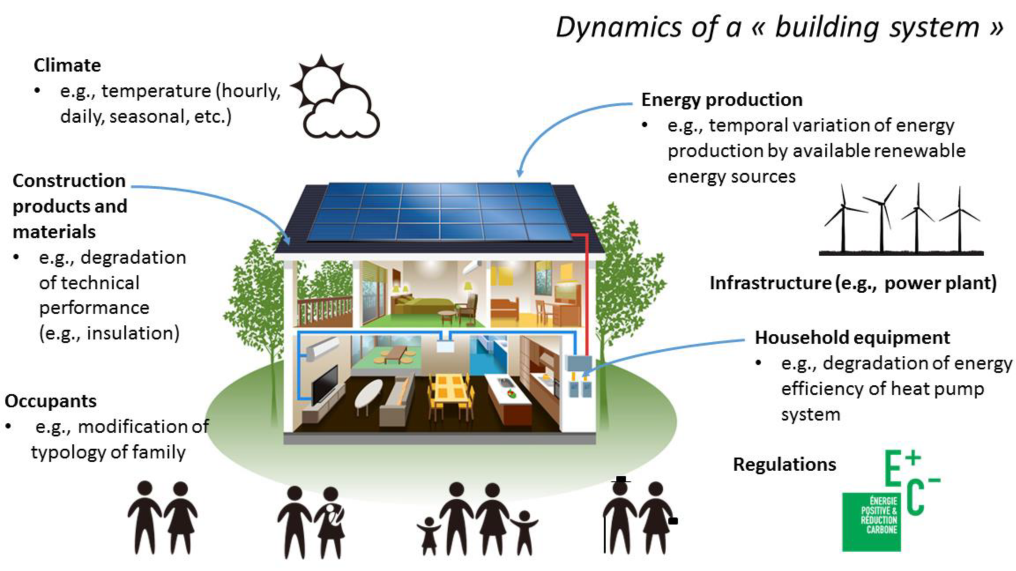


Figure 13 – Dynamic aspect within a building system (Negishi, 2019)

Nevertheless, these dynamic variables introduce additional sources of uncertainty, and it is crucial to quantify and propagate these uncertainties in the models. Sensitivity analysis allows researchers to assess the influence of dynamic variables, model parameters, and input data on the LCA results, enhancing the robustness and reliability of the assessments (Su et al., 2021).

The prevailing approach in dynamic LCA primarily centres around the dynamic nature of the Life Cycle Inventory (LCI) phase. LCI is a component of LCA, which refers to the compilation and quantification of inputs, outputs, and environmental impacts associated with a product or process throughout its entire life cycle. It involves collecting data on the resources consumed, emissions released, and waste generated at each life cycle stage, from raw material extraction to final disposal. This dynamicity can be facilitated by using digital models or sensors, enabling continuous data collection. There are various approaches for incorporating dynamics into LCI:

- Time-based models: To apply this approach, dividing the LCI into specific time intervals is necessary. This involves collecting data on environmental performance over time, such as periodic measurements of energy consumption or emissions. These data can be used to calculate and compare environmental indicators (such as carbon footprint) at different time points. It is also important to consider external factors that may influence environmental performance over time, such as adopting more efficient technologies or changing the composition of the energy mix.
- Scenario-based models: Relevant future scenarios that can impact environmental performance must be identified to apply this approach. These scenarios can include changes in the climate, energy mix, environmental policies, technological developments, and consumer behaviours. Data and information on the predicted environmental performance for each scenario need to be acquired. Using appropriate simulation models or algorithms makes it possible to calculate the environmental impacts based on different scenarios and compare the results to identify more sustainable solutions.
- Hybrid approaches: Hybrid approaches combine features from both time-based and scenario-based models. This means dividing the LCI into specific time intervals and considering different scenarios for each time interval. To apply this approach, data must be collected on the temporal environmental performance and key variables influencing these performances. Simulation models or optimization techniques can be used to calculate the environmental impacts and evaluate optimal solutions based on different temporal scenarios (Cornago et al., 2022).

2.3.5 Energy mix through time

The global energy industry plays a vital role in fulfilling our fundamental needs, encompassing the provision of essential services like electricity for illumination, heating to keep our homes comfortable, and fuel to power our vehicles. It is a vast sector involved in activities ranging from extracting and producing primary energy sources like crude oil, natural gas, and coal to refining and distributing these resources. Additionally, the industry deals with secondary energy sources, such as electricity, which is generated from primary sources. The global energy market is predicted to experience significant growth in the coming years, mainly due to increasing demand resulting from population growth and economic development. However, there will be a noticeable shift towards cleaner and more sustainable energy sources, such as solar, wind, and hydropower, while the importance of fossil fuels is expected to diminish gradually (Figure 14). The prospects of the nuclear power market differ among regions, with countries like China continuing to invest in it, whereas others like Germany and Japan are planning to phase it out. The fossil fuel industry is facing numerous challenges, including competition from renewable energy expansion, growing concerns about climate change, and heightened awareness of environmental impacts. However, in some countries with abundant fossil fuel reserves or heavy reliance on fossil fuel exports, there may be continued use in the short term. Nevertheless, the renewable energy market is set to continue its growth trajectory, driven by declining costs and supportive government policies, particularly after the COVID-19 pandemic highlighted the importance of resilient and sustainable energy systems. Recent events like the Russia-Ukraine war have emphasized the significance of diversifying energy portfolios to ensure long-term stability and reduce reliance on single energy sources or suppliers. This diversification approach has become increasingly crucial in today's rapidly changing energy landscape (Statista, 2023).

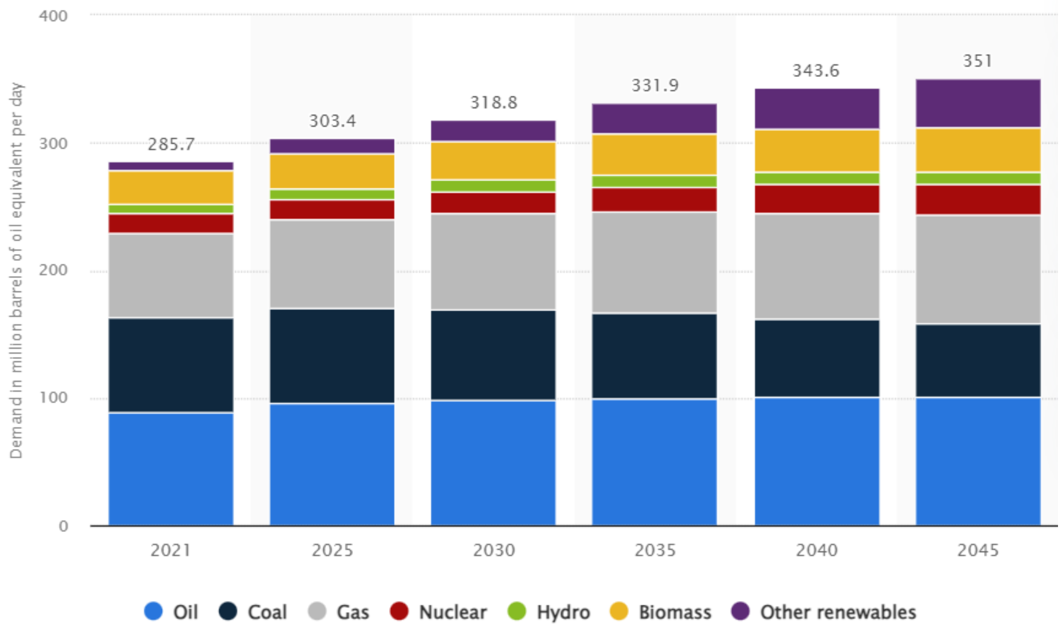


Figure 14 – Primary energy demand worldwide forecast until 2045 (Statista, 2023)

Focusing on Italy's energy landscape, over the last decade it has undergone a significant transformation, marked by a shift in its energy mix (Figure 15). The country has successfully reduced its reliance on coal and oil while embracing natural gas and renewable energy sources. This transition, combined with energy efficiency improvements and a shift towards a service-oriented economy, has led to a notable 15% decrease in energy intensity between 2005 and 2021. Italy is on track to achieve emissions reduction and energy efficiency targets outlined in its National Energy and Climate Plan (NECP) for 2030. However, achieving the more ambitious goals set by the European Union's (EU) Fit-for-55 (FF55) package and the REPowerEU plan will require further substantial efforts to reduce dependence on Russian fossil fuels. Notably, Italy has made significant progress in reducing greenhouse gas (GHG) emissions, despite a temporary dip in 2020 due to the Covid-19 pandemic. The country is committed to achieving carbon neutrality by 2050. Italy's advantageous geographic position offers a promising opportunity to boost renewable energy generation and decrease reliance on natural gas-based electricity. While the period from 2010 to 2013 witnessed significant renewable energy growth, mainly driven by solar photovoltaics (PV), momentum slowed as the EU 2020 targets were met and incentives adjusted. Regulatory changes have recently spurred additional capacity growth, even though further efforts are needed. Italy must accelerate permitting procedures and incentives to meet its 2030 targets, including the NECP's goal of 19 GW wind power capacity by 2030. To attain more ambitious renewable electricity generation targets, the government estimates adding 5 GW of new renewable generation capacity annually from 2020 to 2030. This may necessitate higher annual additions to address previous shortfalls and align with the new REPowerEU plan targets. To foster a more sustainable and resilient energy landscape in Italy, the government should take several critical measures. Firstly, it should revise the National Energy and Climate Plan to align with EU directives, strengthen energy security, and end reliance on Russian fossil fuels while adhering to carbon-neutrality goals. Secondly, policies promoting alternative fuels and vehicles, backed by preferential taxation, should be implemented to reduce carbon emissions in the transport sector. Thirdly, swift reforms in permitting procedures for renewable projects and grid development, along with community engagement and incentives for timely compliance, are essential. Additionally, targeted measures should be adopted to address energy poverty by focusing on vulnerable consumers and encouraging reduced energy consumption through awareness campaigns. Lastly, the tax deduction schemes for energy efficiency investments in buildings should be optimized to maximize energy savings and target low-income households, addressing identified barriers to their effective participation (IEA - International Energy Agency, 2023).

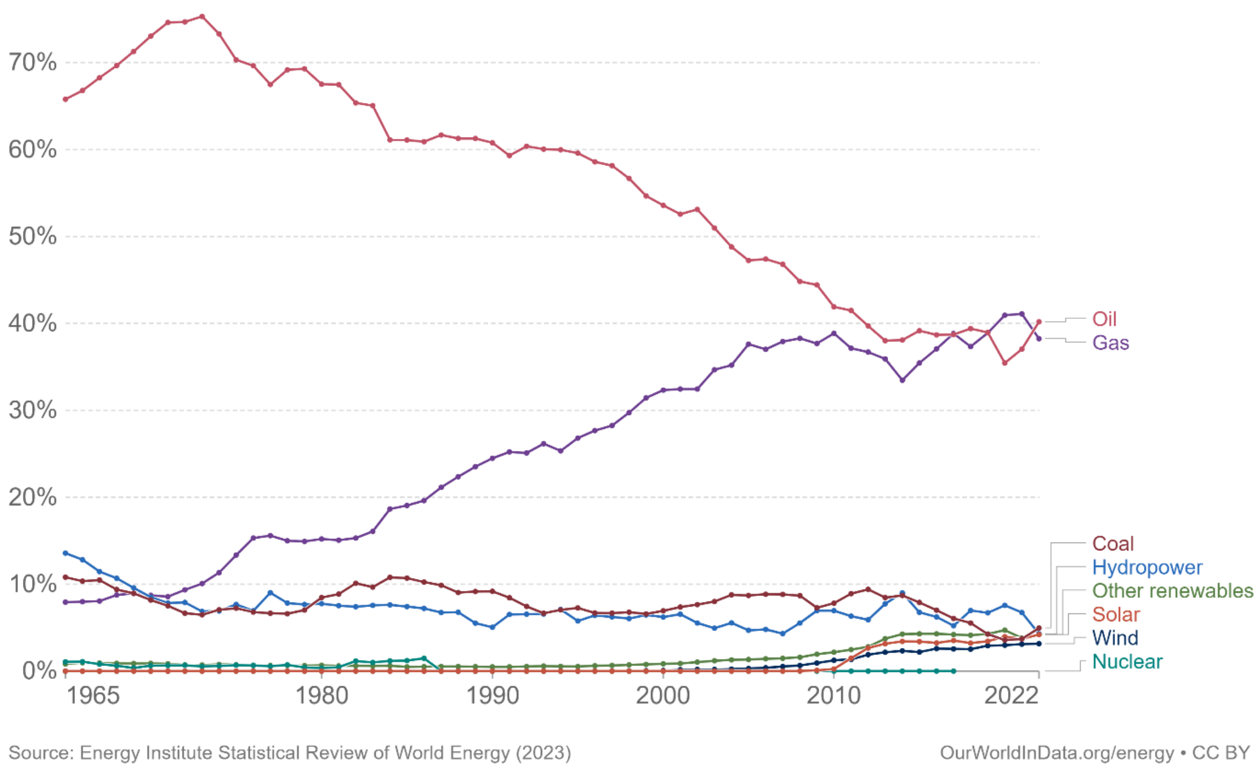


Figure 15 - Share of energy consumption by source, Italy (Our World in Data, 2023)

Dynamic LCA holds immense promise in addressing the evolving nature of energy policies and their impact on the energy mix over time. As highlighted in our study, Italy's energy system has undergone significant changes since 2010, with a notable shift towards more natural gas and renewable energies, while reducing coal and oil consumption. This transition has been driven by various factors, including global demand, economic development, and commitments to climate goals. As national policies continue to support cleaner and more sustainable energy sources, it is very much possible that the energy mix in Italy and other countries will witness further transformation in the coming years. By integrating real-time data on the energy mix into dynamic LCA models, we can effectively capture the shifting environmental impacts of buildings and infrastructure throughout their life cycles, considering the changing composition of energy sources and their associated emissions. Moreover, different energy mixes not only influence the operational phase of buildings but also have far-reaching effects on the entire life cycle. As energy sources for material production and transportation vary with changes in the energy mix, the embodied emissions of materials can differ significantly. For instance, renewable energy-driven manufacturing processes may result in lower embodied carbon, whereas reliance on fossil fuels may lead to higher emissions. Transportation methods utilizing cleaner fuels can further reduce carbon footprints. Incorporating these dynamic factors into EPDs is crucial to providing a comprehensive and up-to-date assessment of the environmental impact of materials used in construction. By embracing dynamic LCA in our study and considering the potential shifts in the energy mix and their influence on materials and transportation, we can offer valuable insights into the environmental performance of buildings and infrastructure. This approach enables more accurate assessments of energy-related emissions and empowers stakeholders to make informed decisions, ensuring that sustainability strategies align with the evolving energy landscape (Negishi, 2019).

2.3.6 Challenges and opportunities

Utilizing LCA and digital twins in building sustainability presents several opportunities and challenges. One key challenge is the limited availability of sensors and data in the early stages of implementation. In certain studies, a few sensors were employed to test the proposed framework, indicating the need for future integration of more sensors and establishing a data analysis module to detect anomalies, possibly utilizing artificial intelligence techniques. Moreover, the construction sector's adoption of the Internet of Things (IoT) paradigm is still in its infancy, which can impede the widespread application of digital twins. The concept of cognitive-based approaches, integrating sensing and connectivity capabilities into building components during renovation, has been explored as a potential strategy. However, implementing and integrating such approaches into the construction industry requires further research and development (Lavinia Chiara Tagliabue et al., 2023). Furthermore, uncertainty and assumptions are inherent in dynamic LCA and digital twins. Future scenarios, including energy use, maintenance practices, and end-of-life disposal, necessitate assumptions and projections, introducing uncertainties into assessment results. It is essential to transparently document and communicate these underlying assumptions to ensure the reliability and robustness of the analysis. Lastly, data availability and quality pose challenges for both LCA and digital twins. Gathering comprehensive and accurate data for various stages of a building's life cycle, such as energy consumption, material inputs, and waste generation, can be time-consuming and requires collaboration among multiple stakeholders. Addressing these challenges necessitates standardized data collection methods, enhanced collaboration, and continuous data availability and quality improvement (Boje et al., 2023). Another problem in applying dynamic LCA is that even though it has been a research subject for a decade and there are some advancements, operational tools for conducting reproducible and multiple case studies are still under development. Previous works have focused on dynamic LCI and LCIA, particularly for climate change impacts. Different approaches have been proposed to address the limitations of traditional metrics like global warming potential (GWP), but further development is needed for more comprehensive and parameterized models. Existing tools lack clear definitions of temporal characteristics for processes, flows, and supply chains, hindering their broader applicability. Additionally, significant efforts are necessary to provide the required information for background systems, further complicating the implementation of dynamic LCA (Negishi, 2019).

3 STEPS TOWARDS GREEN DIGITAL TWINS

3.1 Workflow

Starting with a Revit model, the objective was to analyse the interoperability with an LCA analysis tool, specifically One Click LCA. The flow of data between the two programs was examined, improved, and applied to a real case study. The thesis was organized to include several essential steps, which are outlined in the general workflows explained in Figure 16 and Figure 17.

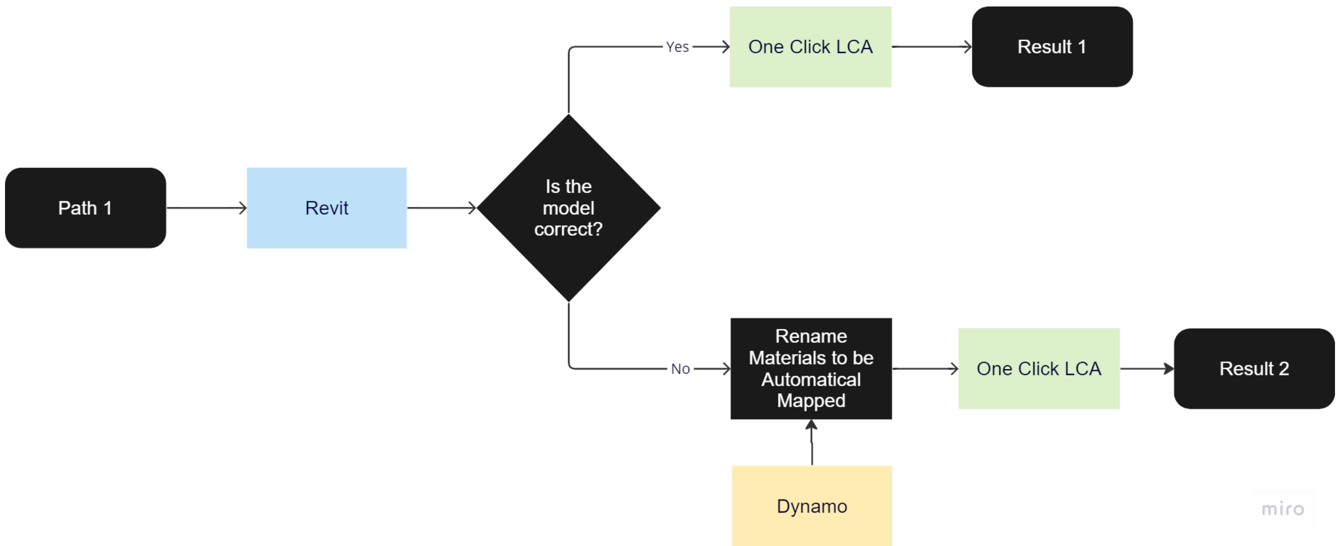


Figure 16 - Workflow 1

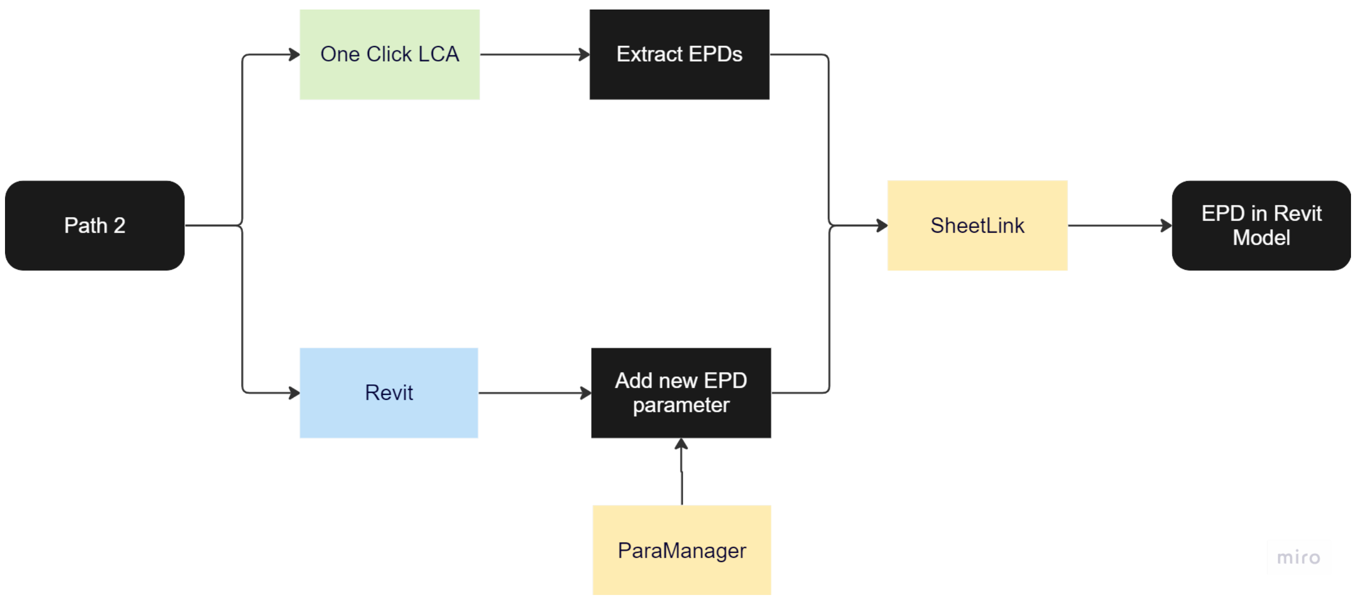


Figure 17 - Workflow 2

The main idea is to extract data from Revit into One Click LCA, where it is possible to download the EPDs in Excel. This Excel file can then be reimported into Revit to populate the parameters created for the materials with information from these EPDs. During the process Dynamo (Dynamo, 2023) and DiRoots Plugin for Revit (DiRoots, 2023), were utilized to facilitate and expedite the process, as illustrated in Figure 18.

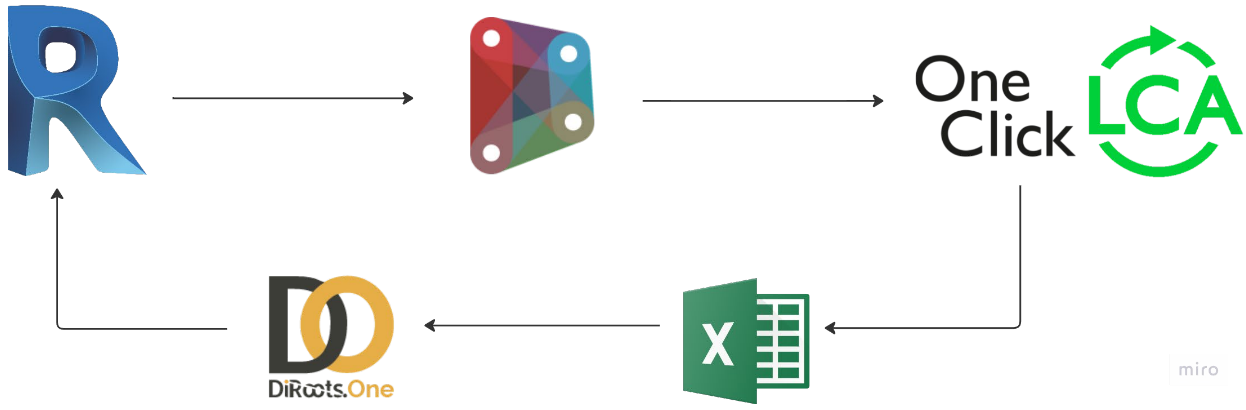


Figure 18 - Interoperability path of the work

In addition to these initial workflows, the last approach involves the creation of a Digital Twin, initiated from the BIM model and incorporating sensor data and projections regarding the future energy mix. This transformation aims to evolve the static analysis into a Dynamic LCA. This workflow remains theoretical due to the unavailability of the required data and tools, preventing its practical application to our case study.

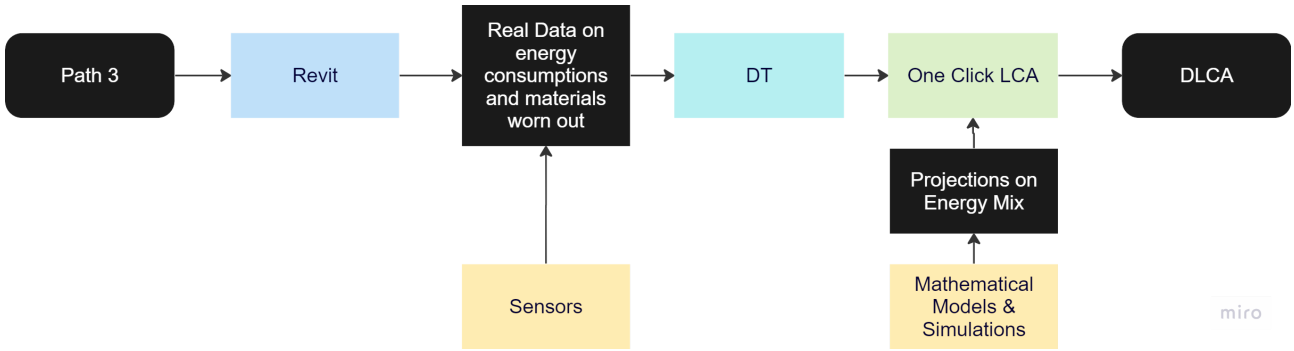


Figure 19 - Workflow 3

Figure 19 illustrates the ideal workflow envisioned for the last part of this dissertation. However, it is crucial to acknowledge that implementing dynamic LCA still encounters several challenges. These challenges include the absence of building sensor data, limitations in simulating the future energy production and consumption trends of the country, and the lack of a suitable tool for comprehensive LCA analysis based on these factors. Despite these obstacles, the decision was made to push the study as far as possible and identify the encountered problematics. The aim is to highlight these challenges and propose potential solutions, thereby laying the groundwork for future investigations in this field.

3.2 LCA analysis through BIM

For this study, we will use a Revit model of a historical building in Verona, illustrated in more detail in paragraph 4.1. The model represents the building after it has been restored. The model was provided by the Coprat company. From this Revit model, we can extract all the necessary information to conduct a LCA analysis, utilizing the One Click LCA tool described in detail in the previous chapters. The One Click LCA tool offers a convenient plugin for Revit, allowing us to easily access all the data on materials and quantities used in the model. Additionally, this tool is connected to an online platform where we can match the materials with their corresponding EPDs and calculate the final results of the LCA analysis. The focus of this work is to show the strengths and weaknesses of this interaction and provide a vade mecum for all the professionals and academics who would like to approach this topic and improve the sustainability of their projects.

The Revit model is divided into two phases: Existing and New Construction (Figure 20 and Figure 21). However, our scope is limited to examining only the elements related to the new construction. These elements encompass insulation, new walls, windows, doors, and any materials involved in the building's intervention. We have excluded the existing parts from our analysis since they are already constructed and do not contribute additional emissions. Nonetheless, should we wish to include the existent parts in the One Click LCA analysis, we can consider them as recycled materials to consider the different ends of life. This approach is supported by a study conducted by Lavinia Chiara Tagliabue et al. in 2023.

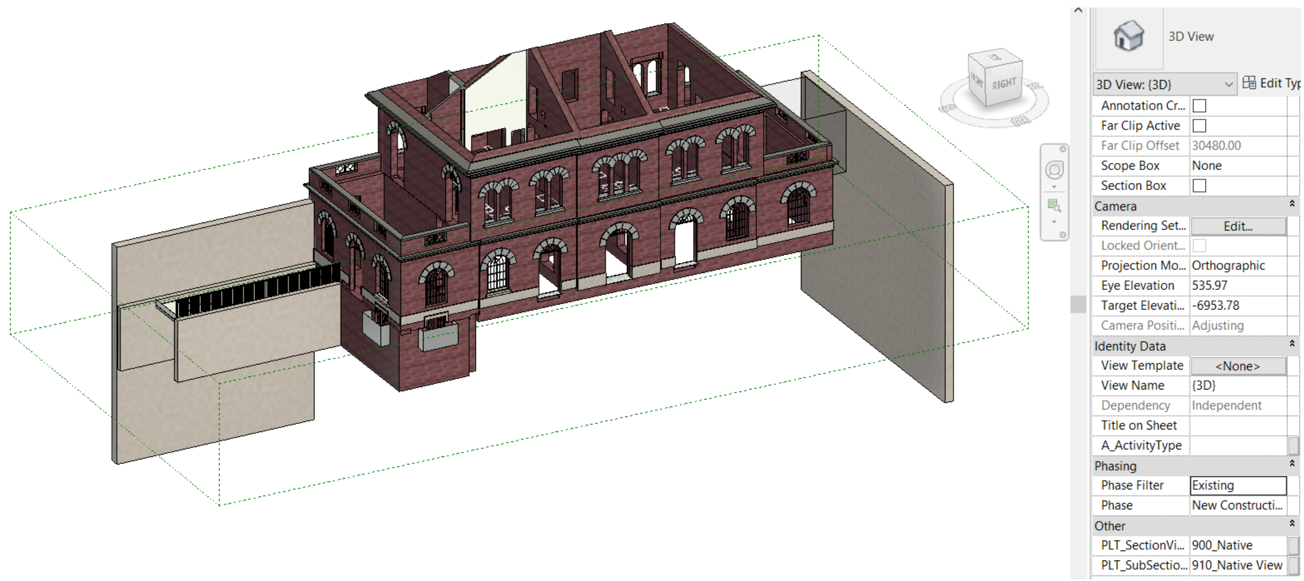


Figure 20 – Project Model filtered by Phase: Existing

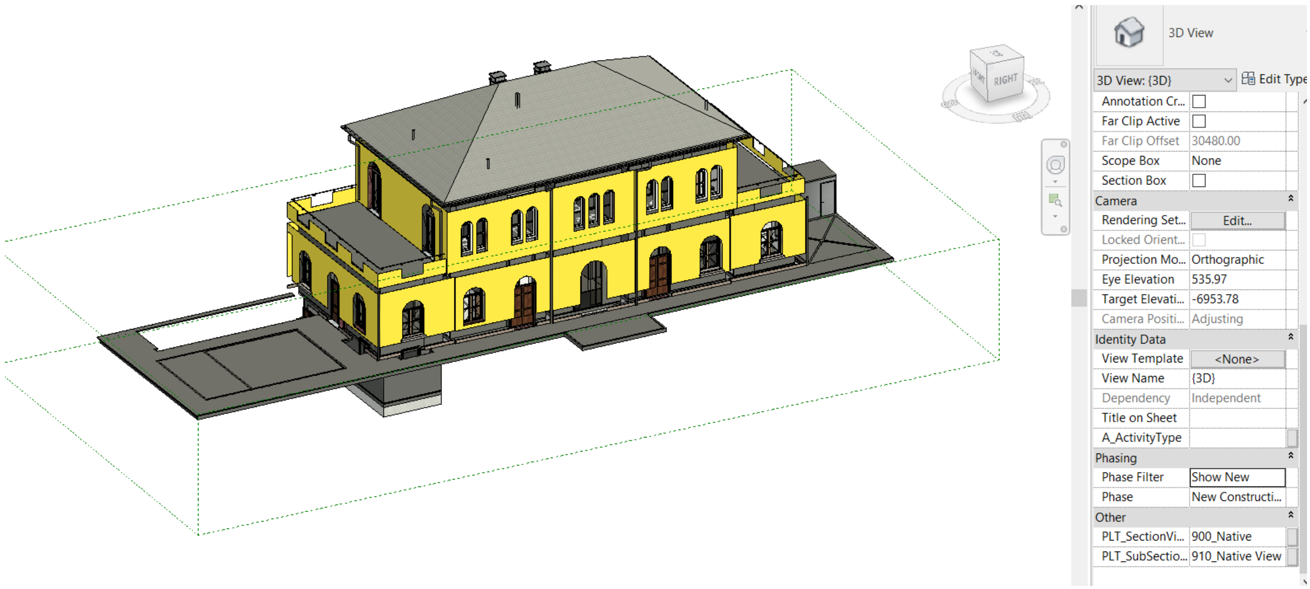


Figure 21 – Project Model filtered by Phase: New

In this dissertation, it will be used the Level(s) certification. Level(s) is a voluntary framework introduced by the European Commission to address the critical issue of lacking a global standard for measuring the sustainability of buildings. From the Level(s) user guide (Figure 22) we can see that compiling the information needed is very time-consuming.

Macro-objective	Indicator	Unit of measurement	Summary information
1: Greenhouse gas and air pollutant emissions along a building's life cycle	1.1 Use stage energy performance	kilowatt hours per square metre per year (kWh/m²/yr)	This indicator measures the primary energy demand of a building in the use stage. In a life cycle approach, this energy demand is also referred to as 'operational energy consumption'. It takes into account the benefits of generating low carbon or renewable energy.
	1.2 Life cycle Global Warming Potential	kg CO_2 equivalents per square metre per year (kg CO_2 eq./m²/yr	This indicator measures the greenhouse gas (GHG) emissions associated with the building at different stages in its life cycle. It therefore measures the building's contribution to emissions that cause the earth's global warming or climate change. This is sometimes also referred to as a 'carbon footprint assessment' or 'whole life carbon measurement'.
2. Resource efficient and circular material life cycles	2.1 Bill of quantities, materials and lifespans	Unit quantities, mass and years	This indicator measures the quantities and mass of construction products and materials necessary to complete defined parts of the building. It also allows for the estimation of the lifespans of defined parts of the building.
	2.2 Construction & demolition waste and materials	kg of waste and materials per m² total useful floor area	This indicator measures the overall quantity of waste and materials generated by construction, renovation and demolition activities. This is then used to calculate the diversion rate to reuse and recycling, in line with the waste hierarchy.
	2.3 Design for adaptability and renovation	Adaptability score	The indicator assesses the extent to which the design of a building could facilitate future adaptation to changing occupier needs and property market conditions. It therefore provides a proxy for the capacity of a building to continue to fulfil its function and for the possibility to extend its useful service life into the future.
	2.4 Design for deconstruction, reuse and recycling	Deconstruction score	The indicator assesses the extent to which the design of a building could facilitate the future recovery of materials for reuse of recycling. This includes assessment of the ease of disassembly for a minimum scope of building parts, followed by the ease of reuse and recycling for these parts and their associated sub-assemblies and materials.
3. Efficient use of water resources	3.1 Use stage water consumption	m³/yr of water per occupant	The indicator measures the total consumption of water for an average building occupant, with the option to split this value into potable and non-potable water that is supplied. It also supports the identification of water scarce locations.
1-3. Full LCA	n/a	10 impact categories	-Climate change; Ozone depletion; Acidification; Eutrophication aquatic freshwater; Eutrophication aquatic marine; Eutrophication terrestrial; Photochemical ozone formation; Depletion of abiotic resources - minerals and metals; Depletion of abiotic resources – fossil fuels; Water use
	4.1 Indoor air quality	Parameters for ventilation, CO2 and humidity	The indicator measures a combination of indoor air conditions and target air pollutants:

Figure 22 – Level(s) User Manual: Overview of macro-objectives and indicators

Instead, when we use One Click LCA in Revit, it is possible to pass the information about our project (such as location, area, etc.) from the model to the LCA tool, and it is easy to choose which level of the project interests us, what is the macro-objective needed and which related categories we would like to analyse. Between the various indicator provided by this framework, we will analyse the Global Warming Potential (GWP) especially, as an indicator of the impact of the building in terms of the increase of the concentration of greenhouse gas in the atmosphere.

3.3 Data and information needed

The first questions we want to address before checking the interoperability between the programmes are:

- Are materials defined in a way that allows them to be identified?
- Is the model resulting in appropriate precision for the quantities considering the design stage?

These questions comprise a set of detailed technical checks, for example, concerning multi-material elements and naming conventions. The last one comes from a more general knowledge of the model and its examination, keeping in mind the stage of the design and the level of detail we could expect. In this specific case, we are dealing with an executive project with a high level of detail, so we can expect that all the quantities for each part composing a material are defined. For the first one, by following the guidelines and assigning appropriate names to materials in the BIM model, One Click LCA will be able to recognize and map the materials accurately, facilitating a more effective assessment of life cycle impacts (One Click LCA, 2022).

We can break down the model verification process into distinct steps, described below, each aimed at assessing specific characteristics. By doing so, we can thoroughly examine the model's performance and ensure it meets our requirements. This systematic approach allows us to enrich the evaluation process, enabling us to gain a deeper understanding of the model's capabilities and limitations.

1. **Verifying the material classifications** is crucial for grouping and allocating data in One Click LCA's input form. Checking the native classification of the modelling software, such as Revit or IFC Class, is essential. This step helps ensure the model contains all necessary classes, like beams, columns, footings, walls, and slabs, appropriately separated to facilitate accurate mapping.
    - **Open the BIM Model in the Modelling Software:** Use the appropriate software, such as Revit or an IFC viewer, to open the BIM model.
    - **Navigate to the Object/Element Browser:** In the modelling software, a browser or object explorer typically shows a hierarchical list of elements in the model. Look for this browser, as it will be essential in checking the native classification.
    - **Check the Native Classification:** In the object browser, locate the elements you want to verify, such as beams, columns, and walls. The native classification of these elements is

usually provided by the modelling software or may have been assigned during the modelling process.

- **Ensure Proper Separation of Classes:** The different material classes must be appropriately separated for accurate mapping in One Click LCA. This means that elements of the same class (e.g., all beams) should be categorized under the correct classification and separated from other classes (e.g., walls, columns, etc.).
- **Verify Consistency:** Check that the classification of elements is consistent throughout the model. For example, all elements representing walls should have the same classification.
- **Correcting Classification Issues:** If any misclassifications or errors are found in the native classification, you may need to correct them in the modelling software. This might involve reassigning elements to the correct classes or adjusting the classification settings.

2. **The scope of the model** must be carefully reviewed. Elements like finishing materials, external walls, the external layer of walls and roof, foundations, windows, doors, light internal walls, and building technology must be present for a comprehensive analysis. Unnecessary materials, such as flow fittings and furniture, can be filtered out to streamline the process.
    - **Define the Analysis Scope:** Determine which elements are essential for the analysis. In this case, the scope may include finishing materials, external walls, the external layer of walls and roof, windows, doors, and light internal walls.
    - **View Templates:** Consider using view templates to apply consistent visibility settings to multiple views. Create a view template that includes only the essential elements for the analysis, and apply it to relevant views. This can save time and ensure consistency across views.
    - **Hiding/Unloading Elements:** For elements that are not essential for the analysis, you can hide them temporarily in the view. Use the "Hide/Unhide Elements" tool to hide elements or "Unload" them from the model temporarily.
    - **Save and Manage Views:** Once the views are set up for analysis, save them as necessary and create a View Set if you want to group related views for better organization.

3. Check **if layered structures have been detailed**, as multi-material objects might be simplified as solid materials. For instance, external walls with multiple layers may be represented as solid blocks. In such cases, mapping the materials to suitable constructions becomes necessary for accurate analysis. Similarly, hollow objects should be assessed, ensuring they are not incorrectly modelled as solids. Steel columns and beams, for example, need to be accurately represented, either as structures or solid blocks, to determine the correct material quantities. For example:

- **External walls**: Sometimes, despite having multiple layers, an external wall may be represented as a simple solid material. In such cases, it should be mapped to a suitable construction instead of a single material.
- **Gypsum board walls/drywalls**: Gypsum board should generally not exceed 24 mm in thickness. However, if it is thicker (e.g., 100 mm), it likely includes the entire structure, including studs. Depending on the presence of studs, it should be mapped to an appropriate construction.
- **Windows:** Check whether the window parts are modelled separately or simplified as a single solid block. For instance, a 2-layer window glazing might be represented as a 5 cm thick block, even though it consists of air and glass layers. Also, verify whether the window frame is modelled separately or if the entire window is a single block. In most cases, it is preferable to map windows to relevant window objects to capture their accurate environmental impact.

4. Ensure that the existing model contains **clear and consistent material labelling.** This involves examining the material list for individual materials, such as "Concrete," "Cast-in-place-concrete," "Steel," and "Gypsum board." If some labels are ambiguous or named differently, like "Default wall" or "White," they might not convey the actual material used. To resolve this, one must access the detailed view of each label and cross-check other material information categories, like type or name, to identify the materials accurately. In case of uncertainty, referring to design documents or collaborating with the modeller can help clarify the material content. Here are some guidelines for naming materials in the BIM model:
    - **Consistency:** Maintain consistency in naming materials across the BIM model. Use the same naming conventions for materials with similar characteristics or from the same manufacturer.
    - **Material Descriptors:** Include relevant descriptors in the material names to provide information about the material's characteristics, such as material type, composition, strength, or colour. This helps One Click LCA identify and differentiate different materials accurately.
    - **Manufacturer Information:** Include the manufacturer's name or brand in the material name if available. This can be helpful in distinguishing materials from different manufacturers or selecting specific products within a material category.
    - **Uniqueness:** Ensure that each material has a unique name within the BIM model. Avoid using generic names that multiple materials may share to prevent confusion during the mapping process.
    - **Alignment with Standards:** Consider using naming conventions that align with industry standards or popular classification systems for materials, such as ASTM, ISO, or specific BIM classification systems like Uniclass or Uniformat. (One Click LCA, 2022)

Many of these properties can be inspected using the schedules tool in Revit (Figure 23). It is possible to analyse the model and highlight the characteristics needed to perform a good LCA analysis.

- **Gypsum board walls/drywalls:** Gypsum board should not be more than 24 mm thick. If it is thicker (for instance 100 mm), it probably contains the full structure including studs. Depending on your studs, map it to suitable construction.

<Wall Schedule>

A	B	C	D
Type	Width	Structural Material: Description	Structural Material: Mat
WA_WI_PLT02_1_hist	10 mm	Gypsum Plaster	
WA_WI_PLT02_1_hist	10 mm	Gypsum Plaster	
WA_WI_PLT02_1_hist	10 mm	Gypsum Plaster	
WA_WI_PLT02_1_hist	10 mm	Gypsum Plaster	
WA_WI_PLT02_1_hist	10 mm	Gypsum Plaster	

Figure 23 – Example of one rule for LCA checked through the model's schedule

More accurate examinations of the model and results are shown in paragraph 4, in the context of an application on a real case study.

3.4 Interoperability

After conducting a thorough analysis of the model, the initial run in One Click LCA revealed several interoperability challenges, primarily arising from the program's difficulty in recognizing and automatically mapping materials. A meticulous approach was adopted to address these issues, involving identifying problematic materials. Through careful analysis and making informed assumptions about the program's recognition limitations, a specific rule for the naming procedure was established. This rule was then implemented using an Excel sheet containing old and new names, along with a Dynamo script (Dynamo, 2023), leading to a subsequent analysis that produced an increased recognition of materials by the LCA tool.

The second phase of the interoperability analysis took a different approach, utilizing the extensive One Click LCA database, which links materials to their respective EPDs. Leveraging the database's features, including the ability to download analysis results, a bridge was created between this data and the model. With the integration of DiRoots Plugins (DiRoots, 2023), new EPD parameters are created, and EPD-related data can be imported to fill parameters in the materials. This crucial linkage established a connection between the cloud-based LCA analysis and the physical model, allowing for seamless updates and potential data exports and imports in case of EPD revisions. As a result, our model evolved into a comprehensive repository for continually updated EPDs, intricately linked to the associated materials, enhancing the overall sustainability and accuracy of our building design process.

3.5 Dynamic LCA: Through digital twins

The possibilities for evolving the model into a digital twin comprehend adding the real-time data from sensors and a projection of future energy scenarios. These projections could be added directly in the tool to perform LCA. For example, One Click LCA in this case. This advancement offers a comprehensive approach to enhance the LCA process by amalgamating real-time data streams and predictive insights, thereby contributing to more accurate and proactive sustainability assessments.

3.5.1 Sensors

The benefits of having sensors in the building are far-reaching, as they enable comprehensive data collection, including external climate influences and occupancy patterns. This data would provide valuable insights into energy consumption patterns and allow a deeper understanding of how external factors affect the building's overall performance. In the proposed framework, this cognitive system (Figure 24) could play a crucial role in detecting deviations in the building's current performance compared to expected standards. By analyzing various factors, such as energy consumption, environmental conditions, and user behaviour, it can identify components that may require interventions to restore the building's optimal behaviour. For instance, the system can track the progressive increase in energy required to heat the building over time, accounting for external climate changes and occupancy variations using IoT sensors. This information can help attribute such changes to potential building envelope or thermal insulation issues, signalling the need for technical intervention. Incorporating sensors to monitor temperature and humidity within the walls and insulation panels can significantly enhance the understanding of the hygrothermal conditions impacting the building's envelope. Consequently, if repairs fail to restore optimal operating conditions, damaged components can be identified for replacement. To streamline the process, a planned maintenance program can be linked to the BIM model, and alerts can be generated when the useful life of a product approaches its end. This transforms the simple BIM model into a Digital Twin of the building, giving us real-time information on its behaviour (Lavinia Chiara Tagliabue et al., 2023).

Moreover, in this specific case and in general, considering the retrofitting process and the end-of-life of specific building components, a valuable opportunity is presented to introduce new materials that can significantly reduce the environmental impact and enhance overall energy performance. By reducing energy demand and incorporating materials with lower embodied energy, the building's sustainability can be significantly improved. The DT platform plays a pivotal role in this process by facilitating the evaluation of LCA for both the new components and potential retrofitting scenarios, as illustrated in previous sections. An option could be to use leveraging Radio-Frequency Identification (RFID) technology: in this way, the DT platform enables real-time asset tracking in construction and the built environment, enhancing efficiency and accuracy in managing the retrofitting process. Utilizing RFID-based digital twin technology, we can envision a seamless LCA evaluation for the building. The LCA database aligns with the granularity of the BIM model, enabling automatic, bi-directional data exchange between the two databases. This integration streamlines the assessment process, providing a comprehensive understanding of the environmental impact and energy performance implications associated with different retrofitting options. (Lavinia Chiara Tagliabue et al., 2023)

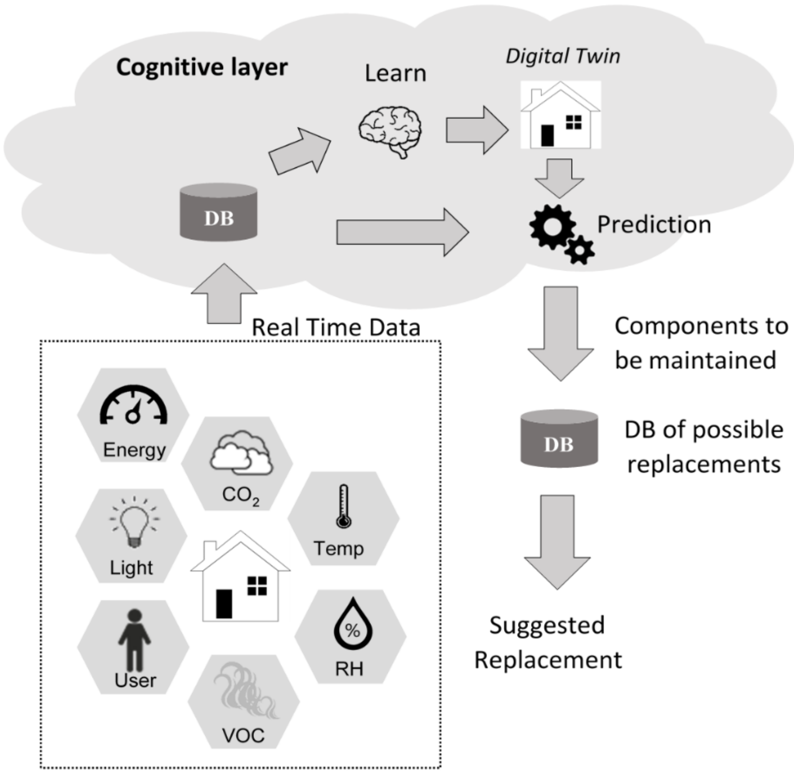


Figure 24 – Sensors and DT relationship (Lavinia Chiara Tagliabue et al., 2023)

3.5.2 Energy Simulation

As explained diffusely in paragraph 2.3.5, the global energy industry, being instrumental in meeting fundamental needs such as electricity, heating, and transportation, is currently undergoing a profound transformation. Notably, Italy's energy landscape has witnessed a significant transition over the past decade, characterized by a discernible shift towards cleaner and more sustainable energy sources while concurrently reducing reliance on coal and oil. This transformation aligns with the nation's commitment to curbing greenhouse gas emissions and striving for carbon neutrality by 2050, facilitated by its favorable geographic positioning for renewable energy generation (IEA - International Energy Agency, 2023). Building upon the theoretical foundation previously cited, this work attempts to construct a framework for comprehensively assessing the potential impact of future shifts in energy sources LCA outcomes, with a particular focus on the utilization of One Click LCA to perform the simulation. The central assumption of this framework lies in the recognition that the changing energy mix exerts a profound influence on the environmental performance of buildings and infrastructure, encompassing their entire life cycles. As such, dynamic LCA stands as a promising approach to address the dynamic nature of energy policies and their evolving impact on LCA analyses. To incorporate future energy scenarios into LCA, a comparative analysis with Spain, a renewable energy leader, was performed. After the calculations of energy consumption for a case study building project were performed, providing data to use Spain's 2020 electricity profile in One Click LCA. Comparing the results with Italy's electricity profile, the differences in environmental impacts were observed, underscoring the importance of considering changing energy mixes.

3.6 Expected results

The results obtained from the improved interoperability between Revit and One Click LCA hold significant implications for designers and sustainability consultants as it paves the way for a more efficient and time-saving LCA analysis. By understanding the critical steps taken to achieve this enhanced interoperability, practitioners can develop clear guidelines and rules to streamline the data exchange process between the two software platforms. This comprehensive approach addresses the initial challenges related to material recognition and mapping, resulting in a smoother and more accurate analysis. Even though some problems were encountered, his research sets the foundation for future improvements, and ongoing efforts will focus on refining the interoperability method to overcome these challenges. The forthcoming chapter will apply this developed methodology to a real case study, illustrating its practicality and relevance in the context of sustainable building design and assessment.

Regarding the dynamic approach to the LCA calculations, a possible framework is provided, combining and analysing the possibilities opened by previous studies on the subject. This framework could be implemented in future with the presence of available data needed. Moreover, the possibility of performing LCA analysis with different electricity conditions is explored to understand if a shift in the energy mix towards a more sustainable approach could improve the results. This is associated with the idea of future developments of tools capable of including this dynamic variable in the calculation to have more precise and reliable data to make decisions about the assessment. The combination of these approaches is expected to improve the accuracy and efficiency of the LCA analysis in practice and contribute to the overall sustainability and effectiveness of our building design process. The results of this endeavour represent an advancement towards more environmentally conscious and data-driven decision-making in architectural and construction practices.

4 CASE STUDY

4.1 Casa Del Capitano, Verona

The case study discussed in this thesis is a historical building which pertains to the former Santa Marta barracks in Verona, known as the "Casa del Capitano" building, which is part of a larger complex. It was provided by Coprat company, which worked on it with F&M Engineering and Politecnica Architecture, especially focusing on energy efficiency and systems improving.

Figure 25 – Santa Marta, Verona (Google Maps)

Figure 26 – Santa Marta Complex, Verona (F&M, 2020)

The general restoration and repurposing project involve the transformation of the "Silos di Levante," "Casa del Capitano," and "Guardiania" buildings within the Former Santa Marta Barracks complex (Figure 26). Situated in the southern part of Veronetta, one of the city's oldest neighbourhoods near the historic centre (Figure 25), the disused military area holds historical and architectural significance. The "Silos di Levante" is slated to become a location for the University of Verona's reading spaces, a museum featuring exhibition areas and a publicly accessible refreshment zone. The "Casa del Capitano" will transform into a polyclinic dedicated to serving the local community. Additionally, the "Guardians" building will remain a hub for the Central Delegation of the Municipal Police and various socio-cultural associations. The project has a dual focus: firstly, to enhance the energy efficiency and structural integrity of these three buildings while preserving their historical value, and secondly, to establish a sustainable urban welfare concept that encourages social inclusivity. This concept involves repurposing the renovated buildings for functions that contribute to the community and neighbourhood life, enriching the overall urban experience. At the moment, the project is under construction (F&M, 2020). As mentioned, the focus will be on "Casa del Capitano", a building shown in Figure 27, Figure 28, Figure 29 and Figure 30 in its original state.

Figure 27 - Casa del Capitano 1 (Coprat, 2023)

Figure 28 - Casa del Capitano 2 (Coprat, 2023)

Figure 29 – Casa del Capitano 3 (Coprat, 2023)

Figure 30 – Casa del Capitano 4 (Coprat, 2023)

The building has undergone conversion into a polyclinic, with ongoing construction activities. Given its historical significance, the building is subject to preservation constraints, which exempted Coprat from specific energy efficiency requirements. Nevertheless, the project incorporates the following interventions:

- Internal partition wall reconstruction
- Window replacement
- Roof reconstruction
- Reconstruction of the ground-floor slab with ventilated crawl space
- Attic insulation

Following the Plans of Floor 0 and 1 are shown in Figure 31 and Figure 32, which are extracted from the Revit model of the building. These plans help understand how the space is divided and make it possible to recognise the new partition walls, the internal insulation layer and the position of doors and windows.

Figure 31 – Floor 0 Plan - Renovation (Coprat, 2023)

Figure 32 – Floor 1 Plan - Renovation (Coprat, 2023)

For the further developments of the work, it is interesting to note the methodology employed for creating the BIM Model of the historic "Casa del Capitano" in Verona, provided by Coprat company. The project was initiated with CAD base files provided by the client, which were subsequently transformed into a comprehensive BIM representation. The process involved on-site inspections and meticulous measurements to ensure accuracy, with necessary adjustments to rectify any discrepancies. In crafting the BIM model, custom families were carefully designed and incorporated. While the project team possessed an existing database, its application to historical structures was limited, given the necessity to align with the coding guidelines stipulated by the BIM Execution Plan (BEP). These guidelines, collectively formulated by the working group and the client, established the model's development and sharing framework.

The absence of a standardized norm has led to diverse practices across various studios, each often adhering to its own unique "standard." This progression typically follows the principle of "from the general to the specific." Many professionals opt for a coding system utilizing separators, similar to the one observed in the resources provided by Politecnica (Figure 33), the lead organization in the project consortium (COPRAT, 2023).

CLASS		DESCRIPTION		DETAIL		EXAMPLE
GENERIC	GN	Color Mass	n			
GYPSUM	GY	Gypsum Board	01			GY.01.03_Gypsum Board_Hydro
INSULATION	IN	Thermal Insulation	01			
		Acoustic Insulation	02	Mineral Fiber	01	
				MDF Fiberboard	02	

Figure 33 – Coding System Used in the Model (Coprat, 2023)

Assigning names to materials and systems is essential in conducting LCA analyses on the BIM model. This is because it directly influences the software's ability to identify elements and establish links with their corresponding EPDs, as will be explored in more detail in sections 4.3 and 4.4.

4.2 Checking the model: Verifying materials classification and name

Following the steps described in paragraph 3.2, it is possible to check the model to understand if all the data are allocated correctly to be read and recognised from One Click LCA. In the Project Browser window, all the project objects can be easily accessed and inspected (Figure 34). Selecting a specific object and isolating it in the view makes it convenient to verify if it possesses all the necessary properties (Figure 35).

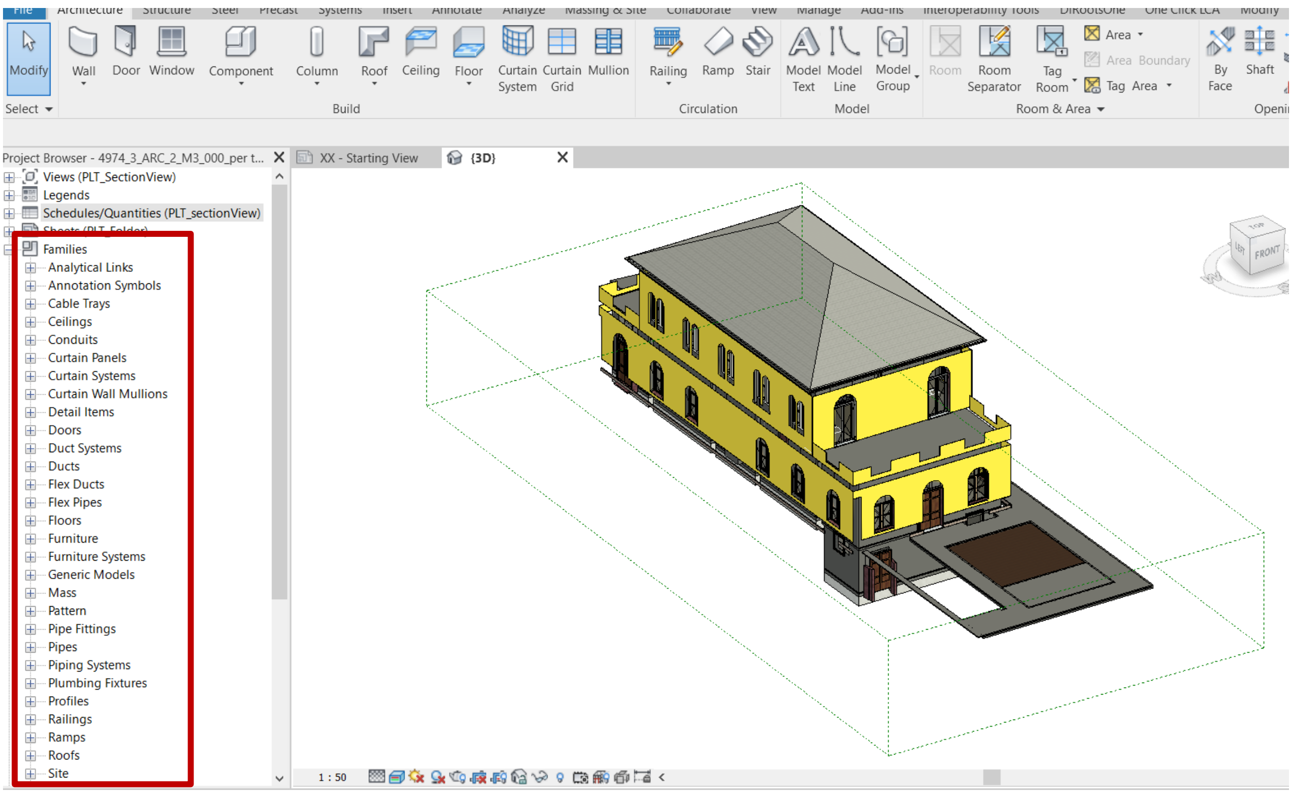


Figure 34 – Search for native configuration

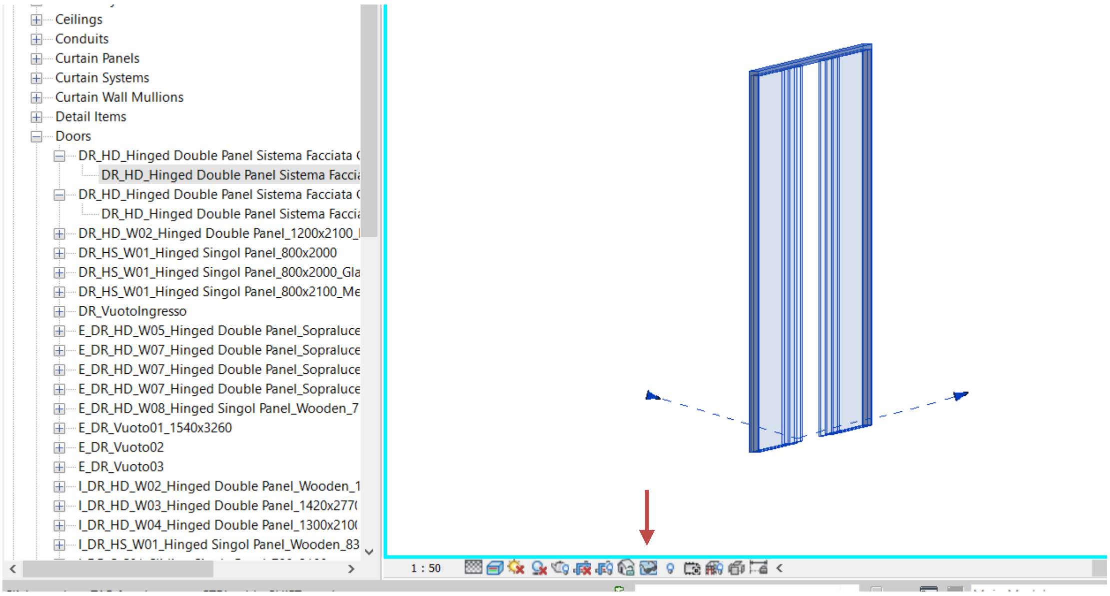


Figure 35 – Example of checking elements

To further examine the elements of interest, dedicated views can be created to isolate them (Figure 36). This isolation facilitates a thorough examination of their properties (Figure 37). Multiple views were set up to analyse individual classes, and a general view was also established to encompass all the analysed classes. This comprehensive view proves especially valuable when utilizing the One Click LCA plugin, as it allows the option to perform LCA exclusively on the objects within the view.

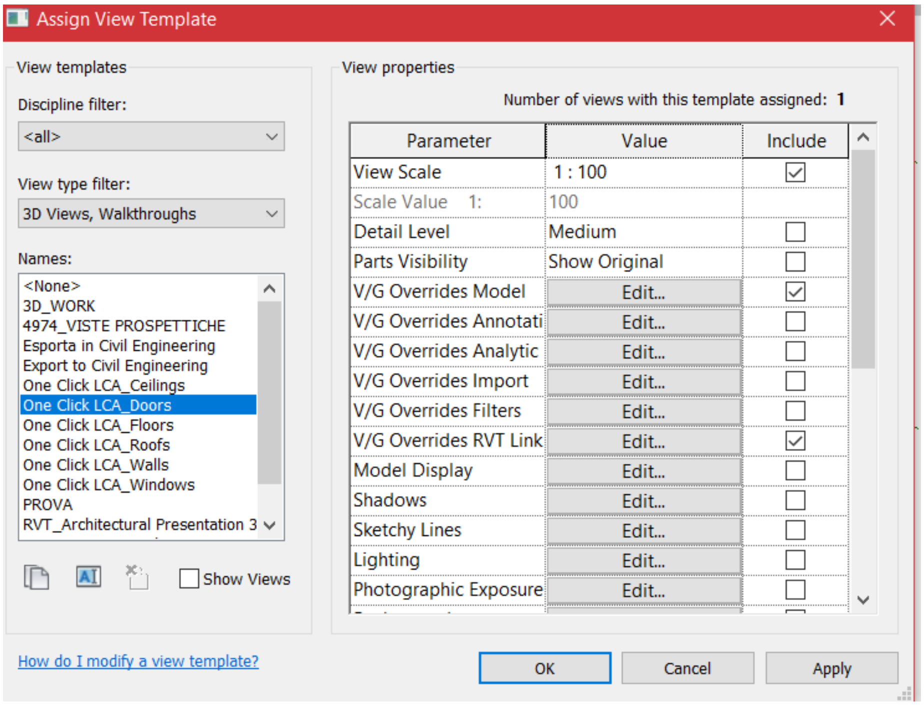


Figure 36 – Assigning View templates

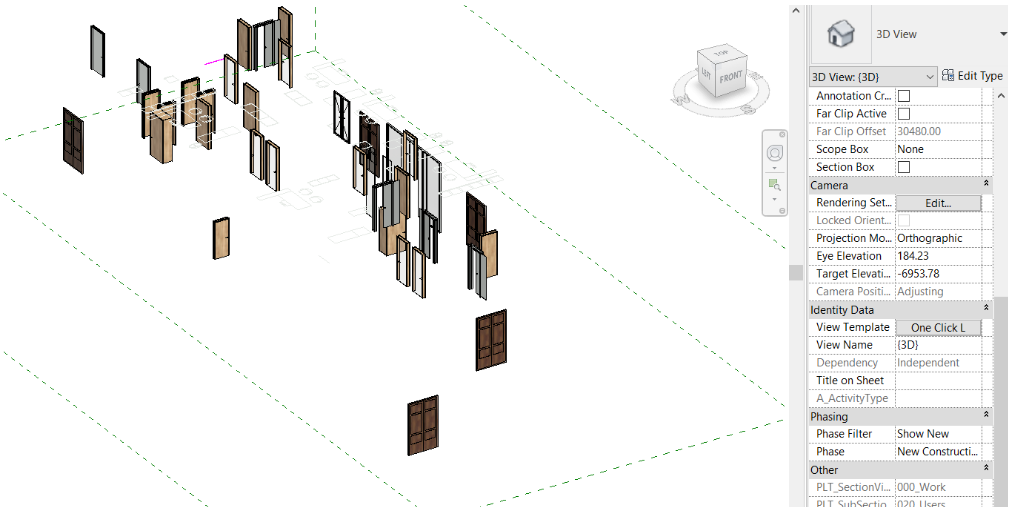


Figure 37 – Isolating elements through view templates

4.3 Running analysis in One Click LCA

After this first review, there is a first ty to run One Click LCA through the plug-in Revit. The first step is to log into the app (Figure 38) and add the project's settings. Since we have a prepared view with only the elements we want to analyse, we can select the option to analyse only the "Active view" (Figure 39). It is possible to set the benchmarks for this project, as shown in Figure 40.

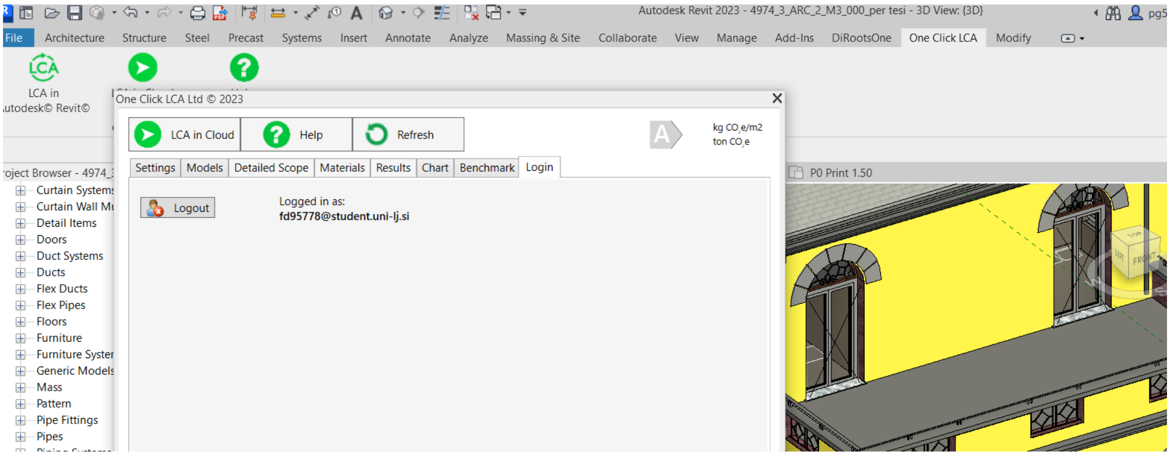


Figure 38 – Login in One Click LCA Plugin

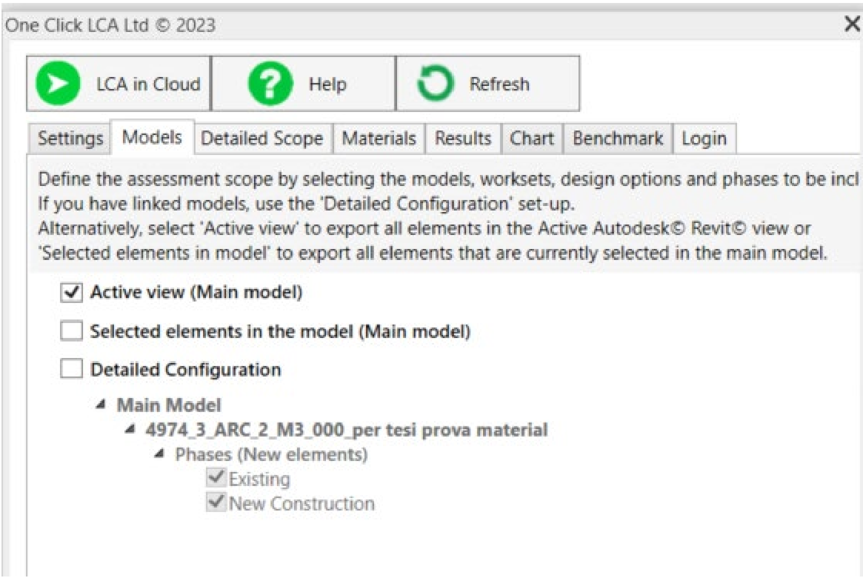


Figure 39 – One Click LCA settings 1

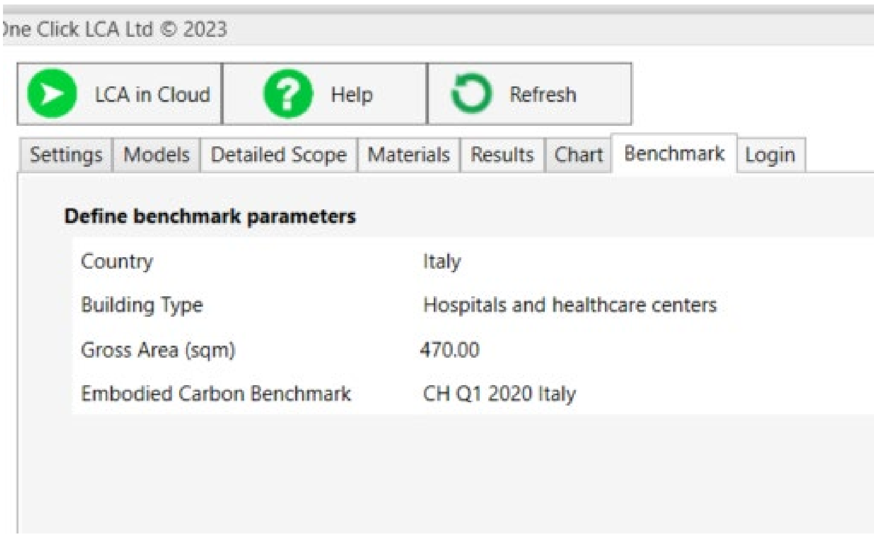


Figure 40 – One Click LCA settings 2

Once we have all set in the online tool (Figure 41 and Figure 42), we can run the LCA in the cloud, where we already created a project for this study.

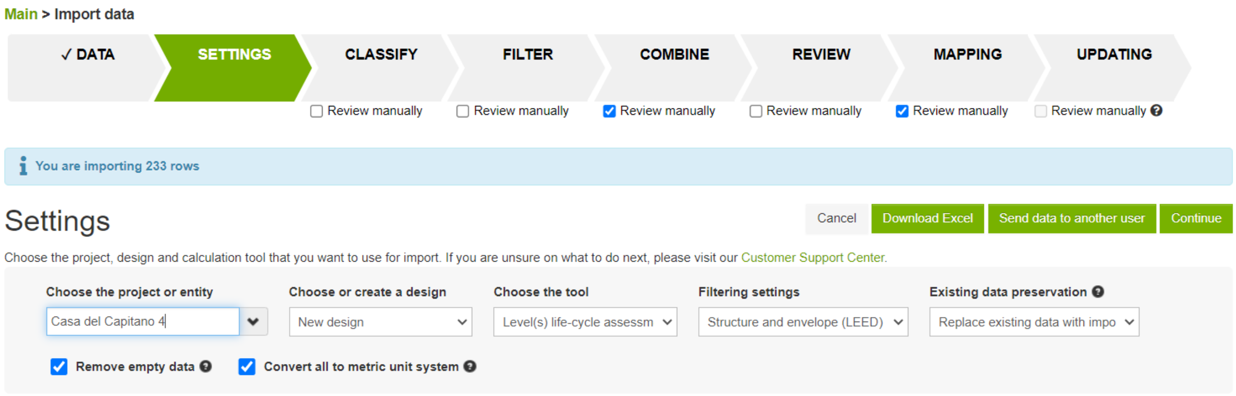


Figure 41 – One Click LCA project settings 1

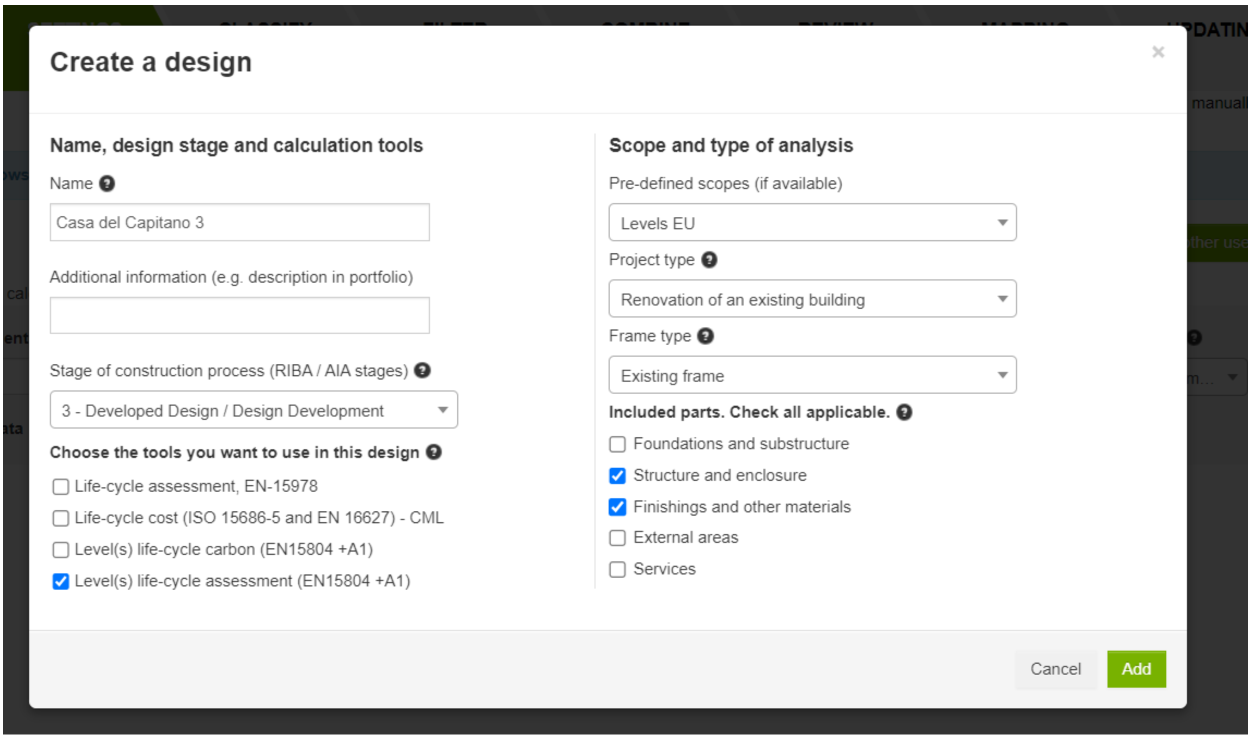


Figure 42 – One Click LCA project settings 2

As shown in Figure 43, 82.94% of the material is unidentified after this first run. This means that the One Click LCA algorithm could not find an automatic mapping for these materials, and it will be required to map them one by one on the website or in the plugin (Figure 44).

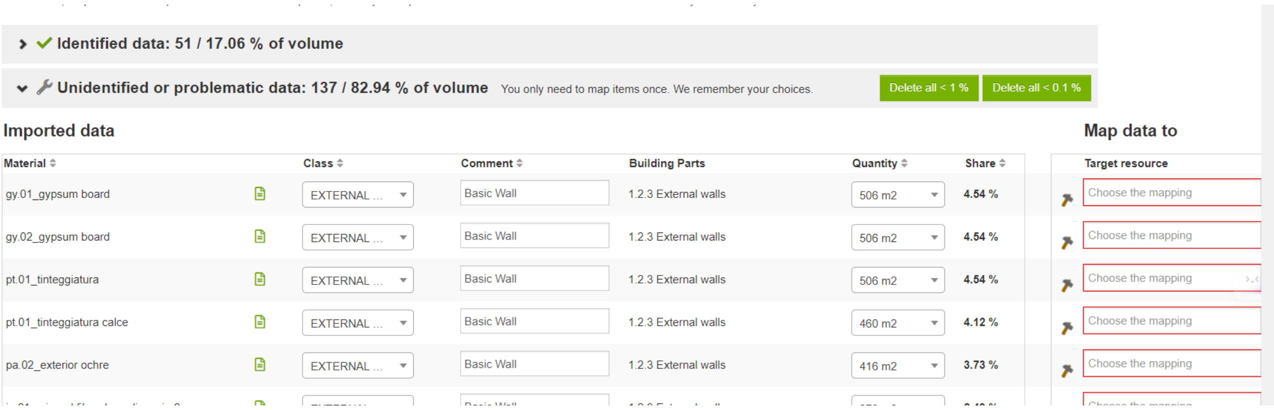


Figure 43 – One Click LCA Unidentified Data

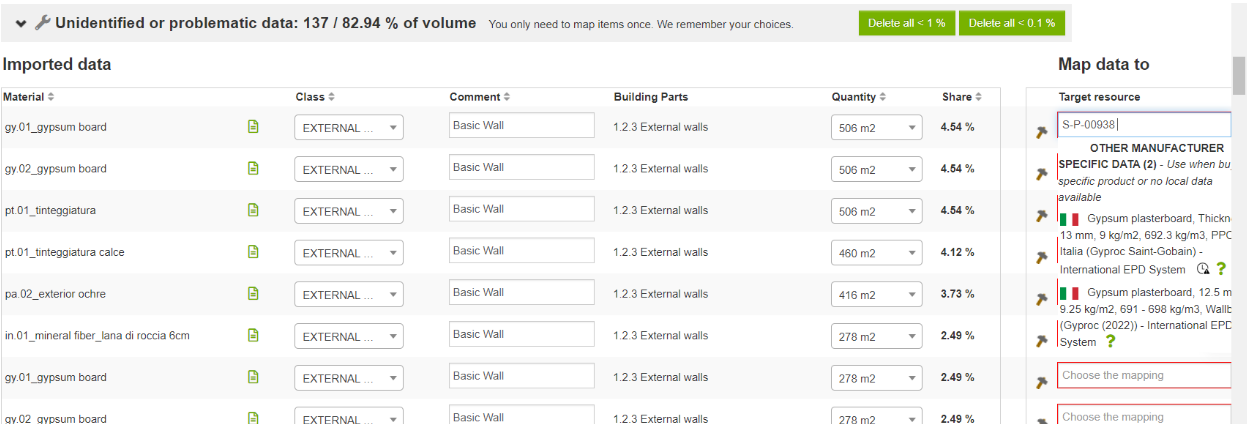


Figure 44 – One Click LCA Manual mapping Example

4.4 Renaming materials for LCA analysis

Various issues were identified during the meticulous examination of the selected project's elements. These ranged from simple misspellings of names (Figure 45) to unclear naming conventions for objects. We focused on addressing these issues to enhance the interaction between the Revit model and the One Click LCA tool, streamlining the process as much as possible.

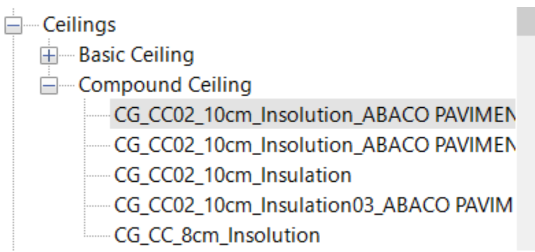


Figure 45 – Errors found in the naming of the ceiling's objects

As shown in the previous chapter, One Click LCA did not recognize some elements. Regarding family systems, such as walls, attempts were made to improve recognition by the One Click LCA software. One approach involved renaming families, to be more specific, using the DiRoots plugin Family Reviser (DiRoots, 2023), as shown in Figure 46 and Figure 47.

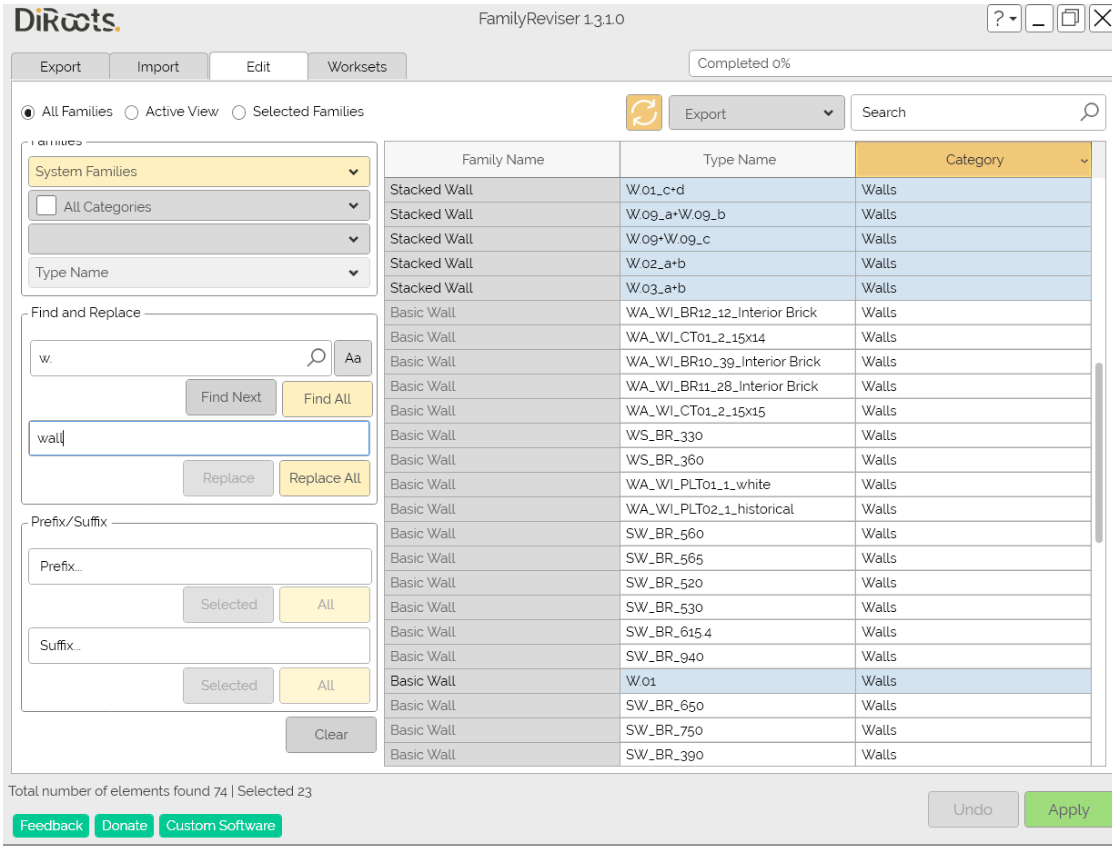


Figure 46 – DiRoots Family Reviser

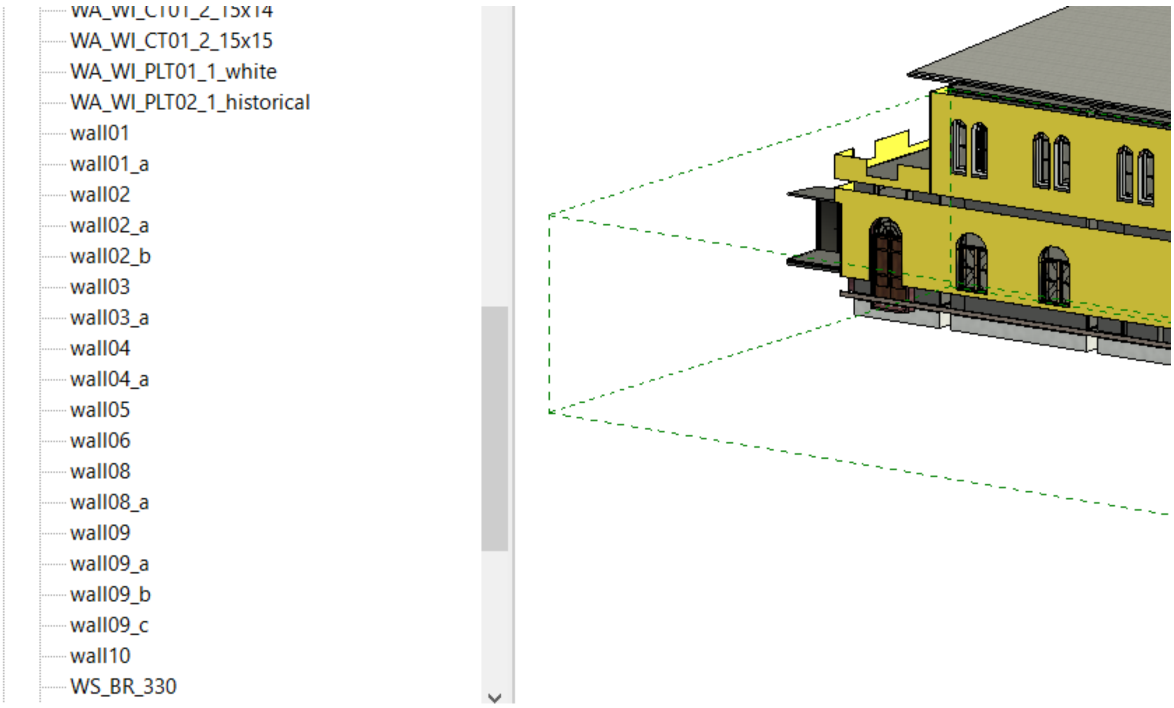


Figure 47 – Renaming of walls families

Despite these efforts, the mapping results in the LCA software remained unchanged, which resulted in a need for manual mapping of materials belonging to the walls, as depicted in Figure 48.

Confirm from the rows with identical label whether to apply the same mapping

Material	Class	Comment	Quantity	Toggle all
gy.01_gypsum board	EXTERNAL WALL	Basic Wall	278 m2 / 278 M2 / 13 mm	☐
gy.01_gypsum board	EXTERNAL WALL	Basic Wall	49 m2 / 49 M2 / 13 mm	☐
gy.01_gypsum board	EXTERNAL WALL	Basic Wall	48 m2 / 48 M2 / 13 mm	☐
gy.01_gypsum board	EXTERNAL WALL	Basic Wall	45 m2 / 45 M2 / 13 mm	☐
gy.01_gypsum board	EXTERNAL WALL	Basic Wall	44 m2 / 44 M2 / 13 mm	☐
gy.01_gypsum board	EXTERNAL WALL	Basic Wall	44 m2 / 44 M2 / 13 mm	☐
gy.01_gypsum board	EXTERNAL WALL	Basic Wall	26 m2 / 26 M2 / 13 mm	☐
gy.01_gypsum board	EXTERNAL WALL	Basic Wall	20 m2 / 20 M2 / 13 mm	☐
gy.01_gypsum board	EXTERNAL WALL	Basic Wall	17 m2 / 17 M2 / 13 mm	☐
gy.01_gypsum board	EXTERNAL WALL	Basic Wall	11 m2 / 11 M2 / 13 mm	☐
gy.01_gypsum board	EXTERNAL WALL	Basic Wall	6.93 m2 / 7 M2 / 13 mm	☐
gy.01_gypsum board	EXTERNAL WALL	Basic Wall	6.55 m2 / 7 M2 / 20 mm	☐
gy.01_gypsum board	EXTERNAL WALL	Basic Wall	2.8 m2 / 3 M2 / 13 mm	☐

Figure 48 – One Click LCA requirement of manual mapping

After conducting a more thorough analysis, it became clear that the issue did not lie in the family names, as they did not influence the tool's ability to recognize objects. Instead, the problem appeared to be related to the naming of materials.

To address this, the following approach involved modifying the names of certain materials not recognized by the tool. The objective was to align the material names more closely with the EPD labelling used in the software. Figure 49, Figure 50 and Figure 51 illustrate an example of this process and how it positively impacted the results within the software. For instance, the gypsum boards were initially not recognized by the software. An adjustment was made after analysing EPD naming conventions, and the material name was changed to "gypsum Plasterboard." This change significantly improved the software's ability to correctly identify and process the gypsum boards.

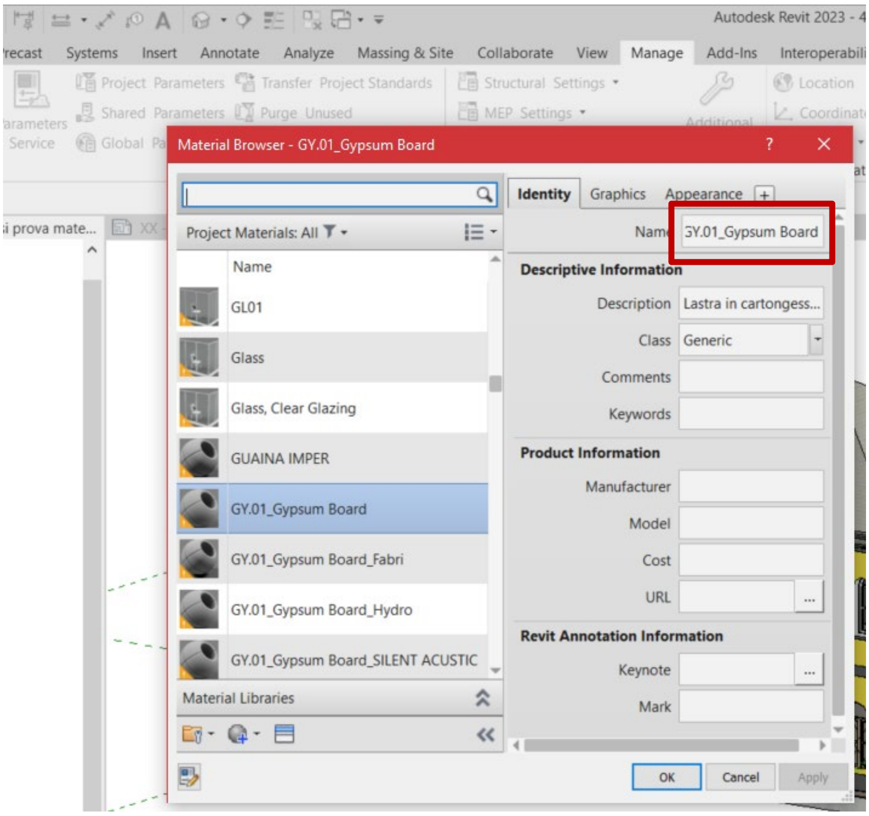


Figure 49 – Materials settings – Original material name

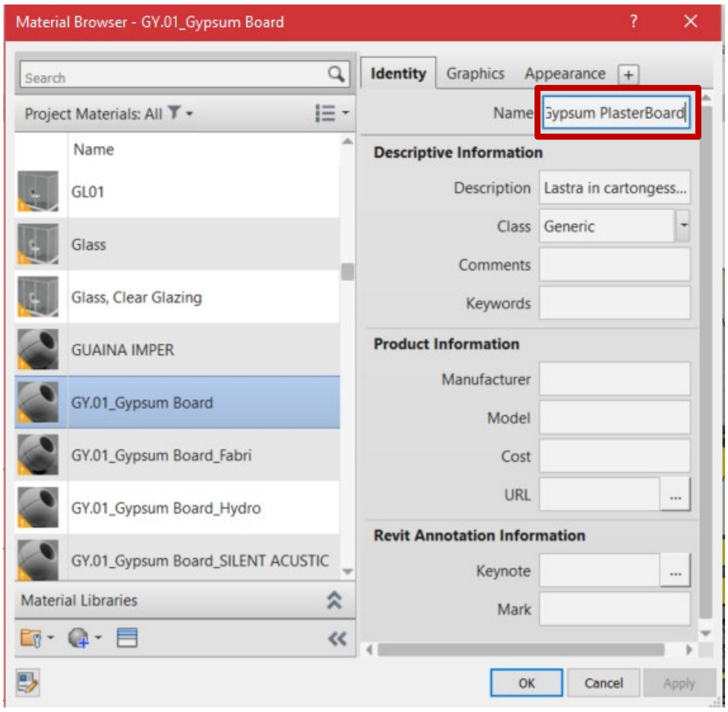


Figure 50 – Materials settings – Renaming the material

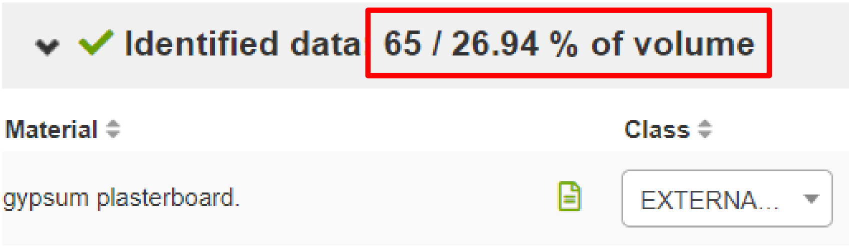


Figure 51 – Material automatically mapped in One Click LCA

The iterative process of refining material names based on standardized labelling conventions proved to be a critical factor in resolving recognition issues within the LCA software. As a result, the model's compatibility and accuracy with the One Click LCA plugin were substantially enhanced, leading to more reliable life cycle assessments. However, it turns out to be a very time-consuming task, but it could be accelerated with a simple Dynamo script, described in Figure 52. This links an Excel file already prepared with the old and new materials names, and substitute all of them in the same moment.

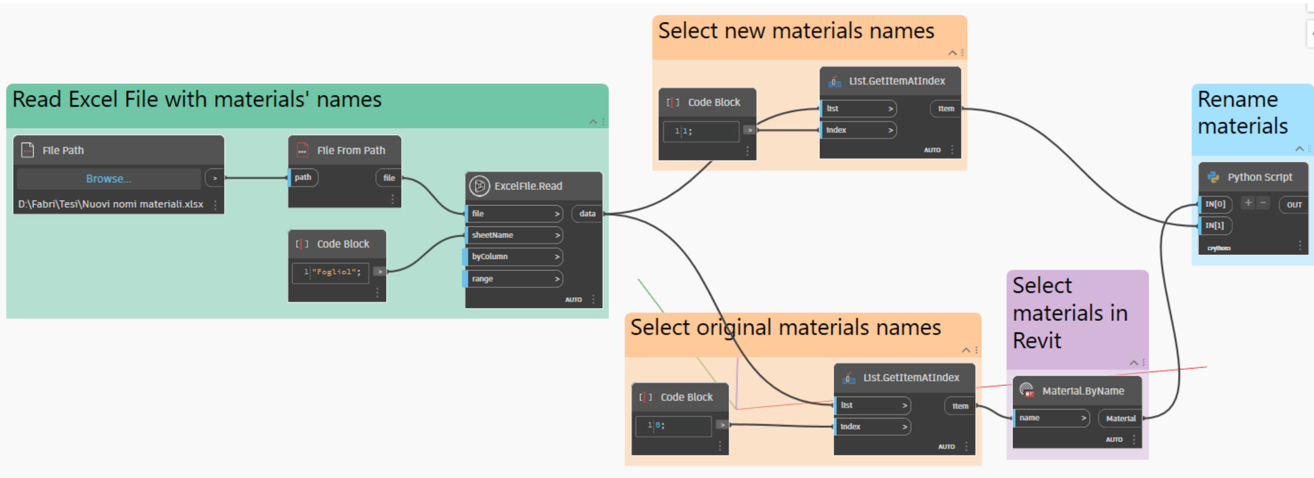


Figure 52 – Dynamo Script to rename materials

As we can see from Figure 53, after this renaming of the materials, the identified data passed from 26.94% to 58.51% of the total volume.

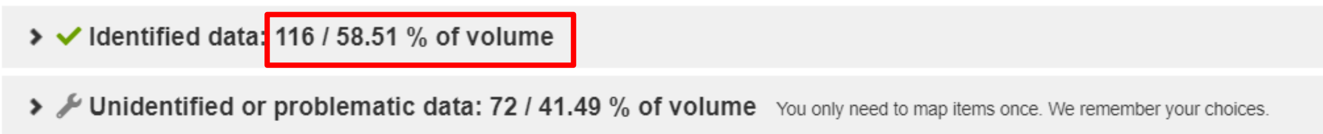


Figure 53 – Materials mapping in One Click LCA after the renaming process

After few reiterations of the process, in order to find the exact way to name all the materials to be recognize, they are all mapped in One Click LCA and the analysis can go on. Another valuable tool of this tool is the model checker (Figure 54), which allows us to understand the completeness of the model and if there are elements that we should still modify to obtain more accurate results.

LCA Checker overall grade: F. Grade is based on data you have provided.

LCA Checker overall grade: F

LCA Checker checks the embodied impacts plausibility. These results reflect plausibility for 1.0 m² project of type renovation of an existing building with frame type existing frame with scope consisting of structure and enclosure, finishings and other materials. To edit these parameters open LCA Parameters query. The result is intended as indicative of the plausibility; and exceptions may occur.

No.	Check description	Project value	Threshold value	Typical value	Unit	Type	Validated ?
1	**Gypsum board mass credible:** Gypsum board mass is unusual	39601.728	3 - 40		kg/m²	×	
2	**Gypsum board and plaster mass credible (no cement):** Gypsum and plaster mass is unusually high	39601.728	0.0 - 80		kg/m²	×	
3	**Insulation mass credible:** Insulation mass is unusual	8529.388	1 - 21		kg/m²	×	
4	**Horizontal materials mass:** Horizontal materials mass unusual	343923.14	100 - 1300		kg/m²	×	
5	**Glass and openings mass credible:** Glass and openings mass unusual	4121.113	2 - 25		kg/m²	×	
6	**Brick mass credible:** Brick mass is unusual	12251.254	0.0 - 100		kg/m²	×	
7	**Vertical materials mass:** Vertical materials mass is unusual	59691.912	50 - 700		kg/m²	×	
8	**Mortar mass credible:** Has no materials	0.0	0.4 - 50		kg/m²	×	

Figure 54 – Model Checker highlighting problems

4.5 Importing EPDs into Revit

To demonstrate the bidirectional interoperability between Revit and One Click LCA, it is crucial to establish not only one-way data exchange but also the capability to seamlessly transfer data back into the authoring software, effectively transforming it into a dynamic repository for continuous updates.

Following the completion of the analysis and the allocation of EPDs to all materials, as detailed in Section 4.4, the initial step involves utilizing the One Click LCA function to retrieve the EPDs, as illustrated in Figure 55. Additionally, a Word report, automatically populated with material information and linked EPDs (as shown in Figure 56), proves instrumental in this process. This report data can be conveniently exported into an Excel file, enhancing the efficiency of data management and update procedures.

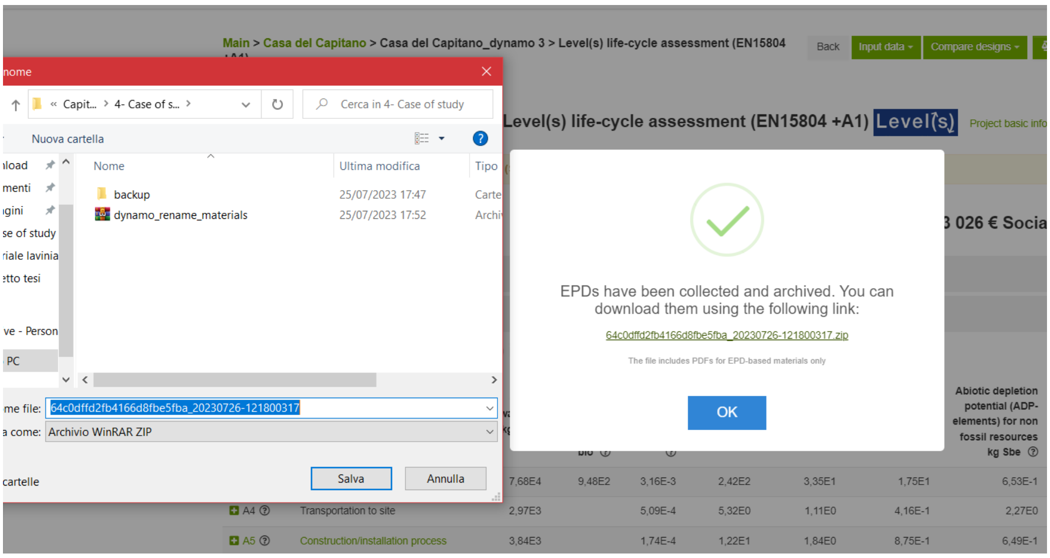
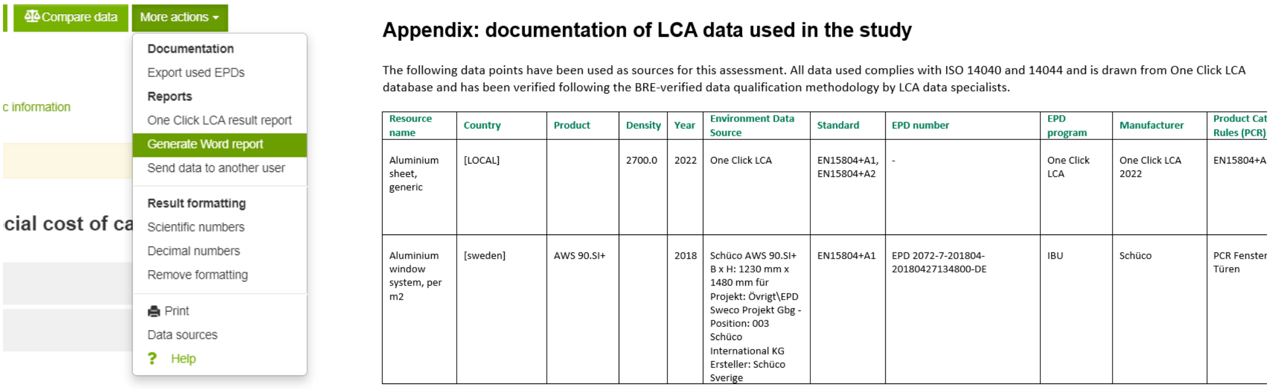


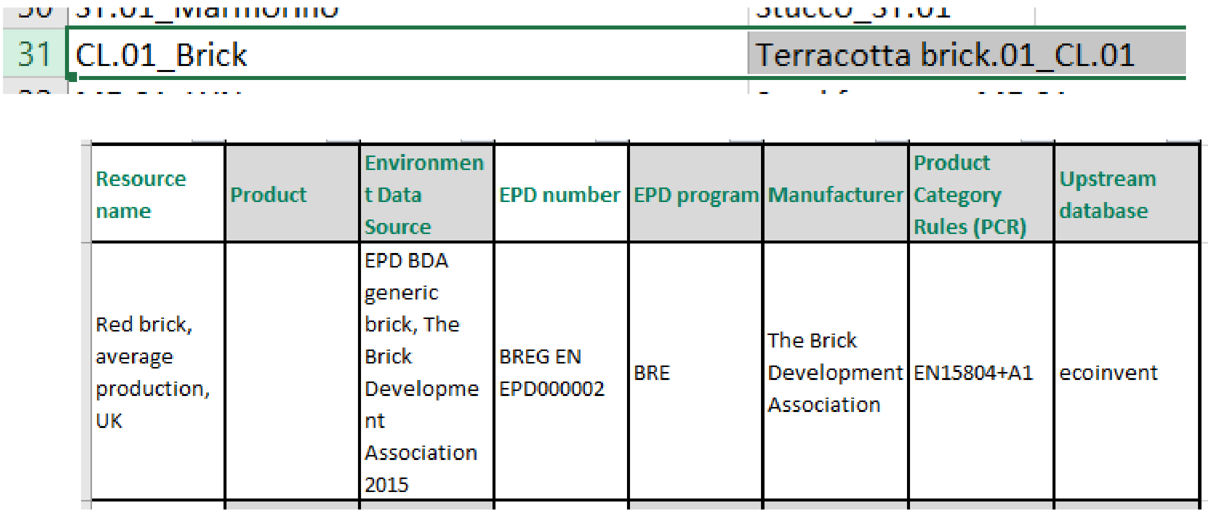
Figure 55– Downloading EPDs from One Click LCA



Resource name	Country	Product	Density	Year	Environment Data Source	Standard	EPD number	EPD program	Manufacturer	Product Cat Rules (PCR)
Aluminium sheet, generic	[LOCAL]		2700.0	2022	One Click LCA	EN15804+A1, EN15804+A2	-	One Click LCA	One Click LCA 2022	EN15804+A
Aluminium window system, per m2	[sweden]	AWS 90.SI+		2018	Schüco AWS 90.SI+ B x H: 1230 mm x 1480 mm für Projekt: Övrigt\EPD Sweco Projekt Gbg - Position: 003 Schüco International KG Ersteller: Schüco Sverige	EN15804+A1	EPD 2072-7-201804-20180427134800-DE	IBU	Schüco	PCR Fenster Türen

Figure 56 – EPDs table in One Click LCA Report

Throughout this procedure, an initial challenge emerged when it became evident that the report downloaded from the online platform contained all the requisite information, although the format was not correct, because it was using the general names of the materials. In contrast, for seamless integration with Revit, a higher degree of precision in naming was desired. This precision should align with the nomenclature employed to ensure recognition by the LCA tool, as illustrated in Figure 57.



Resource name	Product	Environment Data Source	EPD number	EPD program	Manufacturer	Product Category Rules (PCR)	Upstream database
Red brick, average production, UK		EPD BDA generic brick, The Brick Development Association 2015	BREG EN EPD000002	BRE	The Brick Development Association	EN15804+A1	ecoinvent

Figure 57 – Differences between Revit materials names and One Click LCA Report

Nonetheless, a deliberate decision was made to surmount this challenge and devise a strategy to advance our objectives or, at the very least, to progress as far as feasible. To serve as a comprehensive repository, the Revit model needed augmentation with new parameters associated with EPD data, capable of accommodating information imported from One Click LCA. To achieve this enhancement, we employed a plugin provided by DiRoots, known as ParaManager (DiRoots, 2023)(as depicted in Figure 58). This powerful tool facilitates the management, creation, population, and exportation of parameters in a remarkably straightforward and intuitive manner.

Upon activating the ParaManager plugin within Revit, we established new parameters tailored explicitly to EPD data, duly allocated within the materials category (Figure 59 and Figure 60). This systematic process was diligently repeated for all the requisite parameters, each meticulously outlined in Figure 61.

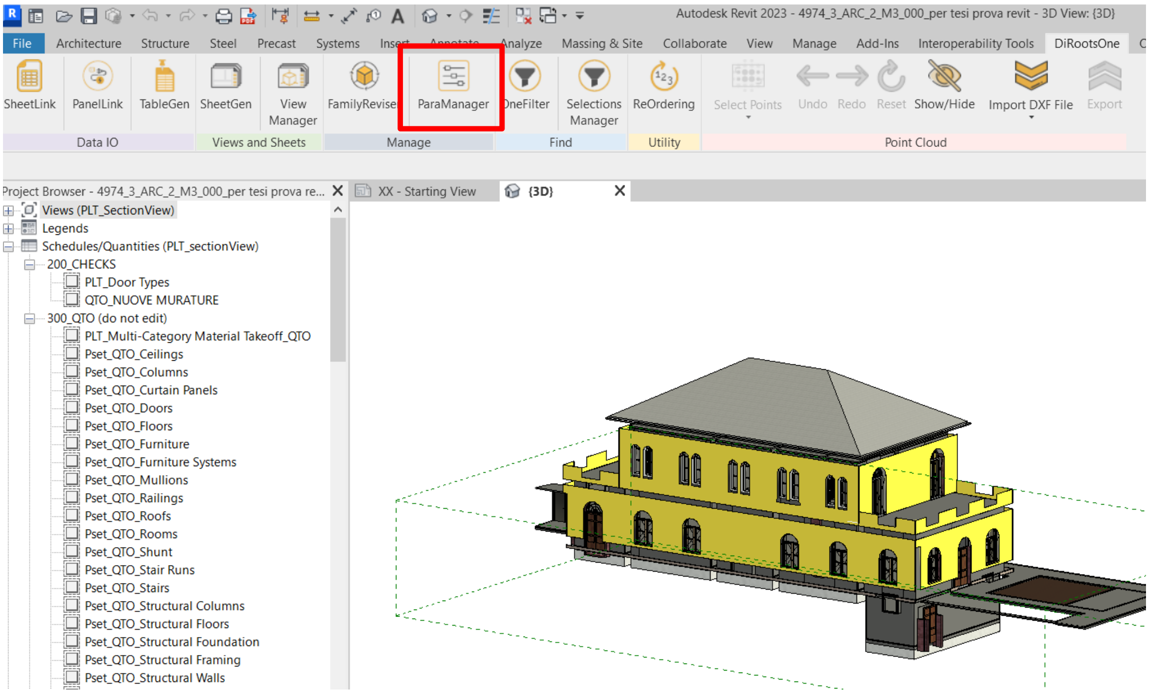


Figure 58 – ParaManager Plugin

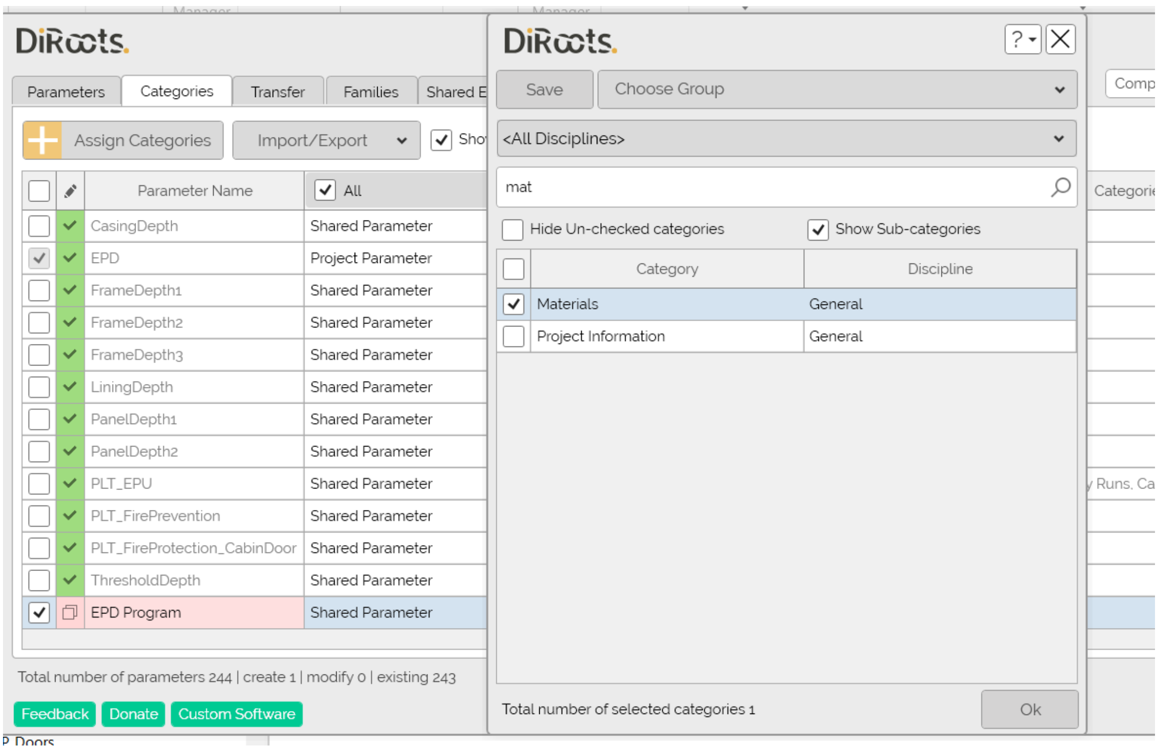


Figure 59 – Assigning new parameter to materials category

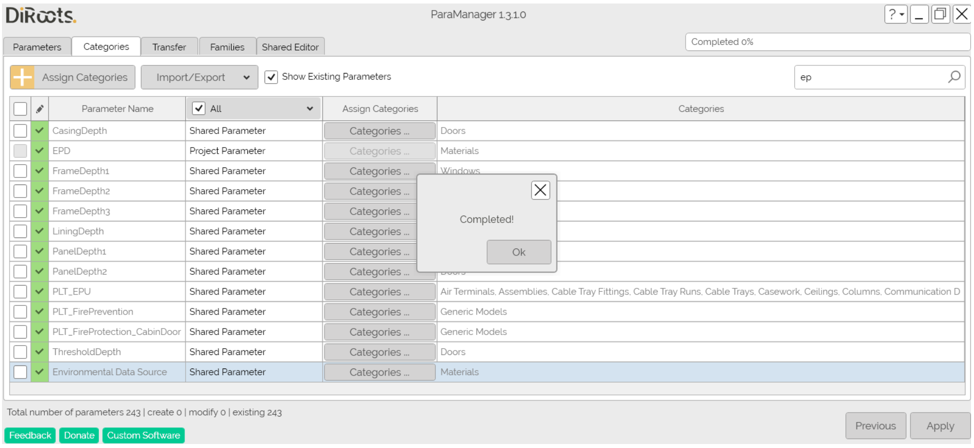


Figure 60 – Finalising the process of assignment

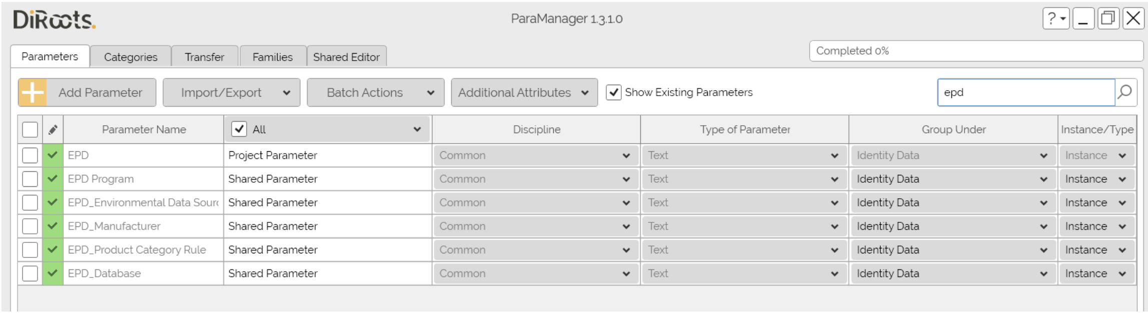


Figure 61 – Finalising the process of assignment

Upon inspecting the material properties, we can readily discern the incorporation of this novel set of parameters linked to EPDs, as illustrated in Figure 62, accessible through the materials manager within Revit. Our current objective centres on populating these parameters in the most straightforward and automated manner feasible. To achieve this, we use DiRoots plugins (DiRoots, 2023) and Excel spreadsheets.

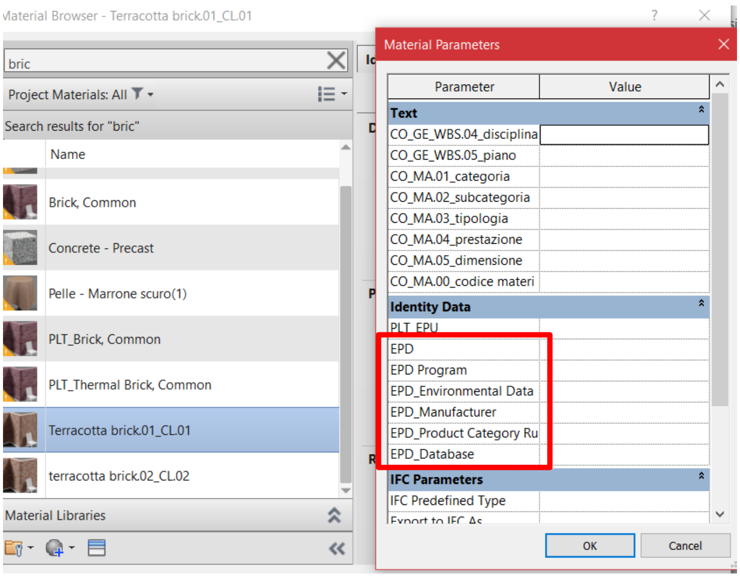


Figure 62 – Finalising the process of assignment

As previously mentioned, the incongruence in naming conventions between Revit and One Click LCA posed a notable challenge, emphasizing once more the imperative need for a standardized nomenclature across all stakeholders in this domain.

The initial endeavour to address this issue involved exporting the parameters and their associated materials to an Excel file facilitated by the SheetLink plugin (DiRoots, 2023), as depicted in Figure 63 and Figure 64.

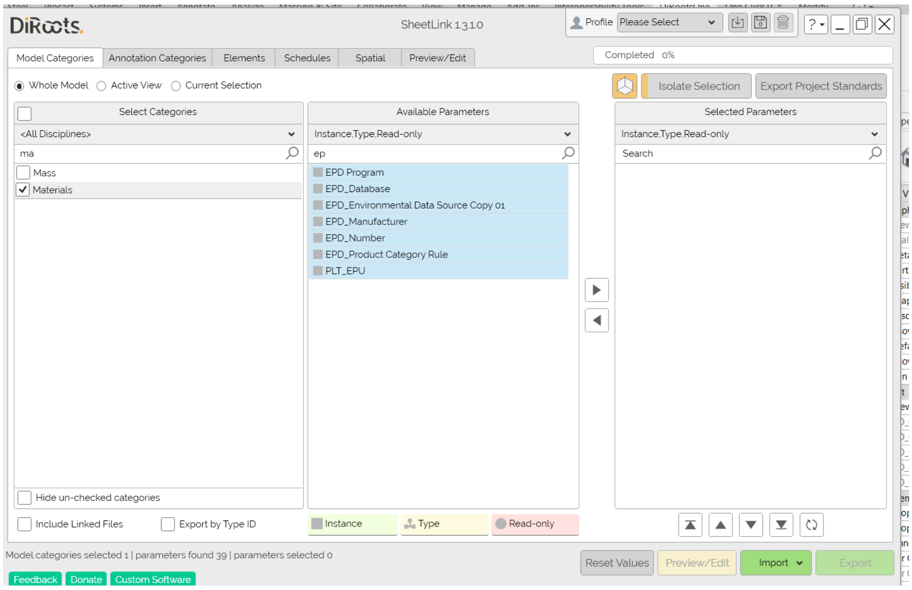
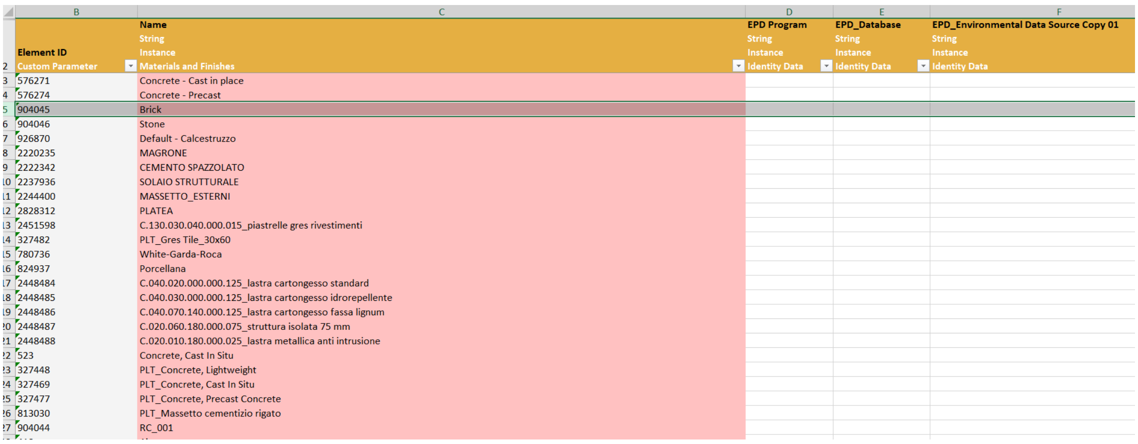


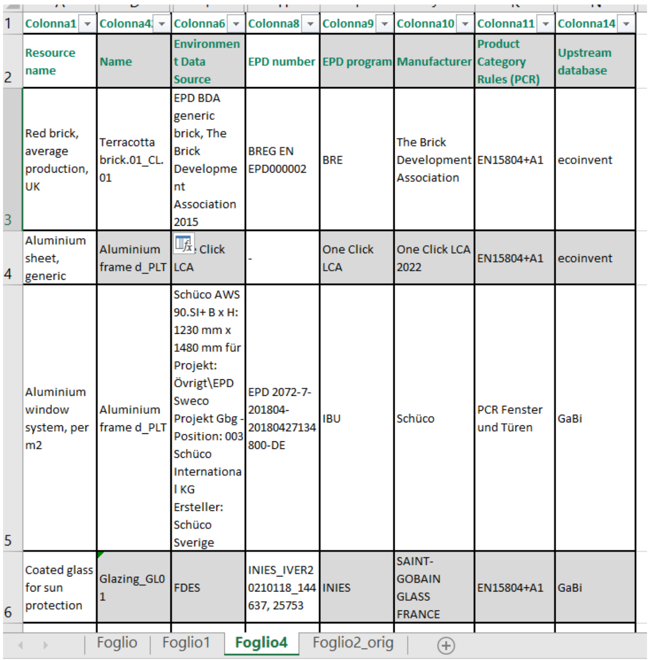
Figure 63 – Exporting Parameters



Element ID Custom Parameter	Name String Instance Materials and Finishes	EPD Program String Instance Identity Data	EPD_Database String Instance Identity Data	EPD_Environmental Data Source Copy 01 String Instance Identity Data
576271	Concrete - Cast in place			
576274	Concrete - Precast			
904045	Brick			
904046	Stone			
926870	Default - Calcestruzzo			
2220235	MAGRONE			
2222342	CEMENTO SPAZZOLATO			
2237936	SOLAIO STRUTTURALE			
2244400	MASSETTO_ESTERNI			
2828312	PLATEA			
2451598	C.130.030.040.000.015_piastrelle gres rivestimenti			
327482	PLT_Gres Tile_30x60			
780736	White-Garda-Roca			
824937	Porcellana			
2448484	C.040.020.000.000.125_lastra cartongesso standard			
2448485	C.040.030.000.000.125_lastra cartongesso idrorepellente			
2448486	C.040.070.140.000.125_lastra cartongesso fassa lignum			
2448487	C.020.060.180.000.075_struttura isolata 75 mm			
2448488	C.020.010.180.000.025_lastra metallica anti intrusione			
523	Concrete, Cast In Situ			
327448	PLT_Concrete, Lightweight			
327469	PLT_Concrete, Cast In Situ			
327477	PLT_Concrete, Precast Concrete			
813030	PLT_Massetto cementizio rigato			
904044	RC_001			

Figure 64 – Excel file exported

If naming conventions were uniform, the process would have been considerably streamlined at this stage, allowing for the straightforward population of the Excel file with data from the One Click LCA Excel sheet. However, an additional step becomes necessary due to the existing incongruence in how materials are designated. The material's name must be assigned to each specific EPD data-related row, as shown in Figure 65. This was a time-consuming task, done through Excel functions but almost one by one for each material and could have been avoided if the EPD downloaded from One Click LCA already had the same nomenclature provided in the Revit model.



Colonna1	Colonna4	Colonna6	Colonna8	Colonna9	Colonna10	Colonna11	Colonna14
Resource name	Name	Environment Data Source	EPD number	EPD program	Manufacturer	Product Category Rules (PCR)	Upstream database
Red brick, average production, UK	Terracotta brick.01_CL.01	EPD BDA generic brick, The Brick Development Association 2015	BREG EN EPD000002	BRE	The Brick Development Association	EN15804+A1	ecoinvent
Aluminium sheet, generic	Aluminium frame d_PLT	Click LCA	-	One Click LCA	One Click LCA 2022	EN15804+A1	ecoinvent
Aluminium window system, per m2	Aluminium frame d_PLT	Schüco AWS 90.SI+ B x H: 1230 mm x 1480 mm für Projekt: Övrigt\EPD Sweco Projekt Gbg - Position: 003 Schüco International KG Ersteller: Schüco Sverige	EPD 2072-7-201804-20180427134800-DE	IBU	Schüco	PCR Fenster und Türen	GaBi
Coated glass for sun protection	Glazing_GL01	FDES	INIES_IVER20210118_144637, 25753	INIES	SAINT-GOBAIN GLASS FRANCE	EN15804+A1	GaBi

Figure 65 – Adding the correct name to materials

Once this table is prepared, the initial export from Revit facilitated by SheetLink allows for the input of accurate values. Subsequently, it can be reimported into Revit, specifically referring to Figure 66 and Figure 67, utilizing the identical DiRoots plugin. Following the import process, the EPD parameters we had previously configured become populated with data obtained from One Click LCA. Consequently, we can ascertain the associated EPD based on the material properties and potentially download all of them for future applications.

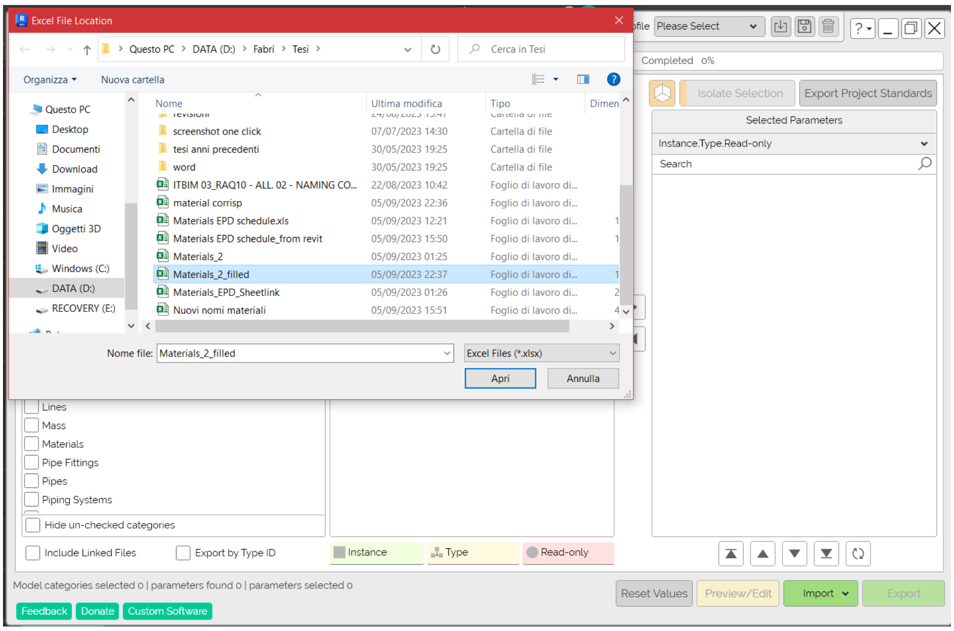


Figure 66 – Importing the EPD values

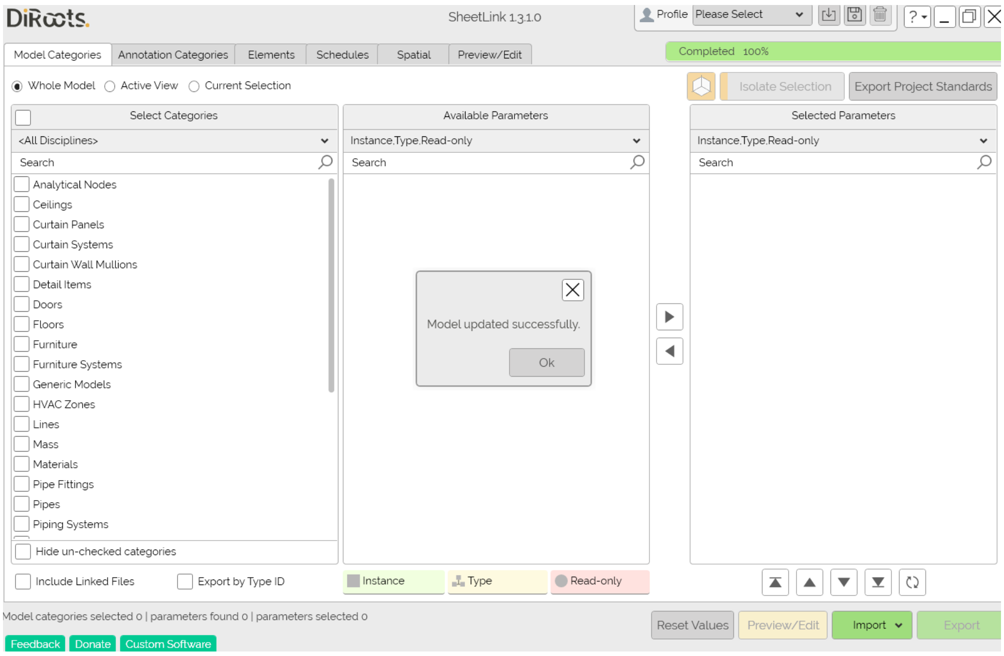


Figure 67 – Updating the model

We can verify this information in the material properties, as demonstrated in Figure 68, where it becomes evident that the parameters are now filled with the necessary information.

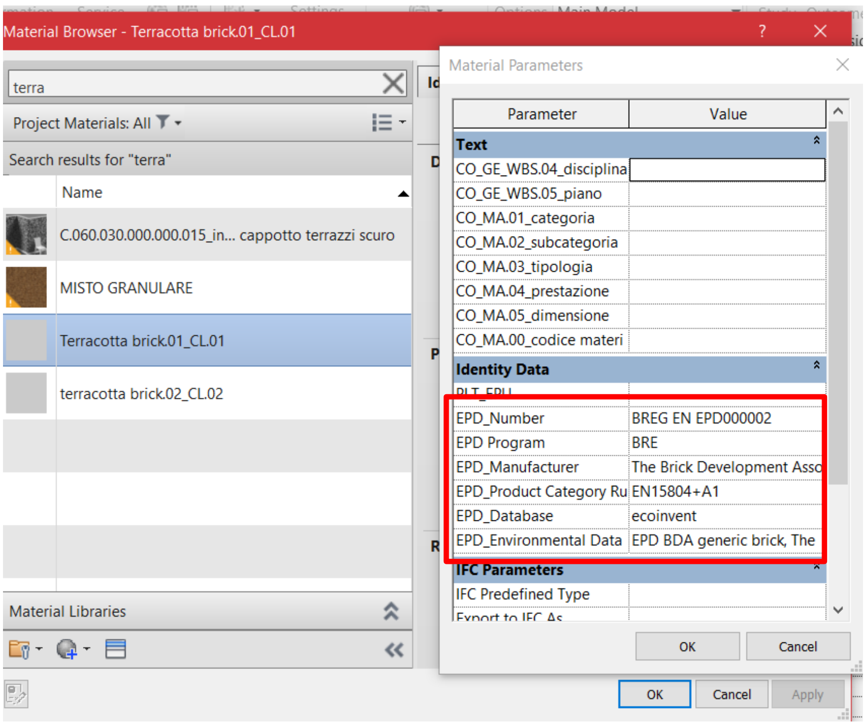


Figure 68 – EPD material properties

To get a comprehensive overview of all materials and ensure their correctness, it is feasible to generate a dedicated schedule, as depicted in Figure 69 and Figure 70.

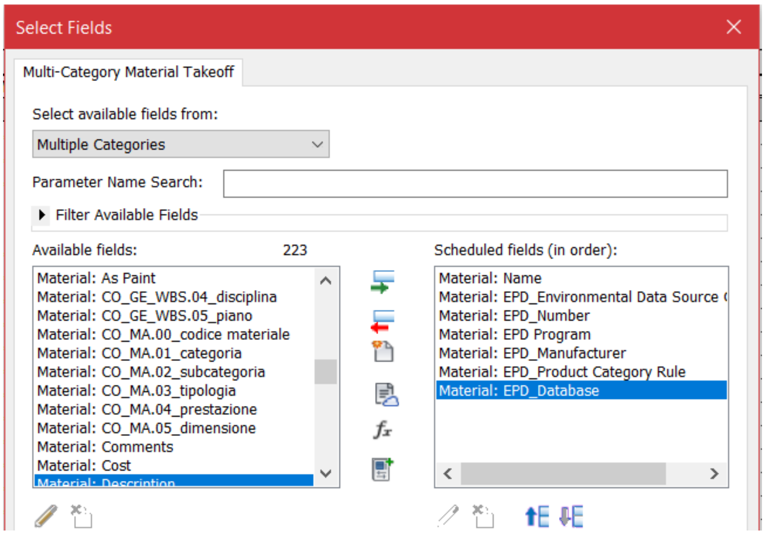


Figure 69 – Creating the EPD properties schedule

A	B	C	D	E	F	G
Material: Name	Material: EPD_Environ	Material: EPD_Number	Material: EPD Program	Material: EPD_Manufa	Material: EPD_Product	Material: EPD_Databas
Concrete cast-in-situ fl	EPD ViroDecs	S-P-01165	Australasian EPD Syste	Holcim (NSW and ACT	PCR 2012:01 Constructi	ecoinvent
Wooden frame window	FDES	INIES_CFEN20200421	INIES	INSTITUT TECHNOLOGI	EN15804+A1	ecoinvent
Paint lime_PT.01	EPD NHL based skim c	EPD-Miniera San Rom	Kiwa BCS	Miniera San Romedio	EN15804+A1	ecoinvent
Wooden frame door_W	Oekobau.dat 2017-I, EP	EPD-EGG-20140248-IB	IBU	Fritz EGGER	PCR Vollholzprodukte,	GaBi
Metal substructure_ME	Schüco AWS 90.SI+ B	EPD 2072-7-201804-20	IBU	Schüco	PCR Fenster und Türen	GaBi
Mineral (glass and sto	EPD Rock Mineral Woo	BREG EN EPD000097	BRE	Knauf	EN15804+A1	ecoinvent
Terracotta brick.01_CL	EPD BDA generic brick,	BREG EN EPD000002	BRE	The Brick Development	EN15804+A1	ecoinvent
Aluminium frame door	One Click LCA	-	One Click LCA	One Click LCA 2022	EN15804+A1	ecoinvent
Gypsum plasterboard,	ÖKOBAUDAT 2021-II (2	-	ÖKOBAUDAT	0	EN15804+A1	GaBi

Figure 70 – Checking the EPD data imported

Upon conducting the check, it becomes evident that the desired data are now present within the model, effectively serving as a repository for EPDs. If this process is initiated in the early project stages and materials are subsequently modified during the construction phases, the only necessary action is updating these properties to maintain alignment with the actual building's status.

4.6 Through green DT to Dynamic LCA

There are several possibilities to use Digital twin technology and LCA to estimate building embodied carbon and reduce carbon emissions in the construction industry. The proposed framework provides a cradle-to-cradle LCA approach that considers the entire life cycle of the building, including the use phase, maintenance, and end-of-life scenarios. This approach includes dynamic factors such as recurrent embodied impacts caused by maintenance and repair activities. The framework comprises three parts: BIM model implementation incorporating additional building objects, attributes, and relationships essential for conducting net-zero-carbon assessments throughout the asset's lifecycle, BIM and IoT integration, and BIM and LCA integration. The framework will be explained in theory since, in this study, there was no access to data to operate it practically.

The Industry Foundation Classes (IFC), developed by BuildingSMART, serves as an open and international schema for data exchange in BIM. Its purpose is to facilitate seamless models and information sharing across asset lifecycles. IFC accommodates various geometric representations and extensive semantic details, describing building elements, their attributes, properties, and interconnections using the EXPRESS specification language. However, the existing IFC schema lacks comprehensive support for conducting whole-life-cycle carbon assessments, particularly during the operational phase. Therefore, it becomes imperative to enhance the current IFC schema by incorporating additional building objects, attributes, and relationships essential for conducting net-zero-carbon assessments throughout the asset's lifecycle. Nonetheless, a research gap exists in integrating DT data with BIM for a comprehensive computational representation of vital decision factors crucial for supporting net-zero-carbon buildings. A pioneering framework is essential, merging BIM/IFC and DT into an internationally standardized computational representation. This integration spans the entire building lifecycle, streamlining decision-making and automated assessments for achieving more efficient buildings. Data obtained from the DT can be harmonized with BIM/IFC by incorporating both existing and new elements, attributes, and connections to model essential decision factors influencing net-zero-carbon outcomes in buildings. This integration follows a three-step process: data capture, processing, and representation. Upon acquiring and processing DT data, an ontology-based representation method is integrated with BIM/IFC extension. This method leverages three ontology components: entities, properties, and relationships. This approach constitutes the core mechanism for linking DT data with newly introduced elements, attributes, and relationships within the IFC extension. Consequently, DT data can be connected to both the 3D model and semantic details in the IFC extension. DT-acquired data can be integrated into an extension to represent crucial subsets of decision variables affecting net-zero-carbon outcomes during the operational phase. For instance, by capturing the building envelope and energy system statuses, DT supports management, maintenance, and retrofit decisions. The collected data informs corresponding key variables in the operational phase, as presented within the BIM/IFC extension. DT captures two types of data: the actual state of the building and upgrades to the building envelope and energy systems. DT gathers data during the operational stage for the existing building conditions, which are then processed and incorporated into the extension. These data pinpoint building faults, aiding maintenance decisions that impact operational or embodied carbon. DT also acquires data on upgrades to the building envelope and energy systems, which are subsequently processed and integrated into the extension. This information supports retrofit decisions based on the original building asset condition, monitors retrofit progress, and updates post-retrofit status, enhancing energy efficiency during building operation. Figure 71 illustrates how these data are captured by DT and represented using ontology-based methods, then integrated into an extension during the operational phase. These data points include upgrading different elements, comprising materials and construction elements replacement. In this way the continuing monitoring of the system could be part of the ontological representation of the model and directly and continuously contribute to the entire LCA assessment of the building, considering not only operational but embodied energy too. (Shen et al., 2022)

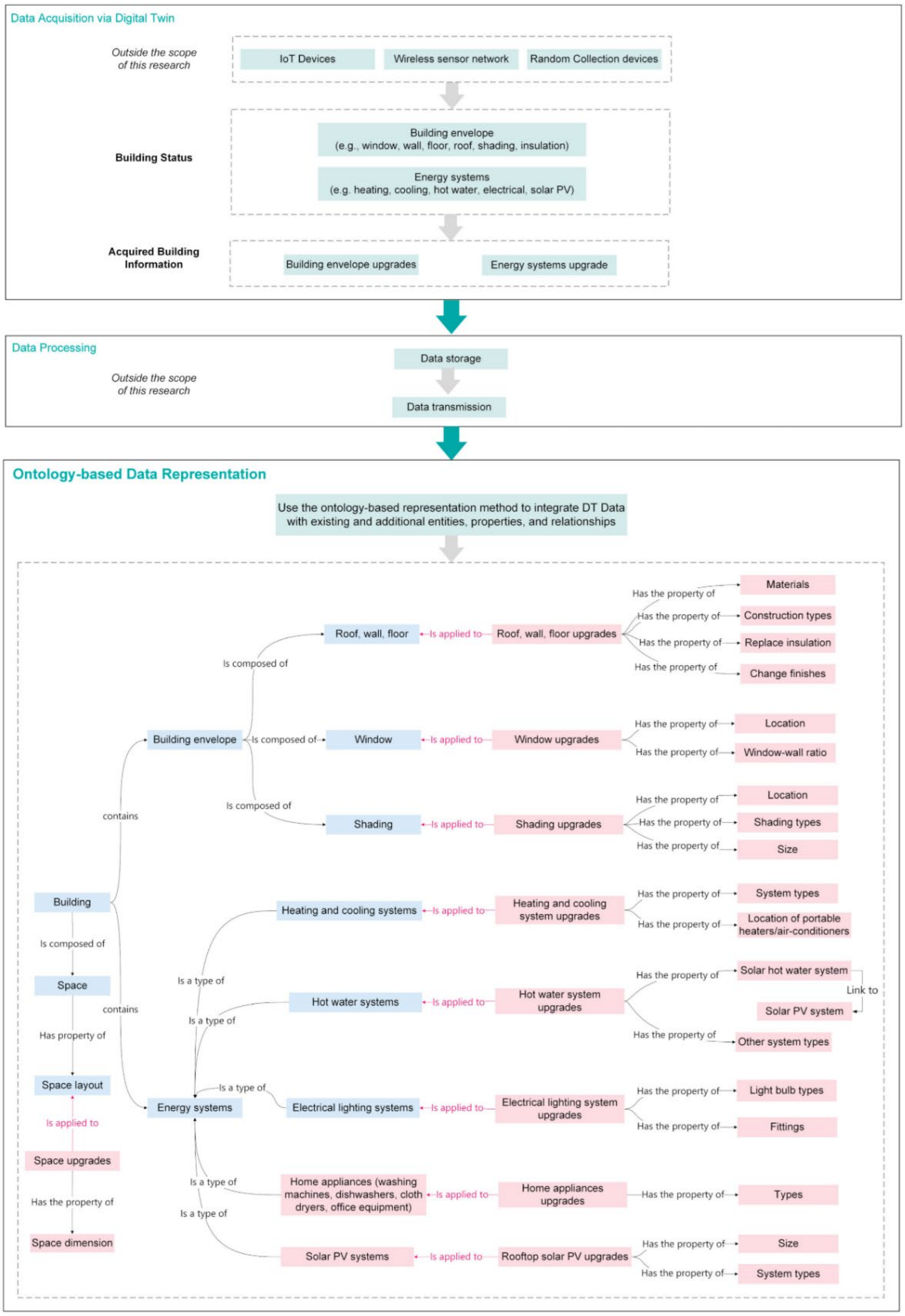


Figure 71 – Illustration of DT data integrated into extension using the ontology-based representation method to represent key decision variables at the operational stage (Shen et al., 2022)

If standardized, the utilization of a precise ontology for describing elements and processes could be replicated in EPDs and, in essence, in product specifications as a whole. This would establish a robust foundation for seamless interoperability between the BIM model and LCA tools. As elucidated in sections 4.4 and 4.5, this automated recognition has not yet been fully achieved and remains a challenge, adding complexity and time requirements to the LCA assessment process.

As said in the previous sections, converting a BIM into a digital twin involves the process of gathering, analysing, and visualizing data. This data, often collected over time by sensors, has the potential to reshape how people engage with constructed environments. For instance, as demonstrated by researchers, this concept is being applied to various domains like smart contracts, facility management, and maintenance. Before deploying a network of sensors, it is crucial to define their scope precisely. This entails determining sensor placement, the data they will collect, and the communication protocol to be used. Common sensor choices encompass temperature, humidity, light, sound, pressure, ultrasound, CO_2, VOC, and motion sensors. However, the level of detail in the data to be gathered should dictate the number of sensors to be installed. Effective communication technology is paramount to real-time data collection. An emerging solution, discussed extensively in recent literature, is using Low Power Wide Area Networks (LPWANs) like LoRa (Low Range). A LoRa (Long Range) network is a wireless technology designed for long-distance, energy-efficient communication between devices. It's optimized for transmitting small amounts of data at low rates and is ideal for applications like IoT and sensor networks. LoRa's features include extended coverage, low power consumption, and the ability to penetrate obstacles. It operates in unlicensed frequency bands, supporting a large number of devices. This makes it cost-effective for applications such as smart cities, agriculture, and industrial monitoring. LoRa facilitates sensor connectivity over considerable distances, often hundreds of meters between nodes. Within this setup, the sensor nodes transmit data via the LoRa network to a designated node responsible for aggregating and integrating the data into a database. This could allow us to monitor the conditions of the indoor environment at each moment, which is also related to the performance of the envelope and of the materials that constitute it, giving us the perception of the behaviour of the different materials during time, of if and when they should be substituted, or comparison between different options choose (Tagliabue et al., 2021). In the LCA field could be also interesting the use of RFID (Radio-Frequency Identification) and blockchain, which are two different technologies with significant potential for various applications, including industrial and logistics sectors. RFID technology uses radio fields to identify and track objects with RFID tags. The RFID tag consists of a microchip containing a unique identification and an antenna to communicate with an RFID reader. When the tag is exposed to the radio field of the reader, it transmits the information stored in the chip, allowing for the identification of the object, its location, and other relevant data. Applications of RFID include tracking goods in the supply chain, managing business assets, monitoring livestock, access control, etc. RFID offers greater efficiency and accuracy in tracking objects compared to traditional methods. Blockchain is a Distributed Ledger Technology (DLT) that enables the creation and maintenance of secure and immutable records of transactions or data. The combined use of RFID and blockchain can bring numerous benefits, especially in supply chain management and product traceability. RFID can provide real-time data on the location and status of objects, while blockchain can ensure the integrity and security of that data. For example, a product can be equipped with an RFID tag to monitor its movement through the supply chain. Whenever an RFID reader scans the object, the information about its location is recorded as a transaction on the blockchain. This way, the product-related information becomes immutable and traceable along the entire journey, providing greater transparency and traceability. In the LCA field, RFID technology has the potential to be utilized in a DT platform designed for real-time asset tracking in construction and the built environment. By integrating RFID-based digital twin technology, conducting LCA evaluations for buildings becomes feasible. This is achieved by ensuring the LCA database aligns with the level of detail present in the BIM model, enabling seamless and bi-directional automatic data exchange between the two databases. This makes the LCA analysis refer to the exact moment it is conducted and is always updated with the latest information in a dynamic context. (Lavinia Chiara Tagliabue et al., 2023)

After adapting the BIM model and its transformation into a DT, with all the necessary information to exchange information with the sensors, which can provide constantly updated and changing data, it is essential that this input can be included in the LCA calculations. To practically implement this framework, a consistent definition and decomposition method for building parts can be used to standardize the data collection and data entry process among different stakeholders in the value chain to ensure and sustain data quality in the system. An aggregated data structure design of the LCA database, which follows the granularity of the BIM model, can facilitate two-way automatic data exchange between the two databases to enable fast assessment of the total embodied impact of the building for different design options in the early design stages. Additionally, a survey on the current status of different types of buildings in the region can be conducted to adapt the LCA database and the classification system for organizing information on buildings to local conditions. The RFID-based digital twin platform could be used to track the materials and products used in a building project in real-time, providing more accurate data on the quantity and type of materials used. This data could then be integrated with One Click LCA to improve the accuracy of the embodied carbon estimates. Additionally, the proposed method for establishing an automated link between BIM and LCA databases could also be used to streamline the data collection and analysis process in One Click LCA. By automating the data exchange between the BIM and LCA databases, users could more efficiently and accurately estimate the embodied carbon of their building designs. (Chen et al., 2021)

Another factor we can keep in mind in the transformation of the LCA analysis into a dynamic one is the energy mix shifting toward more sustainable solutions in the future. The European Commission has put forward a framework for energy pathways towards 2050 to achieve the target of reducing greenhouse gas (GHG) emissions. According to this strategy, the aim is for 75% of European electricity consumption to be supplied by renewable sources. This will involve a transformation in the mix of electricity production and advancements in the efficiency of the energy system. The scenario also involves making temporal changes to heat production systems, which include reducing nuclear production, modernizing power plants, and upgrading existing combined fossil-fuelled heat and power (CHP) plants. Additionally, there are plans to develop renewable heat production (EU, 2019). The Italian government has placed energy and climate issues at the forefront of its political agenda. The national energy and climate plan has set ambitious targets for renewable energy, aiming to achieve 30% of total energy consumption and 55% of electricity generation from renewables by 2030. Italy's energy policy strongly favours renewable energy sources, leading to impressive growth in the renewable energy sector and the successful integration of large amounts of variable renewable generation. Cost containment is a priority, and policies aim to bring deployment costs in line with international benchmarks. The country has made progress in liberalizing the energy market and developing infrastructure, particularly in the electricity market, where transmission improvements and market coupling have resulted in price convergence nationwide. However, advancements in the gas sector have been slower, and further progress is needed to establish Italy as a southern European gas hub. Additionally, there is a need to reform and strengthen institutional arrangements within the energy sector, which are currently complex. The government is reviewing incentives and subsidies that are not considered efficient or aligned with decarbonization goals. Discussions are ongoing regarding taxation in the energy sector, and measures will be taken to protect economically vulnerable categories. Overall, Italy is taking significant steps towards a more sustainable and renewable-focused energy landscape, as shown in Figure 72 below. Considering the objectives of sustainability that the county aims to reach, it is highly likely that the energy mix proportions will change in the future in favour of a more renewable energy-based approach. (IEA - International Energy Agency, 2023)

A pragmatic approach currently involves forecasting the evolution of Italy's energy mix and devising a mechanism to incorporate this projection into our LCA tool. This strategy would provide valuable insights into how environmental impacts are anticipated to change over time, facilitating a comprehensive understanding of the evolving sustainability landscape. To achieve this, a potential way could be to draw comparisons with a country that has made significant strides in the green energy transition, such as Spain. Like Italy's, Spain's favourable geographical positioning positions it as a leader in Europe's renewable energy sector. Both countries strongly emphasise solar and wind power, with considerable solar energy production capabilities and ongoing efforts to curtail fossil fuel consumption. A comparison with Spain could offer insights into the potential trajectory of Italy's energy transition, helping to elucidate the potential impacts of different energy scenarios in Italy's LCA context. Spain's notable success in renewable energy adoption can be exemplified by the significant portion of its energy mix represented by renewable sources, particularly solar and wind power. In 2020, renewables contributed to 43.6% of Spain's total electricity generation, compared to the 37% of Italy, underscoring the country's commitment to sustainable energy practices. Spain's progressive actions include the plan to shutter coal-fired power plants by 2028 and the decision to ban offshore oil and gas extraction by 2040. This forward-thinking approach aligns with the European Union's mandate, as Spain strives to generate at least 74% of its electricity from renewable sources by 2030 (Rystad Energy, 2023).

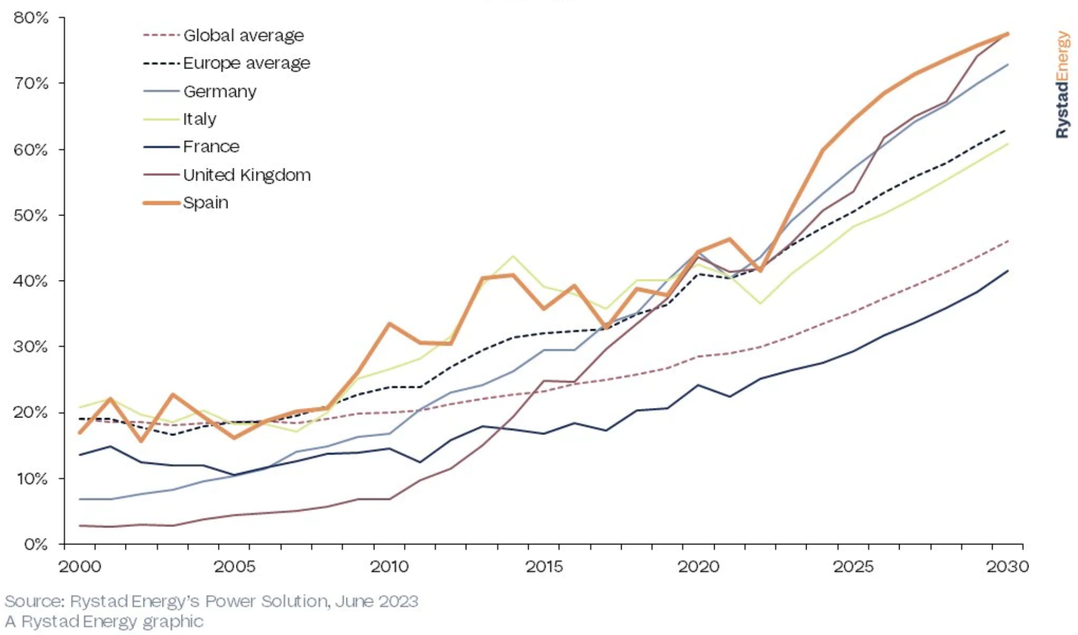


Figure 72 - Spain's share of power generation from renewables in percentage (Rystad Energy, 2023)

With the tool at our disposal, the One Click LCA database, it was an attempt to change the energy mix from Italy to Spain to see if something would be different in the results. The parameter changed was the electric energy used. This change was performed on the same design option in One Click LCA, Casa del Capitano 2 (Figure 73).

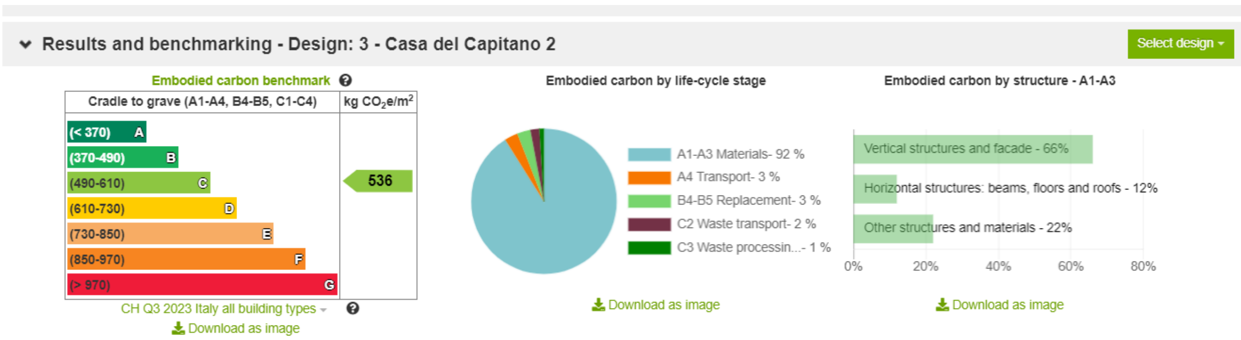


Figure 73 - Casa del Capitano 2

The company Coprat played a pivotal role by providing the data regarding the heating and cooling power requirements as outlined in their comprehensive report. A systematic approach was employed to determine the annual energy consumption for the heating and cooling systems. Firstly, the heating and cooling power, expressed in kilowatts (kW), was acquired. This served as the initial step in the calculation process. Subsequently, the operating time, measured in hours, was determined based on the building's heating and cooling schedule provided in the company's report. The efficiency of all equipment installed was considered remarkably high, a crucial factor that significantly impacts energy consumption. Finally, the formula for electricity consumption was applied, considering the thermal power, operating time, system efficiency, and the conversion factor for electricity. These meticulous calculations were instrumental in arriving at an estimate of the building's annual energy consumption for heating and cooling, through the Equation 1:

$$Electriciy\ Consumption\ (kWh) =$$
$$Heating\ Power\ Requirement\ (kW) x\ Operating\ Time\ (hours) x\ Efficiency\ of\ the\ System\ (90\%)$$
$$x\ Conversion\ Factor (1) \quad (1)$$

where:

Heating Power Requirement: This refers to the amount of heat (in watts or kilowatts) needed to maintain the desired temperature inside a building during winter. It depends on factors like the size of the building, insulation, outdoor temperature, and the desired indoor temperature.

Operating Time: This is the number of hours per day the heating system operates. It depends on the building's heating schedule and how long the heating system needs to run daily.

Efficiency of the System: The efficiency of an electric heating system indicates how effectively it converts electrical energy into useful heat. For instance, if a heating system is 100% efficient, all the electrical energy it consumes is converted into heat with no losses. In real-world scenarios, efficiency values can vary.

Conversion Factor: This factor depends on the type of energy used for heating. In this case, the conversion factor is typically 1 since electricity is used, meaning 1 kWh of electrical energy is equivalent to 1 kWh of heat.

$$E(heating) = 64{,}648\ kW\ x\ 14\ h\ x\ 0{,}9\ x\ 1 = 814{,}56\ kWh \quad (2)$$

$$E(cooling) = 63{,}379\ kW\ x\ 14\ h\ x\ 0{,}9\ x\ 1 = 798{,}57\ kWh \quad (3)$$

Applying these two values, found through the Equation 2 and 3, in the tool with Italian or Spanish electricity profiles shows us the differences in the results. The initial screenshots (Figure 74, Figure 75 and Figure 76) depict the outcomes based on Italy's electricity profile, while the subsequent ones utilize the Spanish profile (Figure 77, Figure 78 and Figure 79). Although the disparity is not substantial, it is essential to highlight that we chose to compare two countries with similar methods of energy production. Nevertheless, there is still a discernible difference when using Spain's 2020 electricity profile, with both the CO_2 equivalent per square meter per year and the social cost of carbon registering a slight decrease. This underscores the significance of incorporating future energy perspectives, providing a more precise and forward-looking assessment of our material choices. This approach can prove invaluable, especially during the design phase and when considering replacements, as it assists in making informed decisions regarding materials in anticipation of evolving energy mixes.

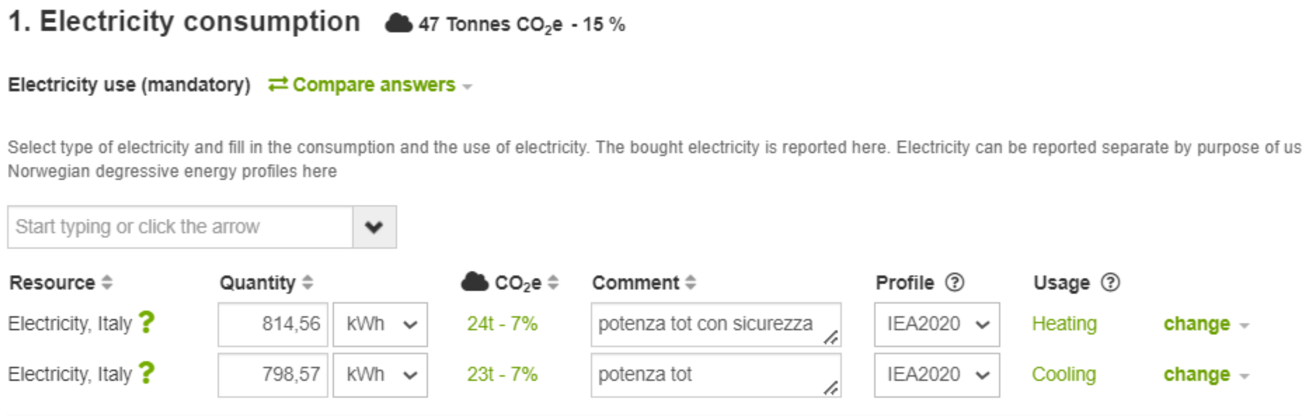


Figure 74 - Electricity, Italy

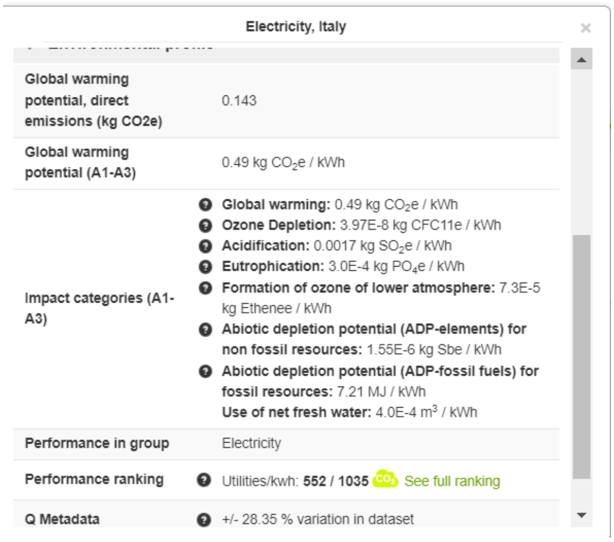


Figure 75 - Electricity, Italy - Specifics

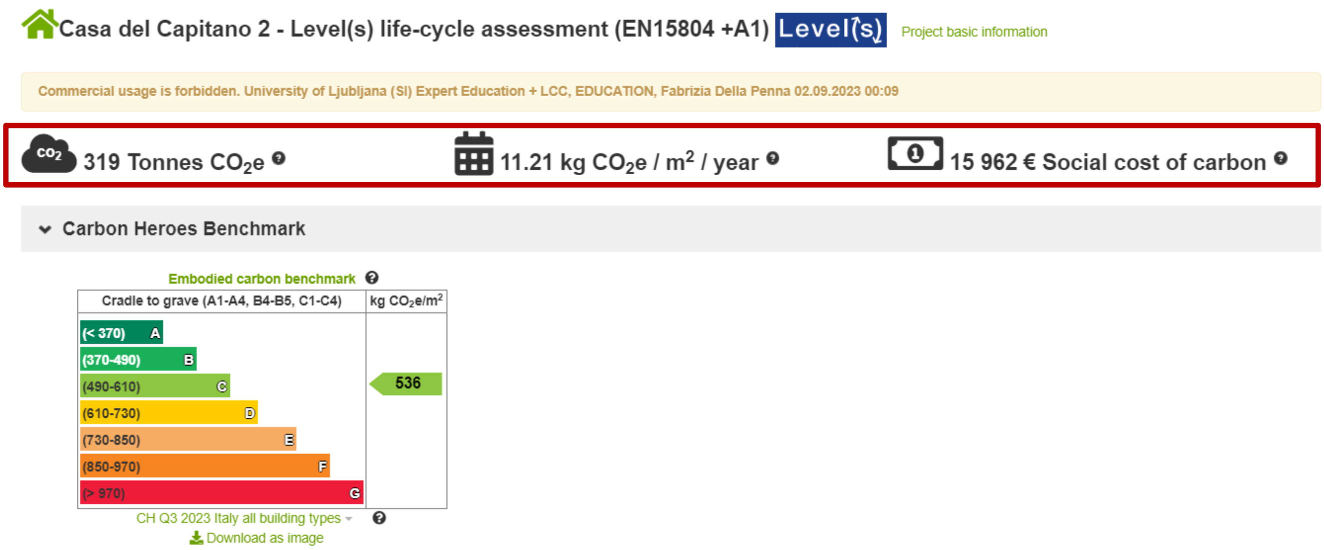


Figure 76 - Electricity, Italy - Results

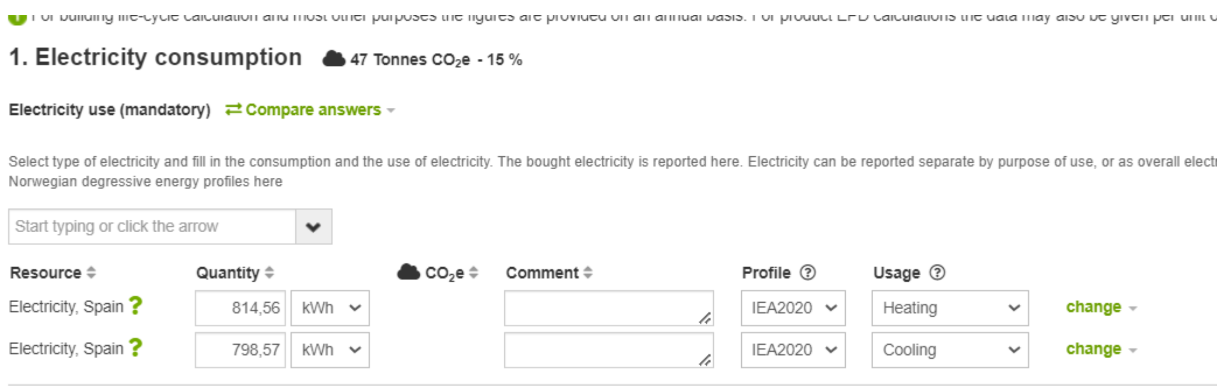


Figure 77 - Electricity, Spain

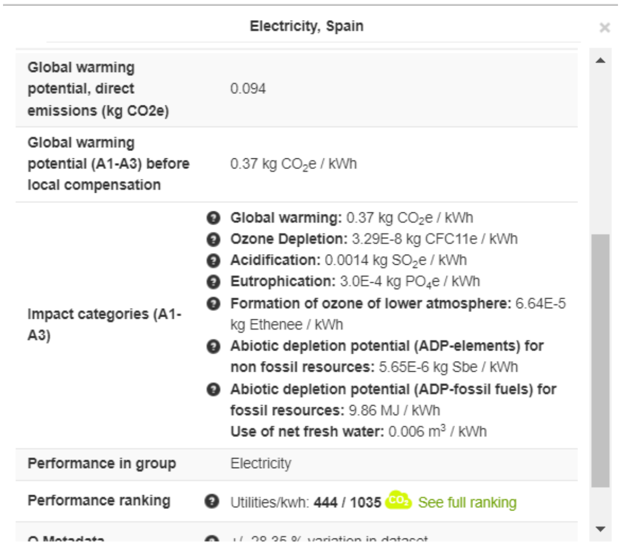


Figure 78 - Electricity, Spain- Specifics

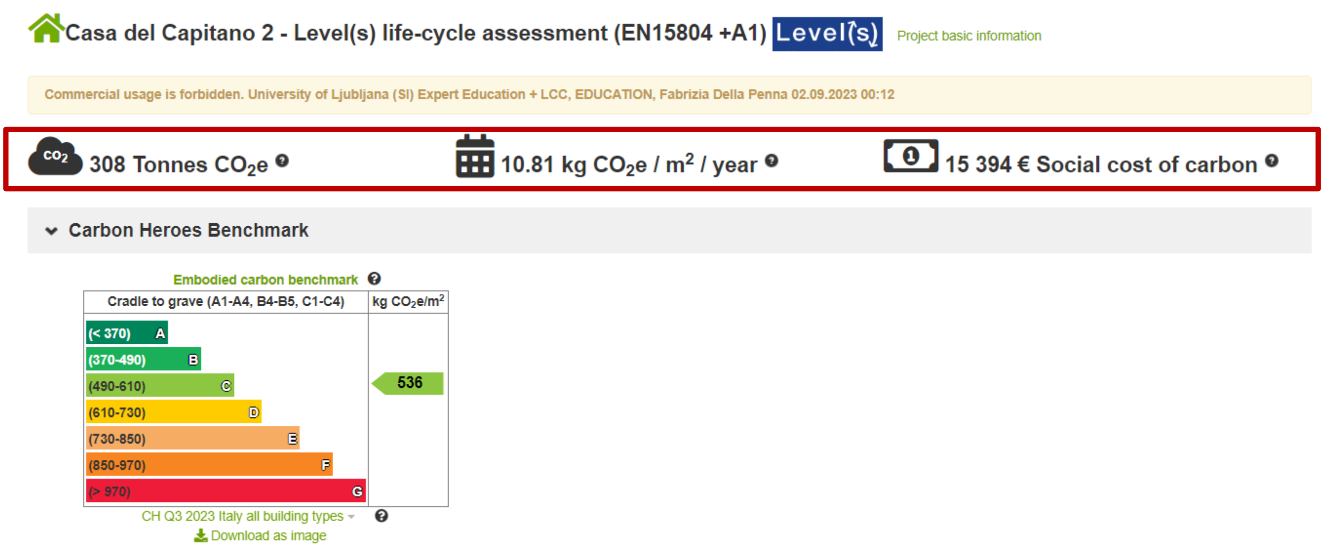


Figure 79 - Electricity, Spain – Results

4.7 Results and challenges

Implementing interoperability between the two software platforms has led to a significant enhancement in the LCA analysis, resulting in improved accuracy and increased ease of use. This critical integration has fostered seamless data exchange and improved recognition of various elements by the program. Consequently, the LCA analysis yields more comprehensive results within the same timeframe. The initial identification of interoperability issues, particularly in recognizing and mapping materials, prompted a meticulous approach to addressing these challenges. A substantial increase in recognised materials has been achieved through the development of specific rules for naming procedures and the use of Dynamo scripts. Moreover, by leveraging the One Click LCA database and a DiRoots Plugin, the link between EPDs and the model has been established, allowing for real-time updates and the creation of a repository for constantly updated EPDs associated with specific materials. However, it is essential to acknowledge that specific weaknesses and issues were encountered during the implementation phase. For instance, some materials still presented difficulties in automatic recognition, requiring additional manual interventions and the reiteration of the process. Furthermore, potential discrepancies in results due to database updates and EPD revisions must be carefully monitored. The enhancement of interoperability extends also beyond material renaming. It encompasses aligning the LCA database with the granularity of the BIM model to address discrepancies identified during the LCA analysis. This alignment ensures that the data structure in the LCA database accurately corresponds to the BIM model's components, facilitating seamless and efficient data exchange between the two platforms. Moreover, it helps standardize the data collection and data entry process among stakeholders in the value chain to ensure and sustain data quality in the system.

This study highlights a crucial finding: the inclusion of material codes within the latter part of their names, contrary to prevailing nomenclature practices in many companies, could be an advantage in recognition of materials during LCA, even though it is clear that could be easier to change the EPD nomenclature. EPDs are named following standard conventions and guidelines to ensure clarity and understanding for users. An EPD's name typically includes the product's name or description, making it clear and concise. It should also include terms like "Environmental Product Declaration" or "EPD" to indicate the document's nature. If applicable, the name may specify the product category, such as "EPD for Thermal Insulation." The manufacturer or company responsible for creating the EPD is often included in the name to identify the source of information and analysis. These naming conventions may vary slightly depending on the issuing organization or relevant regional and sector-specific standards (One Click LCA Academy, 2023a). Adopting a standardized naming convention for EPDs and material nomenclature could prove immensely beneficial. Such standardization would offer a unified approach to addressing various components, thus enhancing the seamless recognition between EPD databases and the components within authoring tools. This harmonization of nomenclature practices could significantly streamline the integration process. Starting from the typical rules in nominating elements during the first phases of the project, which can be defined as follows:

CLASS.CODE_Detail[_Subdetail]_[Additional Details]

It is possible to simply add information about the EPD of the product, for example:

CLASS.CODE_Detail[_Subdetail]_[EPD Elements]_[Additional Details]

Where:

CLASS: Use the abbreviated class name from the table.

CODE: Assign a unique code for each material type within the class. This code should be a two-digit number. If there are multiple subtypes within a material type, use additional numbers (e.g., 01, 02, 03) for subtypes.

Detail: Include the name of the material detail, as mentioned in the table.

Subdetail (Optional): If applicable, include a sub-detail for the material, such as a specific subtype or variation. This is optional but can help distinguish similar materials.

EPD Elements: Add elements commonly found in EPDs to provide environmental and product-related information. These elements can include:

- LCI (Life Cycle Inventory): Include details related to the environmental impacts of the material, such as embodied carbon, energy consumption, or other relevant LCI data.
- PCR (Product Category Rules): Include reference to the specific Product Category Rules followed for conducting the LCA (Life Cycle Assessment) and generating the EPD.
- Manufacturer: Include the name of the manufacturer or supplier of the material.
- Environmental Certifications: Mention any environmental certifications the material may have, such as LEED, BREEAM, or ISO certifications.

Additional Details (Optional): Add any additional details or specifications for the material, such as colour, finish, or specific product names. This is also optional but can provide further clarity.

If this type of nomenclature is common among all the actors involved in the project, then the recognizability of the material is unique, making the process of LCA analysis faster and almost automatic. Using a script to change the materials' names, as done in this thesis, to reach the interoperability of the programs is also an opportunity to keep in mind until the standardization is complete. If the client mandates this information in the EIR and then it is refined in the BEP, integrating these specifics right from the initial stages could streamline the process, saving time for all parts involved. Simultaneously, it would ensure a meticulous analysis, aiming for the highest precision.

The last part of the work, linked with the concept of Green Digital Twins and BIM and IoT integration, proposes an RFID-based digital twin platform for real-time asset tracking in construction and the built environment. While this approach is mainly indicated for tracking the materials along their lifecycle, a LoRa network could be implemented, more related to the analysis of the general indoor performances of the building, giving information on how the materials' behaviour is evolving and if and when it is indicated to replace them. The interaction of these platforms can be used to monitor the processes involved in the building's life cycle and collect data in a standard and consistent way. Previous studies have already proved how this continuous flow of information enhances the knowledge of the general behaviour of the building. Moreover, it seems to bring a good improvement in the LCA results too, in terms of reliability and precision. The integration of IFC standards presents a promising avenue for advancing interoperability and enriching the digital twin concept. By extending IFC schemas to include additional building components, attributes, and relationships, particularly those associated with real-time sensor data, we can pave the way for a more comprehensive representation of the built environment. This enriched data structure enables seamless integration of sensor-generated insights, enhancing the digital twin's accuracy and relevance. With IFC's adaptability and expansiveness, the incorporation of sensor data into the digital twin offers an opportunity to monitor and analyse the building's real-time conditions, allowing for informed decision-making, predictive maintenance, and ultimately fostering sustainability in construction and building management. Unfortunately, in this study this path was only theoretical, since we were missing the sensors' data that would be necessary to trad this path.

Furthermore, a theoretical approach employing the electricity profile of another region is employed to demonstrate that accounting for future shifts in the energy mix within the LCA study could yield more dependable outcomes. Although the impact changes may not be profoundly pronounced, they already indicate that this is the direction to pursue in developing calculation tools and equations, as it allows for considering prospects regarding the energy mix.

5 CONCLUSION

In conclusion, this thesis marks a step towards promoting sustainable construction practices by leveraging the potential of interoperability between Autodesk Revit and One Click LCA, bolstered by the integration of Green Digital Twins. The exploration unfolds through two vital dimensions: 'BIM and LCA Interoperability' and 'Leveraging Green Digital Twins for Dynamic LCA Analysis.'

5.1 BIM and LCA interoperability

The integration of Autodesk Revit and One Click LCA marked a significant advancement in LCA analysis, enhancing accuracy and ease of use. A key achievement was establishing seamless data exchange channels and improving material recognition within the program. Addressing interoperability issues, especially regarding material recognition and mapping, was crucial. Specific rules for naming procedures and Dynamo scripts led to a substantial increase in recognized materials. Leveraging the One Click LCA database and DiRoots Plugin established links between EPDs and the model, allowing for constant updates and a repository of updated EPDs linked to specific materials. Nonetheless, challenges such as material recognition difficulties and potential result discrepancies due to database updates necessitate vigilance and sometimes manual intervention.

The enhancement of interoperability extends beyond material renaming. Aligning the LCA database with the BIM model's granularity is crucial in addressing discrepancies identified during the LCA analysis. This alignment ensures accurate correspondence between the data structure in the LCA database and the BIM model's components, facilitating seamless and efficient data exchange. The proposal of a standardized naming convention for materials could further streamline this process, offering a unified approach and expediting LCA analyses. The proposed standardization of naming involves adopting a consistent and structured approach to naming materials within the BIM model. The conventional practice involves using names that often lack a standardized format, making it challenging for LCA tools to automatically recognize and map materials accurately. The suggested naming convention, exemplified by the format "*CLASS.CODE_Detail_[Subdetail]_[EPD Elements]_[Additional Details]*" provides a clear structure. By implementing this structured naming convention consistently across all project stakeholders, material recognizability could be significantly enhanced, thereby expediting the LCA analysis process. The structure aids in automating the transition of material data into LCA tools, ensuring a smoother interoperability process while also setting the stage for future standardization efforts.

The main strengths, weaknesses and future possibilities found during this work concerning the interoperability are synthetized in Table 4.

Table 4 - BIM and LCA interoperability

Strengths	Weaknesses	Future Possibilities for Improvement
- Improved accuracy and precision in LCA analysis	- Initial identification of interoperability issues, particularly in material recognition and mapping	- Development of standardized data formats and protocols to ensure seamless and reliable data exchange
- Improved automatic recognition of materials and quantities, accounting also for changings during the project	- Potential complexities in mapping and aligning data structures between BIM and LCA systems	- Development of advanced algorithms and methodologies to automate data alignment and quality, making data exchange more efficient and automatic
- Facilitated two-way automatic data exchange between BIM and LCA/EPDs databases	- Can require manual intervention to assure the recognition of all the materials	- Standardize naming conventions for EPDs and relative materials
- Possibility to use Dynamo scripts and plugins to make the process easier and faster	- Potential result discrepancies due to database updates, necessitating vigilant monitoring	- Creation of comprehensive training programs and guides to educate users on standardized data collection and entry

5.2 Leveraging Green Digital Twins for Dynamic LCA analysis

In tandem with BIM and LCA tool interoperability, this study explores the dynamic facet of Life Cycle Assessment. In alignment with the foundational questions of this study regarding Green Digital Twins, real-time asset tracking, and the potential integration of the Internet of Things (IoT), the research embarked on a theoretical exploration. A conceptual RFID-based digital twin platform for real-time asset tracking in construction and the built environment was proposed, showcasing a promising avenue for future endeavours. Furthermore, envisioning the integration of LoRa networks for continuous monitoring of indoor building performance enriched this theoretical approach. Although this exploration remained in the realm of theory, it illustrated a compelling vision of how seamlessly integrating these technologies can provide a holistic understanding of environmental impacts throughout a building's lifecycle.

Furthermore, this work proposes the formulation of a consistent method to define and decompose building components, streamlining data collection and entry across the construction value chain. This standardization, entailing IFC schema enhancement for LCA, could maintain data quality and facilitate efficient integration of environmental impact information throughout a building's lifecycle. Enriching the process involves integrating a broader range of entities, properties, and relationships, pivotal for seamless assimilation of Digital Twin data, significantly advancing sustainability efforts.

Lastly, considering the question about shifts in the energy mix within LCA studies, the study emphasized the importance of incorporating these changes for more robust and dependable results. It's crucial to develop new tools and integrate this approach into existing tools to ensure comprehensive analysis.

Moreover, this work has delved into the importance of accounting for shifts in the energy mix within LCA studies. By considering future developments in energy sources, LCA results become more robust and dependable. While these changes may remain challenging to incorporate, this theoretical consideration lays the foundation for future advancements in LCA tools and equations, aligning them with the evolving energy landscape. Table 5 shows the main key features of the aspects analysed theoretically in this dissertation and possible advancements that could be made in the future to spread and ease the use of these practices.

Table 5 - DT and Dynamic LCA

Aspect	Key Features	Potential Advancements
Integration of sensors for real-time data and asset tracking	- Holistic understanding of environmental impact throughout building materials' lifecycle - Continuous monitoring of indoor building performance with the integration of real-time asset tracking and sensor data	- Develop and promote the use of integrated platforms that seamlessly combine real-time sensor data and asset tracking for a comprehensive understanding of building performance through the whole life cycle
Standardized Data & IFC Schema for LCA	- Consistent method for defining and decomposing building components and their relative properties - Standardized approach to data collection and entry across stakeholders - Integration of standardized material naming conventions	- Enhance the method to cover a broader range of building types and materials - Use additional entities, properties and relationships to easily integrate DT data
Energy Mix & Dynamic Analysis	- Implementation of a theoretical and practical framework to include dynamic shifting of the energy mix in LCA tools for more reliable results	- Collaborate with energy industry stakeholders to access real-time and forecasted energy mix data for inclusion in LCA analyses - Develop mathematical models and user-friendly tools that predict dynamic energy mix shifts and their impact on LCA results

5.3 Future developments

There are several promising avenues for future studies and advancements in this field. One critical area of exploration involves the standardization and enhancement of material naming conventions. This standardization would encompass not only the identification of building materials but also incorporate information related to EPDs. The aim is to establish a consistent and universally understandable way to denote materials and their life cycle attributes across all stakeholders involved in a project.

Additionally, enhancing the existing IFC schema is crucial. This enhancement would entail integrating additional building components, attributes, and relationships essential for conducting comprehensive net-zero-carbon assessments throughout an asset's lifecycle. The goal is to adapt the schema to align with evolving requirements, particularly in rigorous energy analysis and continuous lifecycle evaluation.

Furthermore, exploring the integration of sensors for real-time monitoring of building conditions and their seamless connection with the BIM model is a vital area for future research. This integration can significantly improve the accuracy and utility of Digital Twins used for sustainability practices, providing a more precise understanding of a building's performance.

Lastly, a practical framework for integrating the dynamic shifting of the energy mix into LCA tools is essential for more reliable LCA results. This could involve developing mathematical models or enhancing existing tools to incorporate real-time or forecasted data regarding changes in the energy mix. Such integration would significantly enhance the accuracy and relevance of LCA results, aligning them with the evolving energy landscape.

To resume, this research signifies a step towards sustainable architecture and construction. The fusion of BIM and LCA tool interoperability and dynamic LCA analysis emphasizes the intrinsic connection between design, assessment, and real-time monitoring. This work underscores the importance of continued exploration and innovation in the quest for a sustainable built environment that thrives on interoperability and dynamic analysis, all while keeping an eye on the ever-evolving energy landscape. While challenges persist, the benefits are undeniable, paving the way for greener, more environmentally conscious building practices.

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