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Silvia Vilčeková, Miguel Ángel Pardo Picazo, Dorin Beu, Svitlana Delehan, Florin Domnița, Adriana Eštoková, Horațiu Albu, Eva Krídlová Burdová, Tania Rus, Raluca Moldovan, Myroslava Lendel, Oksana Sviezhentseva, Daniel Benalcázar, Andrii Khorolskyi, Martin Kováč, Veronika Merjavá, Anna Sedláková, Jana Budajová, Katarína Harčárová, Saturnino D. Fuster-Casas, Oscar Galao Malo

Carbon Footprint

GHG of building materials and services, structures and whole buildings GHG of organizations and neighbourhoods and cities

volum 2

Support of higher education system in a context of climate change mitigation through regional level of carbon footprint caused by a product, building and organization.

Hi-EduCarbon

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Ș.l.dr.ing. Maria Bot

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Content

Preface

> ***Sustainable building design and construction refers to the use of processes and technologies that are environmentally friendly and use natural resources efficiently throughout the life cycle of a building, i.e. from extraction of raw materials, through construction, operation, maintenance, renovation, to demolition of the building and waste recovery. Sustainable construction aims to reduce the overall impact of the built environment on human health and the natural environment by using energy, water and other resources efficiently, eliminating pollution of environmental components, reducing waste and protecting the health of building occupants.***

Sustainable construction is a balance between the built environment and the built environment. By adopting sustainable construction strategies, environmental, social and economic benefits can be maximised. However, this process requires close collaboration between a team of architects, engineers, builders, ecologists and building owners at all stages of the project, with the most significant benefits being achieved through an integrated design approach from the earliest stages of a building project. The ways to reduce the environmental burden of construction are very diverse. The common feature should be compliance with broadly formulated sustainability requirements and criteria, where social and economic issues can be included in addition to environmental quality and low pollutant production.

Sustainable building design relies on renewable resources for energy systems, recycling and reuse of water and materials, minimal landscaping requirements, passive heating, cooling and ventilation of buildings, and other approaches that minimize environmental impacts and resource consumption. Currently, sustainable buildings are defined by assessment and certification systems that evaluate and certify them. Building assessment systems used around the world evaluate different types of buildings (residential buildings, office buildings, hotels, education buildings, industrial facilities and halls, healthcare facilities, and others), assessing them in different phases (new buildings, major renovations or existing buildings).

A prerequisite for ensuring the functional, structural, physical and social sustainability of works of modern architecture is the development of a flexible strategy to be applied in relation to the conservation and restoration of these works. The starting point for such a strategy is the identification of concepts and functionality in modern architecture and the categorisation of technical and material solutions used in works of modern architecture in terms of the effects of time, renewability and durability.

The aim of this book is to present current knowledge on the assessment of buildings and their environment and organisations with respect to greenhouse gas emissions. Quantifying the carbon footprint of buildings, environments and organisations leads to support the objectives of the European Commission, which has adopted a set of proposals to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, by adapting EU policies on climate, energy, transport and taxation. In the face of climate change and environmental degradation, a European Green Deal has been adopted to transform the EU into a modern and competitive economy by using resources efficiently, ensuring zero net greenhouse gas emissions by 2050, ensuring resource-neutral economic growth and leaving no individual or region behind.

In 2018, the European Commission launched the Sustainable Finance Initiative. This was in response to the objectives of the European Green Deal, which aims to make Europe the world's first climate-neutral continent by 2050. It has developed a Financing Strategy for the transition to a sustainable economy. Its core element is the Sustainable Investment Taxonomy, which is intended to serve as a classification system that sets out, based on scientific knowledge, what criteria an economic activity must meet to be judged sustainable. The Taxonomy aims to provide a harmonised framework for companies to know whether an activity contributes to the transition to carbon neutrality. Thus, the aim is to enable investors to redirect investments towards more sustainable technologies and businesses. It will help the EU become climate neutral by 2050 and achieve the 2030 targets of the Paris Agreement. These targets include a 40% reduction in greenhouse gas emissions, for which the European Commission estimates that the EU needs to fill an investment gap of around €180 billion per year. The framework is based on six EU environmental targets, which are illustrated in the figure below (Figure 0.1).

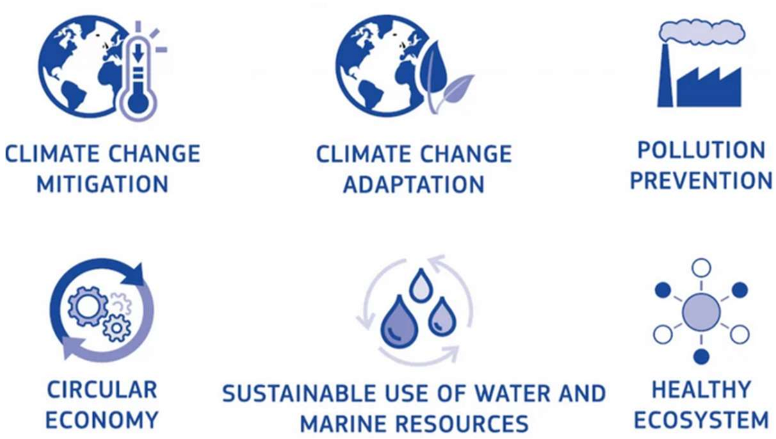

Figure 0.1. The EU's six environmental objectives

The taxonomy is a key measure of the action plan in the regulation of sustainable finance, allowing to define a method common to all market participants to identify "green" activities. A taxonomy is a classification system for economic activities that face environmental constraints. It lists the activities concerned (energy production and use, transport, metallurgy) and the level of environmental performance to ensure that global warming is mitigated. In addition, it defines a green vision at European level and will serve as a benchmark in regulation, as regards green bonds, eco-labels, climate benchmarks and climate reports.

Chapter 01

Life Cycle Assessment of Building Sustainability

Silvia Vilčeková[1], Eva Krídlová Burdová[1], Anna Sedláková[2]
1 Institute for Sustainable and Circular Construction, Faculty of Civil Engineering, Technical University of Kosice, Vysokoskolska 4, 04200 Kosice, Slovakia
silvia.vilcekova@tuke.sk, eva.kridlova.burdova@tuke.sk
2 Institute of Architectural Engineering, Faculty of Civil Engineering, Technical University of Kosice, Vysokoskolska 4, 04200 Kosice, Slovakia
anna.sedlakova@tuke.sk

> *Sustainable Building refers to the practice of designing, constructing, and operating buildings with the aim to minimize its environmental impact, maximize energy efficiency, and enhance the health and well-being of occupants. It involves using resources more efficiently, reducing energy consumption, using environmentally responsible materials throughout their whole lifecycle.*

Life Cycle Assessment (LCA) is a methodology for assessing the environmental impacts associated with all stages of the life of a product, process, or service, from raw material extraction through production, use, and disposal. It helps assess the overall sustainability of a product or process by considering material and energy flows, emissions, waste generation, and resource consumption and so on. It consists of 4 mains steps: (i) Goal and Scope Definition; (ii) Life Cycle Inventory; (iii) Life Cycle Impact Assessment and (iv) Inventory.

Sustainable Building Life Cycle Assessment is a specific application of the LCA methodology to assess environmental, economic, and social impacts of a building throughout its entire lifecycle - from raw material extraction and construction, through operation and maintenance, to demolition, deconstruction and end-of-life disposal or reuse. Building LCA provides a comprehensive understanding of a building’s sustainability performance and helps identify opportunities to reduce environmental impacts, improve resource efficiency, and support long-term sustainability goals.

1.1 Introduction to LCA

Main phases in LCA process are:

1. *Goal and Scope Definition:*

This phase outlines the objectives of the LCA study, the system boundaries (what is included or excluded) and the functional unit. In addition, intended audience and any assumptions have to be made in this first step.

2. *Life Cycle Inventory (LCI):*

LCI is the data collection phase of a LCA. It involves detailed data regarding all the inputs and outputs of the system, including materials, resources, energy and emissions throughout the process or product life cycle. It corresponds to the identification and quantification of all flows of materials, energy, water and contaminants entering and leaving the system. This includes processes like extraction of resources, manufacturing, transportation, usage, and disposal/recycling.

3. *Life Cycle Impact Assessment (LCIA):*

LCIA is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of the studied system. This step involves accounting, assessing, and interpreting the potential environmental impacts. The most quantified impact categories are: global warming potential, eutrophication, acidification, photochemical ozone creation potential, ozone depletion potential, human toxicity potential, ecotoxicity potential, land use and water use.

4. *Interpretation:*

The results are analyzed and interpreted to make recommendations or guide decision-making. This phase also involves identifying any uncertainties, limitations, or data gaps.

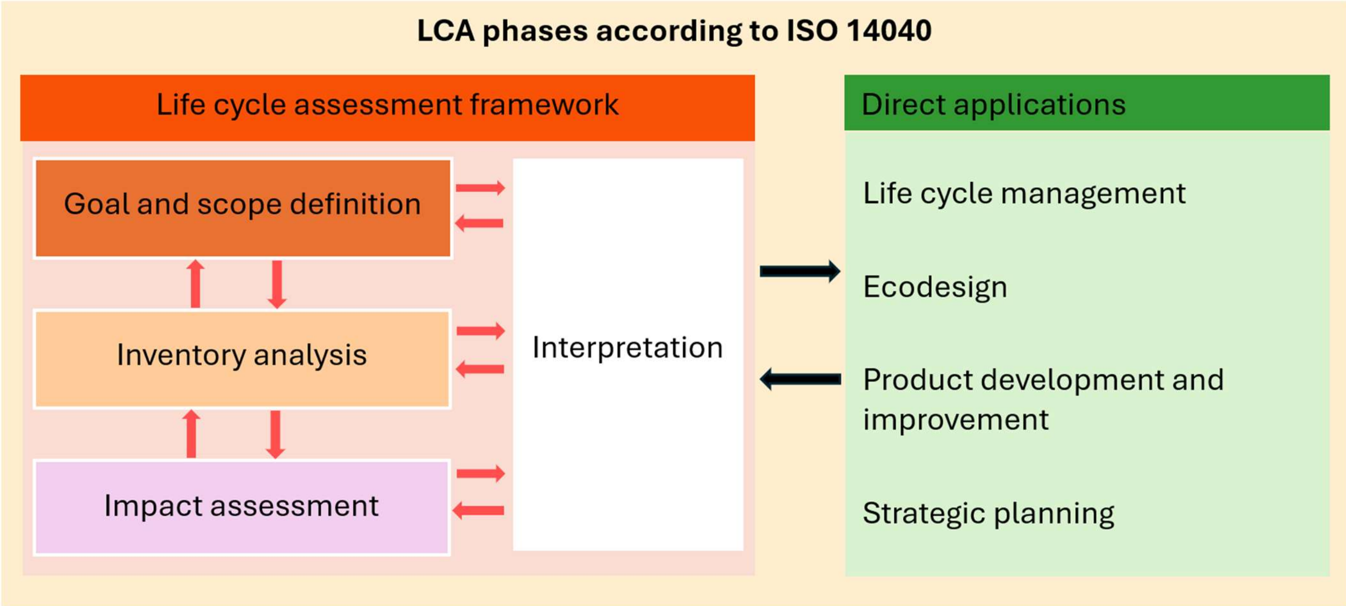

Figure 1.1 LCA phases according to ISO 14040

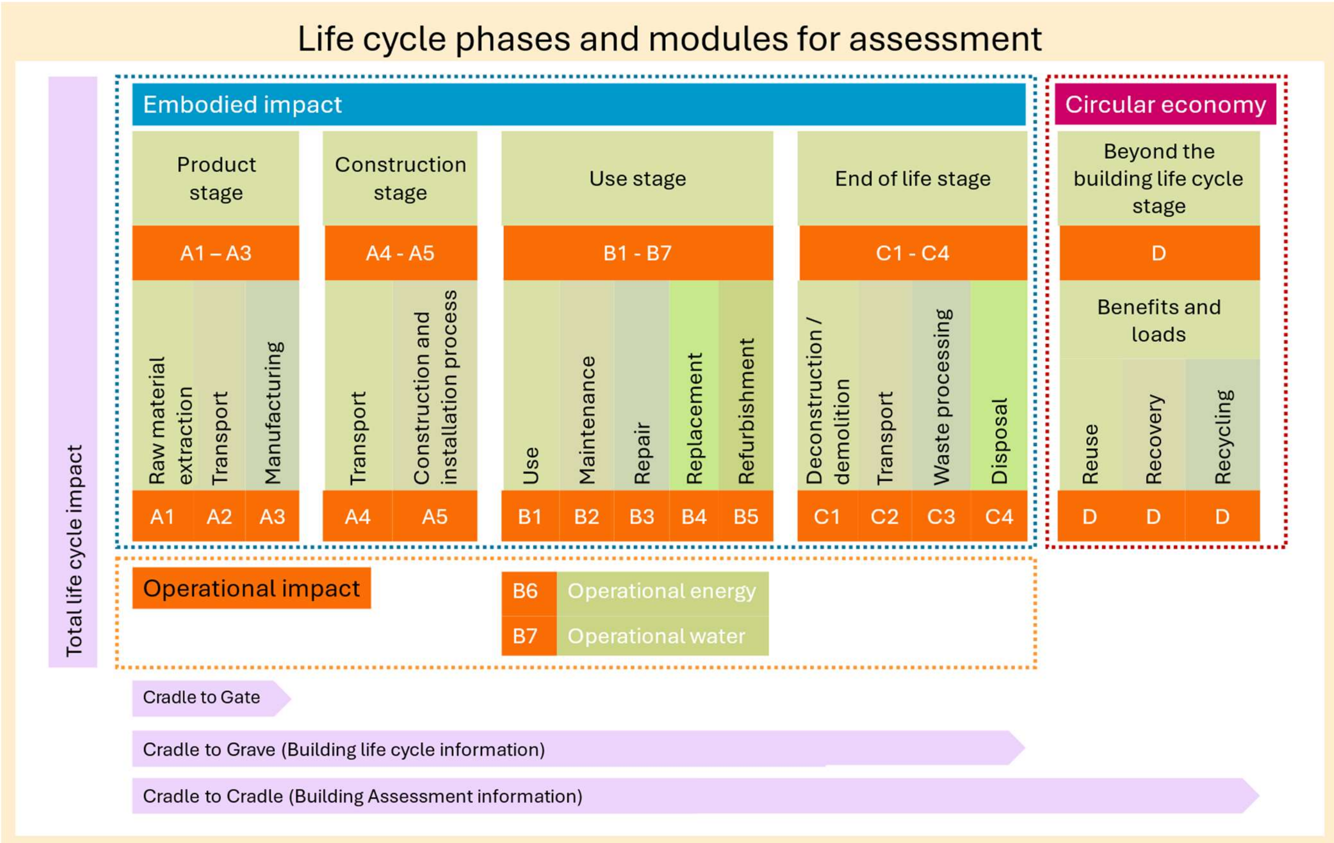

Figure 1.2 LCA phases and modules included in the assessment

1.2 Key Reasons to Perform LCA Analysis

1.2.1. Environmental impact reduction

- Holistic view of sustainability

LCA evaluates the building's environmental impacts across all phases of its life cycle - from raw material extraction and acquisition, material production, transportation and building construction, through its operation, maintenance, and demolition and final disposal. This allows for a more complete picture of the building's sustainability performance.

- Carbon footprint minimization

LCA helps identify key areas of energy consumption and carbon emissions, particularly in operational energy (heating, cooling, lighting), material use, and construction processes. By optimizing these areas, buildings can achieve lower carbon emissions and contribute to climate change mitigation.

- Resource efficiency

LCA helps assess the depletion of natural resources (e.g., water, raw materials, fossil fuels) and encourages the use of sustainable, renewable, and recyclable materials. It can lead to more responsible sourcing and reduce waste generation during construction and operation.

1.2.2. Energy and water efficiency improvement

- Energy performance

Energy consumption in buildings accounts for a large portion of the environmental impact, particularly in terms of carbon emissions. LCA can identify opportunities to improve energy efficiency through better building envelope insulation, energy-efficient HVAC systems, renewable energy integration (e.g., solar energy, geothermal energy, water and wind energy), and the use of low-energy appliances.

- Water management

Water consumption during a building's lifecycle, particularly during its operation, can be optimized through LCA. This includes installing water-efficient fixtures, rainwater harvesting, greywater recycling systems, and using drought-resistant landscaping. LCA can help track the effectiveness of these measures in reducing overall water consumption.

1.2.3. Identification for improvement

- Material selection

The building LCA process identifies which materials (e.g., concrete, steel, wood, insulation) have the highest environmental impact in terms of energy use, emissions, and resource depletion. This allows designers to make informed decisions about the choice of materials and choose those that have lower embodied energy or come from sustainable sources (e.g. recycled or rapidly renewable materials).

- Construction methods

LCA can reveal which construction techniques are more resource- and energy-intensive. This can guide decisions on using modular construction, reducing construction waste, and optimizing construction processes for sustainability.

1.2.4. Enhance indoor environmental quality (IEQ)

- Health and comfort

LCA is not just about the building's environmental impact; it also considers the well-being of the building users. This includes factors such as indoor air quality, lighting quality, thermal comfort, and acoustics. By improving these aspects, LCA can help ensure that buildings create a healthier and more productive environment for occupants, which is critical for commercial buildings, schools, and healthcare facilities.

- Improved productivity

Research shows that buildings designed with a focus on human well-being (e.g., better air quality, natural light, and thermal comfort) lead to higher productivity and lower absenteeism, especially in offices and workspaces.

1.2.5. Economic costs and benefits optimization

- Cost-benefit analysis

LCA can help quantify the long-term financial benefits of sustainability initiatives. For example, energy-efficient designs, while requiring higher investment costs, can result in lower operating costs over the building's lifetime. By considering both initial construction costs and long-term operating costs, an LCA can demonstrate the overall value of sustainable building design choices.

- Operating costs reduction

By optimizing energy and water consumption, as well as reducing waste and maintenance costs, buildings that undergo LCA can lower operating costs and provide a better return on investment over time. This is increasingly important for owners, investors, and tenants who seek long-term savings.

1.2.6. Support long-term building performance and durability

- Building Resilience

LCA can evaluate the resilience of a building to environmental factors such as extreme weather events, climate change, or natural disasters. A sustainable building design should not only reduce environmental impact but also be adaptable and resilient to future changes.

- Extended building lifetime

By built-in durable materials and designing with maintenance and repair needs in mind, LCA can help ensure the long-term performance of a building, reducing the need for major renovations or replacements. This supports the concept of a circular economy in the construction industry, where buildings are designed to last longer and be repurposed or reused.

1.2.7. Encourage innovation and sustainable design

- Innovation

LCA challenges designers, architects, and engineers to innovate and look beyond conventional practices. It encourages the use of cutting-edge technologies, materials, and systems that may otherwise be overlooked in traditional building design. This innovation can lead to breakthroughs in construction methods, energy-saving technologies, and more sustainable materials.

- Life cycle thinking

Adopting life cycle thinking early in the design process can help shift focus from just initial construction costs to long-term sustainability and performance. This mindset encourages a deeper commitment to minimizing negative environmental impacts and optimizing resource use.

1.2.8. Regulatory compliance and certification support

- Green/Sustainable building certifications

Most of green building rating systems, like LEED, BREEAM, Level(s) and Living Building Challenge, require LCA or related assessments as part of their certification process. Performing an LCA is essential for obtaining higher level these certifications and demonstrating the building's commitment to sustainability.

- Compliance with environmental regulations

Governments and municipalities are increasingly requiring buildings to meet rigorous sustainability criteria. Conducting an LCA can help ensure compliance with local building codes, energy standards, environmental regulations and prepare for potential future regulations focusing on building environmental impacts reduction.

1.2.9. Boost attractivenss and reputation in the market

- Attract tenants or buyers

In the caurrent market, sustainability is becoming a key differentiator for both residential and commercial properties. Buildings that have green certification are more likely to attract tenants or buyers who prioritize sustainability.

- Corporate social responsibility (CSR)

For developers and companies, performing an LCA and achieving sustainable building certifications can demonstrate commitment to corporate social responsibility (CSR) and environmental stewardship. This can enhance the company's reputation, attract investors, and build trust with the public.

1.2.10. Informed decision-making and transparency

- Data-driven decisions

LCA provides a clear, data-driven framework for decision-making. By having access to detailed, scientifically-based insights into a building’s environmental impacts, stakeholders can make informed choices that balance environmental, economic, and social considerations.

- *Transparency*

Conducting an LCA provides transparency into the building's sustainability performance. This is particularly important for investors or occupants who have a vested interest in knowing how the building contributes to environmental goals or sustainability targets.

By demonstrating a lower environmental impacts of the building compared to others, it can gain a competitive advantage in the market and appeal to environmentally conscious users. LCA can also help to identify areas of the building life cycle with the highest environmental impacts. Use this information to prioritize initiatives aimed at reducing environmental footprints, optimizing resource use, and enhancing overall sustainability performance.

Currently, the use of LCA models is applied in all sectors of the economy as they simplify the decision-making process for the future use of green practices and products. LCA analytical tools allow to understand the impact of products from their extraction to the final stage, thus contributing to the promotion and adaptation of green practices for sustainable development at a global level.

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Chapter 02

Carbon Footprint of Building Products - a Case Study for Cultural Heritage in Ukraine with a Comparison of European and Ukrainian Standards

Svitlana Delehan[1], Myroslava Lendel[2], Oksana Sviezhentseva[3] and Andrii Khorolskyi[4]
1 Centre for Interdisciplinary Research of Uzhhorod National University, Uzhhorod National University, 88000 Uzhhorod, Ukraine; svitlana.delehan-kokaiko@uzhnu.edu.ua
2 Faculty of Social Sciences, Department of Political Science and Public Administration of Uzhhorod National University, Uzhhorod National University, 88000 Uzhhorod, Ukraine;
3 Department of International Studies and Public Communications, Uzhhorod National University, 88000, Uzhhorod, Ukraine;
4 Laboratory of Mining Problems, Branch for Physics of Mining Processes of the National Academy of Sciences of Ukraine, 49005 Dnipro, Ukraine; andreykh918@gmail.com

This study examines the carbon footprint of building materials used in the modernization of cultural heritage sites in Uzhhorod, Ukraine, comparing Ukrainian and European standards. Utilizing Life Cycle Assessment (LCA) and One Click LCA software, the research evaluates environmental impacts, emphasizing energy efficiency and CO_2 reduction. The findings highlight the potential for harmonizing Ukrainian regulations with EU directives to enhance sustainability in heritage conservation. The study demonstrates that modernizing historical buildings can significantly reduce emissions while preserving architectural integrity.

The preservation and modernisation of cultural heritage sites are critical aspects of sustainable development, especially in regions with a rich historical heritage, such as western Ukraine. This study examines the carbon footprint associated with the building materials used in the modernisation of a cultural heritage site, Uzhhorod in the Zakarpattia region. This analysis is contextualised by comparing the relevant standards in Ukraine with European norms.

Since the outbreak of the war in Ukraine, western cities such as Uzhhorod have become overcrowded due to the large flow of internally displaced persons, and the density of urban development has increased significantly, necessitating a detailed assessment of the existing infrastructure to implement measures to modernise it, including cultural heritage sites. Such measures include improving the thermal insulation of buildings, replacing windows and doors, installing individual heating systems, and introducing modern ventilation and automatic balancing technologies, among others. One of the important goals of these efforts is to improve energy efficiency and preserve cultural heritage sites while reducing environmental impact, including CO_2 emissions [1, 2].

This study contributes to the wider discourse on sustainability by demonstrating how retrofit efforts can improve the energy efficiency of cultural heritage buildings, thereby reducing energy consumption and CO_2 emissions. The findings of this case study are important as they provide a basis for similar projects across Europe and Ukraine, contributing to the protection and sustainable use of cultural heritage in compliance with modern environmental standards.

Based on a study of changes in the landscape of Uzhhorod over the past two years, it was found that cities in western Ukraine are characterised by high building density, an increase in the number of people living in apartment buildings, and, as a result, the problem of energy efficiency. As a result of military operations on the territory of Ukraine, the population of Uzhhorod has increased significantly, which has had a negative impact on the city's infrastructure. There is a problem of comprehensive support for public utilities and housing, but there are no measures to meet the needs of cultural heritage sites. The existing building density and tectonic features of the region do not allow for an increase in construction but have a significant impact on the historical buildings. That is why we proposed modernisation measures for the building according to Ukrainian and EU standards using One Click LCA [3]. The experience of modernisation of cultural heritage sites demonstrated in this paper opens up prospects for the implementation of a comprehensive programme at the state level and confirms the need for faster adaptation of Ukrainian standards to EU standards in the construction industry.

Lorem Ipsum is simply dummy text of the printing and typesetting industry. Lorem Ipsum has been the industry's standard dummy text ever since the 1500s, when an unknown printer took a galley of type and scrambled it to make a type specimen book. It has survived not only five centuries, but also the leap into electronic typesetting, remaining essentially unchanged.

2.1 Analysis of European Building Standards for Cultural Heritage Modernisation

Life Cycle Assessment (LCA), also known as life cycle analysis, is a method used to evaluate the environmental impact of a commercial product, process, or service across all stages of its existence. For instance, in the case of industrial products, this evaluation encompasses every phase, from raw material extraction and processing to production, distribution, use, and the final treatment or disposal of materials [4].

During the life cycle assessment, a detailed analysis of the energy and material resources involved at each stage of the product's life cycle is conducted, followed by a calculation of the corresponding environmental emissions. The goal of this approach is to assess the cumulative potential environmental impact, which helps to document and improve the overall environmental profile of the product.

LCA procedures are part of a series of environmental management standards developed by the International Organization for Standardization (ISO). Specifically, ISO 14040 and ISO 14044 standards outline the principles, framework, requirements, and guidelines for conducting LCA. ISO 14040 is primarily aimed at managers, while ISO 14044 is designed for practitioners.

LCA covers the analysis of environmental aspects and potential impacts throughout the product's life cycle—from raw material acquisition to final disposal. Key impact categories that must be considered include resource use, human health, and environmental effects [5].

In scientific literature [6-8], LCA is often synonymous with life cycle analysis, and due to its comprehensive nature, it is sometimes referred to as a "cradle-to-grave" analysis. The term "life cycle" implies that a complete assessment should take into account all phases of the product's existence, including raw material extraction, production, distribution, use, maintenance, and disposal, as well as the associated transportation processes.

According to the National Risk Management Research Laboratory of the EPA, LCA is defined as a method for assessing the environmental aspects and potential impacts associated with a product, process, or service through:

1) The identification and inventory of relevant energy and material resources and environmental emissions.

2) The assessment of potential environmental impacts associated with those resources and emissions.

3) The interpretation of results to support informed decision-making.

Thus, LCA serves as a crucial tool for comparing the environmental impacts of products and services, enabling the quantitative assessment of all material flows and their effects on the environment.

The LCA methodology is divided into two main approaches: attributional and consequential. Attributional LCA focuses on evaluating the impact associated with existing products or processes over a specific period. In contrast, consequential LCA aims to explore the potential environmental outcomes of decisions that may be made in the future [9].

There is also a developing approach known as social LCA, designed to assess the social and socio-economic impacts of products or services throughout their life cycle. This method is based on international guidelines and standards such as ISO 26000:2010 and UNEP/CETAC Recommendations.

The limitations of LCA, related to its exclusive focus on environmental aspects, highlight the need to integrate economic and social factors into product decision-making processes. Nevertheless, standards such as ISO 14040 and 14044, along with other specifications like PAS 2050, provide a solid foundation for evaluating the climate impact and environmental sustainability of products [10, 11].

In addition to life cycle assessment, the European Union has developed a comprehensive regulatory framework for the protection and preservation of cultural heritage, which also includes aspects of energy modernization. One of the key documents is Directive 2012/27/EU on energy efficiency, which requires Member States to take measures to enhance the energy efficiency of buildings, including those of historical and cultural significance.

Particular attention is given in the EU to preserving the authenticity of cultural heritage during energy modernization projects. This means that all modernization efforts must be carefully planned and executed with consideration of the historical, architectural, and cultural aspects of the sites. An example of this is the application of standard EN 16883:2017, which provides guidelines for improving the energy efficiency of historic buildings. This standard takes into account the importance of preserving the cultural value of buildings and offers a methodology that balances energy savings with the preservation of authenticity.

Moreover, the EU actively employs life cycle assessment (LCA) approaches for cultural heritage, allowing the evaluation of not only the environmental but also the social and economic impacts of energy modernization. This supports decision-making processes that promote sustainable development and the preservation of cultural values.

It is also worth noting EU programs such as Horizon 2020, which fund research and the implementation of innovative solutions for the energy modernization of cultural heritage buildings. Projects supported by these programs often focus on integrating modern energy-efficient technologies into historic buildings with minimal intervention in their architectural integrity.

Thus, the EU's standards and guidelines for the protection and energy modernization of cultural heritage aim to achieve a balance between the need to preserve historical sites and attain high levels of energy efficiency, contributing to Europe's broader strategy for sustainable development [12, 13].

2.2 Analysis of Ukrainian Building Standards for Cultural Heritage Modernisation

Legislative acts are an integral part of the regulatory framework governing the preservation and modernization of historic cities in Ukraine. Given the unique nature and significance of these cities, the legislation outlines fundamental principles for their development, reconstruction, and protection of cultural heritage. Key legal instruments, such as the Laws "On the Protection of Cultural Heritage," "On Architectural Activity," "On Investment Activities in Construction," and "On Urban Planning Regulation," establish the rules for the use and conservation of historic areas.

One of the primary tasks within this framework is the development of the historical and architectural master plan for the city of Uzhhorod. This plan involves identifying protected zones for monuments, historic districts, and conducting an inventory of cultural heritage assets. These processes are guided by a series of legal documents that constitute the current regulatory base for research and preservation efforts in historic urban areas.

These laws and regulations set the standards and procedures that must be considered during the planning, reconstruction, and conservation of historical sites. They provide scientific and practical guidelines for conducting architectural and archaeological research, determining the boundaries of protected zones, and executing restoration projects.

Ukraine's status as a candidate for European Union membership, a critical objective is the integration of international humanitarian law norms, particularly those concerning the protection of cultural heritage. Amendments to national legislation aimed at preserving and protecting Ukraine's cultural heritage must align with the challenges posed by Russian aggression against Ukraine.

The resilience of the Ukrainian people in the face of Russian aggression and the threats to their identity and territorial integrity has fostered an awareness that cultural heritage is an inseparable component of national security. Proposals are being considered in the Verkhovna Rada to amend the Law "On National Security of Ukraine" to include the preservation of the Ukrainian people's cultural heritage and national memory.

This will contribute to harmonizing approaches to cultural heritage protection within the context of Ukraine's European and Euro-Atlantic integration.

It is necessary to reassess the conceptual approaches in national legislation regarding the protection of cultural heritage in accordance with Ukraine's European and Euro-Atlantic aspirations and the threats posed by Russian aggression to Ukrainian identity.

The term "cultural heritage" is defined as the collection of cultural heritage objects inherited from previous generations. However, the law currently does not explicitly define "cultural heritage of the Ukrainian people" and fails to adequately recognize the significance of cultural heritage for the Ukrainian nation or the protection of intangible cultural heritage. Consequently, the fundamental document on cultural heritage protection does not fully comply with the UNESCO Convention for the Safeguarding of the Intangible Cultural Heritage and the Council of Europe's Framework Convention on the Value of Cultural Heritage for Society.

Amendments to the Law of Ukraine "On the Protection of Cultural Heritage" are proposed to align it with ratified international conventions. However, the Committee on Ukraine's Integration into the European Union of the Verkhovna Rada considers that it does not fall under Ukraine's international legal obligations in the field of European integration.

The marking of cultural property is governed by the Cabinet of Ministers of Ukraine Resolution dated October 21, 2022. Cultural property is defined as objects of material and spiritual culture that hold significant value for the cultural heritage of nations and play a crucial role in the spiritual life of people.

The directive includes provisions that comply with international humanitarian law norms regarding cultural property in the context of armed conflict. These provisions address issues such as the prohibition of using cultural property for military purposes, enhanced protection for objects listed in the International Register of Cultural Property under special protection, and the responsibility of occupying states for the protection of these assets. Additionally, the directive considers extending protection to personnel responsible for safeguardig cultural property.

Regarding the armed forces, it recommends providing them with the necessary information, including the texts of cultural property registers. However, national legislation pertaining to the International Register of Cultural Property lacks practical significance as it does not specify a register of assets within Ukraine.

Ukraine currently lacks specialized legislation for implementing the 1954 Hague Convention for the Protection of Cultural Property in the Event of Armed Conflict and its Protocols.

While these international documents are directly applicable within national law, they require formal implementation. For example, no list of national cultural property subject to protection under the Convention and Protocols has been compiled.

The Armed Forces of Ukraine are expected to establish a specialized military unit and train personnel in cultural property protection, as stipulated by the 1954 Hague Convention.

Criminal liability can be applied for violations of cultural property protection norms under the Criminal Code of Ukraine. Such liability may be invoked in cases like the looting of national treasures in occupied territories, smuggling, illegal appropriation, unauthorized archaeological research on cultural heritage sites, or the destruction or damage of cultural heritage objects.

The protection of cultural property during wartime is integrated into the national doctrine of civil-military cooperation of the Armed Forces of Ukraine. This doctrine aims to shape positive public opinion and support the actions of troops both locally and internationally. It includes the identification of cultural heritage sites, consideration of combat operation restrictions, cooperation with government authorities and local organizations, prevention of fire damage, and other measures. The uncertainty in the system of cultural property accounting, including both movable and immovable objects, complicates their identification and consideration in developing strategies for resolution and compensation for destruction that occurred during the war [14, 15].

Standards currently guiding the assessment of building energy efficiency in Ukraine, including cultural heritage sites, include:

- DSTU B V.2.2-39:2016 "Methods and Stages of Conducting Energy Audits of Buildings";
- DSTU B V.2.2-19:2007 "Method for Determining the Air Permeability of Enclosing Structures Under Natural Conditions";
- DSTU-N B V.2.6-191:2016 "Guidelines for Calculating the Air Permeability of Enclosing Structures";
- DSTU B EN 13187:2011 "Thermal Performance of Buildings. Qualitative Detection of Thermal Irregularities in Enclosing Structures. Infrared Method";
- DSTU B EN 15251:2011 "Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings for Indoor Air Quality, Thermal Comfort, Lighting, and Acoustics";
- DBN V.2.6-31-2016 "Thermal Insulation of Buildings";
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- DBN V.2.5-64:2012 "Internal Water Supply and Sewerage";
- DBN V.2.5-67:2013 "Heating, Ventilation, and Air Conditioning";
- DSTU ISO 50002:2016 "Energy Audits. Requirements with Guidance for Use";
- DSTU ISO 50004:2016 (ISO 50004:2014, IDT) "Guidance for the Implementation, Maintenance, and Improvement of an Energy Management System";
- DSTU B V.2.6-189:2013 "Methods for Selecting Thermal Insulation Material for Building Insulation";
- DSTU-N B V.2.6-146:2010 "Building Structures. Guidelines for the Design and

Installation of Windows and Doors";

- DSTU-N B A.2.2-13:2015 "Guidelines for Conducting Energy Assessments of Buildings";
- DSTU B EN ISO 13790:2011 "Energy Performance of Buildings. Calculation of Energy
- Use for Heating and Cooling (EN ISO 13790:2008, IDT)";
- DBN V.2.5-28-2006 "Engineering Equipment of Buildings and Structures. Natural and Artificial Lighting";
- DSTU B V.2.6-101:2010 "Building Structures. Method for Determining the Thermal Resistance of Enclosing Structures";
- DSTU-N B V.1.1-27:2010 "Building Climatology";
- DSTU B EN ISO 13790:2011 "Energy Performance of Buildings. Calculation of Energy Use for Heating and Cooling (EN ISO 13790:2008, IDT)".

The lack of alignment between Ukrainian and European building standards poses significant environmental challenges, particularly in the context of modernizing cultural heritage buildings. The absence of harmonization with European norms can lead to insufficient consideration of current requirements for energy efficiency and environmental sustainability. This, in turn, may result in excessive energy consumption, increased greenhouse gas emissions, and a deterioration of environmental quality.

Additionally, there is a risk of using outdated materials and technologies that do not meet European ecological standards, which could have adverse effects on the environment and escalate environmental costs in the future.

2.3 The Object of the Study is the Old Galagov Building - the Austro-Hungarian Heritage in Uzhhorod

The city of Uzhhorod in Ukraine boasts a rich architectural heritage from the Czechoslovak interwar modernism era, with the Maly Galagov district standing out as a significant example. Local urban planners and cultural heritage advocates aspire to have this area recognized as a UNESCO World Heritage site.

Key structures in this district include:

1. Masaryk Bridge;
2. Rafanda;
3. Zemstvo Gendarmerie Command of Subcarpathian Rus;
4. House of Public Health;
5. Zemstvo Government of Subcarpathian Rus;
6. Justice Block;
7. Residential Buildings of Maly Galagov;
8. House for Military Personnel;
9. Masaryk School;
10. Linden Alley;
11. National Bank;
12. Zemstvo Financial Administration of Subcarpathian Rus;
13. Command of the 12th Czechoslovak Infantry Division;
14. Temporary Government Building;
15. State Police Department of Subcarpathian Ruthenia;
16. Postal and Telegraphic Government;
17. The Building of the Legio Cooperative;
18. City Cinema and Library;
19. Baty Palace;
20. House of Dr. Shalamon;
21. People's House of the O. Dukhnovich Society;
22. Craft School;
23. Hebrew-speaking Gymnasium;
24. City Swimming Pool;
25. Ivan Olbracht Street;
26. Jewish School and Community Centre;
27. People's House of the Prosvita Society;
28. Lesser Prague;
29. Villa of Antony Beskyd;
30. Municipal Water Supply Building and Hydrant Network.

Ukrainian artists and cultural researchers have launched a campaign to preserve Maly Galagov, the central modernist district of Uzhhorod, which was developed between 1919 and 1938. However, due to ineffective legislation regarding the reconstruction of historical buildings and frequent unauthorized alterations by new property owners, many of these structures have irreversibly lost their unique character.

With the onset of the war, Uzhhorod has become a refuge for thousands of Ukrainians, being one of the safest cities. This influx has exacerbated the housing shortage, leading to an urgent need for the energy modernization of older buildings. Yet, this necessity raises a complex dilemma: how to balance the preservation of the city's unique historical heritage with the demands for modern living conditions and energy efficiency [16].

The challenge is further complicated by the lack of robust legal frameworks and enforcement mechanisms, which has allowed for the degradation of Maly Galagov's architectural heritage. There is a pressing need for a comprehensive strategy that not only protects these historic buildings from further damage but also integrates sustainable practices to meet contemporary energy needs without compromising their cultural significance.

2.4 Assessment of a Cultural Heritage Building in Uzhhorod in Accordance with Ukrainian Building Standards for Energy Modernisation

The primary objective of conducting an energy audit (EA) is to assess the energy consumption of a building, develop a step-by-step plan for energy modernization, provide a technical and economic justification for these measures, and analyze potential cost-saving opportunities for heating, as well as identify possible funding sources for implementing energy efficiency improvements [17-19].

During the energy audit, data on energy consumption were collected and systematized, an analysis of the existing technical and operational documentation was carried out, and an instrumental inspection was performed in accordance with the approved measurement program. The building's energy efficiency class was determined, and the level of energy resource accounting systems was evaluated. An energy balance for the use of thermal energy was constructed, and an energy profile of the building was created. Based on these findings, a series of energy-efficient measures aimed at reducing the building's energy consumption was proposed. The energy audit also included an economic evaluation of the proposed energy efficiency measures, assessing their profitability.

The profitability indicators were calculated based on energy tariffs as of March 2020, with a projected real discount rate of 4.8% (nominal discount rate of 10%, expected inflation rate of 5%), and a planning horizon of 20 years. The indicators calculated include Pb (simple payback period), PP (discounted payback period), n (economic service life), NPV (net present value), NPVQ (net present value coefficient), and IRR (internal rate of return). In table 2.1 next information is presented.

Table 2.1. Indicators of profitability from the implementation of energy efficiency measures

Indicators of profitability from the implementation of energy efficiency measures									
Name of the measure	Total efficiency, kWh/year	Implementation, UAH cost	Total efficiency, UAH/year	b, years	P, years	RR, %	NPV, UAH	NNPVQ	The term of service, years
Installation of an individual heating point	134469	860100	118564	7,3	9,1	10,8	390601	0,41	≤15
Door replacement	8861	78100	8861	9,3	12.6	9,7	28474	0,36	≤15
Installation of automatic balancing valves	15920	134400	14037	9,6	13,1	6,2	13673	0,1	≤15
Installation of thermostatic regulators	19485	212400	17180	12,4	12,2	2,5	49270	0,31	≤15
Insulation attic ceiling	120645	1434700	114160	12,6	19,6	6,2	213372	0,15	≤25
Replace-ment of windows	105543	2509400	99870	25,1	<20	-5,8	-455897	-0,58	≤15
Installation of ventilation system	12385	4272800	93010	45,9	<20	-11,6	-3291661	-0,77	≤15
Total:	503220	9481,9	8183400	11,6	-	-	-	-	-

The following requirements were considered during the energy audit:

- The indoor air temperature in rooms, depending on their purpose, was set at 18-20°C
- The calculated average indoor air temperature in the building's rooms was set at 20°C
- The minimum allowable thermal resistance value for enclosing structures in residential and public buildings in the second temperature zone was:
- For external walls: 2.8 $m^2 \cdot K/W$
- For transparent enclosing structures: 0.6 $m^2 \cdot K/W$
- For entrance doors: 0.5 $m^2 \cdot K/W$
- For attic coverings and unheated attic floors: 4.5 $m^2 \cdot K/W$
- For floors over passageways and unheated basements: 3.3 $m^2 \cdot K/W$
- For combined coverings: 5.5 $m^2 \cdot K/W$
- Ensuring adequate air exchange rates in rooms according to their purpose.
- The allowable difference between the indoor air temperature and the surface temperature of enclosing structures, as per sanitary and hygienic standards, was: For walls: 4°C; For coverings: 3°C; For floors: 2°C.
- The normative maximum specific energy demand for educational institutions in the second temperature zone was 30 kWh/m^3.
- Thermal insulation materials used in the building's thermal envelope must comply with the requirements of DGN 6.6.1-6.5.001, DBN V.1.4-0.01, DBN V.1.4-0.02, DBN V.1.4-2.2.01, and must be accompanied by conclusions from the State Sanitary and Epidemiological Expertise of the Ministry of Health of Ukraine.
- Thermal insulation materials must meet fire safety requirements in accordance with DBN V.1.1-7-2002 "Fire Safety of Construction Sites." The environmental benefits of the measures are shown in Figure 2.1.

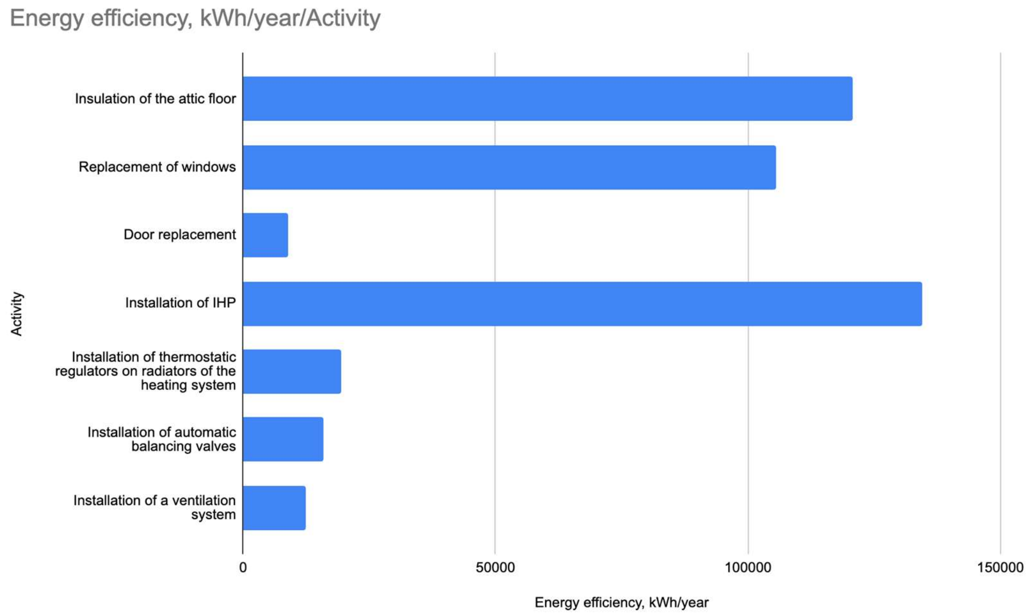

Figure 2.1. Energy efficiency of the measures, kWh/year

This comprehensive approach to the energy audit not only enhances the building's energy efficiency but also ensures compliance with modern environmental and technical standards, which is especially important in the context of increasing demands for sustainable development and energy security.

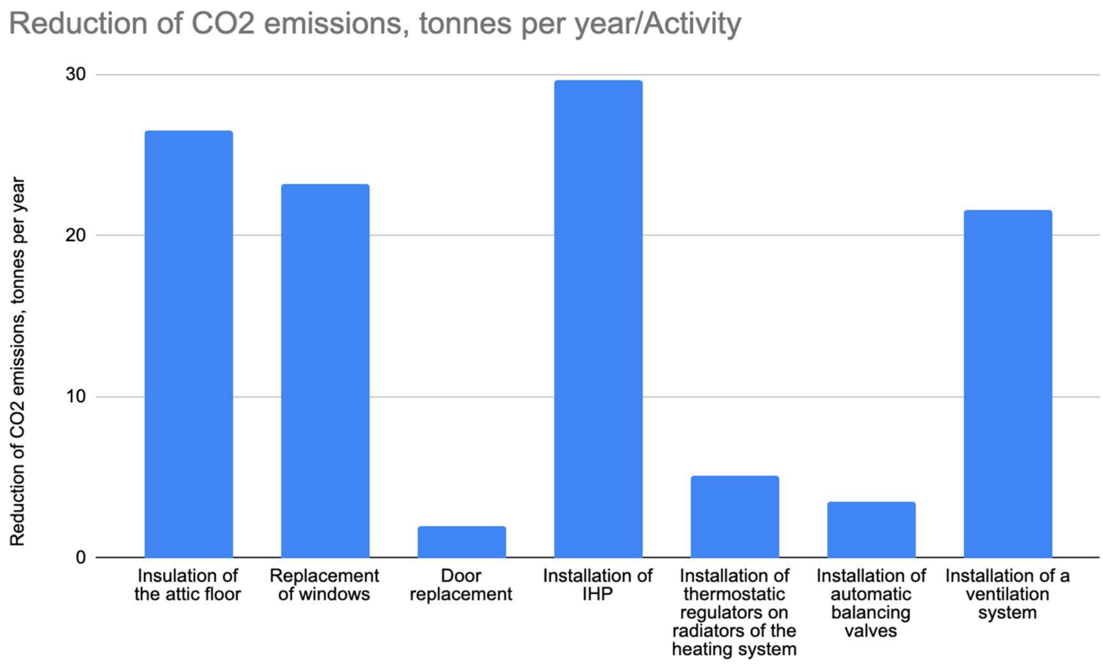

Figure 2.2. Reduction of CO_2 emissions, tonnes per year

The provided diagram on Figure 2.2 illustrates the reduction of CO_2 emissions, measured in tonnes per year, resulting from various energy efficiency activities. The diagram evaluates the impact of specific interventions on lowering CO_2 emissions, highlighting the following activities:

1. Insulation of the attic floor: This measure appears to contribute significantly to CO_2 emission reduction, with a notable decrease in emissions.

2. Replacement of windows: Window replacement also plays a crucial role in reducing emissions, indicating the importance of improved insulation and energy efficiency in this area.

3. Door replacement: The replacement of doors further contributes to emission reductions, though to a slightly lesser extent than the previous measures.

4. Installation of an Individual Heating Point (IHP): This installation demonstrates a moderate impact on reducing CO_2 emissions, reflecting the benefits of optimizing heating systems.

5. Installation of thermostatic regulators on radiators: This activity shows a substantial reduction in emissions, emphasizing the efficiency gains from better temperature control in heating systems.

6. Installation of automatic balancing valves: The installation of these valves has a measurable impact on emission reductions, suggesting improved distribution efficiency within the heating system.

7. Installation of a ventilation system: Although this measure has the least impact on CO2 emission reduction among the listed activities, it still contributes positively to the overall decrease in emissions.

The diagram underscores the cumulative impact of various energy-saving measures on reducing CO2 emissions, with insulation and improved heating system controls standing out as particularly effective strategies [19, 20].

According to the results of the energy audit, the primary objectives include:

1. Assessment of the building envelope and determination of thermal characteristics: This involves analyzing the materials used in the construction of the building envelope and evaluating their capacity to provide adequate thermal insulation.

2. Examination of the building's heating system: The efficiency of the heating system, including boilers, pipelines, and radiators, is assessed to identify potential heat losses and

optimize energy consumption.

3. Analysis of the ventilation system: The effectiveness of the ventilation system is evaluated, focusing on its ability to maintain the required air exchange rates and minimize heat loss through ventilation ducts.

4. Investigation of the hot water supply system: The performance and efficiency of the hot water supply system are evaluated, considering potential heat losses and the efficiency of heat exchange processes.

This section includes the results of the visual and instrumental examination of the building, which enable the assessment of energy resource efficiency. The current condition and insulation levels of the building structures were analyzed during the inspection. To determine air infiltration levels and test the airtightness of windows and exterior doors, an air permeability test of the building was conducted. Due to the specific characteristics of the building and its operational conditions, the test was conducted selectively [21-24]. Air leaks through the building envelope were detected using a thermal imaging camera and anemometer. To determine the geometric characteristics of the building envelope, technical passports, working projects, and measurements using a laser distance meter were used. Additionally, measurements of relative humidity and CO_2 concentration in the indoor air were performed [25, 26].

Measurement Plan:

1. Conducting an air permeability test of the building envelope.
2. Inspecting wall structures with a thermodetector to identify thermal anomalies.
3. Thermal imaging of areas with external air infiltration to detect potential heat leaks.
4. Thermal imaging of the external building envelope to assess heat losses.
5. Measuring indoor air temperature to determine comfort levels.
6. Measuring relative indoor air humidity, CO_2 concentration, and surface moisture levels in the building’s wall structures.
7. Measuring the actual geometric parameters of the building envelope.

This approach allows for a comprehensive assessment of the building's energy efficiency and the development of recommendations for further improvement of its energy performance.

2.5 Air Permeability Test of the Building Envelope

The building exhibits several structural issues, including cracks, areas of detachment, dampness, and degradation of the finishing layer. There are also signs of moisture infiltration in the structures and deterioration of the mortar joints in the brickwork. Additionally, certain sections of the foundation are experiencing moisture accumulation, which accelerates the wear and tear of the building envelope. The thermal resistance of the external wall structures does not meet the minimum requirements set by DBN V.2.6-31-2016.

The window structures in the building are wooden with double glazing. Visual inspection has revealed deficiencies in the window sill finishing, including damage to the finishing layer of the external window sills. This compromises the airtightness of the building by increasing air infiltration and leading to moisture penetration into the wall structure. Some of the inspected windows also have damaged glazing units. The thermal resistance of all window structures falls short of the minimum standards required by DBN V.2.6-31-2016.

The ceiling of the unheated attic is in satisfactory condition, though there are areas where construction debris has accumulated, as well as minor signs of moisture. During the inspection of the pitched roof covering, significant damage to the wind barrier was identified. The thermal resistance of the unheated attic floor does not comply with the minimum standards of DBN V.2.6-31-2016.

The building's door structures are wooden with single glazing. The thermal resistance of the wooden door structures does not meet the minimum requirements specified by DBN V.2.6-31-2016.

These issues collectively contribute to the building's reduced energy efficiency and increased vulnerability to environmental stressors, necessitating urgent remediation to prevent further deterioration and to ensure compliance with current building standards.

2.6 Inspecting Wall Structures with a Thermodetector to Identify Thermal Anomalies

The measuring instrument is designed for non-contact measurement of surface temperature, ambient temperature, and relative humidity. It calculates the dew point temperature and identifies thermal bridges, indicating the risk of mold formation. In the mold warning mode, the instrument measures the ambient temperature and relative humidity. Based on these two values, the dew point is calculated. Additionally, the surface temperature is measured. The dew point is compared with the surface temperature, and the result is evaluated in terms of the potential risk of mold development. The risk of mold growth on the internal surfaces of external walls, particularly in corner areas where thermal bridges occur, is considered low (Figure 2.3). Similarly, the risk of mold formation on the surface of window sills, which are also thermal bridges, is assessed as low [27].

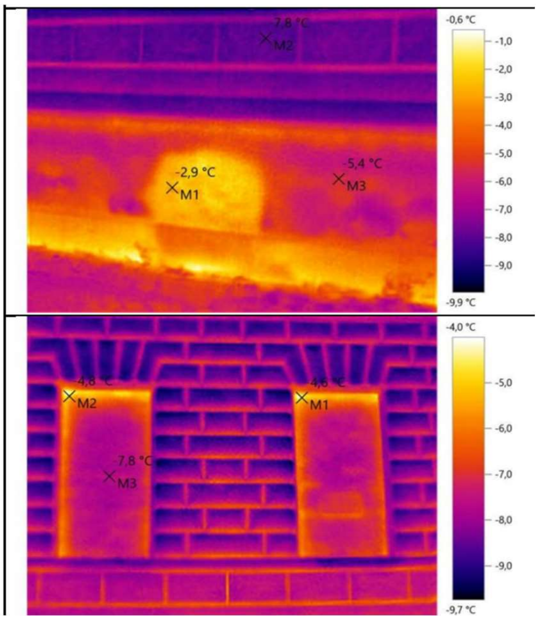

Figure 2.3. Results of thermographic inspection of the building envelope (Energy audit. Cross-Border Cooperation Program Smart Energy 2SOFT/1.2/52 "Smart Energy of Cross-Border Cooperation between Ukraine and Romania")

Increased heat loss through wall sections where cold bridges are located, and heat loss through wall sections where heating appliances are installed.

To ensure the accuracy of mold risk assessment, the instrument provides real-time data on environmental conditions, allowing for early detection of problematic areas where heat loss might occur. This capability is critical for maintaining building integrity, as it helps prevent both structural damage and potential health hazards caused by mold growth. The use of such instruments is essential in energy audits and building diagnostics to identify and mitigate risks related to inadequate insulation and moisture accumulation.

2.7 Inspecting of Air Permeability of Building Envelopes

The essence of the test lies in passing a controlled airflow through the tested object and, once a steady-state flow is established, measuring the air leakage rate and the pressure differential between the internal volume and the external environment or between opposite surfaces of the structure. The test is conducted by either reducing or increasing the internal pressure relative to outdoor conditions. Based on the measurements, the overall characteristics of the building's air permeability are calculated.

The building's premises were tested for the air permeability of the envelope structures. During the test, areas of external air infiltration were identified using thermal imaging. The air leakage rate, measured in cubic meters of air per hour (SMN50), was determined under a pressure differential of 50 Pascals between the building's interior and the external environment. This indicator was obtained through a blower door test. A pressure difference of 50 Pascals simulates the effect of wind acting on the building at a speed of 9.2 m/s (Figure 2.4).

This method provides a quantitative evaluation of the building's air tightness and helps to identify weak points in the building envelope where air infiltration occurs. By determining the air permeability, the test allows for the assessment of heat loss due to uncontrolled airflow, which is crucial for improving the building's energy efficiency and comfort levels. The results can then be used to recommend measures to enhance the airtightness of the building, reduce heat loss, and increase overall energy performance.

It is noticeable infiltration of external air through gaps at the junctions between window frames and wall structures. Additionally, air leakage is observed through the sashes of the window units.

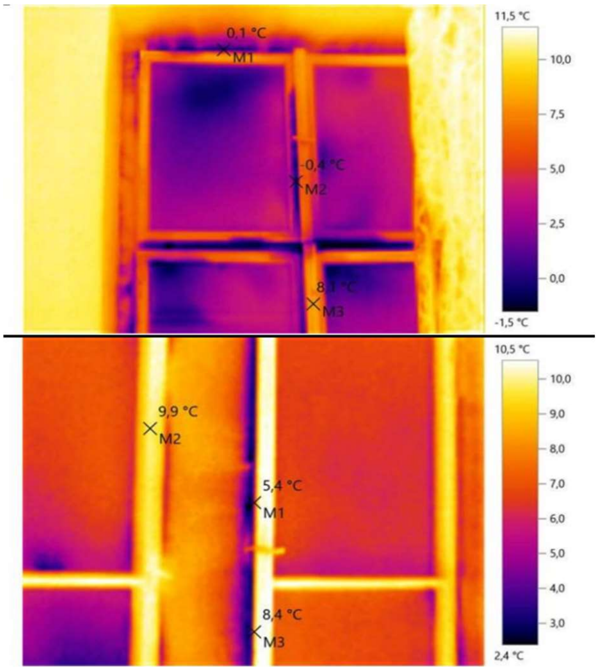

Figure 2.4. Air leakage points (Energy audit. Cross-Border Cooperation Program Smart Energy 2SOFT/1.2/52 "Smart Energy of Cross-Border Cooperation between Ukraine and Romania")

This air infiltration indicates a compromise in the building envelope's airtightness, which can lead to increased heat loss and a reduction in overall energy efficiency. Such infiltration points are critical as they not only affect thermal comfort within the building but also contribute to higher energy consumption for heating and cooling [28-30]. Addressing these issues, particularly at the window-to-wall interfaces and window sashes, is essential for improving the airtightness of the structure. The use of advanced sealing techniques, high-quality insulation materials, and proper installation practices can help mitigate these air leaks, enhancing both the energy performance and indoor air quality of the building.

2.8 The Energy Consumption of Buildings Depends on the Microclimate Parameters of the Premises: Temperature, Ventilation, Lighting

Energy consumption in buildings is largely influenced by indoor microclimate parameters, including temperature, ventilation, and lighting, as well as the building's intended use.

The primary parameter in determining the indoor microclimate is air temperature (Figure 13.5). The average indoor temperature is typically measured at a height of 1.5 meters from the floor. During the energy audit, continuous temperature measurements were taken over a 24-hour period using temperature sensors (loggers).

One of the key indicators of indoor air quality is the concentration of carbon dioxide (CO_2) in relation to outdoor air. The recommended threshold for CO_2 levels is no more than 500 ppm above outdoor air levels. CO_2 naturally comprises approximately 0.035% (or 350 ppm) of the Earth's atmosphere. However, insufficient CO_2 levels can lead to a range of health issues affecting the endocrine, nervous, cardiovascular, digestive, and musculoskeletal systems. Conversely, a significant increase in CO_2 concentration can lead to a rapid decline in well-being, with levels exceeding 5% (50,000 ppm) being fatal to humans. At concentrations above 1,000 ppm, a person's attention span decreases by 30%, and at levels above 1,500 ppm, fatigue sets in quickly. Concentrations of 2,000 ppm impair the ability to focus. CO_2 levels were measured in rooms where occupants spend extended periods, and the recorded concentration of CO_2 was 450 ppm, which falls within acceptable limits. Throughout the day, room temperatures remained stable, with a noticeable drop at night. This phenomenon is due to the rise in outdoor temperatures during daylight hours, which increases heat gains from solar energy, while the heating system lacks proper regulation. Indoor humidity was within the acceptable range throughout the assessment. The consistency of temperature during the day, combined with appropriate humidity levels, suggests a stable indoor environment, although opportunities for optimizing heating control remain. The heating requirements of the building are met through a centralized system, supplied by a boiler plant located in a separate structure on the adjacent premises. This boiler plant also provides heating for two other neighboring buildings, which are part of the same institutional property. During the inspection, several key factors were evaluated: the type of heating system, the efficiency of heat carrier regulation, the presence and effectiveness of thermal insulation on the main pipelines and risers in unheated spaces, as well as the condition of the pipes and radiators. The centralized heating system's ability to regulate the heat supply is crucial for maintaining energy efficiency and indoor comfort. Special attention was paid to the insulation of the heating pipes, especially in unheated areas, as poor insulation can lead to significant heat losses, increasing the overall energy demand. The condition of the pipelines and radiators was also examined to assess the potential for heat loss through aging or damaged components, which can further reduce the system's efficiency.

Evaluating these elements helps in identifying opportunities for optimizing the heating system, such as improving insulation, upgrading outdated components, or installing modern heat regulation devices. This is essential for minimizing energy waste, reducing operational costs, and enhancing the sustainability of the building's heating system.

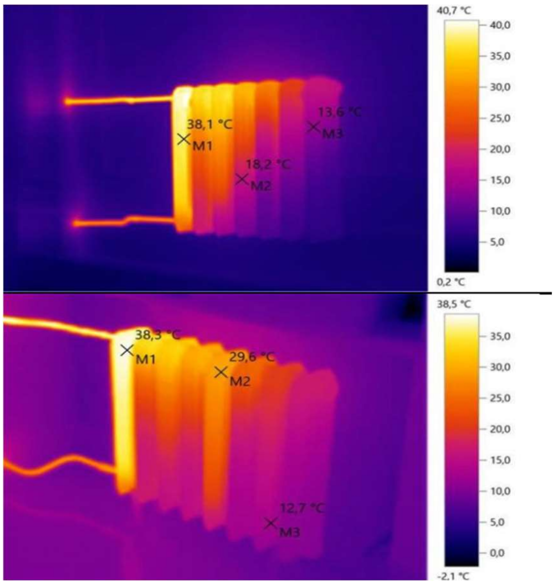

Figure 2.5. Thermographic inspection of heating system elements (Energy audit. Cross-Border Cooperation Program Smart Energy 2SOFT/1.2/52 "Smart Energy of Cross-Border Cooperation between Ukraine and Romania")

The heat transfer devices are obstructed, and it is recommended to perform chemical cleaning to restore their efficiency. Additionally, it is advisable to install chemical water treatment systems in the boiler room, which supplies thermal energy to the building in question. Implementing chemical water treatment would significantly improve the overall efficiency and longevity of the heating system by preventing scale formation and corrosion in the pipes and heat exchangers. This, in turn, would enhance the heat transfer performance, reduce maintenance costs, and ensure a more stable and efficient supply of thermal energy to the building. Such measures are crucial for maintaining optimal system functionality and improving energy efficiency in the long term.

The educational facility lacks a centralized hot water supply system, and no local water heaters are installed.

Ventilation in the building occurs naturally, driven by pressure differences between the interior and exterior, as well as air permeability through the building envelope, primarily due to gaps in the window structures and openings in the window and door assemblies. There is no central cooling system in place, and local air conditioning units are also absent.

Given the absence of dedicated systems for hot water and air conditioning, the building relies heavily on passive ventilation methods, which may result in uncontrolled air infiltration, reduced thermal comfort, and increased energy loss. Installing modern systems, such as energy-efficient ventilation with heat recovery or localized water heating solutions, could significantly improve indoor environmental quality and enhance energy efficiency, reducing the building's operational costs and improving occupant comfort.

2.9 Lighting System in the Building

The lighting system in the building utilizes a combined approach, incorporating both natural and artificial lighting, which complies with the requirements of DBN B.2.5-28. Natural lighting is provided through side windows.

The windows in the rooms are generally kept clean, and curtains are installed above them. In addition to natural light, artificial electric lighting is used throughout the building. The electrical wiring for the lighting system is primarily concealed within the walls under plaster, with some sections routed externally in protective conduits, in accordance with the 2009 PUE of Ukraine (Article 681, "Rules for the Installation of Electrical Installations"). The artificial lighting system operates on a zonal control basis, allowing different sections of the building to be lit independently.

Electricity for the main building is supplied by the city's electrical grid via 0.4 kV cable lines, which are routed underground from the transformer substation to the building's entrance. The cable connects to the main input distribution board at the busbars of the main circuit breaker. Electricity usage is monitored at the point of connection with the external grid through a meter located at the boundary of responsibility.

Lighting within the building is manually controlled by switches that operate groups of light fixtures. The lighting system is divided into two categories: interior lighting for the rooms and exterior lighting for the surrounding area.

It is recommended that when fluorescent or incandescent bulbs fail, they should be replaced with more energy-efficient LED lamps, which would significantly reduce energy consumption and enhance the overall energy efficiency of the lighting system. This transition to LED lighting would not only lower operational costs but also contribute to extending the lifespan of the lighting fixtures, improving sustainability.

2.10 Assessment of Estimated Energy Consumption, Baseline Energy Consumption and Energy Consumption After Implementation of Measures

Actual Calculated Energy Consumption of the Building:

The actual calculated energy consumption of the building takes into account real operational conditions, including actual microclimate parameters and indoor thermal comfort (referred to as "as-is" baseline energy consumption). This value may vary, being either higher or lower than the baseline consumption, depending on the factors mentioned above.

Baseline Energy Consumption of the Building:

Baseline energy consumption refers to the calculated energy usage under standardized microclimate conditions, internal thermal comfort, and normative (design) operational conditions of the building (referred to as "as-designed" baseline consumption).

The key parameters defining the "as-designed" baseline microclimate and internal thermal comfort that should not fall below the regulatory or design values include:

- Indoor air temperature;
- Air exchange rate.

Post-Modernization Energy Consumption:

This refers to the projected energy consumption of the building after the implementation of energy modernization measures, as recommended following the building's assessment. The calculations are based on maintaining regulatory microclimate parameters, internal thermal comfort, and normative operational conditions (Figure 2.6).

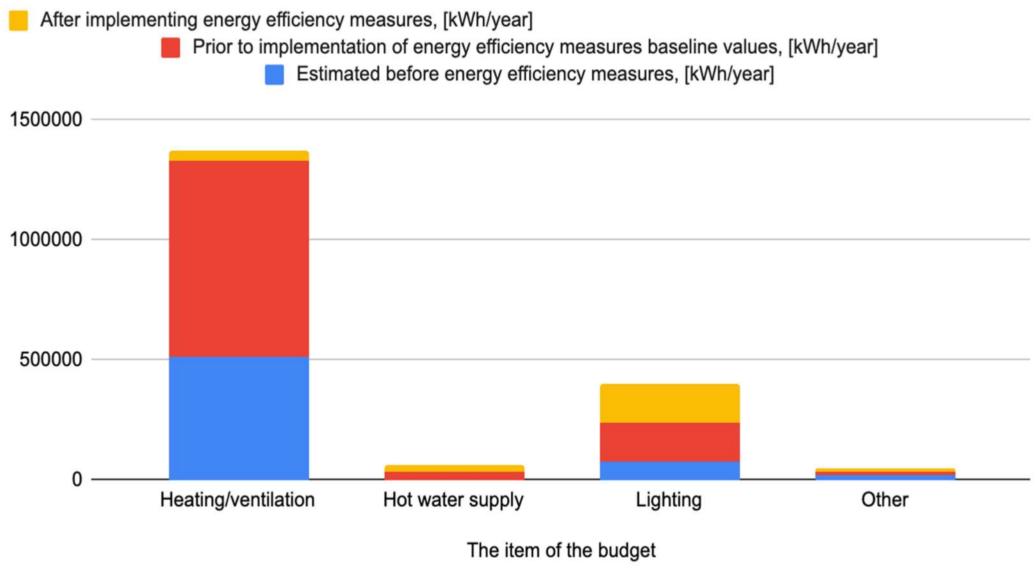

Figure 2.6. Assessment of estimated (actual) energy consumption, baseline energy consumption and energy consumption after implementation of measures

Energy Efficiency Class of the Building:

The energy efficiency class of the building is determined based on the range of energy performance values, as specified by DBN V.2.6-31-2016 "Thermal Insulation of Buildings." According to DBN V.2.6-31-2016, the normative maximum energy demand for educational institutions in the second temperature zone is set at Emax = 30 kWh/m³. Based on the analysis of the building's actual condition, the following measures and recommendations are proposed to improve its energy efficiency:

1. Insulation of the building's ceiling;
2. Replacement of windows;
3. Replacement of doors;
4. Installation of an individual heating point (IHP);
5. Installation of thermostatic regulators on the heating system's radiators;
6. Installation of a ventilation system;
7. Installation of automatic balancing valves on the heating system risers;

Before implementing these measures, it is recommended to conduct a thorough technical inspection of the building's structures. The proposed list of measures has been developed with consideration of the building's status as a "cultural heritage site," ensuring that the energy modernization respects the building's architectural significance while improving its overall energy performance.

Assessment of a Cultural Heritage Building in Uzhhorod in Accordance with EU Building Standards and Life Cycle Assessment

Among all building types, historic structures pose greater challenges in energy retrofitting due to their protection under heritage conservation laws and regulations. Key interventions, such as the insulation of walls and roofs, and installations like photovoltaic panels or new windows, are often restricted for buildings with significant historical and artistic features. Additionally, retrofitting costs for such buildings tend to be higher, as they require specialized solutions, materials, and technologies that preserve cultural values while improving energy performance. Recent studies and practices in the energy retrofitting of historic buildings aim to achieve ambitious goals, such as "net-zero carbon" or "near-zero emissions" targets.

Several factors contribute to energy inefficiency in historic buildings, including orientation, sun exposure, wind and rain, shape, construction materials, and heating and cooling systems. Sustainable retrofitting solutions for historic buildings often incorporate hygroscopic insulation, wood fiber panels, mineral wool, and lime plasters with cork or hemp. While "net-zero carbon" is more commonly associated with new construction, the concept of reducing greenhouse gas (GHG) emissions is crucial across all stages of a building's life cycle—from construction to operation and eventual demolition. This highlights the need for comprehensive accounting of GHG emissions throughout the building's entire life cycle to make more sustainable choices in building management.

In recent years, the concept of "embodied carbon" has gained prominence. This refers to the amount of CO_2 embedded in materials and production processes, including extraction, transportation, processing, and eventual demolition and disposal (end-of-life) phases. The Life-Cycle Assessment (LCA) approach evaluates various environmental impacts, including CO_2 and other GHG emissions, throughout the entire life cycle of a product or building. Historically, this method has been applied to industrial production and buildings, using different tools and methodologies. In the context of historic buildings, GHG emissions are considered not only during the operational phase but also from material extraction to end-of-life. This life-cycle perspective shifts the focus in sustainability assessments, emphasizing the environmental benefits of reusing existing structures with high embodied carbon over producing new ones. This aligns with the principles of the circular economy, which aims to minimize resource depletion and GHG emissions by reusing, repairing, and refurbishing existing products and buildings.

The European Standard EN 16883:2017 provides guidelines for sustainably improving the energy performance of historic buildings—those with historical, architectural, or cultural significance—while respecting their heritage value. It highlights the importance of considering the entire life cycle of a building, stating that "historic buildings should be sustained by respecting the existing materials and construction, discouraging the removal or replacement of materials which require reinvestment of resources and energy with additional carbon emissions". However, methodologies for assessing embodied carbon in buildings can vary, underscoring the need for harmonization and the establishment of benchmarks to ensure consistency in evaluation.

The aim is to test the Life-Cycle Assessment (LCA) methodology for the evaluation of the embodied carbon in historic buildings towards a circular economy approach in the adaptive reuse of cultural heritage, applying it to the case study of an heritage building in Uzhhorod. As for the conceptual level, the specific contribution of this paper is framed into the context of evaluating the feasibility and effectiveness of heritage buildings reuse strategies, that is, calculating embodied carbon in historical buildings, within the overall framework of how LCA may support urban planning and design for heritage conservation. Cultural heritage buildings and sites are considered a "cultural capital" for present and future generations and the option of "demolishing and new build" is not covered in this study, while only conservation measures are taken into account with different intervention measures. Thus, this paper investigates the embodied carbon in restore and re-use projects of existing heritage buildings to test the hypothesis that they are a better option on environmental and climate change grounds, when compared to new construction projects of buildings (in nearby locations) to cater for similar uses.

The objective of this study is to apply the Life-Cycle Assessment (LCA) methodology to evaluate the embodied carbon in historic buildings, emphasizing a circular economy approach in the adaptive reuse of cultural heritage. The focus is on a case study of a heritage building in Uzhhorod. This paper aims to assess the feasibility and effectiveness of strategies for the reuse of heritage buildings, specifically by calculating the embodied carbon within the broader framework of how LCA can inform urban planning and design for heritage conservation.

One of the key contributions of this research is to underscore the importance of utilizing superior European Union building standards compared to those currently in place in Ukraine.

EU standards provide advanced methods for modeling the environmental impacts of the construction industry, enabling more accurate projections and the minimization of the carbon footprint. These standards allow for a more comprehensive analysis of how building materials, energy use, and operational factors contribute to the overall environmental performance of construction projects. By adopting these standards, it becomes possible to make more informed decisions about the ecological consequences of building interventions.

Cultural heritage buildings are seen as "cultural capital" for both present and future generations. Therefore, this study does not explore the option of "demolish and rebuild" but focuses solely on conservation strategies with various intervention measures. The research investigates embodied carbon in the restoration and adaptive reuse of existing heritage buildings, testing the hypothesis that such projects are more environmentally sustainable and climate-friendly than new construction in similar contexts. By focusing on the restoration of heritage buildings, the study seeks to demonstrate that reusing and conserving historical structures is a more sustainable option, particularly when compared to the carbon emissions associated with constructing new buildings.

An optimal approach was selected for the modernization of the heritage building, focusing on improving energy efficiency while preserving its historical value. This was achieved using the Life Cycle Assessment (LCA) methodology, which allows for an in-depth evaluation of environmental impacts over the building's entire life cycle. The selected scenario involves maintaining the heritage building in its current state with minimal conservation work aimed at preventing further deterioration. This approach represents a conservative but balanced option, ensuring the protection of the cultural heritage for future generations while addressing sustainability concerns.

The scenario was compared with alternative modernization strategies in terms of environmental impacts, specifically considering both embodied and operational energy and their associated carbon emissions. The rules for conducting LCA are defined by internationally recognized standards, including ISO 14040 and ISO 14044. In addition, standards specific to construction works, such as EN 15978 (LCA for construction projects), ISO 21929-1, and ISO 21931-1, were applied. Environmental Product Declaration (EPD) standards, such as ISO 14025, EN 15804, and EN 15942, were also integrated into the LCA software used for the analysis (One-Click LCA). Embodied carbon was calculated using the metric "kg CO_2e/m^2," considering the building's Gross Internal Floor Area of 4789.4 m^2. This standardized unit allows for effective comparison and benchmarking of different design scenarios. The results of the LCA were used to determine the most environmentally favorable scenario, taking into account the life cycle of each option presented (Table 2.2).

Table 2.2. Historic building data for LCA.

Data of the building	Case study
Address	Ukraine, Uzhhorod
Type Historic or protected monument	Historic
Age/Period Year built	1855
Use	Yes
Number of buildings on site	1
Number of floors	3
Gross floor area (m2)	4789,4

From a construction standpoint, the building's size and structural composition suggest the use of local and traditional construction techniques. The masonry and vaulted elements were likely constructed using conglomerate techniques, involving a mix of freshly hewn stones of varying sizes, bricks, and lime mortar. The roof is assumed to be a wooden structure with a brick covering. The benchmark for embodied carbon was calculated over a fixed 50-year assessment period for all building materials used in the project.

By selecting this approach, the study not only highlights the importance of improving energy efficiency but also emphasizes the need to minimize environmental impacts in line with European Union building standards. These standards offer superior methods for modeling and reducing the carbon footprint of construction activities, making this scenario the most suitable from both a cultural and ecological perspective.

The Life Cycle Assessment (LCA) protocol for the construction project, as generated by the One Click LCA, is an analytical report focused on evaluating the environmental impact of a building across its operational stages, particularly in terms of energy consumption and greenhouse gas (GHG) emissions. This report adheres to the Greenhouse Gas Protocol and assesses emissions under Scope 1, 2, and 3. The presented information shown at Figure 2.7. The project of the modernisation heritage building was carried out in Ukraine, with the report dated

2024.

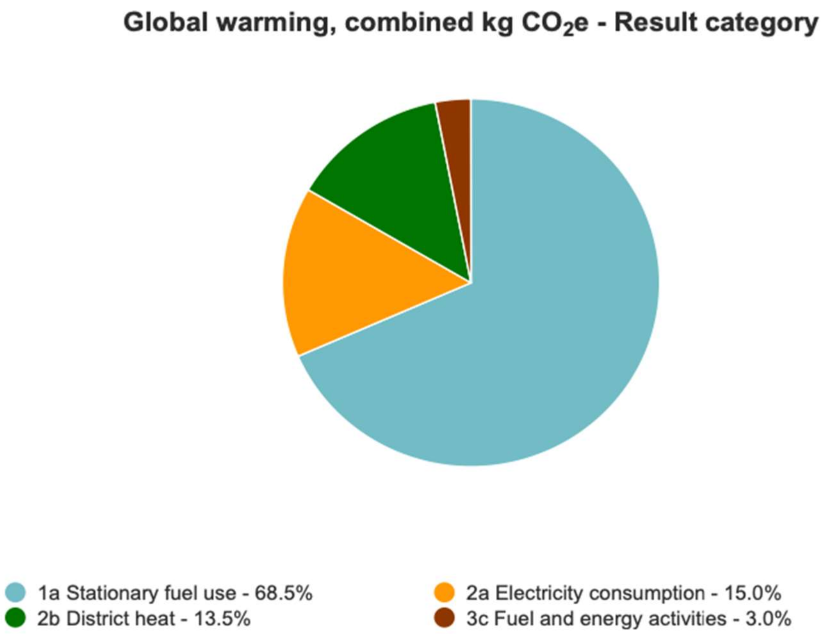

Figure 2.7. Breakdown of CO_2 Emissions by Energy Source in Building Modernization: A Life Cycle Assessment (LCA) Approach

It includes emissions from various sources, such as stationary fuel use, electricity consumption, and district heating, within the operational scope of the building. Emission Categories:

Scope 1 includes direct emissions from sources such as stationary fuel use.

Scope 2 covers indirect emissions from the consumption of purchased electricity, heating, and cooling.

Scope 3 involves other indirect emissions, including upstream activities like fuel and energy production, transportation, and employee commuting.

The most significant contribution to global warming was from stationary fuel use, responsible for 68.47% of the total emissions (98,000 kg CO_2e). Electricity consumption accounted for 14.98%, while district heating contributed 13.5%. Other minor contributions came from transmission losses and upstream energy activities (3.05%). The total emissions for 2024 amounted to 142,434 kg CO_2e, which marked a 68% reduction compared to the heritage building characteristics without energy modernisation, when total emissions were 450,130 kg CO_2e. Natural gas was the primary source of energy, contributing to 68.47% of emissions, followed by district heat (16.55%) and electricity (14.98%).

The evaluation includes key Kyoto Protocol gasses, such as CO_2, CH_4, and N_2O, over a 100-year timeframe. The report takes into account biogenic carbon where available but notes that not all data sources provide such information. This protocol highlights a significant reduction in energy consumption and greenhouse gas emissions through the building's operational efficiency and the use of sustainable energy sources. The comprehensive breakdown of emission sources and resource types offers insights into how the project aligns with environmental sustainability goals.

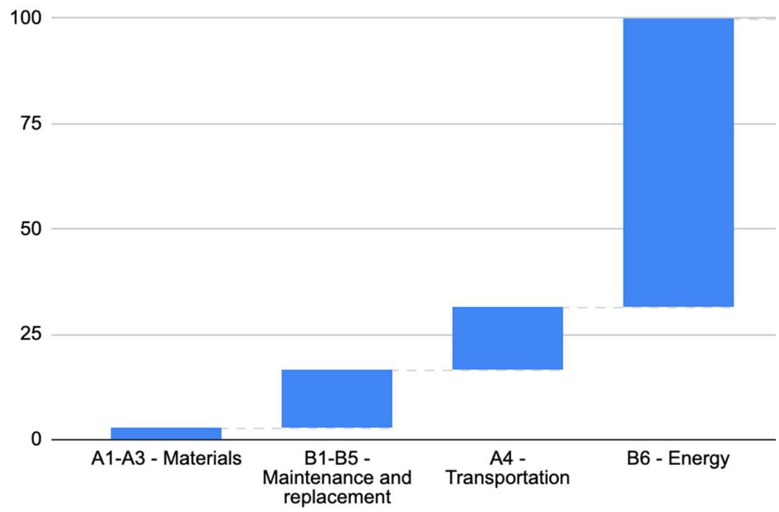

Figure 2.8. CO_2 Emissions Reduction Across Lifecycle Stages for a Historic Building Modernization in Uzhhorod: A Life Cycle Assessment (LCA) Approach

Figure 2.8 presented in the document provides an analysis of CO_2 emissions reduction following energy efficiency measures for a historic cultural heritage building in Uzhhorod, Ukraine. The diagram categorizes emissions according to the lifecycle stages of building materials, construction elements, and resource types. This analysis uses Life Cycle Assessment (LCA) methodologies to assess both the embodied and operational carbon of the building throughout its lifecycle. The building's energy consumption before and after modernization was calculated, with specific attention to key interventions such as:

1. Insulation of the attic floor: This intervention had the largest impact on reducing CO_2 emissions, emphasizing the importance of thermal insulation in energy conservation.

2. Replacement of windows and doors: These upgrades significantly contributed to the reduction of emissions by improving the building's thermal envelope, thus minimizing heat

loss.

3. Installation of thermostatic regulators and automatic balancing valves: These measures improved the efficiency of the heating system, allowing for more precise temperature control and reduction in fuel consumption.

4. Installation of a ventilation system: Though contributing the least to CO_2 reduction, it still enhanced overall energy efficiency by maintaining optimal indoor air quality and preventing heat loss.

The overall impact of these measures resulted in a substantial reduction in emissions, demonstrating the importance of targeted energy efficiency interventions in historic buildings, where structural and architectural constraints may limit the scope of modifications.

The simulations of cultural heritage building conservation alternatives presented in this study yielded intriguing results that support the initial hypotheses and align with findings from previous research. The life cycle assessment approach proves highly beneficial for designers and decision-makers by enabling them to account for not only the greenhouse gas emissions and environmental impacts associated with the building's operational energy performance after construction, known as the "energy performance" level, but also the emissions generated throughout the entire life cycle of the construction works and building (re)use. Furthermore, the European Union's legislation on cultural heritage conservation and energy efficiency is more advanced and comprehensive, ensuring the integration of energy efficiency standards and environmental protection at every stage of a building's life cycle. Ukraine must progressively adapt its building standards and requirements to meet those of the European Union, thereby addressing modern environmental challenges and promoting the reduction of greenhouse gas emissions through energy-efficient solutions, especially in the context of modernizing cultural heritage sites.

2.11 Discussion

The analysis highlights the complexity of modernizing historic buildings to meet modern energy efficiency standards while preserving their cultural and architectural significance. The findings emphasize that substantial reductions in greenhouse gas emissions can be achieved through a combination of envelope upgrades, heating system improvements, and proper ventilation control. The use of LCA methodologies allows for a comprehensive assessment of both the operational and embodied carbon, offering a holistic view of the building's environmental footprint over its lifecycle.

However, the preservation of cultural heritage imposes additional challenges, as certain invasive interventions (e.g., changes to the building's exterior) are restricted. This necessitates innovative solutions such as the use of minimal-impact insulation materials and advanced heating and ventilation systems. The results demonstrate that energy efficiency improvements can be successfully implemented in historic buildings while respecting their historical integrity. Furthermore, the findings underscore the importance of harmonizing national standards with EU regulations, particularly in terms of building retrofitting for energy efficiency. Ukrainian standards currently lag behind their European counterparts, and adopting more stringent EU norms could further enhance the environmental performance of such projects.

The modernisation of a historic building in Uzhhorod demonstrated a notable reduction in CO_2 emissions, with energy efficiency measures resulting in a 68% decrease. Key interventions, such as enhancing the building's insulation, replacing windows and doors, and optimising the heating system, proved highly effective in reducing both operational and embodied carbon. These findings underscore the importance of integrating such measures in the restoration of cultural heritage buildings. This case study also highlights the critical role of Life Cycle Assessment (LCA) as a comprehensive tool for evaluating the full environmental impact of building modernisation projects, particularly for heritage sites where the preservation of historical authenticity is crucial. The ability to assess emissions across the entire lifecycle, from construction to operational phases, allows stakeholders to make informed decisions that not only improve energy performance but also contribute to long-term sustainability by significantly lowering greenhouse gas emissions.

In the context of heritage conservation, where structural and aesthetic constraints often limit the scope of interventions, this study provides evidence that energy-efficient retrofitting is not only feasible but also highly beneficial. This finding is particularly important given the growing need to reconcile the conservation of historic buildings with the urgent demand for reduced carbon footprints. Moreover, aligning national building standards with more stringent European Union regulations could enhance the environmental performance of similar projects, ensuring that heritage buildings contribute to broader sustainability goals while maintaining their cultural significance.

In addition to reducing operational emissions, this research also focuses on assessing embodied carbon—an often overlooked aspect in the adaptive reuse of historic buildings. The study emphasizes that LCA offers valuable insights during the design phase, enabling decision-makers to consider carbon emissions as a key criterion when evaluating alternative reuse strategies. The anticipatory approach adopted in this research highlights the potential of LCA to guide decisions not only at the macro level (such as whether to pursue adaptive reuse, demolition, or maintenance) but also at the micro level, involving choices related to materials and technologies. The inclusion of embodied carbon considerations further enriches the environmental assessment by capturing emissions associated with the construction and renovation phases, which are especially relevant in heritage buildings where material conservation is a priority.

The study also identifies the need for greater investment in innovative materials and technologies, particularly those aligned with the principles of sustainable and circular design. Biomaterials and nanotechnology, for instance, offer promising avenues for reducing the environmental impact of historic building modernisation. The use of bio-based materials, which store biogenic carbon, can contribute to reducing atmospheric CO_2 levels, further enhancing the environmental benefits of retrofitting projects. However, there remains a significant variance in the methods used to assess biogenic carbon, and further research is needed to improve the accuracy and reliability of these evaluations.

While this research provides important insights into the adaptive reuse of historic buildings, it also acknowledges certain limitations. Specifically, the choice of materials and technologies, though suitable for the preliminary stage, should be further refined during advanced design phases. Future studies should focus on expanding the application of LCA to more case studies, enabling the development of benchmarks and best practices for both traditional and innovative materials used in heritage conservation.

In conclusion, the modernisation of historic buildings presents unique challenges, but the use of energy-efficient technologies, guided by comprehensive environmental assessments such as LCA, offers a viable path forward. By integrating LCA with advanced design tools and aligning national standards with European norms, future projects can achieve significant reductions in greenhouse gas emissions while preserving the cultural and historical value of heritage sites. This study contributes to the growing body of research on sustainable heritage conservation, offering a detailed evaluation of how environmental, social, and economic factors can be harmonised in the adaptive reuse of historic buildings.

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Chapter 03

Carbon Footprint of Construction Products - Case Study for a Circular Ventilation Duct in Romania

Tania Rus, Dorin Beu, Raluca Moldovan, Florin Domnița, Horațiu Albu

Faculty of Building Services Engineering, Technical University of Cluj-Napoca, 21 December 1989 Avenue 128-130 no., 400114 Cluj-Napoca, Romania

The escalating demand for raw materials, driven by economic growth and increasing living standards, is projected to nearly double by 2060. This surge in raw material consumption will further amplify the environmental burdens we already grapple with (OECD 2019) [1]. The reliance on resource-intensive extractive processes for building construction poses significant environmental threats throughout the material life cycle, including biodiversity loss, water scarcity, and carbon emissions. Additionally, the disposal of building materials at landfills exacerbates the environmental footprint of the current linear material production model while digitalization in the construction process facilitates prefabrication and modular construction have been shown to reduce material waste by 23 up to 100% [2-5]. Globally, around 100 billion tonnes of construction waste is generated annually, with about 35% of it ending up in landfills, while it could be recovered and repurposed.

Even in industries with high levels of secondary material reuse, the primary strategy should be waste avoidance. For instance, in the iron and steel sector, where over 90% of materials are reused, a widening gap exists between increasing demand and the dwindling supply of secondary scrap steel. Greater collaboration between the construction, forestry, and agricultural sectors is necessary to develop supply chains and building products derived from earth-based materials, forestry byproducts, and agricultural residues. This approach can significantly reduce carbon emissions from forest fires and crop burning. Decarbonization of the cement industry and other major emitters is being pursued through the adoption of hybrid biomaterials and other low-carbon alternatives [6, 7]. However, these emerging methods are not yet cost-competitive, and entrenched industry practices pose obstacles to their widespread adoption. Substantial investments in research and development, coupled with incentives and/or enforceable building codes, are required to accelerate the adoption of these decarbonization strategies. As net-zero targets approach, demand for carbon offsets is expected to surge.

However, there is a risk that an overreliance on carbon offsets could hinder the actual decarbonization of building materials and their production processes [8]. To address this issue, stricter regulations and certifications are needed to ensure the integrity and effectiveness of carbon offset programs.

To extend the lifespan of materials and reduce associated greenhouse gas emissions from construction, a holistic approach that considers the entire building lifecycle, from design to demolition, is crucial for transitioning to a low-carbon building future. This approach envisions a future where waste materials are eliminated from the built environment by actively utilizing construction components and extending the lifespan of buildings to the maximum extent [9]. In essence, leveraging material reuse and recovery strategies promotes a circular economy for building materials, while simultaneously improving the energy performance of buildings, the lower the overall embodied carbon footprint over its lifetime.

3.1 The Whole-Life Cycle Analysis Approach

Despite its substantial environmental footprint, embodied carbon has received insufficient attention in strategies to minimize building emissions. While building codes and regulations primarily address operational carbon, associated with energy use, they often neglect embodied carbon, generated from the life cycle of materials. Therefore, industry leaders are increasingly adopting a whole-life cycle analysis approach to guide strategies that simultaneously address embodied and operational carbon. These measures range from constructing fewer buildings, using less material, and opting for low-carbon materials to adopting circular approaches and designing buildings with longer lifespans and lower operational emissions during their use.

To decarbonize the building materials sector, all stakeholders must take greater responsibility for comprehending the environmental impact of their material selection decisions across the building lifecycle. This requires providing relevant data to the appropriate stakeholders at critical decision-making stages. Built environment carbon rating systems should be modified to provide greater rewards for avoiding new construction when feasible, transitioning to low-carbon bio-based solutions, and enhancing the production methods for conventional materials. To achieve a sustainable construction industry, all participants along the building process must recognize the environmental footprint of material choices throughout the product's life cycle.

Given the intricate supply chains of building materials and systems, advanced computational tools and data visualization frameworks are essential for decision-makers to evaluate the advantages and disadvantages of different materials based on their embodied, operational, and end-of-life environmental impact. Data management and visualization tools play a crucial role in involving multiple stakeholders in the decision-making process and providing real-time insights for informed choices [10, 11]. While transparency and data quality in construction material assessments have improved, there remain significant challenges in comparing material impacts using third-party certifications like Environmental Product Declarations. These certifications, though developed as verifiable life cycle assessment reporting mechanisms, face limitations in procurement decision-making due to inconsistencies in data quality, methodologies, functional equivalencies, and product category guidelines.

There is growing momentum for establishing an international standards committee to standardize embodied carbon labelling for building materials. This initiative aims to address the inconsistencies in existing methods and ensure consistent and reliable data on the embodied carbon emissions of various materials. However, for certification to effectively incentivize the use of low-carbon materials, more work is needed to address the "carbon loophole" that exists between countries with strict pollution controls and those with laxer regulations. This necessitates developing methods that hold producers from all regions equally accountable for their environmental impact.

Existing embodied carbon assessments can be broadly categorized into two approaches:

1. *Expert assessments*: These assessments involve sophisticated modeling and analysis techniques, often conducted by specialized consultants. While they provide detailed insights into the complexities of material impacts, they are time-consuming and expensive, limiting their broader applicability.
2. *Easy-to-use tools*: These tools offer simplified assessments that provide quick and practical guidance for typical construction projects. Although they may not provide the same level of granularity as expert assessments, they can democratize the process of evaluating embodied carbon emissions and make it accessible to a wider range of stakeholders.

In addition to these two approaches, the development of accounting tools is crucial for capturing the full life-cycle carbon impacts of both traditional and prefabricated building materials. These tools allow for a more comprehensive assessment of emissions generated throughout a material's lifecycle, from extraction and production to transportation, use, and eventual disposal.

However, accurately predicting the impact of materials on a building's operational performance is a complex task that requires consideration of various factors, including local climate, building typology, system integration, occupant behavior, and usage patterns. These factors can significantly influence the energy efficiency and carbon footprint of a building over its lifespan. To address this challenge, tools like EC3 Carbon Calculator, WoodWorks Carbon Calculator, OneClick LCA, SimaPro and GLAD are being developed to provide more comprehensive life-cycle assessment capabilities.

Shifting from prescriptive building codes to performance-based ones offers an opportunity for emerging economies to leapfrog outdated regulations and adopt more flexible and sustainable approaches. Prescriptive codes typically specify minimum requirements for materials and energy efficiency, while performance-based codes focus on achieving specific energy and environmental performance targets. This approach empowers designers and builders to explore innovative solutions tailored to specific project requirements and local contexts. Tools like EnergyPlus, Building Energy Modelling, Zero Tool, PV Calculator, and DSIRE Efficiency / Energy Incentives Database are playing a crucial role in enabling performance-based building codes. These tools provide powerful modeling capabilities and access to real-time data, enabling the evaluation and optimization of building performance.

Low-carbon public procurement practices are emerging as a critical driver of change. Governments at various levels are setting ambitious targets for decarbonizing their infrastructure and building stock. Public procurement, which involves the government's purchase of materials, products, and services, represents a significant opportunity to influence the market towards low-carbon choices. To effectively leverage public procurement for sustainability, rigorous whole-life-cycle assessments should be integrated into the planning phases of public projects. This will provide valuable data on the embodied carbon and operational performance of various materials and construction methods. Such assessments can also stimulate the development of innovative solutions tailored to specific local climate conditions and building traditions.

By establishing an international standards committee, developing robust assessment tools, embracing performance-based building codes, and implementing low-carbon public procurement practices, we can effectively address the carbon loophole, accelerate the transition to low-carbon materials, and build a more sustainable built environment.

3.2 Environmental Product Declaration

In the context, conducting an Environmental Product Declaration (EPD) for a building or a services material would play a crucial role in accelerating the transition to low-carbon materials and building a more sustainable built environment. By providing a detailed assessment of the environmental impact of the product, it would empower architects, engineers, and building professionals to make informed decisions about the materials they use. This, in turn, would lead to a reduction in the carbon footprint of the built environment.

An EPD is a comprehensive document that assesses the environmental impact of a product throughout its entire life cycle, from raw material extraction to manufacturing, use, and disposal. It provides transparent and comparable information to help consumers and businesses make informed choices about environmentally preferable products for several reasons:

- *Transparency and Accountability:* EPDs provide comprehensive and transparent information about the environmental impact of a product throughout its life cycle, from raw material extraction to manufacturing, transportation, use, and end-of-life. This transparency empowers building professionals and consumers to make informed decisions about low-carbon building materials.
- *Performance Benchmarking*: EPDs allow manufacturers to compare the environmental performance of their products against industry standards and competitors. This benchmarking helps identify areas for improvement and prioritize sustainability initiatives.
- *Sustainable Procurement*: EPDs are increasingly becoming a requirement for low-carbon public procurement practices. By demonstrating a low environmental footprint of a product, the manufacturer can gain a competitive edge and secure contracts for sustainable projects.
- *Environmental Stewardship*: Conducting an EPD demonstrates the manufacturer's commitment to environmental responsibility and transparency. It signals to customers,

investors, and stakeholders that the company is actively taking steps to reduce its environmental impact and contribute to a more sustainable future.

- *Product Differentiation*: In an increasingly eco-conscious market, EPDs can serve as a powerful marketing tool and differentiate from competitors. Customers are increasingly seeking products with proven sustainability credentials, and an EPD provides clear evidence of a company's commitment to environmental performance.

3.3 Lindab Manufacturer

Despite the prevailing perception that outdoor air is more hazardous due to emissions, smog, and toxic chemicals, the reality is that indoor air in homes, workplaces, schools, and factories harbors up to five times more pollutants. Despite this, people spend most of their lives indoors, inadvertently exposing themselves to these harmful contaminants. The primary sources of indoor air pollution include mold, chemicals found in furniture and building materials, dust, radon, and cigarette smoke. However, the most concerning pollutants are airborne particles arising from combustion and industrial processes, as they are so minute that they can penetrate the human bloodstream through the respiratory system. These airborne particles are linked to several of the world's leading causes of death, including heart disease, pneumonia, stroke, diabetes, and lung cancer. Ventilation stands as an effective and convenient method to eliminate these indoor air contaminants [12].

Lindab, a Swedish company, is a frontrunner in European ventilation, which offers innovative solutions that promote energy efficiency and a healthy indoor climate. Their products are meticulously crafted for superior quality, simplified installation, and a strong environmental focus. Additionally, Lindab provides a comprehensive range of roofing, wall, and rainwater systems tailored to northern European environments.

Empowering a healthier future, both indoors and for our planet, is the driving force behind Lindab's commitment to developing innovative solutions. Despite its invisibility, the indoor climate holds immense power over our energy levels, mood, and overall well-being. Embracing this responsibility, the company is dedicated to creating energy-efficient solutions that foster healthy indoor environments, shaping a brighter tomorrow for all.

In their Sustainability Plan, Lindab has set a goal to reduce its carbon dioxide emissions by half between 2019 and 2030. By 2022, the company had already achieved a 16% reduction in total tons of emissions.

Lindab's Quality and Environmental Policy, along with its Sustainability Plan, serves as the foundation for the company's environmental efforts. While Lindab's steel manufacturing operations have a relatively small direct impact on the environment, there is an indirect footprint due to greenhouse gas emissions from the steel industry.

Two key strategies that the company is employing to minimize its environmental footprint include transitioning to low-impact steel as it becomes available and optimizing transportation by adopting more environmentally friendly modes. Lindab's move to fossil-free steel is their single most impactful action to safeguard the environment.

They are actively engaged with their steel suppliers to become a frontrunner in Europe for fossil-free steel availability. The company actively collaborates with its suppliers to reduce environmental impact across the supply chain, which is a crucial area for mitigating biodiversity risks.

In the 2023 annual report [12], Lindab declared that have issued 11 Environmental Product Declarations (EPDs) that provide comprehensive information on the environmental footprint of its products throughout their entire lifecycle.

This commitment to transparency and sustainability is driven by strong market demand for EPDs. Lindab's first EPD was released six years ago, marking the beginning of its ongoing effort to promote sustainable product choices and reduce its environmental impact.

Case study – Circular ventilation duct by Lindab Romania

This study aims to assess the environmental footprint of products produced by the manufacturer and generate corresponding EPD based on the Product Category Rules (PCRs). The study focused on a specific set of products outlined below, and this report was finalized in June 2023.

Inventory data

The case study refers to a circular ventilation duct manufactured by Lindab Romania, a branch of Lindab Sweden, located in Stefanestii de Jos, Ilfov, Romania. The product’s information is listed in Table 3.1.

Table 3.1 – Product’s information

Product name	Circular ventilation duct, folded, made of hot-dipped galvanized steel
Declared unit	1 m of product dimension 125 mm
Declared unit mass	1,41 kg
Date period	2021
Reference service life	60 years

Inventory data for the product stage was gathered through a questionnaire and direct interaction with representatives of the manufacturer. The questionnaire included sections for recording annual quantities of raw materials, supplementary materials, and material losses, as well as information on material suppliers, transportation distances, and transportation modes.

Additionally, annual energy consumption, water consumption, and waste generation data was collected through the questionnaire. Information required for allocating material flows was obtained through personal interviews.

The circular ventilation duct is made of a core of steel, encased in a protective cloak of zinc, providing an impenetrable shield against rust's destructive touch. This is hot-dipped galvanized (HDG) steel, a remarkable material born from the fusion of steel and molten zinc at a scorching temperature of around 450°C. Available in wide coils, slit coils, or sheets, HDG steel seamlessly blends into conventional processing operations like bending, drawing, clinching, profiling, stamping, and welding. The zinc coat reacts to form protective compounds, effectively halting any further corrosion attempts. This zinc armor safeguards the steel from both sides, providing comprehensive protection. Furthermore, a zinc coating enhances the steel's formability, resistance welding properties, and paintability. HDG steel comes in a symphony of qualities, thicknesses, widths, and coating masses, catering to a diverse range of applications.

Scope and system boundary

This EPD provides a comprehensive assessment of the product's environmental footprint from cradle to gate, covering the extraction of raw materials (A1), transportation to the manufacturer (A2), manufacturing (A4), transportation to the site (A4), installation (A5) and end-of-life (C1-C4) considerations. It also incorporates the benefits and loads associated with the product beyond the immediate production process (D). This EPD covers the life-cycle modules listed in the Table 3.2. The technical flowchart of the product's life cycle is presented in Figure 3.1.

Table 3.2 – System boundary

Product stage			Assembly stage		Use stage							End of life stage				Beyond the system boundaries		
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D		
x	x	x	x	x	MND	MND	MND	MND	MND	MND	MND	x	x	x	x	x		
Raw materials	Transport	Manufacturing	Transport	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/demolition	Transport	Waste processing	Disposal	Reuse	Recovery	Recycling

Modules not declared = MND.

Figure 3.1. The process diagram [13].

As it can be observed from Figure 1, the product's life-cycle process respects the principles of a circular economy, encompassing the stages from raw material extraction to recycling. Lindab procures high-quality steel (raw or recycled), ensuring compliance with environmental regulations and quality standards, and transports it to the Sweeden facility. Here, after quality control, the raw or recycled steel is turned into sheets which are meticulously cut, rolled, packaged and shipped to local factories (Lindab Romania for the present case). Each local duct manufacturer, after quality control, cuts and folds the steel sheets into ductworks. A new qulity control is employed for the final ventilation ducts, then are packaged and sent to the warehouse or contruction site (depending on the situation). The circular ventilation duct has a reference life-time of sixty years. In the deconstruction process, the ducts are dissassemblied and transported to the recycling facilities. From here, only a small fration of the product gets to be landfilled, therefore a closed loop of the circular economy is achieved.

Software and database

The upstream (A1-A5) and downstream (C1-C4,D) processes were evaluated using the One Click LCA tool and database, which draws upon the most up-to-date data available in the form of EN 15804-compliant EPDs and supplementary data from Ecoinvent. Data sources are meticulously documented for each data point in subsequent sections. Ecoinvent is a widely recognized database frequently cited in published life cycle assessments.

Its data adheres to ISO14040/14044 standards and has been tailored for compatibility with One Click LCA. The data retrieved from Ecoinvent primarily represents European regions and is therefore well-suited to model the countries examined in this assessment. For calculations, the Ecoinvent 3.6 (2019) version of resources was selected. It is crucial to note that Ecoinvent does not provide year-specific data, but its data represents a sustained period, allowing it to be considered temporally relevant.

Description of manufacturing (A1-A3/D)

The environmental impact assessment for the product stage encompasses the manufacturing of raw materials, packaging materials, and other ancillary materials used in the production process. Additionally, it considers the fuel consumption of machinery, waste management practices within manufacturing facilities, and material losses during production and electricity transmission.

Raw material supply (A1)

Lindab Group receives steel raw materials from its own steel service center, Lindab Steel AB. After quality control, the most suitable steel sheet is selected for each manufacturing order to minimize scrap. The sheet is then slit into the correct dimensions, coiled, or cut to length. For protection and transportation purposes, the units are wrapped in a composite material made from paper and plastic, placed on wooden pallets, and secured with steel straps and edge protectors. The list of materials for the circular ventilation duct is listed in Table 3.3.

Table 3.3. List of materials and processes included in A1

Stage	Resource name	Quantity	Allocation, %	Production losses, %	Region	Date	Data Source
A1	Hot dip galvanised steel	1.41 kg	100.0	0.0	Europ e	2021	Worldsteel LCA Methodology Report

Transportation (A2)

The analysis of transportation impacts encompasses exhaust emissions from transporting raw materials to production sites, as well as the environmental impact of diesel production. Manufacturing, maintenance, and vehicle disposal, along with tire and road wear during transportation, were also considered. The manufacturer provided information on transportation distances and methods which are presented in Table 3.4.

Table 3.4. List of transport processes included in A2

Resource name	Quantity	Distance (km)	Transport	Data source	Date
Hot-dip galvanized structural steel	1.41 kg	2244	Transport, freight, lorry >32 metric ton, euro5	ecoinvent 3.6	2019
Transported mass	0.4943 kg	30	Transport, freight, lorry >32 metric ton, euro5	ecoinvent 3.6	2019

Manufacturing (A3)

The environmental impacts of the production stage encompass the manufacturing of materials that are employed in the production process (Table 3.5) but not incorporated into the final product, such as packaging materials and other ancillary substances. Additionally, this stage includes the fuels consumed by machinery, waste management from production processes at manufacturing facilities, and losses incurred during manufacturing processes (Table 3.6). Energy transmission losses are also factored into the study.

Table 3.5. List of transport processes included in A3

Resource name	Quantity	Distance (km)	Transport	Data source	Date	Comment
Treatment of scrap steel, inert material landfill	0.0324 kg	30	Transport, freight, lorry 3.5-7.5 metric ton, euro5	ecoinvent 3.6	2019	Remat Bucuresti Sud SRL

Table 3.6. List of materials and processes included in A3

Stage	Resource name	Quantity	Comment	Allocation %	Region	Date	Data Source
A3	Diesel, burned in building machine	0.2 kWh	Forklift	100.0	world	2019	ecoinvent 3.6
A3	District Heat, Romania	4.64 kWh		100.0	Romania	2019	LCA study for country
A3	Electricity, Romania, residual mix	0.46 kWh		100.0	Romania	2019	LCA study for country specific
A3	Eur-flat pallet production	0.01669 unit	Wooden pallets	100.0	world	2019	ecoinvent 3.6
A3	Steel production, converter, unalloyed	0.02 kg	Tape	100.0	Europe	2019	ecoinvent 3.6
A3	Treatment of scrap steel, inert material landfill	0.0324 kg	REMAT Bucuresti Sud SRL	100.0	Europe, Romania	2019	ecoinvent 3.6
A3	Wire drawing, steel	0.02 kg	Tape	100.0	Europe	2019	ecoinvent 3.6

Description of construction (A4-A5)

Transportation to construction site (A4)

Transportation to the construction site (A4) contributes to environmental impacts through three main channels: the direct emissions from fuel combustion, the environmental impact of fuel production, and emissions from related infrastructure (Table 3.7). Spills during installation and handling of packaging materials are also considered. Material loss during installation is estimated to be negligible.

Table 3.7. List of transport processes included in A4

Resource name	Quantity	Distance (km)	Transport	Data source	Date
Transported mass	1.44669 kg	200	Transport, freight, lorry >32 metric ton, euro5	ecoinvent 3.6	2019

Installation into the building (A5)

Environmental impacts during the installation phase (A5) include product waste, energy consumption, and waste generation can be seen in Table 3.8.

Table 3.8. List of materials and processes included in A5

Stage	Resource name	Quantity	Comment	Region	Date	Data Source
A5	Treatment of scrap steel, inert material landfill	0.02 kg	Tape	world	2019	ecoinvent 3.6
A5	Wood waste	0.4943 kg	Created on 21.10.2022, Lindab Steel	local		One Click LCA generic
A5	Direct emission to air: Carbon dioxide, biogenic/non-fossil	0.0816 kg	Biogenic carbon mass balance	world	2019	
A5	Wood chipping, industrial residual wood, stationary electric chipper	0.0361 kg		Europe	2019	ecoinvent 3.6
A5	Wood chipping, industrial residual wood, stationary electric chipper	0.0133 kg		Europe	2019	ecoinvent 3.6

Description of use stage (B1-B7)

While this EPD provides information about the product's environmental impact during manufacturing and transportation, it does not account for the environmental impact of the product's use. This is because the environmental impact of the use phase depends on a variety of factors, such as the specific application of the product, the maintenance practices used, and the energy efficiency of the building or structure in which the product is used. A more comprehensive assessment of the product's environmental impact would need to consider all these factors.

Description of the end of life (C1-C4, D)

The energy used to deconstruct the product is included in module C1, the distance for transportation to treatment is comprised in module C2 and the activities related to steel recycling are included in module C3. For the purposes of this analysis, we have assumed a 95% recycling rate for the product's materials. This means that we have factored in the potential for repurposing or recycling the product's components. External scrap in the raw material is also deducted.

The environmental benefits of recycling steel from module C3 are factored into module D. The recycled steel is considered equivalent to primary steel, reducing the need for raw material extraction. To prevent double counting, only the mass of primary steel in the final product is credited for recycling benefits.

LCA results and discussions

The environmental impacts of the LCA simulations are listed in Table 3.9. The results of the B1-B7 stages were not included since the usage stage is not part of this EPD.

The results of life cycle assessment (LCA) calculations are not always consistent across different environmental impact categories. While some categories, like Ozone Depletion Potential (ODP) for the stratospheric layer or Abiotic Depletion Potential for material resources (ADP-elements), might show minimal impact and can potentially be disregarded, others are critical and demand deeper analysis.

This is particularly the case for Abiotic Depletion Potential for fossil fuels (ADP-fossil) and Global Warming Potential (GWP). As Table 3.9 demonstrates, these two categories consistently contribute the highest values within the LCA, especially during the raw material supply and manufacturing stages. This implies that the product or process under evaluation has a significant impact on fossil fuel depletion and global warming, highlighting the need for further investigation and potential optimization in these areas. In simpler terms, not all environmental concerns matter equally for every product or process. While some issues might be negligible, others, like fossil fuel use and greenhouse gas emissions, are major contributors to the overall environmental footprint and require our attention.

Table 3.9. Environmental impacts of the ventilation duct

Impact category	GWP	ODP	AP	EP	POCP ("smog")	ADP-elements	ADP-fossil
A1	3,3	0,000000000000036	0,00633	0,000605	0,0011	0,0000204	34,3
A2	0,286	0,000000054	0,000588	0,000119	0,0000372	0,00000493	4,49
A3	1,17	0,00000000821	0,005	0,001,11	0,000297	0,00000413	16,6
A1-A3	4,76	0,000000136	0,0119	0,00184	0,00144	0,0000295	55,4
A4	0,0261	0,000000004,91	0,0000535	0,0000108	0,00000339	0,000000449	0,409
A5	0,00052	0,0000000000769	0,0000024	0,0000015	0,00000011	0,0000000026	0,0117
C1	0,046	0,00000000133	0,0003	0,000293	0,0000112	0,000000369	0,87
C2	0,017	0,00000000212	0,0000236	0,00000484	0,00000155	0,000000318	0,177
C3	0,0325	0,00000000403	0,000249	0,000102	0,0000117	0,000000183	0,458
C4	0,00036	0,000000000121	0,0000014	0,000000284	0,000000108	0,0000000033	0,0104
D	-2	-0,0000000606	-0,00838	-0,00571	-0,00136	-0,0000373	-0,173

GWP = Global Warming Potential [kgCO2e]; ODP = Depletion potential of the stratospheric ozone layer [kg CFC-11e]; AP = Acidification potential of soil and water [kg SO2e]; EP = Eutrophication potential [kg PO43e]; POCP = Photochemical ozone creation [kg C2H4e]; ADP-elements = Abiotic Depletion Potential, include all non-renewable (i.e. excepting fossil resources) material resources [kg Sbe]; ADP-fossil = Abiotic Depletion Potential fossil fuels (MJ net calorific value): include all fossil resources [MJ].

The data in Table 3.9 emphasizes this point by showing that these two categories have the highest impact, demanding further scrutiny and possible improvement efforts.

The product's carbon footprint, Global Warming Potential fossil kg CO2e, for life-cycle stages are presented in Figure 3.2.

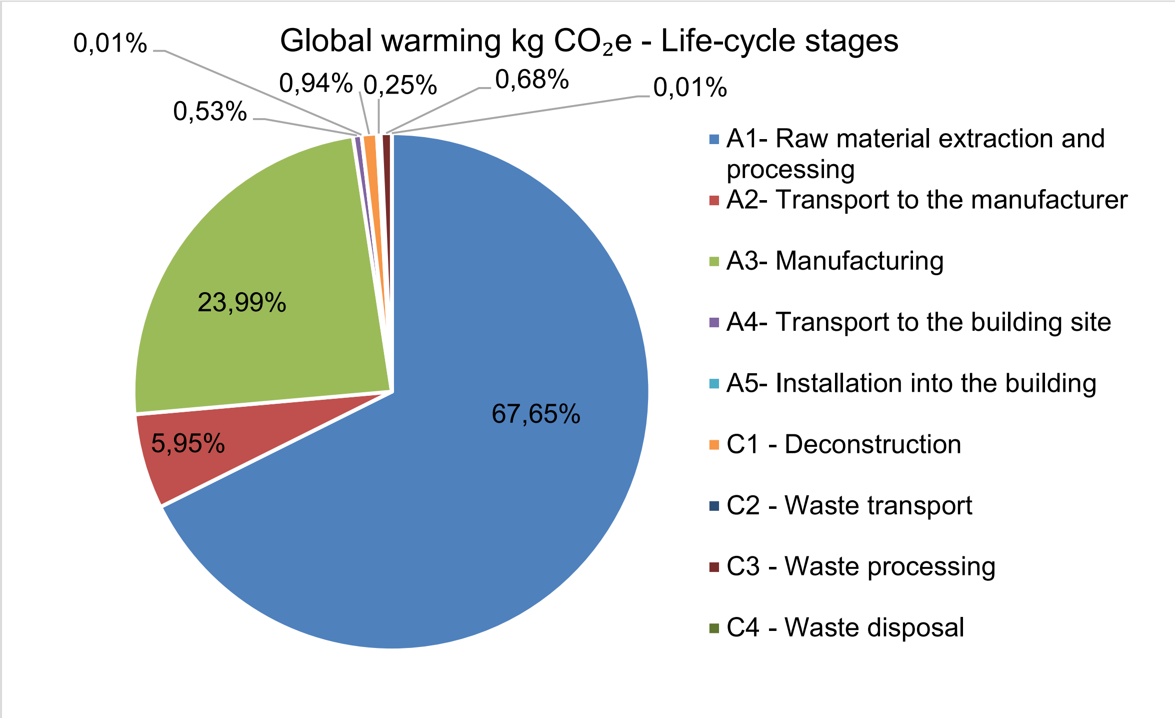

Figure 3.2. Global Warming Potential fossil kg CO2e – Life-cycle stages.

As Figure 3.2 shows, the highest contributor to the Global Warming Potential fossil kg CO2e by life-cycle stages of the circular ventilation duct are the A1 to A3 stages by 97.59%. The impacts of the other life-cycle stages are negligible as their amounts contribute with less than 2.5%. The transportation impacts are directly proportional to the transported masses and distances: the transportation of the steel causes the highest impacts due to their large mass. The manufacturing impacts are correspondent with the consumption of materials and fuels. The highest contribution to Global Warming Potential fossil kg CO2e – Life-cycle stages is given by the raw material extraction and processing (A1).

The chart (Figure 3.2) highlights the environmental impact of the circular ventilation duct throughout its entire lifespan. We can see that the most significant stages contributing to the product's Global Warming Potential measured in fossil CO2 equivalents (kg CO2e) are the early stages, specifically A1 to A3.

- Stage A1, which encompasses raw material extraction and processing, is the single biggest culprit, responsible for a whopping 67.65% of the total GWP impact. This suggests that the environmental cost of obtaining and preparing the raw materials for the duct is the most significant factor.

- Stage A3, manufacturing, comes in second with a 23.99% contribution. This indicates that the processes involved in creating the duct itself also play a major role in its overall GWP footprint.
- Stage A2, transportation to the manufacturer, contributes 5.95% to the GWP. While less impactful compared to the previous two stages, it emphasizes the importance of optimizing transportation distances and methods to minimize environmental burden.
- The impact of transport is directly related to two factors: the weight of the materials being transported and the distance they travel. Steel, due to its heavier mass, contributes the most to the GWP impact during transportation.
- Similarly, the environmental impact of the manufacturing stage (A3) is directly linked to the amount of materials and fuels consumed during the production process. The higher the consumption, the greater the GWP impact.

The remaining stages have a negligible impact as their amounts is less than 2.5% to the total GWP. This suggests that the end-of-life phases and potential benefits of the circular design have a relatively small impact on the overall climate change contribution.

In conclusion, the figure clearly demonstrates that the greatest contributor to the GWP of a circular ventilation duct lies in the initial stages of its life cycle, particularly the extraction and processing of raw materials (A1).

Comparisons with other EPDs

To get a clearer picture of how circular ventilation ducts impacts the environment, researchers compared products made by the same company in different countries. This comparison helps us understand how factors like a country's environmental regulations, how far a product travels, and the types of energy used in production can affect the environmental footprint of what seems like an identical product. To gain a wider perspective, the environmental impacts data from three other EPDs (Sweden, Norway, and Denmark [13-15]) were included in the analysis (Figure 3.3).

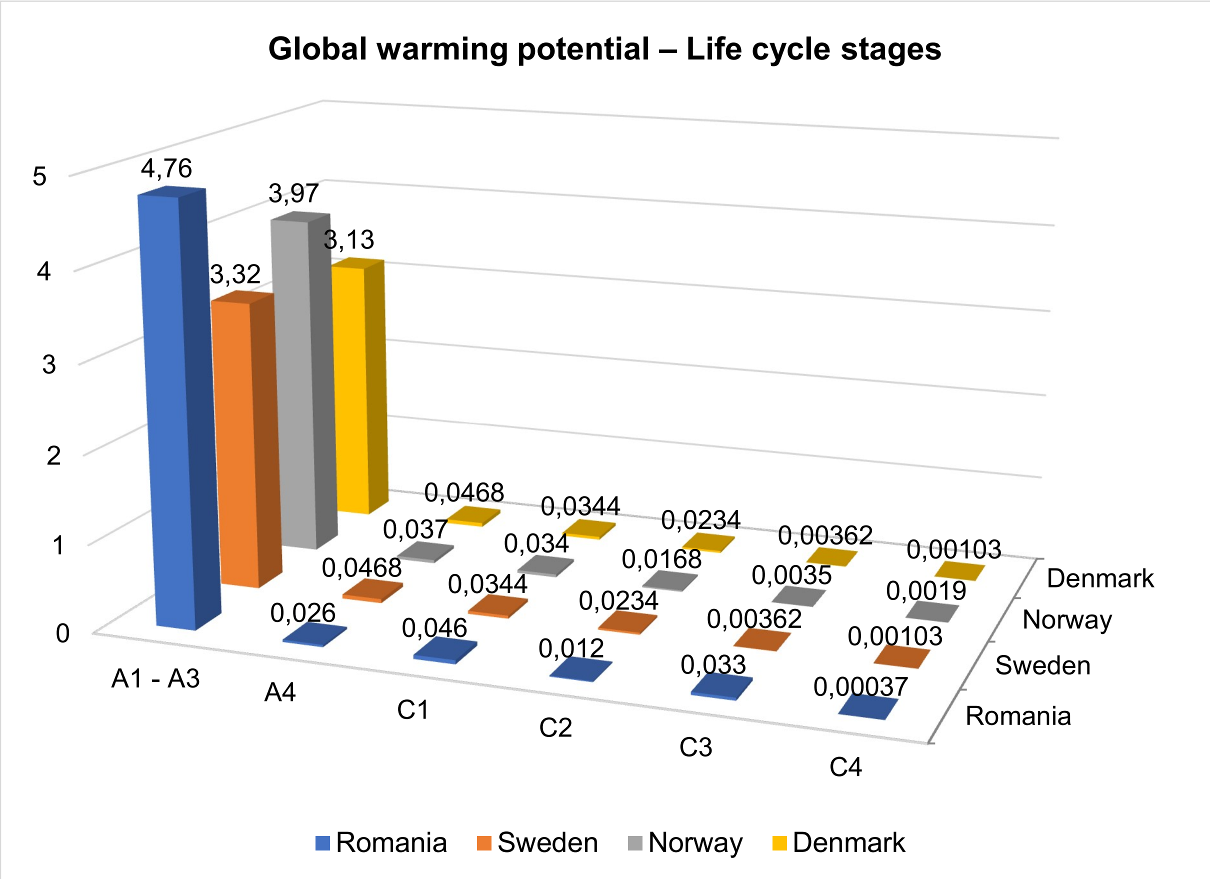

Figure 3.3. Comparison of Global Warming Potential fossil in kg CO2e by life-cycle stages.

This analysis examines the life cycle carbon footprint (stages A1-A3) of ventilation ducts across various countries. Romania emerges as a nation with ducts exhibiting the highest contribution to global warming potential (measured in fossil CO_2 kg). Conversely, Denmark boasts the lowest footprint. This disparity can be attributed to two key factors:

- *Transportation Distance*: The geographic separation between the raw material extraction site and the manufacturing facility significantly impacts the carbon footprint. Longer distances necessitate greater fuel consumption during transportation, leading to increased emissions.
- *Energy Mix for Manufacturing*: The energy sources used to power the manufacturing process play a crucial role. Countries like Sweden, which heavily rely on renewable sources like wind power, exhibit a lower carbon footprint compared to nations dependent on fossil fuels or imported electricity with transmission losses.

The analysis underscores the significance of local sourcing for hot-dip galvanized steel.

By minimizing transportation distances, manufacturers can effectively reduce the embodied carbon emissions associated with ventilation ducts.

Furthermore, the national energy mix employed during production (A3 stage) also plays a critical role. Utilizing clean energy sources like wind power, as practiced in Sweden, significantly minimizes the carbon footprint compared to relying on fossil fuels or imported electricity with transmission losses within the grid.

In conclusion, promoting local sourcing of raw materials and fostering a shift towards renewable energy sources within manufacturing facilities are critical steps to reduce the environmental impact of ventilation ducts throughout their life cycle.

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Chapter 04

Carbon Footprint of Construction Products - Case Study for a LED Luminaire Produced in Romania

Horațiu Albu, Dorin Beu, Tania Rus, Raluca Moldovan, Florin Domnița
Faculty of Building Services Engineering, Technical University of Cluj-Napoca, 21 December 1989 Avenue 128-130 no., 400114 Cluj-Napoca, Romania

The construction sector represents one of the most significant sectors to improve in terms of CO_2 reduction and climate change mitigation. Depending on the construction standard, CO_2 emissions vary for the used materials between 20 and 55%, and, for the operation stage, between 45 and 80%. According to, focusing on better building design and use could result in reduction up to 42% of the energy use, 35% of the CO_2 emissions, as well as significant reduction in the extraction of new raw materials. According to, the use of different materials or technologies can decrease the CO_2 emissions by as much as 90%. Natural resources play a crucial role in enhancing the quality of life, supporting economies, enabling the functioning of societies, and driving planetary development. Resource efficiency, on the other hand, emphasizes the creation of products and services while optimizing the use of natural resources to minimize waste and environmental impact. It also includes reducing waste, increasing recycling, and managing side-streams effectively.

The building sector represents 40% of the energy use in the European Union and contributes to 36% of CO_2 emissions [9-11]. The residential and commercial sectors in the United States accounted for 39% of the total energy use in 2021, resulting in 40% of CO_2 emissions [13]. Within buildings, the primary energy consumers are, as follows: HVAC (35% of energy use), lighting (11% of energy use), water heating, refrigerators, and freezers (18% of energy use) and other (36% of energy use) [14].

Efficient lighting systems offer significant potential for energy savings. Depending on the control systems employed, lighting energy can be reduced by 20% to 60% [15-20].

The control strategies fall into two main categories [17]:

- Occupancy-based control strategies which utilize sensors such as passive infrared, RFID, and mobile devices to detect the presence of occupants. The control allow the adjustment of lighting based on occupancy, ensuring lights are on only when needed;
- Illuminance-based control strategies which employ sensors to assess the illuminance value (artificial light and daylight) in a space. The control allows the transmission of the information to a controller, which manages artificial lighting levels accordingly.

By enabling a daylighting control system, the energy consumption of the artificial lighting can be reduced by 20 ÷ 70 % [17, 21 - 23].

4.1. Life Cycle Assessment

The Life Cycle Assessment (LCA) allows for the measurement of their environmental impact of a product or building over a specified period of time. The assessment covers all stages from development to disposal, including production, assembly, usage, and end-of-life. The LCA was conducted following the guidelines of EN 15804+A2 [24], ISO 14025 [25], and ISO 21930 [26], utilizing the One Click Life Cycle Assessment software [27 - 29]. The global warming potential is indicated in kilograms of CO2 equivalent emissions within the "Cradle to Grave" system boundary, with the functional unit being the LED luminaire. The reference year chosen was 2021, and the considered steps are presented in Figure 4.1.

Product stage			Assembly stage		Use stage							End of life stage			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
Raw materials	Transport	Manufacturing	Transport	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction /demolition	Transport	Waste processing	Disposal

Figure 4.1. Life cycle steps considered for the product

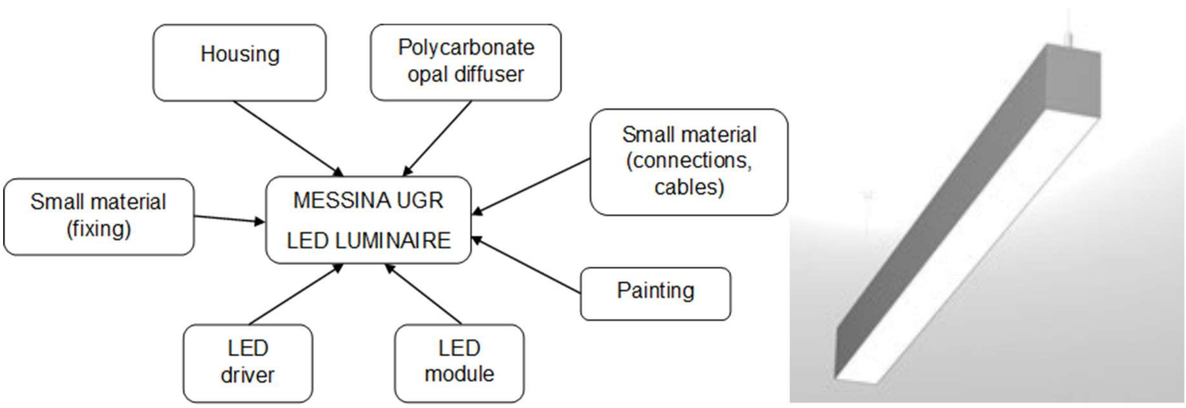
Initially, the inventory encompasses the measurement of materials, transportation, manufacturing procedures, as well as the energy usage during the product and montage stages. The use stage accounts for the operational energy and water use. The end-of-life stage involves the dismantling, transportation to the waste treatment facility, and ultimately recycling, reusing, or disposing of the product. The selected luminaire characteristics are presented in Figure 4.2.

The luminaire is suitable for use in offices, educational rooms, homes, and shopping centers, and it can also be used in environments with higher-than-average dust and humidity levels, due to the IP 43 protection class.

Luminaire luminous flux	3950 lm
Correlated color temperature	4000 K
LED module luminous efficacy	166 lm/W
Luminaire luminous efficacy	94 lm/W
Electrical installed power	42 W
Electrical product protection class	IP 43
R_{UGL} index	<19
Mechanical protection degree	IK 02
Ambient temperature	-20 ... +40 °C
IEC protection class	Safety class I
Lumen depreciation	L90F10 at 65°C > 60.000 h

Figure 4.2. LED suspended luminaire characteristics [30]

The LED suspended luminaire consists of the following components: aluminum housing, power supply, LED linear module, diffuser, as well as materials used for connection and montage.



a) b)

Figure 4.3. LED suspended luminaire: a) components; b) picture [30]

The LED housing is produced from aluminum extruded profile, important to the transfer and dissipation of heat. The material is also completely recyclable and free of corrosion [31]. The extrusion technique for aluminum involves heating the metal and exerting force on it using a hydraulic ram inserted into a die's shaped opening [32].

Through the conversion of the input voltage, the LED driver acts as a bridge between the power source and the LEDs [33, 34].

The manufacturing process of LED lights involves a series of precise steps, ensuring the creation of high-quality LED lighting products:

- stencil printing: the application of solder pastes to the printed circuit board (PCB) using a stencil.
- placement of small chip elements: high-speed placement machines accurately position tiny chip components (resistors, capacitors, and diodes) onto the PCB.
- placement of small integrated components: integrated components (ICs or microcontrollers) are placed on the PCB during assembly.
- wave soldering;
- potting: encapsulating sensitive components (drivers or power supplies) in protective materials (epoxy resin) to enhance durability and environmental resistance.
- aging: the assembled LED product undergoes an aging process to ensure stability and reliability over time. During aging, the product operates continuously to identify any potential issues.
- automatic optical inspection (AOI): AOI systems scan the assembled PCB to detect defects, misalignments, or soldering issues. This automated inspection ensures product quality [35].

LEDs are joined on a printed circuit board to form the LED linear module. A different option are the LEDs which come with separate optical components installed. In addition, the LED module has mechanical support, electrical connections, and a thermal management system. [36, 37].

With its highly transparent qualities and micro-structured prismatic surface, the polycarbonate opal diffuser allows light from an optical light source that has been fed into it axially to be emitted radially. The polycarbonate is is synthesized through chemical reactions involving bisphenol A (BPA) and phosgene ($COCl_2$) [39]. Operations such as drying, dosing, extrusion, die, calibrating and cooling, and cutting are all part of the manufacturing process [40].

Figure 4.4 displays the LED suspended luminaire's flow diagram.

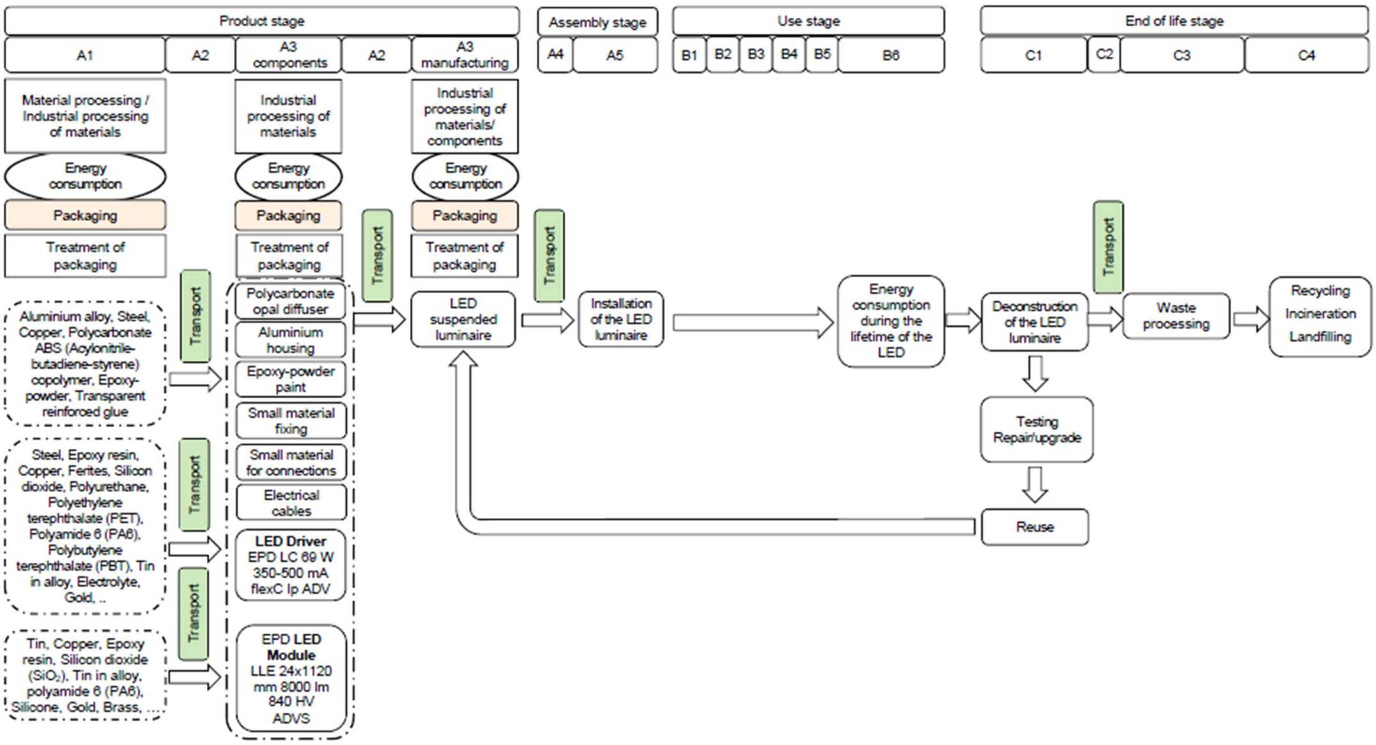


Figure 4.4. The LED suspended luminaire flow diagram [30]

The manufacturer provided details regarding the materials used in the product, including their functions, weights, origin, transport method and distances, as well as energy consumption. This information is quantified in kilograms and presented in Figure 3.5. In the One Click LCA simulation, the data points were selected similar or close to the information provided by the manufacturer. By utilizing this database, the environmental impacts can be estimated for each component [40].

The manufacturer also provided information regarding transportation and distances. The luminaire parts are transported from various locations in Romania and different countries in Europe to the manufacturer facility situated in Bucharest. The transportation of the luminaire components to the factory is performed via lorries weighing between 16 and 32 metric tons, with Euro 5 standards. The distances for transportation are listed in Figure 3.5. Packaging is also included for each component, with cardboard being the main packaging material. It is estimated that packaging constitutes approximately 10% of the weight of the components, based on similar studies [41].

The LED module and LED driver consist of various raw materials used and different manufacturer procedures employed, as described in [30, 42 - 44]. The environmental impacts associated with both equipment are included in the EPDs provided by the component manufacturers. These EPDs have been incorporated into the One Click LCA database and included in the modeling of the luminaire.

Raw material	Quantity [kg]	Transport distance [km]
Aluminium extruded profile (body)	1.93	193
Epoxy powder paint	0.04	1196
Aluminium extruded profile (fixing clips)	0.46	193
Polycarbonate cable connector 2p+n	0.005	542
ABS cable gland	0.005	19
Copper electric cable FY 0.5mm	0.05	11
Copper electric ground wire	0.1	11
Copper electric cable 3X0.5 mm	0.01	11
Polycarbonate opal dispenser	0.13	1881
Iron screws M4	0.01	591
ABS Plastic taps	0.08	19
ABS plastic clips	0.08	19
LED Module	0.07	1690
LED Driver	0.18	1690
Driver selector plug	0.001	1690
Paper adhesive label 50X32 mm	0.02	12

Figure 4.5. Raw materials of the LED suspended luminaire [30]

During the manufacturing phase of the luminaire, various operations are carried out such as foundry, machining, injection, assembly, mounting, and epoxy painting. Details regarding energy use during manufacturing have been included into the calculations: electrical energy used in the production process (0.9 kWh per luminaire), electrical energy used for utilities (0.06 kWh per luminaire), methane gas consumption for production (0.324 kWh per luminaire), and for heating (0.72 kWh per luminaire). After the manufacturing process and final quality inspection are finalized, the LED luminaire is packaged in preparation for transportation.

During the transportation and montage phase, the equipments are typically transported as multiple units on wooden pallets to the installation site. Transport data, distances, and transportation methods were obtained from the manufacturer. For simulation purposes, it was considered that the luminaire was transported within Romania via a lorry (>32 metric ton, euro

5) covering 400 km. The installation process of the LED suspended luminaire considers the handling and disposal of packaging materials (wood pallets, polyethylene, and paperboard).

In the usage stage, the energy use is modeled based on energy usage and product lifespan. The estimated lifespan of the LED luminaire for this study is 50,000 hours (equivalent to 20 years). As per manufacturer specifications, at the end of its operational life (60,000 hours), the LED luminaire is considered to maintain at least 90% of its initial luminous flux, with a 10% failure rate of LED chips. No luminaires are anticipated to be replaced during the lifespan of the product.

The lifespan of the luminaire components is equivalent to that of the LED luminaire. The environmental impact of the LED luminaire on an annual basis is determined by its electrical energy consumption, which is influenced by the number of operating hours per year.

In the education sector, the standard operating hours, as stated in the EN 15193 standard [45], are approximately 2,000 hours per year. However, the actual operating hours may vary depending on the specific usage and activities [46].

The LED suspended luminaire consumes 42 watts per hour. The electrical energy consumed is considered as the average production mix of electricity in Romania, which consists of hydropower (36.3%), hydrocarbon (14.3%), coal (16.9%), nuclear (7.7%), wind (16.5%), biomass (0.7%), and solar (7.6%) [47]. In terms of electricity, the European Union's electricity sector is expected to make substantial contributions towards addressing climate change by 2030 and attain a net zero carbon effect by 2050 [48].

The End-of-Life scenario involves the proper handling and recycling of materials. The luminaire is transported to a waste treatment facility where it is dismantled. The treatment process includes recycling of aluminum scrap, cables, plastic, electronics, bulk iron, and wastepaper.

According to the component manufacturer's recommendations, 70% of the glass and metal parts of the LED module and LED driver will be recycled. The plastics will be incinerated, and the remaining parts will be disposed of in landfills [42,43]. The energy required for material treatment, such as shredding processes, is taken into account in the calculations.

4.2 Life Cycle Impact Assessment

The calculation of environmental impact parameters was carried out utilizing the One Click LCA software. This software allows users to input materials information and access a comprehensive database to choose the suitable environmental statement for the majority of materials used. Additionally, it permits the incorporation of data from EPDs if the product being assessed in the LCA calculation consists of various components with existing EPDs. The popularity of One Click LCA tools is also attributed to their user-friendly interface, quick operation, and precise outcomes. Several studies that consider the LCA computation of lighting technologies have been conducted in recent years. According to a study [49] that examined the possible effects of various light sources on the environment, incandescent lamps have the greatest environmental impact. This is largely because of their higher energy consumption, which results in 3.3 times more CO2 emissions in New Zealand than CFLs and outdated LEDs.

A study [50] that looked at an industrial LED luminaire found that, because of the electricity consumption, the use stage had the most influence. Additionally, raw materials are mostly used in the production of metals and electronic components. A research [40] presents the life cycle assessment of a recessed LED luminaire.

The study's findings indicated that the majority of the environmental effects were caused by use-stage energy consumption, which was mostly caused by the driver and aluminum parts. The manufacturing stage, which is mostly caused by the driver and aluminum parts, accounts for the largest share of the life cycle impacts for both hazardous and non-hazardous waste categories. The life cycle analysis of an LED outdoor luminaire, as reported in study [51], further supported the idea that the most important component affecting the environmental impact is electricity consumption. The study's findings highlight the necessity of limiting the extraction of fundamental raw resources.

The following are some of the environmental impacts that the LCA research consider [52,53,54]: Global Warming Potential (GWP) [kg CO_{2eq}]; Ozone Depletion Potential (ODP) [kg CFC_{11eq}]; Acidification Potential (AP) [kg SO_{2eq}]; Eutrophication Potential (EP) [kg $PO_4^{3-}{}_{eq}$]; Photochemical Ozone Creation Potential (POCP) [kg C_2H_{4eq}]; Abiotic Depletion Potential – Elements (ADP-elements) [Sb_{eq}]; Abiotic Depletion Potential – Fossil fuels (ADP-fossil fuels) [MJ]; Net use of freshwater (FW) [m^3].

4.3 Results and Discussion

The environmental impacts at the manufacturing stage are presented in Figure 4.6.

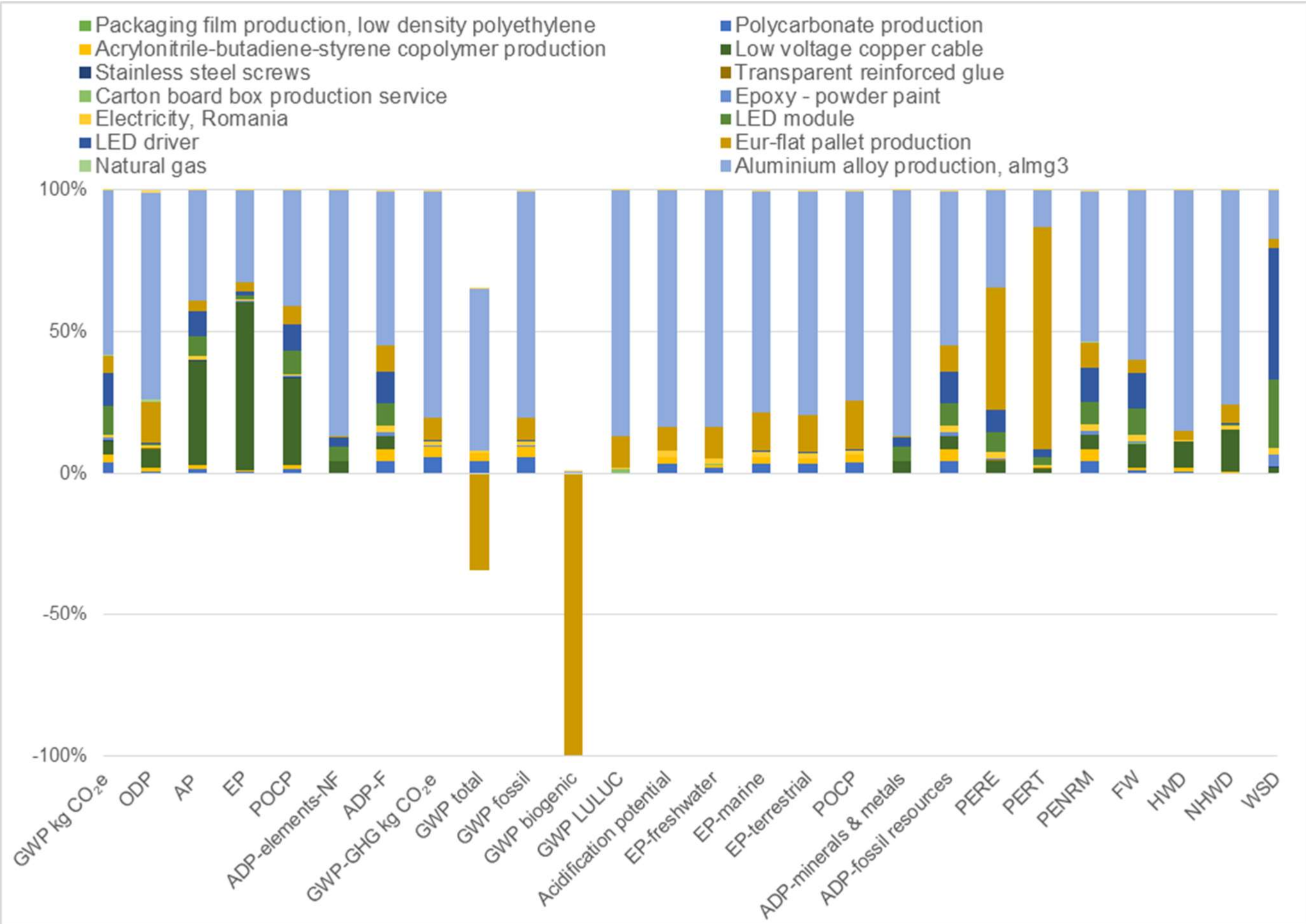


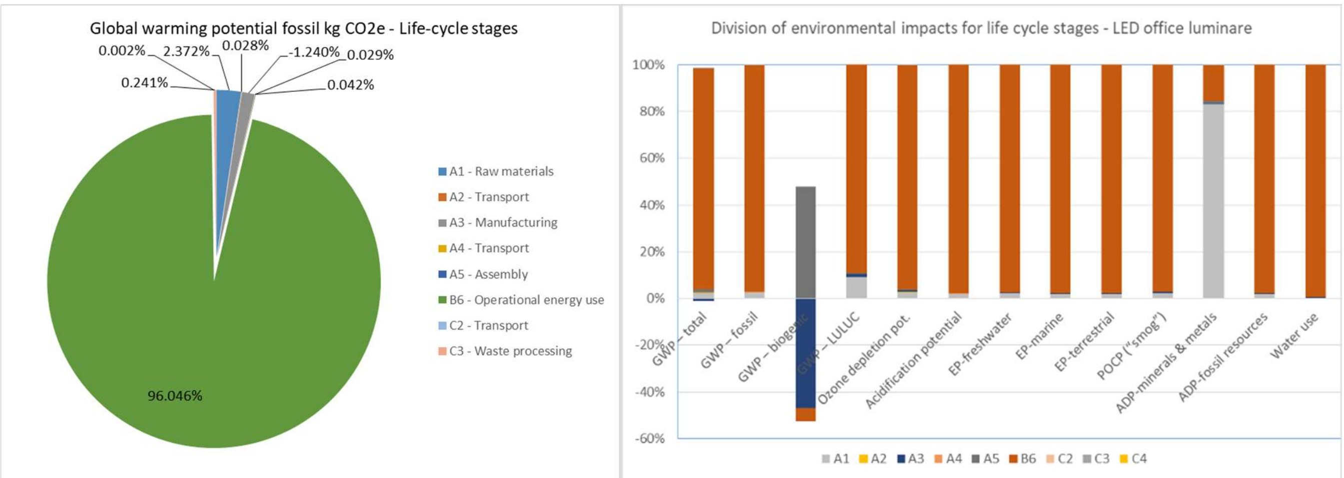
Figure 4.6. Environmental impacts for the LED suspended luminaire – manufacturing stage

The luminaire body, fixing clips, LED module, and LED driver are made of aluminum, contributing to around 15 to 75% of the environmental effects. The LED driver has a more significant impact, particularly on ozone depletion and eutrophication potential. Research [39,55] also shows that the electrolyte capacitors, steel, and glass diodes in the LED module and LED driver have the most substantial environmental footprint.

Module	GWP	ODP	AP	EP	ADP-elements	ADP-fossil fuels	REPE	NRE	HW	NHW
A1	25.3	0.00000087	0.2	0.087	0.0084	298.31	37.05	305.8	3.56	40.76
A2	0.22	0.000000041	0.00045	0.000092	0.0000056	3.38	0.047	3.38	0.0034	0.26
A3	2.1006	1.7798E-07	0.010166	0.003421	0.00003105	39.41	145.1941	39.55	0.1361708	3.5936
A4	0.33	0.000000062	0.00068	0.00014	0.0000065	5.15	0.068	5.15	0.0052	0.54
A5	0.34301	1.76668E-08	0.0023884	0.00112097	8.43634E-05	4.7444	2.036788	4.8226	0.0416136	0.759132
B6	747.8	0.000024	5.2	1.24	0.00156	15961.4	3537.4	15961.4	32.8	1399
C2	0.018	3.3E-09	0.000036	0.0000074	0.00000031	0.28	0.0035	0.28	0.00027	0.03
C3	1.89142	4.49307E-08	0.00283628	0.001177433	1.34181E-05	5.65323	0.602015	5.65323	0	0

Figure 4.7. Environmental impacts for the LED suspended luminaire

Figure 4.8 shows the environmental impact indicators of the equipment, including the energy use during the 50,000-h lifetime operation.



a) b)

Figure 4.8. LED suspended luminaire environmental impact indicators for the life cycle stages: a) GWP-fossil; b) Division of environmental impact indicators

Figures 4.7 and 4.8 illustrate that the primary contributor to the environmental impact in most categories throughout the entire lifetime of the LED suspended luminaire is the electrical energy used for its operation.

The LED suspended luminaire's effects on the environment varies depending on the environmental category. With the exception of abiotic depletion potential, operational energy use is the highest proportion in most categories. Of the life cycle impact in this category, the manufacturing stage accounts for about 85% of it. The aluminum enclosure, LED driver, and LED module are mainly responsible for this high percentage.

The analysis of reducing high operational energy use can be approached from various angles. Firstly, the selected product has a luminous efficacy of 94 lm/W. By using luminaires with higher luminous efficacy, fewer luminaires will be needed in a room, resulting in lower installed power.

Secondly, the implementation of daylight system control can result also in reduction of the used energy. As mentioned in [56], when adopting a lighting control system, user behavior should be taken into consideration as their acceptance of the system interventions can impact its performance.

The LCA calculation considered the 2022 Romanian production mix when selecting the energy production mix. According to [57], the European Commission has proposed the REPowerEU Plan, which aims to reduce emissions by 2030 and increase the use of renewable energy sources. Romania aims to increase the installed capacity of wind and photovoltaic power plants and the number of prosumers by 2030 [58]. Additionally, Romania aims to phase-out of both lignite and hard coal by 2032 [59].

The current technologies available can economically recover approximately 55% of the materials found in LEDs, as mentioned in [60]. According to research [61], gold is among the valuable materials that can be extracted from LEDs. However, materials such as indium, gallium, and rare earth elements have low concentrations, resulting in minimal potential revenue from the recovery process. The focus of new recycling technologies for LEDs should be on maximizing the recovery of precious and rare elements. [62,63,64].

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Chapter 05

Evaluating the Environmental Impact of Roof-Mounted PV Systems: Romanian Case Analysis

Tania Rus[1], Raluca-Paula Moldovan[1] and Miguel Ángel Pardo Picazo[2]
1Department of Building Services Engineering, Technical University of Cluj-Napoca, Cluj-Napoca, Romania
2Department of Civil Engineering, University of Alicante, Alicante, Spain

5.1 Introduction

Solar photovoltaic (PV) installations have become widely adopted for their zero-emission electricity generation, though it's important to recognise the environmental impacts associated with their entire lifecycle, from manufacturing to disposal. PV systems are increasingly popular as individuals and businesses seek to reduce their carbon footprint and adopt greener energy sources. The advancement of PV technology is partly driven by decreasing installation costs, which can vary based on factors like location, electricity prices, and government subsidies (Kim et al., 2020). Additionally, the desire for energy independence grows as electricity costs become more volatile.

Several factors must be considered when planning a PV facility, including material selection and the system's tilt and azimuth angles (Ebhota and Tabakov, 2022). In the northern hemisphere, solar panels are typically oriented southward, with tilt angles optimized for the installation site's latitude. Adjusting the angle and orientation of PV systems can significantly enhance performance in different regions (Tillmann et al., 2019). Many studies (Ben Amara et al., 2021; Pardo et al., 2022) suggest that an azimuth of 0º is ideal for maximizing energy production in PV systems.

PV panels convert some of the absorbed solar radiation into heat, which can decrease the efficiency of PV systems. Solar panel efficiency typically decreases by about 0.5% per degree Celsius increase in temperature, depending on the type of solar cells used. Thus, temperature regulation is crucial for maintaining PV efficiency, particularly in warmer climates (Lv et al., 2023). Various materials and installation locations have been evaluated for their environmental impact. Müller et al.,(2021) compared the environmental impact of single-crystalline silicon (sc-Si) glass-back sheets and glass-glass modules manufactured in China, Germany, and the EU, finding that glass-glass modules in the EU and Germany had the lowest environmental impact. Additionally, Koester et al., (2022) studied solar panel degradation, highlighting the importance of recognizing and assessing their financial impact.

Solar photovoltaic systems generate no operational emissions since they rely on renewable energy instead of fossil fuels, making them environmentally friendly. However, debates continue around the most sustainable PV system designs. To address this, many experts use life cycle assessment (LCA) analysis (Bracquene et al., 2018). The production and transport of PV system components, including panels, batteries, charge regulators, inverters, and supporting structures, consume significant energy. This embodied energy includes the energy required to extract, process, manufacture, assemble, and transport these components. Research indicates that a solar PV system's embodied energy is only a small portion of its total energy generation (Rahman et al., 2019). Efforts continue to further reduce the embodied energy of PV systems, enhancing their overall sustainability.

Significant gaps remain in studying the lifecycle of PV plants, particularly at the end-of-life (EoL) stage, because of the limited availability of discarded panels for research (Latunussa et al., 2016). Life cycle assessment (LCA) evaluates the environmental impact of a product or process from production through disposal. Experts anticipate that managing the EoL phase for PV panels will present challenges beginning in the early 2030s. Proper disposal is essential to prevent environmental hazards, especially for crystalline silicon (c-Si) PV panels. Effective EoL management should prioritize recovering valuable materials and minimizing environmental impact (Ansanelli et al., 2021). Recovery treatments for silicon metal, silver, copper, and aluminium can follow the incineration of a panel's layers. A novel approach to EoL management for crystalline silicon PV panels has been introduced (Ganesan and Valderrama, 2022), enabling more sustainable decision-making for emerging technologies by incorporating stakeholder input.

LCA reveals that industrial-scale PV processes come with environmental responsibilities. To achieve meaningful results, PV waste volumes need to reach around 20,000 tonnes (Mahmoudi et al., 2020). The research conducted by (Paiano et al., 2023) underscores that PV systems cannot be assumed to have zero emissions, as emissions from both production and end-of-life stages must be considered. Various factors influence the environmental performance of PV technology, including energy payback time (EPBT) and greenhouse gas (GHG) emissions.

Among PV technologies, thin-film PV systems are the most eco-friendly, with an EPBT of 0.75 to 3.5 years and a low GHG emission rate (GHGER) of 10.5 to 50 gCO_2-eq/kWh (Peng et al., 2013). Alternative materials, such as multi-crystalline silicon (multi-Si) and mono-crystalline silicon (mono-Si) photovoltaic (PV) systems, exhibit energy payback times (EPBTs) of 1.5 to 2.6 years and 1.7 to 2.7 years, respectively. Their greenhouse gas emission rates (GHGERs) range from 23 to 44 g CO_2-equivalent per kilowatt-hour (gCO_2-eq/kWh) for multi-Si and 29 to 45 gCO_2-eq/kWh for mono-Si. As photovoltaic technologies evolve, experts expect enhancements in their environmental impact. A detailed study by Turconi et al. (2013) analyzed 167 life cycle assessment cases across different electricity generation methods, which included 22 PV cases. The main source of emissions in PV technologies stems from the production of solar cells, with greenhouse gas emissions for solar PV electricity generation varying between 13 to 190 g CO_2-eq/kWh.

When performing a LCA for PV technology, it is crucial to consider the structural requirements associated with different installation types, whether ground-mounted, roof-mounted, or facade-mounted. Typically, the structure pertains to the physical supports that hold the solar panels in place. However, in the case of building-integrated photovoltaic (BIPV) systems, the solar panels are incorporated directly into the building's design, which eliminates the necessity for separate mounting supports. This integration not only minimizes material consumption but also affects the environmental impact and structural efficiency in the LCA.

Structures like fixed-tilt, single-axis tracking, and dual-axis tracking provide essential support for solar panels. These designs must be structurally robust to guarantee the safety and stability of the system while maximizing exposure to sunlight. Each structure is required to endure the weight of the panels, wind loads, and other environmental pressures, but they each come with specific advantages and disadvantages. Decision-makers should evaluate the energy production potential, structural requirements, and weight considerations of the photovoltaic system, especially for roof-mounted installations. Adding significant weight to secure PV systems on an existing roof may affect the overall load capacity of the building. Furthermore, if the roof manufacturer indicates that the roof membrane should remain unpierced for PV support, the use of ballast becomes crucial.

Ballast plays a key role in keeping solar panels anchored and stable in the face of environmental forces (Fanney et al., 2003). Utilizing ballast in PV installations improves their durability and performance, safeguarding the system against severe conditions and ensuring consistent energy generation. Consequently, when performing a LCA for a PV system, it is essential to account for all elements, including modules, structural components, ballast, electrical components, and inverters. The results of the LCA for a PV installation may vary by location, as factors such as the national energy mix and grid energy utilization at the time of installation can affect these outcomes.

In Romania, renewable energy sources accounted for 42% of electricity production in 2022, with solar contributing approximately 3.2%. Solar photovoltaic technologies have experienced some of the most rapid growth rates in electricity generation. The cumulative capacity of solar PV reached 1.4 GW in 2021 2021 (Ritchie et al., 2020) and surpassed 1.7 GW in 2022 (Renewable Market Watch, 2023). Experts anticipate that this capacity will expand to 4.25 GW by 2030 (Vladimir Spasić, 2021).

Selecting an appropriate energy mix is essential for transitioning from fossil fuels to lower-carbon alternatives. Romania's electricity mix is notable for being one of the most comprehensive in the European Union (Stochitoiu and UȚU, 2018), featuring balanced contributions from several sources: hydro (25.2%), nuclear (20%), coal (18.5%), gas (17.6%), and wind (12.5%). While electricity prices have increased, the cost of photovoltaic systems has declined, and carbon intensity has also reduced significantly, dropping from 441 gCO2-eq/kWh in 2000 to 264 gCO2-eq/kWh in 2022 (Ritchie et al., 2020). This trend underscores the significance of utilizing solar energy through PV power plants. Fossil fuels such as coal, oil, and gas have higher carbon intensity, with values of 1260, 1125, and 808 gCO2-eq/kWh. In contrast, renewable energy sources like solar, wind, hydro, and nuclear have lower carbon intensity, with values of 30, 13, 11, and 5 gCO2-eq/kWh, respectively. In Romania in 2022, coal was responsible for 60% of electricity-related emissions, while gas contributed 38%, and solar accounted for less than 1%. Other low-carbon energy sources comprised the remaining share of emissions.

A study by the National Renewable Energy Laboratory (Nicholson and Heath, 2012a), found that fewer than 15% of 3,000 electricity production studies met the review criteria. The Intergovernmental Panel on Climate Change reported that rooftop PV systems emit between 26 and 60 gCO2-eq/kWh, with an average emission of 41 gCO2-eq/kWh (Schlömer et al., 2014). Various studies examining the environmental impacts associated with the materials used in net-zero energy buildings have identified that the most significant effects arise from concrete, structural steel, PV panels, inverters, and gravel (Thiel et al., 2013). Additionally, numerous methods for conducting cost-benefit analyses have been explored by practitioners, researchers, and professionals to inform decision-making.

Decision-making tools are essential for planning photovoltaic (PV) installations during the initial stages of site selection to maximize energy yield while minimizing structural stress on buildings. Building performance simulation tools play a vital role in facilitating collaboration among architectural, construction, and facilities teams, allowing professionals to create sustainable (Fernandez-Antolin et al., 2022). These tools assist in evaluating the technical feasibility, cost-effectiveness, and environmental impact of various options, thereby supporting informed decision-making.

In this chapter is compared the energy production of panels oriented south (azimuth 0º) with those oriented east-west. Specifically, it seeks to answer the following questions: (i) What are the benefits of an east-west orientation? (ii) Which orientation (south or east-west) is more profitable in terms of energy production? (iii) Which is more helpful in terms of emissions reduction? (iv) How do the structural requirements differ between these two orientations? and (v) What role does ballast play in choosing between these alternatives?

Professionals designing a solar power station on a roof can utilize this information to determine whether to orient solar panels towards the South (S) or in an East-West (E-W) alignment. In off-grid installations, as well as others, using East-West oriented panels (azimuth 270°–90°) can help achieve higher energy production at sunrise and sunset. East-facing panels generate electricity in the morning, while West-facing panels produce energy in the evening. Additionally, other stakeholders may adopt this approach to evaluate surplus energy fed into their grids, which can aid in grid management and help prevent blackouts or overload situations.

5.2 Materials and Methods

The study seeks to evaluate and compare the environmental impacts of a roof-mounted photovoltaic system under two different scenarios: South-oriented panels and East-West oriented panels. To facilitate a comprehensive assessment, a multi-criteria analysis was conducted utilizing various tools and software to emphasize the distinctions between the two scenarios.

Firstly, was the employment of K2 Base, a widely adopted tool among professionals for facilitating the design and development of assembly plans, conducting structural analyses, and determining the necessary ballast for securing the photovoltaic system to the roof (BaseK2-systems, 2023). Version 3.1.70.2 of this free planning software was utilized. The design criteria of the software comply with the guidelines established in the Romanian Standard (SR EN 1990/NA, 1990). Furthermore, snow load calculations were performed following the recommendations of the Romanian Standard (SR EN, 1991-1-3/NA, 1991), while wind load assessments were based on the specifications outlined in the Romanian Standard (SR EN, 1991-1-4/NB, 2006). A benefit of this tool is that it generates a comprehensive report that includes a bill of quantities for the structure, along with precise information on the location and weight of the ballast required to stabilize the photovoltaic installation. The use of K2 Base in this study demonstrates the practicality and significance of the research findings. It highlights the researchers' expertise with industry-standard tools and their capacity to convert theoretical concepts into actionable solutions for photovoltaic installers and developers.

The subsequent step in the research methodology involved utilizing PVsyst software version 7.1.0. This software, which is commonly employed by engineers, professionals, and researchers, offers a user-friendly interface along with a range of features (Villoz et al., 2022). The PVsyst software simulates PV system design, loss determination, shading studies, and economic evaluation. The calculation involves a variety of factors, such as site features (location, altitude, shading, and orientation), PV module details (type, efficiency, power rating), inverter specifics (type, capacity, efficiency), climate data (solar radiation, temperature, wind speed), and grid connection parameters (voltage level, grid code, interconnection requirements). By considering these factors, the PVsyst software produced a comprehensive design for the photovoltaic installation, outlining the optimal number and arrangement of PV modules, inverter sizing, and electrical connections.

The simulation covers an entire year and yields a comprehensive report with information, such as energy and specific production, performance ratio, and losses along the system.

To assess the environmental performance of the two scenarios, OneClick LCA software was utilized. This software analyzes life cycle carbon (LCC) and conducts life cycle assessments in accordance with EN 15978 guidelines (European Committee for Standardization, 2011).

The standard encompasses the entire life cycle of a building and utilizes data from Environmental Product Declarations (EPDs) established under EN 15804 (CEN, 2019). The two indicators differ depending on the environmental impact category being evaluated: LCC primarily concentrates on greenhouse gas emissions, whereas LCA examines a range of impact categories. In this study, twelve factors were analyzed within the life cycle assessment: Global Warming Potential (GWP) [kgCO2-eq]; Acidification Potential (AP) [kgSO2-eq]; Ozone Depletion Potential (ODP) [kgCFC11-eq]; Eutrophication Potential (EP) [kgPO4-eq]; Photochemical Ozone Creation Potential (POCP) [kgC2H4-eq]; Abiotic Depletion Potential for Fossil Resources (ADPF) [MJ]; Abiotic Depletion Potential for Non-Fossil Resources (ADPE) [kgSb-eq]; Total Use of Renewable Primary Energy Resources (PERT) [MJ]; Total Use of Non-Renewable Primary Energy Resources (PENRT) [MJ]; Renewable Primary Energy Resources as Raw Materials (PERM) [MJ]; Renewable Primary Energy Resources excluding Raw Materials (PERE) [MJ]; Net Fresh Water (FW) [m3].

Nevertheless, OneClick LCA software had its constraints. The EPDs for the PV system lacked coverage for some materials, notably the electrical components. We tackled this by utilizing products with comparable features as points of reference. Furthermore, the software had a scarcity of EPDs for PV modules. To solve this, verified EPD by third parties were used. This issue is common in scientific studies because of the lack of a comprehensive database. Our approach included studying module degradation on energy production, which helped avoid overestimating the PV system's service life (Nordin et al., 2022). The software's approximations for scenario comparisons remained unaffected by these limitations. This study assesses how the PV system affects energy production, payback period, and carbon emissions in South and East-West orientations. Equation (5.1) calculates the total energy produced by a single PV panel over its reference service life.:

$$E_{RLS} = E_1 \times (1 + \sum_{n=1}^{RLS-1}(1 - deg)^n)\ [kWh] \tag{5.1}$$

where:
RLS is the reference service life [years];
n is the year of operation;
deg is the yearly degradation rate;
E_1 denotes the energy produced in the first year [kWh/year].

The system had a service life of 30 years, with a degradation rate of 0.55% according to the EPD from Canadian Solar. We simulated the specific production in PVsyst software for both South-oriented and East-West oriented scenarios at a site in Romania.

By utilizing the impact indicators and the national electricity mix, both the EPBT and GHGER can be calculated. The EPBT indicator reveals the number of years required for the renewable energy system to generate the equivalent amount of energy that was consumed during its production (Frischknecht, 2020):

$$EPBT = (E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL})/((E_{agen}/\eta_G) - E_{O\&M}) \tag{5.2}$$

where:

E_{mat} – primary energy demand to produce materials comprising PV system [MJ oil-eq];
E_{manuf} – primary energy demand to manufacture PV system [MJ oil-eq];
E_{trans} – primary energy demand to transport materials used during the life cycle [MJ oil-eq];
E_{inst} – primary energy demand to install the system [MJ oil-eq];
E_{EOL} – primary energy demand for end-of-life management [MJ oil-eq];
$E_{O\&M}$ – annual primary energy demand for operation and maintenance [MJ oil-eq];
E_{agen} – mean annual electricity generation [kWh]
η_G – grid efficiency (the primary energy to electricity conversion efficiency at the demand side) [kWh electricity/ MJ oil-eq].

As per the national conversion factors, electricity generated by photovoltaic panels and consumed for a specific purpose has a conversion factor of 1. However, when this electricity is injected into the National Energy System, the conversion factor increases to 2.5 (Mc 001-2022, 2023). To evaluate the performance of the PV system in terms of global warming impact, researchers calculated the greenhouse gas (GHG) emission rate using Equation 5.3 (Peng et al., 2013).

$$GHG_{ER} = \frac{GHG_{E\_LC}}{E_{gen}} \tag{5.3}$$

where:

GHG_{ER} [gCO2-eq/kWh] is the GHG emission rate;
GHG_{E_LC} [kgCO2-eq] is the total GHG emissions during the life cycle of the PV modules
E_{gen} [kWh] is the total electricity power generated.

5.3 Case Study

In 2022, the Romanian Government approved the construction of a new building to house multiple research centres and labs, known as the Artificial Intelligence Research Institute (Figure 5.1 (a) and (b)). The Technical University of Cluj-Napoca owns the building in the city of Cluj-Napoca. The building's construction will include different green technologies like heat pumps and photovoltaic systems to meet its yearly energy needs. The current research focuses on comparing the installation of the PV system from different viewpoints. The goal is to optimise the number of solar panels and total energy production from two sections of a divided roof totalling 506.2 m2. Figure 5.1 (b) shows the placement of the solar panels facing South in the architectural design of the building.

(a)

(b)

Figure 5.1. Building location (a); Architectural design (b)

With the swift development of the solar PV panel sector, it is vital to conduct a thorough evaluation to pick the best panel for particular needs. Panel manufacturers are now making panels with power outputs as high as 700–800 watts peak (Wp). Nevertheless, these panels with high capacity are bigger and heavier, causing installation difficulties on roofs and the risk of structural problems like bending from wind or snow loads. Opting for smaller panels can help reduce these impacts, although utilising less powerful panels will necessitate a greater number of units to reach the equivalent system capacity, resulting in higher labour and structural expenses. Striking a balance between panel size and power output is crucial. In this study, we used a 550 Wp photovoltaic panel, chosen for its robust mechanical strength—capable of withstanding snow loads up to 5400 Pa and wind loads up to 2400 Pa, standard for the Cluj area. These panels also provide sufficient power to help reduce labour and structural costs.

A fixed structure supports the solar panels, and the installation involves both direct and alternating currents. The perfect choice of solar panels for installation is determined by different factors, such as manufacturing emissions and power generation efficiency.

The initial task was to identify the two accessible roofs for optimal placement of the PV modules on the new building. By utilising geographical coordinates and consulting placement and situation plans, we were able to accomplish this. Two solar panel configurations were analysed for the AI Research Institute building. The building's roof measurements constrain the dimensions of the installation, and this size remains consistent for all configurations, resulting in a combined area of 506.2 m^2. Out of this total, the lower roof is allocated 325.1 m^2, while the upper roof has 181.1 m^2.

a) b)

Figure 5.2. PV modules oriented South a) oriented East-West b)

The initial scenario being examined includes incorporating a South orientation, shown in Figure 5.2 (A). In this setup, solar panels are located on the northern and southern roofs of the building. Due to the limited surface area, we assign fewer panels to the northern roof:

- On the north roof, there are 36 PV modules with a nominal power of 19.8 kWp;
- On the southern roof, there are 72 PV modules with a nominal power of 39.6 kWp;
- In total, this orientation includes 108 PV modules, resulting in a combined nominal power of 59.4 kWp.
- The installation needs to be reoriented to face East-West in the second scenario, as depicted in Figure 5.2 (B):
- On the north roof, there are 36 PV modules, contributing 19.8 kWp of nominal power.
- On the southern roof, there are 80 PV modules with a nominal power of 44 kWp.
- Overall, this orientation features 116 PV modules, yielding a total nominal power of 63.8 kWp.

The number of materials required for installation depends on how the system is positioned. The number of panels that can be installed depends on the available surface area and their size. As a result, the amount of installation materials needed will adjust accordingly.

5.4 Results

The results of the study are divided into three parts to improve understanding of the decision-making factors examined. The initial one displays the planning and simulation results for every scenario of the PV system, including the bill of quantities and generated energy. The following section shows the LCC outcomes for the PV systems parts (excluding PV panels). The final part displays the results of the life cycle evaluation for the complete PV systems. By breaking down the results section in this way, we can carry out a detailed analysis to assist in decision-making for the sustainable development of a PV setup.

5.4.1 Photovoltaic system

The optimal design configuration of a photovoltaic (PV) system is influenced by several key factors. Among these are the energy demand profile, roof area and structural capacity, solar irradiance patterns, budget constraints, system efficiency, maintenance needs, and potential for expansion. Nevertheless, these factors might require prioritization depending on specific site limitations. The main limitation for PV installation in the Cluj-Napoca Artificial Intelligence Institute case study was the restricted roof space available. As a result, the design phase overlooked factors such as total energy requirements and potential for future growth. **Chyba! Nenašiel sa žiaden zdroj odkazov.** presents the results obtained for the structure and ballast obtained by the planning tool K2 Base for the two scenarios.

Table 5.1 Total weight of the structure and ballast for the PV system in South and E-W orientation

Orientation	South		East-West	
Placement	Top roof	Bottom roof	Top roof	Bottom roof
Aluminium structure [kg]	365.8	697.4	192.4	414.1
Ballast [kg]	2561.0	4359.0	258.0	1036.0
Total weight per roof [kg]	2926.8	5056.4	450.4	1450.1
Total weight [kg]	7983.2		1900.5	

The research emphasizes the notable weight contrast between PV installations facing South and those facing East-West, due to the distinct structural needs linked to various orientations. When the PV faces South, the aluminium structure and ballast weigh 8 tonnes, but only 2 tonnes when it faces E-W. Due to their increased exposure to snow and wind loads, south-facing installations require larger and heavier structures to withstand these forces. Conversely, lighter structures can be used for East-West-facing installations due to reduced exposure to snow and wind, leading to a significant contrast in total weight. The weight difference affects the cost and sustainability of PV installations. Structures with more weight require increased material and labour, resulting in elevated installation expenses. Furthermore, more substantial constructions may lead to higher carbon emissions linked to material manufacturing and delivery. These factors highlight the significance of assessing structural needs when planning and choosing PV systems. By considering the specific site conditions, orientation, and local weather patterns, installers can enhance structural design to reduce weight, cost, and environmental impact.

The region where Cluj-Napoca, Romania is located receives an annual solar irradiation between 1200 kWh/m² and 1300 kWh/m². PVsyst, a software for modelling photovoltaic systems, was employed to simulate solar radiation on a particular building in Cluj-Napoca, Romania. The simulation results indicated a global horizontal irradiation of 1270 kWh/m² for the east-west system and 1269 kWh/m² for the south-facing system. The PVsyst simulations confirm the software's precision in predicting solar energy availability for Cluj-Napoca, Romania by matching the anticipated solar irradiation values. The simulations indicated that a south-oriented solar panel setup would collect less sunlight than an east-west system in Cluj-Napoca.

PVsyst software simulations suggest that PV panels facing south generate more electricity compared to East-West panels with the same kWp capacity. South-facing panels produce 1162 kWh/kWp/year, while east-west panels produce 1095 kWh/kWp/year. The East-West solar system produces more energy per year (69.86 MWh) compared to the South-facing system (69.04 MWh) due to the difference in the number of panels installed —116 panels versus 108 panels—. Although the yearly energy production of PV systems is important, the dependability of renewable energy sources is equally critical. By installing PV panels in an east-west orientation, peak demand effects on the grid can be reduced and solar energy self-consumption can be optimised. Consequently, they can decrease their dependence on grid electricity, which may result in cost savings and greater energy self-sufficiency. Energy generation can be boosted on cloudy days by capturing sunlight from different angles throughout the day, starting from east to west. Acknowledging the stability aspect of PV installations is vital, as it tackles a primary issue linked to incorporating renewable energy into the grid. Understanding how energy production varies from different angles helps us make better decisions on PV deployment strategies for optimal energy output and system stability.

A comparative graph of energy production per month for the two scenarios is shown in Figure 5.3. Additionally, this data emphasizes that PV systems facing south provide a steady and predictable energy yield.

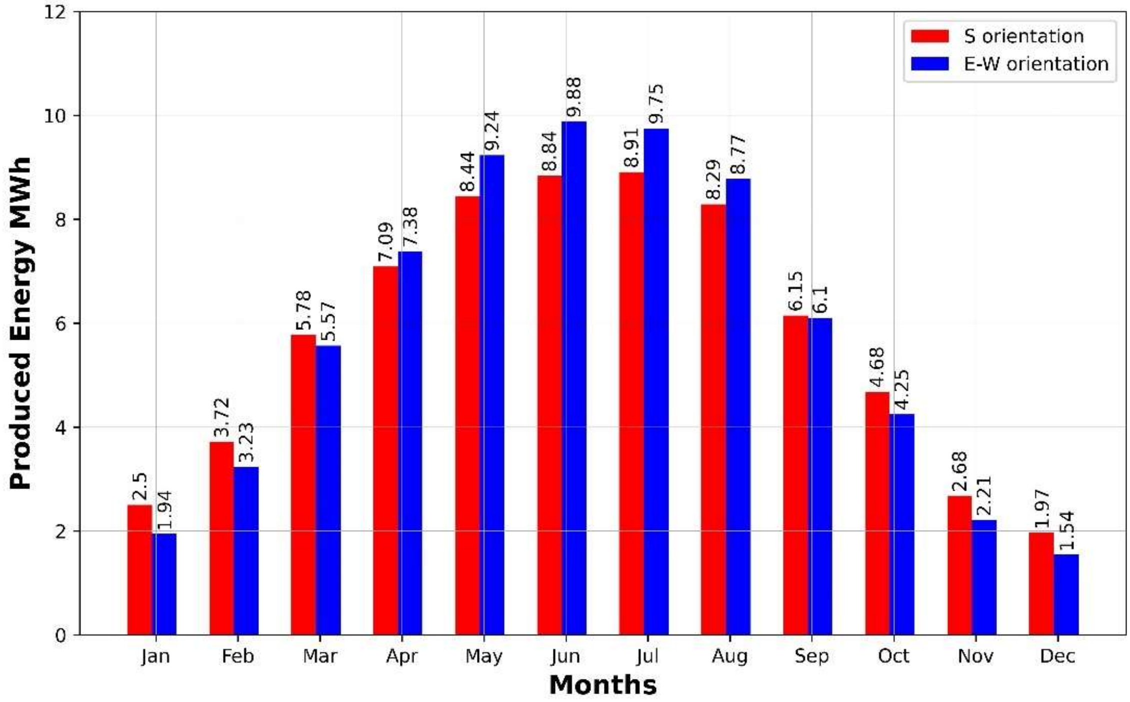

Figure 5.3. Comparative graph of the energy production for both scenarios

When assessing the solar installation's orientation, it is important to consider multiple key points. The South-facing direction needs nearly twice as many aluminium profiles as the East-West direction for solar panel support. Setting up the aluminium structure demands more than five times the amount of ballast. Remarkably, despite the South orientation generating less energy and using fewer panels. These discrepancies occur within the same installation surface area. Concluding that positioning the solar installation in an East-West orientation is logical, as it reduces stress on the building while maintaining sufficient power generation. Nevertheless, we evaluated the global warming impact (GWP) of both configurations to compare solar installations.

We extracted the fixed elements, such as the panel support structure, from the software database. Some materials will have a fixed amount in the installation like electrical box, fuse switch disconnector, power supply distributor, switches / circuit breakers, inverter, and perforated metal cable bed. Other materials will vary depending on the final orientation of the panels, such as solar cable Black for Direct Current (DC), solar cable Red for Alternative Current (AC), solar cable protector, cover clamp, aluminium structure for PV panels, and ballast for aluminium structure.

5.4.2 Life-Cycle Carbon

According to the LCC results on global warming emissions, the E-W scenario has less impact (**Chyba! Nenašiel sa žiaden zdroj odkazov.**Table 5.2) compared to the southern scenario due to needing less aluminium and ballast for installation. As a result, the emissions from transporting the South-oriented panels (A4) are increased. A larger construction is necessary to accommodate more materials on site, which explains the increase in emissions during both the construction stage (A5) and the materials stage (A1-A3). The Table 5.2 also shows the results of external influences: gains from D (materials installed), A5 (construction site - waste materials), B4-B5 (material substitution), and D2 (energy exported).

Table 5.2 Level(s) life-cycle carbon results [kgCO2-eq]

	Module	Stage	Orientation South	Orientation E-W
Structure and electrical equipment of PV system	A1-A3	Materials	28386.35 (58.79%)	24906.45 (56.02%)
	A4	Transport	458.77 (0.95%)	277.77 (0.62%)
	A5	Construction	922.8 (1.91%)	613.59 (1.38%)
	B4-B5	Replacement	16584.55 (34.35%)	16607.43 (37.35%)
	C1-C4 End of life	Waste disposal	1930.29 (4%)	2055.27 (4.62%)
		TOTAL	48,282.76	44,460.51
Benefits	D	Installed materials	-11,346.01	-7532.7
	A5	Constr.- material wastage	-694.16	-404.72
	B4-B5	Mat. Replac.	-2246.82	-2249.94
	D2	Exported Energy	-804,706.98	-814,479.19
		TOTAL	-818,994	-824,667

In our examination of global warming impact by resource in Figure 5.4, we discovered that electrification components and systems were the primary contributors in both scenarios, with aluminium, cables, and other building technology systems following closely behind. In the East-West orientation, these electrification components and systems accounted for nearly 67% of the global warming impact, higher than in the South orientation. Aluminium and natural stone (ballast) had a greater environmental impact in the South orientation. In the South setup, ballast accounted for less than 2% of global warming, whereas in the East-West layout, this effect decreased by 81%.

According to the cradle-to-gate assessment (Table 5), aluminium profiles in the South scenario account for 31.6% of global warming emissions. It accounts for 28462.23 kgCO2-eq while for the East-West scenario it accounts for 24916.23 kgCO2-eq. The contribution from the inverter, solar cables, cable protection, and ballast are displayed in

Table 4.3. Solar cables make up 32.51% of emissions in the East-West orientation. The inverter, aluminium profiles, cable protection, perforated metal cable tray, mounting plate cover for electrical devices, and stone pavement tiles also conform.

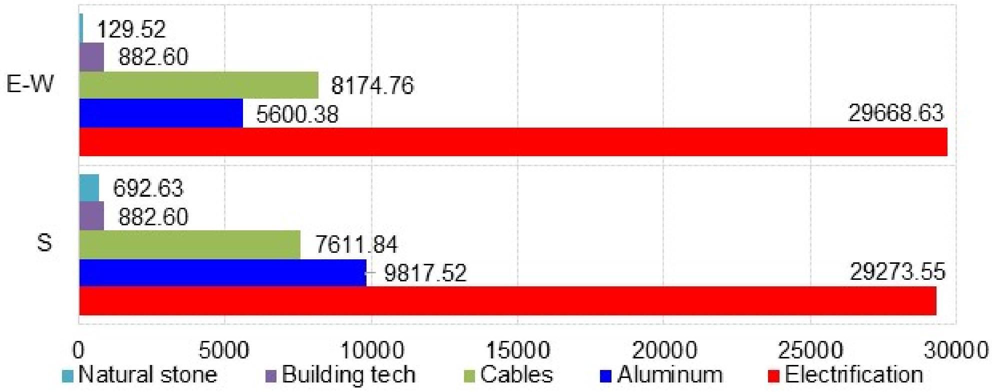

Figure 5.4. Life-cycle carbon by resource [$kgCO_2$-eq]

Table 4.3 Global warming for most contributing materials [kgCO2-eq]

Material	Orientation		Material	Orientation	
	S	E-W		S	E-W
Aluminium profiles	9000	5100	Plate cover for electrical equipment	250	270
Solar cable	7568	8101	Power supply distributor	43	43
Three-phase inverter	7800	7800	Cables connectors	25.84	25.84
Cable protection hoses and sleeves	2800	3000	Switches/Circuit breakers	31	31
Stone pavement / Ballast	490	91	Fuse switch disconnector	24	24
Perforated metal cable bed	430	430	Electrical box	0.39	0.39

5.4.3 Life-Cycle Assessment

The evaluation of the components in the photovoltaic installation covered twelve different impact categories. Figure 5.5 shows how these twelve indicators affect different life-cycle stages and materials. The materials stage (A1-A3) made the largest contribution across all indicators except ADPE, while the replacement stage (B4-B5) recorded the highest value for ADPE. E-W orientation results in lower contributions for most indicators (A1-A3), except for ODP, EP, POCP, and ADPE. For E-W, the replacement stage was the biggest contributor, while for transport (A4), excluding POCP and ADPE, all the rest indicators recorded lower values. About the construction stage (A5), for all indicators, E-W orientation causes lower impacts than S, while for the end-of-life stage (C1-C4), for all indicators excluding GWP, PERT and FW.

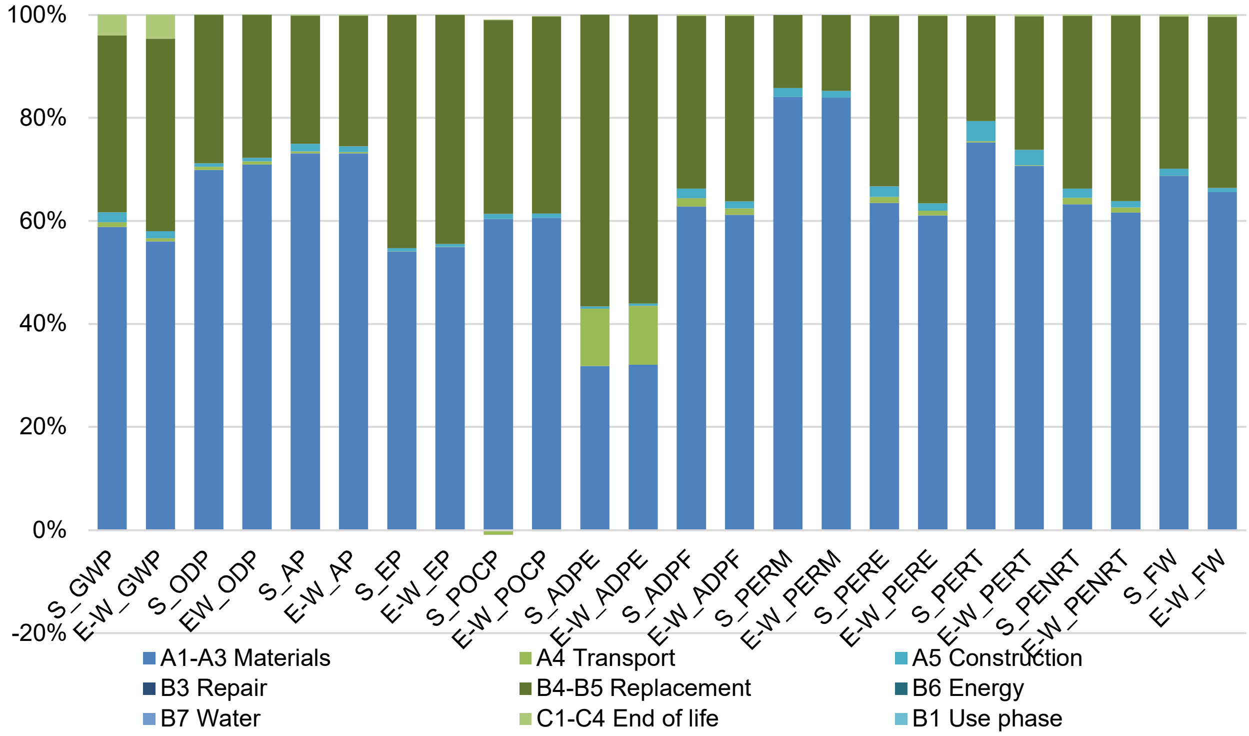

Figure 5.5. Life cycle impacts by stage for South (S) and East-West (E-W) orientation

Negative values are observed for Photochemical Ozone Creation Potential (POCP) in Figure 5.5. By examining the Module A4 calculation, we can illustrate how NOx emissions are divided into NO2 and NO emissions for the environmental category of truck POCP (DNV, 2021). Due to NO emissions, a negative value is observed as they provide a credit for POCP by decreasing near-ground ozone formation. During the night, NO and O2 react to form NO2 and O2, resulting in reduce the POCP. Net negative effects happen if NO levels exceed NO2 levels. NOx is emitted by transportation processes and contributes to ozone depletion (Gervasio and Dimova, 2018).

Nevertheless, it is important to note that POCP is just one of the environmental impact categories being analysed, despite the apparent unusual negative values.

Table 5.4 offers a thorough summary of the complete assessment of the PV system, covering all twelve impact categories. The life cycle assessment results show that the E-W orientation decreases impact categories compared to the South orientation, reducing GWP by 4.08%, ADPF by 3.52%, AP by 0.67%, and all environmental resource use indicators by 0.73 to 14%. The E-W scenario has the potential to have better environmental outcomes compared to the South scenario.

Table 5.4. LCA results for PV system

Category	Units	Orientation South	Orientation E-W
GWPtotal	kg CO_2-eq	8.32E+04	7.98E+04
ODP	kg CFC11-eq	1.08E-02	1.11E-02
AP	kg SO2-eq	6.16E+02	6.12E+02
EP	kg PO4-eq	3.74E+02	3.80E+02
POCP	kg NMVOC	2.12E+02	2.14E+02
ADP-minerals and metals	kg Sb-eq	1.70E+01	1.72E+01
ADP-fossil	MJ	9.18E+05	8.86E+05
PERM	MJ	2.39E+03	2.37E+03
PERE	MJ	8.02E+05	7.35E+05
PERT	MJ	1.43E+05	1.23E+05
PENRT	MJ	1.07E+06	1.03E+06
FW	m^3	2.46E+03	2.32E+03

PV panels were discovered to have the greatest effect on four of the seven environmental indicators by researchers: global warming, ozone depletion, lower-atmosphere ozone formation, and abiotic depletion of fossil resources. Alternatively, the inverter was mainly responsible for the abiotic depletion of non-fossil resources, eutrophication, and acidification (Figure 5.6). Aluminium profiles are the third most impactful in causing global warming, acidification, and fossil abiotic depletion. Low voltage cables ranked as the second highest contributors to eutrophication potential (EP), with PV panels and inverters having a greater impact on ozone depletion potential (ODP).

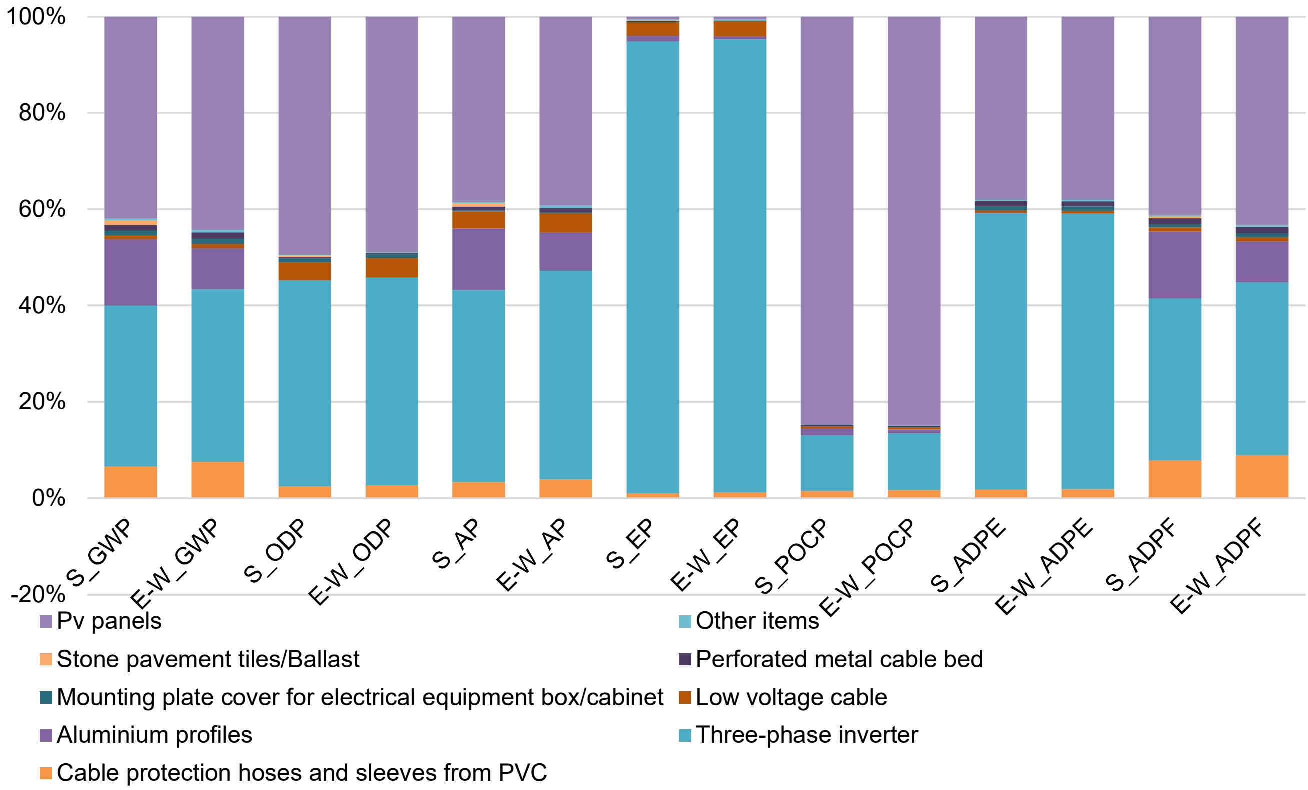

Figure 5.6. Contribution of PV system's components to the environmental impact indicators for South (S) and East-West (E-W) orientation

Cable protection hoses and sleeves dominated the environmental resource use indicators in PERM, while inverters did so in PERE for both orientations. South orientation in PERT primarily used aluminium profiles, while E-W orientation relied on PV panels. PV panels required the highest energy use among all non-renewable primary energy sources and net fresh water, for both orientations (

Figure 5.7).

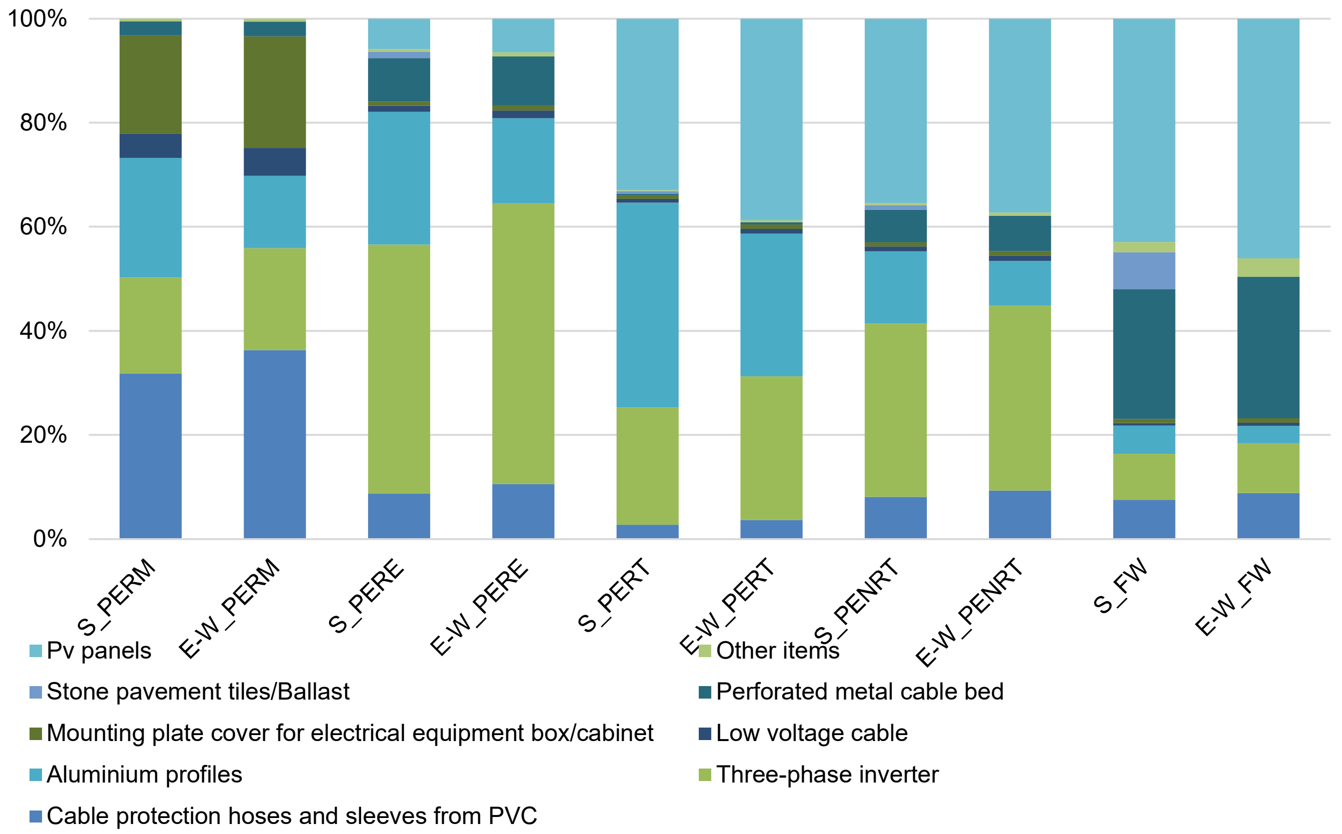

Figure 5.7. Contribution of PV system's components to the environmental resource use indicators for South (S) and East-West (E-W) orientation

Table 5.5 shows the calculated results of the PV system's energy production, energy payback time (Equation (5.2)), and the carbon emission rate (Equation (5.3)) for both South and East-West scenarios. The energy production calculated using (Equation (5.1)). The PV system-oriented East-West produces more energy and has lower EPBT and GHG emission rates than the South-oriented PV system.

Table 5.5 Assessment of the PV system

	Unit	South	East-West
Energy production	[MWh]	1913.72	1936.96
GHG emission rate	[gCO_2-eq/kWh]	43.53	41.75
EPBT (consumed directly)	[years]	2.54	2.39
EPBT (injected)	[years]	6.36	5.97

5.5 Discussion

This study focused on utilizing the previously unused roof space at the Artificial Intelligence Research Institute in Cluj-Napoca, Romania, in order to tackle electricity consumption and lower carbon emissions, contributing to the goal of achieving carbon neutrality (De La Peña et al., 2022). The study aimed to meet part of the electricity demand and aid in reducing carbon emissions by installing photovoltaic systems (Cristea et al., 2022) on a building associated with the Technical University in Cluj-Napoca, Romania.

The analysis of the support structure's life cycle revealed an 8% decrease in global warming in the East-West scenario compared to the South orientation. The most significant decreases were observed in specific life-cycle phases: transportation (A4) saw a 39% reduction, construction/ installation (A5) experienced a 34% decrease, and materials (A1-A3) had a 12% decrease. When considering different resource types, global warming potential was lower for aluminium and ballast but higher for cables, electrification components, and systems in the East-West orientation.

From a cradle-to-gate perspective, the main materials for the East-West orientation were the solar cables (32.51%), three-phase inverter (31.3%), and aluminium profiles (20.5%). On the other hand, aluminium profiles made up 31.6%, the inverter 27.4%, and the cables 26.59% of the cradle-to-gate impact for South orientation.

PV panels are the primary contributor to global warming, ozone depletion, and fossil fuel depletion within the PV system (Alam and Xu, 2023; Palanov, 2014). The GHGER of 43.53 gCO2-eq/kWh for the South-oriented system and 41.75 gCO2-eq/kWh for East-West for the East-West system align with the average values reported in the literature, which range from 29-45 gCO2-eq/kWh (Peng and Lu, 2013), 13-190 gCO2-eq/kWh (Turconi et al., 2013), 42 gCO2-eq/kWh (Nicholson and Heath, 2012b), 41 gCO2-eq/kWh (IPCC, 2014), 30-45 gCO2-eq/kWh (Fthenakis and Alsema, 2006), 42.5 gCO2-eq/kWh (Frischknecht, 2020), 21-107 gCO2-eq/kWh (Jones and Gilbert, 2018).

Romania's photovoltaic system emits less greenhouse gases than fossil fuels but more than hydropower, wind, or nuclear energy. This observation aligns with a similar comparison made by (Ali et al., 2022). By assessing various electricity generation methods, researchers determined that a PV system has the ability to cut GHG emissions by almost 97% when contrasted with coal, achieving reductions of 96.55% for South orientation and 96.69% for East-West.

The EPBT is a useful tool for evaluating a PV system's sustainability. EPBT calculates how long a PV system needs to generate energy to offset the energy consumed during its production and setup, leading to a surplus of energy for the user. Yet, the calculation of this indicator depends on numerous influencing factors, such as:

Type of PV Module: Various PV modules offer different characteristics in terms of energy production and efficiency.

Efficiency of Conversion: The effectiveness of converting sunlight into electricity by PV panels significantly impacts overall performance.

Insolation: The level of solar irradiance received at a specific location directly affects the energy output of the PV system.

Performance Ratio: This ratio, which compares the actual energy output to the expected output, plays a crucial role in determining energy payback time.

Installation Type: The method of installing the PV system—whether on a roof, ground-mounted, or integrated into a building—can influence its energy production capacity.

Support Structure: The design and materials used in the support structure can affect the system's overall efficiency.

Application: The operational mode of the PV system, whether grid-connected (on-grid) or independent (off-grid), impacts its energy contribution.

Grid Efficiency: The efficiency of the local electricity grid can play a role in the overall energy balance of the PV system.

By considering these factors, the system's sustainability and EPBT can be determined, demonstrating its potential to generate a net energy gain during its operational lifespan (Peng et al., 2013; Salibi et al., 2021). According to national conversion factors, if the generated energy is consumed directly, the energy payback time for electricity produced with PV panels is 2.4-2.5 years (Mc 001-2022, 2023). However, when the energy is integrated into the National Energy System, the EPBT period ranges from 6 to 6.4 years, showing superior outcomes for the East-West alignment over the Southern orientation. According to the literature, energy payback time values vary significantly, ranging from 1.7-2.7 years (Peng and Lu, 2013), 1.6-3.3 years for rooftop installations, 2.7-4.7 years for façade (Gaiddon and Jedliczka, 2006), 1-4.1 years (Bhandari et al., 2015), 8-12 years for a campus university of 67.27 kW in the U.S. (Lee et al., 2016), and 5.5 for an on-grid PV system of 56.7 kW at a faculty in Jordan (Al-Najideen and Alrwashdeh, 2017).

The waste disposal numbers for South orientation (stages C1-C4) are 1930.29 (4%) and for E-W orientation are 2055.27 (4.62%) (Table 5.4). These values are lower compared to 30% due to post-incineration treatments and other processes like sandwich layer incineration (Latunussa et al., 2016). The transport stage (A4) represents 458.77 (0.95%) for the South orientation and 277.77 (0.62%) for the East-West orientation, reflecting identical values corresponding to the 10% achieved in (Latunussa et al., 2016).

We evaluated the environmental advantages of implementing a solar panel system by examining both emissions and external factors. These external factors encompass the efficient use of materials, waste reduction, and the benefits of energy exportation. Figure 5.8 illustrates how the global warming potential of photovoltaic panels and related components changes throughout the system's life cycle. More precisely, the graph ranges from year 0, reflecting impacts prior to system implementation, to year 31, signifying the end of the system's active lifespan. Moreover, we will assess the 10th and 20th years for replacing certain electrical parts, focusing mainly on the inverter.

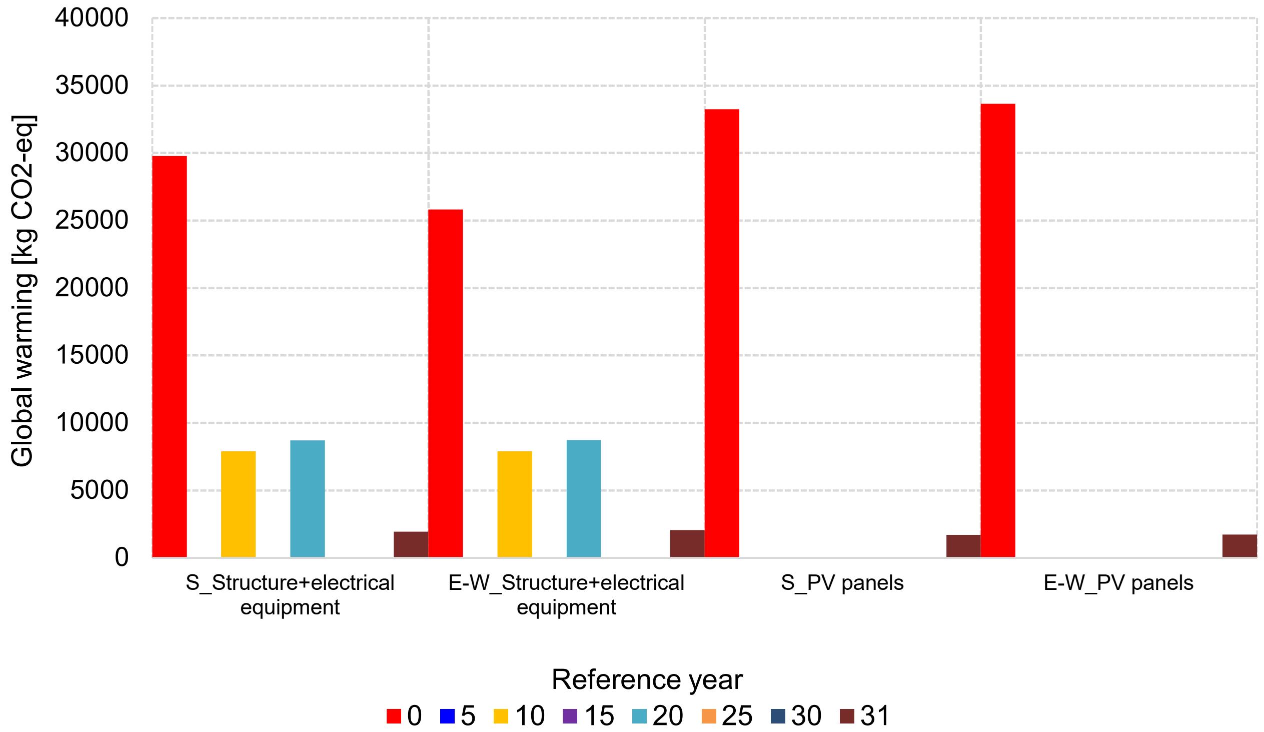

Figure 5.8. Yearly global warming potential of PV panels and auxiliary components for South (S) and East-West (E-W) orientation

Utilising a PV system helps reduce emissions by generating electricity. According to the yearly results, using this system results in notable savings, especially in the East-West scenario. Emission reductions from using PV systems are shown in Figure 5.9 with a lifecycle perspective.

Building upon earlier investigations (Zhang et al., 2023)), photovoltaic systems offer greater energy savings and environmental advantages than their life cycle investment or traditional fossil fuel technologies. Cusenza et al., (2019) suggested a possible remedy for the rising need for storage systems in buildings by repurposing the surplus automotive batteries. In their second life, these batteries could retain up to 80% of their original energy capacity. This strategy enables us to recycle batteries for storage requirements.

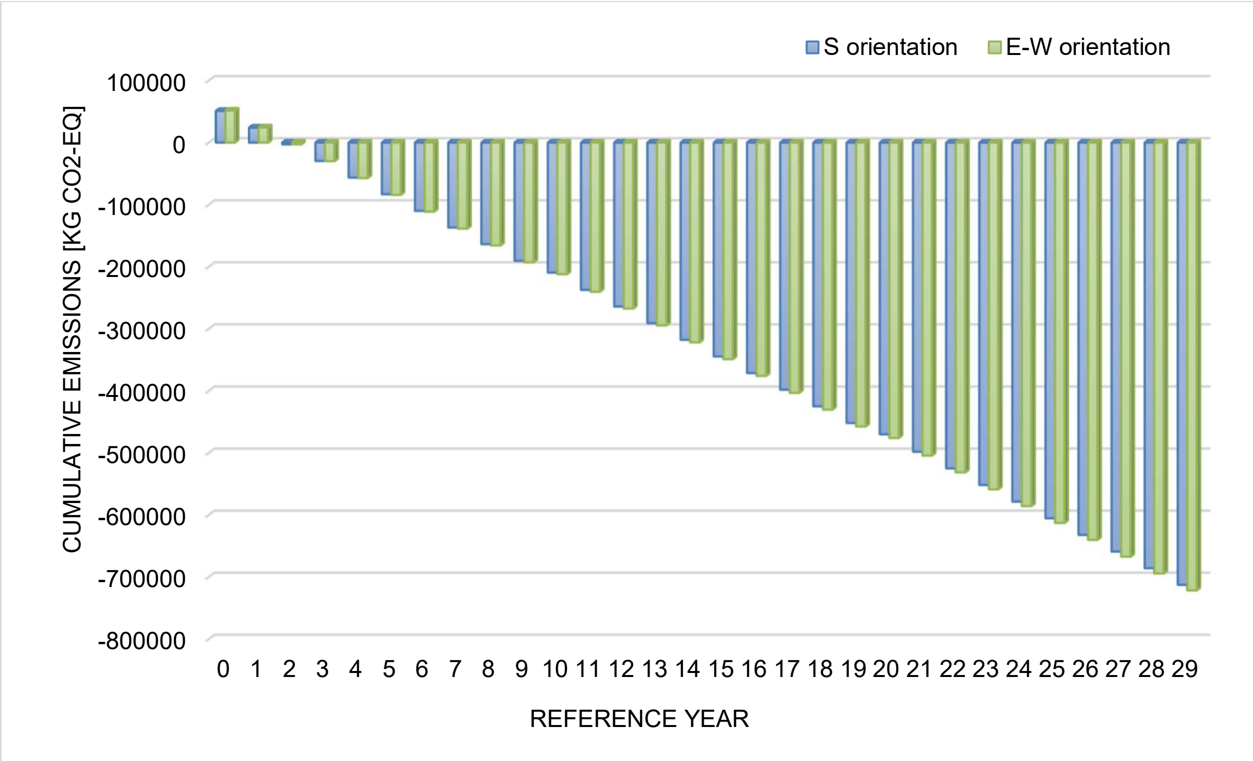

Figure 5.9. Yearly global warming and benefits of PV system for South (S) and East-West (E-W) orientation

The preference for E-W orientation over south orientation is highlighted by numerous practical applications. In residential areas with small or irregularly shaped rooftops, individuals often opt for an east-west alignment to maximize the limited space they have. In off-grid or remote locations where energy storage is imperative, E-W orientation facilitates a more equitable distribution of energy production throughout the day. By doing this, energy storage systems can be utilized more effectively and reduce the need for backup generators or expensive battery replacements. In off-grid irrigation systems utilizing solar panels, the east-west setup allows for extended periods of irrigation. E-W orientation is beneficial for commercial establishments like restaurants, theatres, or shopping malls facing evening energy spikes. It matches energy generation with peak demand times, decreasing reliance on grid power in expensive peak hours.

Future studies on rooftop Pv panels need to explore more than just single systems. Rather, it should take into account the complete energy system. This might require examining how PV systems, tracking devices, and energy storage can be combined to generate, consume, and interact with the grid. PV tracking systems can improve the performance of PV installations by increasing annual energy production and stability. We need to evaluate the impact of different energy sources and grids on the sustainability of solar panels. This information could improve decision-making regarding policies and infrastructure planning. By using the information acquired in this research, we can adopt sustainable methods. To reduce the environmental effects and increase long-term advantages, it's crucial to make well-informed choices at every stage of a product's lifespan, from sourcing materials to disposal. Prioritising the selection of materials for all PV system components is what a sustainable approach entails. This involves evaluating the environmental effects of various materials, such as seeking those with reduced carbon footprint, integrating recycled silicon, and opting for steel over aluminium in the mounting structure.

Another option involves looking into different transportation methods with reduced emissions, like electric cars or trains for long trips. Moreover, utilizing materials sourced locally can reduce the environmental impact linked to transportation. Adopting a circular economy for PV systems is crucial for reducing emissions. Recycling system's components instead of disposal not only lowers the environmental impact but also promote resource management. By analysing different perspectives, researchers from diverse fields can provide precise and comprehensive information. This manuscript enhances decision-making processes and fosters the development of more sustainable PV systems in various ways. The study compares energy production from various orientations to offer guidance on maximizing energy generation, especially vital for off-grid setups requiring consistent energy availability. By doing this, stakeholders can make informed decisions on system design to ensure a reliable power supply.

The examination of greenhouse gas emissions linked to various orientations reveals the environmental impact of PV system setups. The results suggest that specific orientations could lead to decreased emissions, offering a method to lower the carbon footprint of PV systems. Because of lighter panels and structures in the east-west orientation, installations become safer and more efficient. For rooftop installations, structural integrity and weight factors are crucial. Lighter panels not just reduce the stress on building frames but also simplify maintenance and handling. This could enhance system performance and lifespan, decreasing downtime and maintenance expenses. According to the research, aligning in an east-west direction may boost yearly energy output with less materials, leading to long-term cost savings. This is significant given the usual favouring of a South orientation in unified energy generation. The thorough examination of the study provides valuable insights into PV system performance and emission profiles. This enables stakeholders to make knowledgeable choices regarding system design, setup, and function. The study's findings make a substantial contribution to the progress of sustainable PV systems. The acquired knowledge aids in improving performance, reducing environmental harm, strengthening structural stability, and guiding decision-making. These discoveries are crucial for advancing more efficient and sustainable solar technologies.

5.6 Conclusions

Picking the layout for a photovoltaic system involves using the right evaluation tools and making decisions with input from different stakeholders and decision-makers. The research analyses the potential and environmental impact of two solar PV systems: one with south-oriented panels and the other with east-west-oriented panels. The results obtained provide answers to the set questions, and these findings reveal:

(i) Being oriented towards the East-West allows for increased power production during sunrise and sunset. This particular point holds significance for off-grid systems (which can be powered at different hours of the day).

(ii) The E-W scenario with 116 modules generates more annual energy (69.86 MWh/year) than the South scenario with 108 modules (69.04 MWh/year). Yet, the South orientation of the panels is preferred when considering unitary energy production.

(iii) The PV system facing east-west has reduced emissions due to the aluminum structure, with emissions of 5100 kg CO_2-eq for the E-W orientation and 9000 kg CO_2-eq for the south orientation as shown in Table 5.5. The GHG emission rate is lower for E-W at 4.08% compared to the South. The alignment from East to West helps decrease carbon emissions, offering an eco-friendlier choice.

(iv) The aluminum structures for accommodating the modules in the E-W option weigh less at 606.5 kg compared to 1063.2 kg in the South scenario (Table 5.2).

(v) The ballast needed for the setup is 1294 kg for the E-W panels and 6920 kg for the S panels (Table 5.2).

The main benefit of an E-W orientation is lighter solar panels on the roof and increased yearly energy output. This enhancement boosts the structural strength of the building, resulting in a safer and more effective installation process while also lessening the pressure on the building's frame. Furthermore, lighter panels make it easier to handle and maintain, improving the system's performance overall. Picking the appropriate design configuration is vital for solar panels, as it influences efficiency, surroundings, and how well they work.

In conclusion, the paper provides a valuable addition to our knowledge of PV performance and emission profiles. Although the information regarding south orientation is widely known, the paper's analysis provides further insights for decision-making and sustainable PV systems. Exploring various options can enhance the progress in comprehending and enhancing decision-making on comparing South-facing PV modules with East-West-facing ones. Certain tasks include optimizing hybrid orientations such as tilted panels or variable tilt angles, incorporating energy storage to maximize self-consumption and grid independence, emphasizing technological advancements, and assessing long-term performance and durability.

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Chapter 06

Environmental Pollution and Climate Change: Life Cycle Assessment of the Ukrainian War Impact

Svitlana Delehan[1], Myroslava Lendel[2], Oksana Sviezhentseva[3] and Andrii Khorolskyi[4]

1 Centre for Interdisciplinary Research of Uzhhorod National University, Uzhhorod National University, 88000 Uzhhorod, Ukraine; svitlana.delehan-kokaiko@uzhnu.edu.ua

2 Faculty of Social Sciences, Department of Political Science and Public Administration of Uzhhorod National University, Uzhhorod National University, 88000 Uzhhorod, Ukraine;

3 Department of International Studies and Public Communications, Uzhhorod National University, 88000, Uzhhorod, Ukraine;

4 Laboratory of Mining Problems, Branch for Physics of Mining Processes of the National Academy of Sciences of Ukraine, 49005 Dnipro, Ukraine; andreykh918@gmail.com

This chapter evaluates the environmental impacts of military activities during the Ukraine war using Life Cycle Assessment (LCA) methodology. It provides comprehensive estimates of greenhouse gas (GHG) emissions caused by military operations, infrastructure destruction, and reconstruction efforts. The analysis highlights the global implications of these emissions, emphasizing transboundary pollution and its contribution to climate change. The chapter underscores the importance of international cooperation in addressing the environmental damages of war and presents strategies for post-war ecosystem restoration using sustainable, low-carbon technologies.

The preservation and modernisation of cultural heritage sites are critical aspects of sustainable development, especially in regions with a rich historical heritage, such as western Ukraine. This study examines the carbon footprint associated with the building materials used in the modernisation of a cultural heritage site, Uzhhorod in the Zakarpattia region. This analysis is contextualised by comparing the relevant standards in Ukraine with European norms.

Since the outbreak of the war in Ukraine, western cities such as Uzhhorod have become overcrowded due to the large flow of internally displaced persons, and the density of urban development has increased significantly, necessitating a detailed assessment of the existing infrastructure to implement measures to modernise it, including cultural heritage sites. Such measures include improving the thermal insulation of buildings, replacing windows and doors,

6.1 Introduction

The lack of consistent reporting and the presence of significant data gaps present considerable challenges in accurately estimating the total greenhouse gas (GHG) emissions attributable to global military activities. Despite these challenges, existing data suggest that the contribution of the military sector to global emissions could be substantial. Recent studies have highlighted the military sector's carbon footprint as accounting for approximately 5.5% of global emissions. If considered as a separate entity, the global military sector would rank as the fourth-largest emitter of GHGs worldwide, surpassing the national emissions of Russia [1]. This substantial contribution underscores the urgent need for both robust measurement and targeted reduction of military-related emissions.

Tackling the climate crisis necessitates comprehensive action across all sectors, including the military, which is a major consumer of fossil fuels and a significant component of government expenditure. However, current practices for reporting military GHG emissions are inadequate. Often, the available data are of low quality, incomplete, or concealed within civilian categories, if collected at all [2]. Historically, this lack of transparency can be traced back to exemptions provided under international agreements such as the Kyoto Protocol, where military emissions were excluded from mandatory reporting. Although the Paris Agreement introduced voluntary reporting for military emissions, the absence of a binding requirement has resulted in continued data gaps [3].

This issue is exacerbated by the fact that the Intergovernmental Panel on Climate Change (IPCC) and other international bodies have largely neglected military emissions in their assessments. For instance, the IPCC's Sixth Assessment Report offers only minimal discussion on this topic, further contributing to the sector's exclusion from global emissions reduction strategies [4]. Given that approximately 60% of global GHG emissions originate from just ten countries—many of which have substantial military expenditures—addressing military emissions is crucial for global climate action [5].

This study aims to provide a comprehensive estimate of military GHG emissions on a global scale, utilizing available data from a limited number of countries. The findings emphasize the need for increased research and policy attention to reduce military emissions as part of broader efforts to combat climate change.

6.2 Overview of the Situation in Ukraine, Europe and Other Countries

Despite the limited availability of data on military greenhouse gas (GHG) emissions, some data has been compiled for countries such as the USA, the UK, and some EU nations.

In certain cases, this data has been reported directly by military agencies, while in other cases, independent researchers have calculated emissions based on energy and fuel usage data published by military bodies. In this study, we extrapolate from these datasets to generate global estimates; however, this methodology has its limitations due to significant variations between countries, including [6]:

- Differences in military structure, including the type and quantity of equipment and number of personnel;
- Mobilization rates, operational and training activities;
- The accuracy and transparency of military expenditure reporting;
- The carbon intensity of national economies.

Considered several approaches for estimating global military GHG emissions. The most promising is:

1) emissions per unit currency—based on national military expenditures;

2) emissions per head of personnel—based on the number of personnel in active service within national armed forces.

Due to significant fluctuations in financial data (e.g., currency exchange rates, inflation rates, and GDP growth rates) and limited data availability in certain key nations (e.g., China, Saudi Arabia, North Korea, and Vietnam), the currency-based approach was rejected in favor of the personnel-based approach [7].

The military carbon footprint for a given nation or region (Fn) is then estimated by multiplying these data as follows:

$$Fn = es \times p \times rms \times s$$

The global military carbon footprint (Fg) is the sum of all national (or regional) footprints:

$$Fg=\sum Fn$$

The personnel-based approach utilizes the following key datasets [8]:

- Operational GHG emissions (Scopes 1 and 2) per head of active military personnel for military bases, also known as "stationary emissions" (es);
- Number of active military personnel (p);
- The ratio of operational GHG emissions between mobile military activities (use of aircraft, marine vessels, land vehicles, and spacecraft) and stationary activities (rms);
- Supply-chain multiplier, which reflects the ratio of the "carbon footprint" (the sum of Scopes 1, 2, and the upstream component of Scope 3 emissions) to the sum of Scopes 1 and 2 emissions (s).

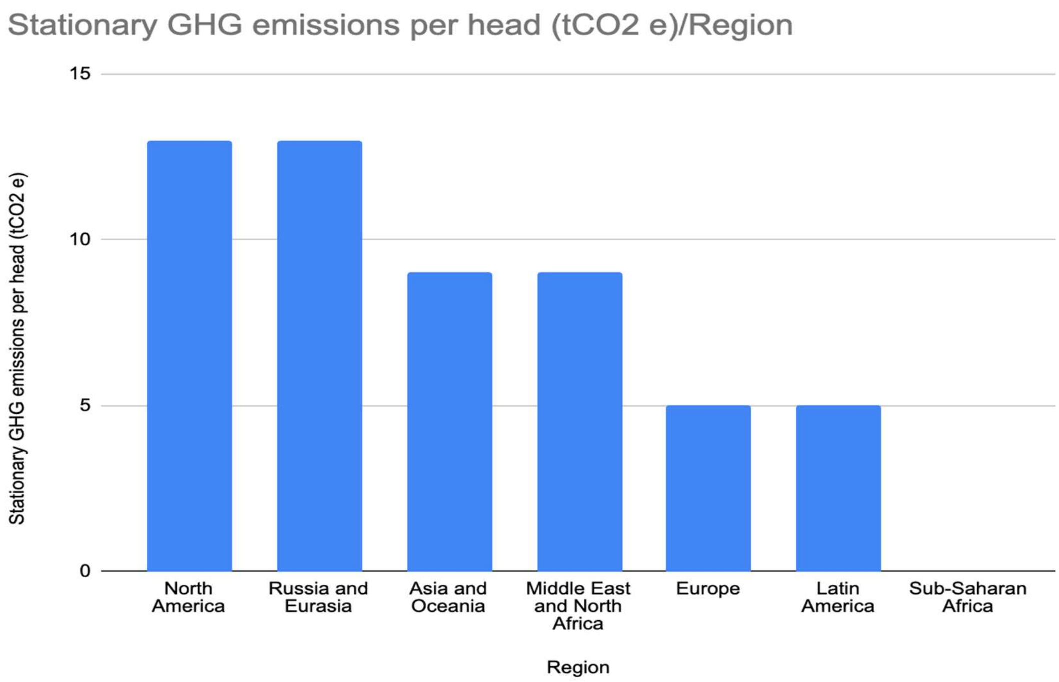

Figure 6.1. Estimating greenhouse gas emissions per capita from military personnel in different regions of the world

Figure 6.1 illustrates the distribution of stationary greenhouse gas (GHG) emissions per military personnel across different geopolitical regions of the world. The data is presented as a bar chart, where each bar represents the average amount of emissions (in tonnes of CO2 equivalent) per person:

1. Highest Emission Levels: North America, Russia, Ukraine and Eurasia exhibit the highest levels of stationary emissions per military personnel, reaching 13 tCO2e per person. This could indicate more intensive infrastructure or higher energy consumption levels at military bases in these regions.

2. Moderate Emission Levels: Asia, Oceania and Middle East and North Africa show moderate emission levels, approximately 9 tCO_{2e} per person. These regions have large armed forces, which likely contribute to the overall emissions.

3. Lower Emission Levels: Europe and Latin America display lower emission levels, around 5 tCO_{2e} per person. This may reflect greater energy efficiency at military bases or a smaller scale of energy use per person in these regions.

4. Lowest Emission Levels: Sub-Saharan Africa has the lowest stationary emissions level, approximately 2.5 tCO_{2e} per person. This may be due to less developed military infrastructure or lower intensity of energy use [9, 10].

This chart highlights the differences in military GHG emissions across various regions, indicating significant variations in the structure and scale of military activities that contribute to their carbon footprint.

6.3 The War in Ukraine: A Brief Overview of Industry and Infrastructure Damages

The Ukrainian economy has sustained extensive direct and indirect losses as a result of the destruction of assets during Russia's military aggression. Direct losses are estimated to exceed $95.5 billion, equivalent to approximately UAH 2.6 trillion at replacement value. The majority of these losses are attributed to residential buildings and infrastructure, presenting significant challenges for the economy and citizens of Ukraine [11, 12].

Indirect economic losses, which amount to approximately $126.8 billion (UAH 3.7 trillion), reflect the broader impact of the conflict on various sectors. Missile strikes and ongoing military activities have led to the suspension or disruption of numerous businesses, contributing to these substantial indirect losses.

Regions most affected by the conflict include those directly involved in combat operations, such as Donetsk, Kharkiv, Luhansk, Mykolaiv, Zaporizhzhia, Kyiv, and Chernihiv. The financial requirements for rebuilding the destroyed assets are estimated at $165.1 billion (UAH 4.8 trillion), with the most urgent needs being in the housing, infrastructure, agriculture, and business sectors.

It is important to note that these figures do not encompass the total economic losses, such as reductions in GDP, investment, labor force depletion, and other related factors. Additionally, as the situation evolves, recovery needs are likely to change.

Figure 6.2 depicts the total amount of infrastructure damage by industry as of January 2024 (billion USD).

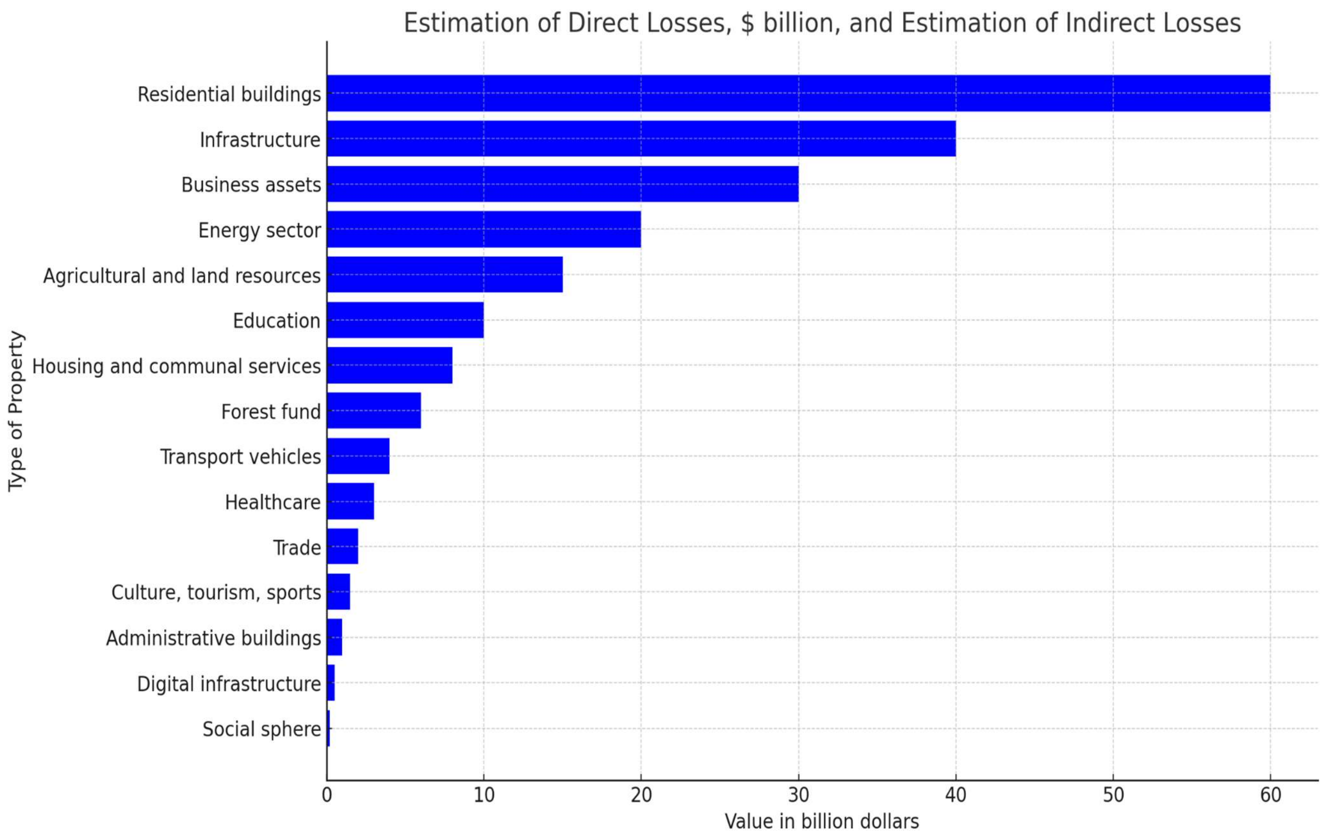

Figure 6.2. Total amount of infrastructure damage by industry as of January 2024 (billion USD)

Estimating the direct economic losses resulting from the destruction of facilities is a complex, multi-phase process that relies on detailed analysis of data from various sources.

Primarily, these estimates are grounded in reports from citizens, governmental bodies, local authorities, and private enterprises across the country. In addition to direct data collection, indirect estimation methods are employed, including assessments of the area of damaged properties in heavily impacted cities. For example, direct economic losses from physical destruction are calculated using the replacement cost methodology, with prices reflecting the cost of restoring similar assets as of late 2021 [13].

Indirect estimation approaches also utilize data on the total number of certain categories of assets at the onset of the conflict. Preliminary damage assessments incorporate various coefficients that estimate the level of damage, with specialized coefficients applied to large infrastructure projects [14-17].

Where available, microdata on damage levels for specific assets is used to enhance the accuracy of estimates. For large facilities such as airports or industrial plants, individualized estimation techniques are employed, drawing on financial records and other pertinent data.

In regions lacking microdata, damage assumptions are informed by public reports and information from civil-military administrations.

Satellite and aerial imagery further refine these damage assessments, providing detailed insights into the extent of destruction across different types of facilities within individual settlements.

Collaboration with international partners such as the World Bank and Maxar is crucial for refining damage estimates across Ukrainian cities. Additionally, data collection and in-depth interviews with stakeholders and businesses are conducted to deepen the understanding of the extent of damage.

The methodology for calculating indirect losses by industry adopts a comprehensive approach to assessing the economic impact of the conflict across various sectors. This assessment aligns with World Bank and FAO methodologies and follows the Post-Disaster Needs Assessments Guidelines, considering the primary side effects of the conflict, such as lost potential income for citizens, the state, and businesses, as well as additional costs incurred due to the war, including support programs, relocation, and evacuation expenses [18-20].

To estimate indirect losses by sector, a regional approach is utilized, applying differentiated loss factors based on the duration and intensity of hostilities in each region. This includes accounting for losses to physical infrastructure across all forms of ownership.

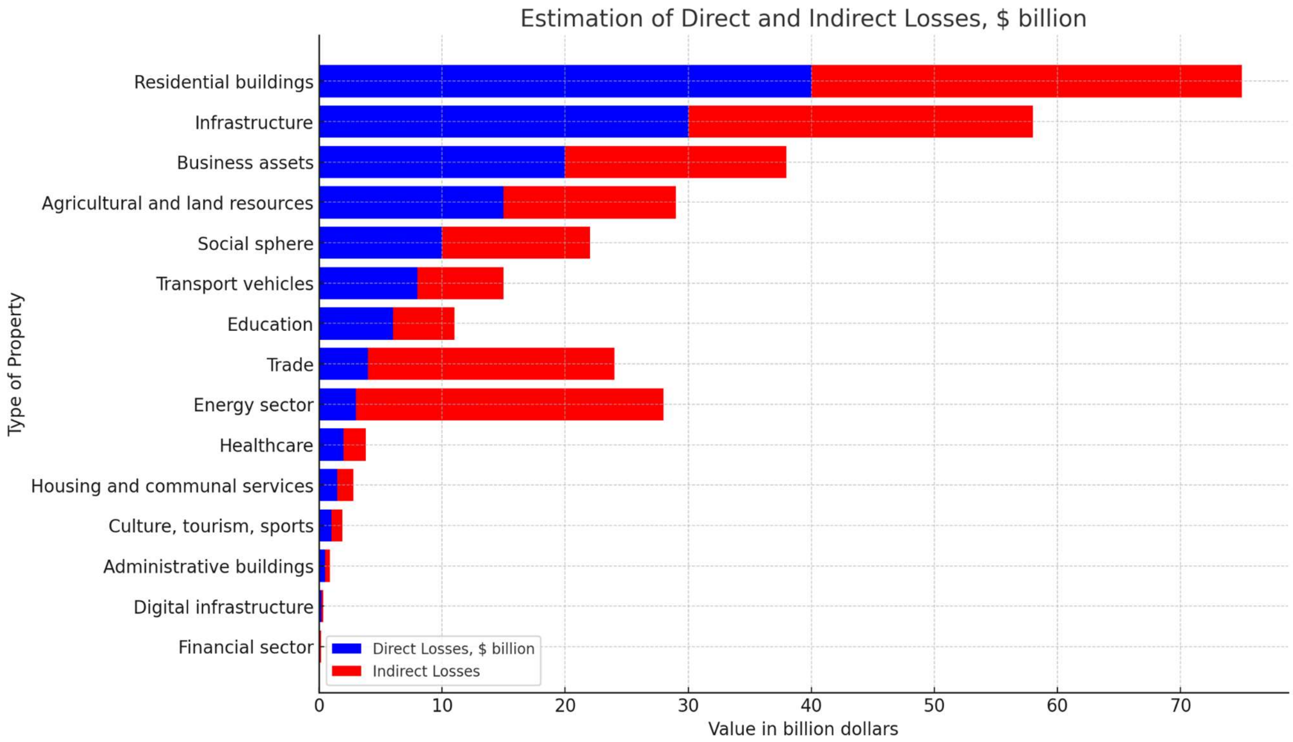

Figure 6.3. Total amount of direct and indirect losses by industry as of January 2024 (USD billion)

Figure 6.3 depicted the total amount of direct and indirect losses by industry as of January 2024 (USD billion).

Indirect economic losses are evaluated against a baseline scenario of economic development in the absence of war. This baseline is determined using data on production, consumption, and trade from the most recent reporting year. The starting point for loss estimation spans from the war's commencement to the expected full recovery of the economy and infrastructure, projected to be at least 18 months after the war began [21]. Sector-specific recovery needs are assessed with consideration of both Ukraine's overarching recovery strategy and sector-specific plans. These recovery needs are grounded in estimates of physical infrastructure losses and indirect economic impacts.

The Rapid Economic Recovery Needs Assessment adheres to international standards and is conducted in accordance with World Bank and FAO methodologies. It encompasses various aspects, including immediate rebuilding costs, accounting for the Build Back Better principle, long-term inflation, and the government's vision for structural changes in the recovery process.

Preliminary data indicates that around 121,000 residential buildings have been destroyed or damaged, encompassing 107,800 private homes, 13,100 apartment buildings, and 100 dormitories. The affected area totals approximately 61.0 million square meters, representing 6.0% of Ukraine's total housing stock [22].

Direct losses to the housing sector are estimated at $36.8 billion, which includes costs for both immediate and major repairs, new construction, and the restoration of surrounding infrastructure. Indirect losses, such as costs for dismantling destroyed buildings and debris removal, are estimated at $2.5 billion.

Administrative buildings, including those housing state and local government offices and service centers, have also sustained significant damage. Preliminary estimates indicate that 511 administrative buildings have been destroyed or damaged, with direct losses estimated at $0.9 billion.

To support temporarily displaced populations, the government is implementing measures to provide temporary housing and compensate for utility costs. However, the cost of rebuilding is increasing due to heightened requirements for safety, energy efficiency, and inclusivity, alongside rising construction material prices.

Ukraine's healthcare sector has also suffered extensive damage due to the conflict, with direct damage to healthcare facilities estimated at $1.5 billion. At least 779 healthcare facilities have been affected, including hospitals, clinics, dental offices, diagnostic centers, outpatient clinics, rehabilitation centers, laboratory centers, blood centers, and auxiliary healthcare buildings.

The assessment of healthcare sector losses incorporates data on the number and cost of hospital beds, procurement costs for similar facilities, and the degree of damage to the facilities. The damage to healthcare facilities accounts for approximately 1.3% of the total cost of losses in Ukraine. Among the most affected are outpatient clinics (268) and hospitals (227), with hospitals accounting for over 34% of the sector's total damage costs. At least 24 private healthcare facilities have also been damaged, though the documented losses predominantly pertain to public facilities.

Indirect losses in the healthcare sector are estimated to be more than twice the direct losses, amounting to $2.7 billion. These costs are largely borne by private healthcare facilities due to business interruptions, security threats, occupation, and reduced consumer demand caused by population displacement and declining incomes. Other indirect losses are due to budget cuts in certain healthcare programs.

The total estimated need for restoring the healthcare sector is approximately UAH 68.4 billion, or $2.3 billion, with nearly UAH 62 billion required for reconstructing destroyed and damaged facilities. These reconstruction needs include costs for rebuilding infrastructure to meet modern energy efficiency and safety standards, as well as restoring working capital for healthcare facilities.

Social protection infrastructure has also been severely impacted by hostilities in various regions of Ukraine. Destruction and damage have affected a range of social facilities, including social security institutions, geriatric facilities, sanatoriums, children's camps and orphanages, and boarding schools.

Preliminary estimates place the direct losses to social services infrastructure at UAH 5.1 billion, or $0.2 billion. This assessment includes damage to social infrastructure facilities managed by the Ministry of Social Policy.

Social protection and geriatric facilities represent the largest share of the total damage in terms of both number and cost. Although the number of damaged social facilities is relatively small compared to other infrastructure, significant damage has been recorded in Kyiv, Donetsk, Luhansk, Mykolaiv, Sumy, Zaporizhzhia, Vinnytsia, and Chernihiv regions.

Indirect losses in the social sector, however, are significantly higher than direct losses, with total estimated indirect losses amounting to UAH 186.4 billion, or $6.4 billion. These indirect costs include additional social expenditures necessary to support citizens affected by the conflict, as well as costs for restoring damaged facilities.

Restoring social infrastructure will be crucial to meeting service demands, particularly in the context of prolonged military conflict and economic instability.

Failure to adequately restore these facilities could lead to a significant gap between the number of people in need of social services and those who actually receive them, negatively impacting the quality of life and the adaptive capacity of the population.

One of the sectors most heavily impacted by the war is transport infrastructure as you can see from Figure 6.4. In the early weeks of the invasion, Russian forces conducted widespread attacks on aviation infrastructure, targeting military, civilian, and dual-use airfields. Subsequent assaults focused on railway infrastructure, including electrical substations. Road infrastructure has also been severely damaged due to both artillery shelling and the movement of Russian military vehicles along Ukrainian roads, which serve as key logistical routes between Russian forces in Ukraine and their supply lines in Russia and Belarus.

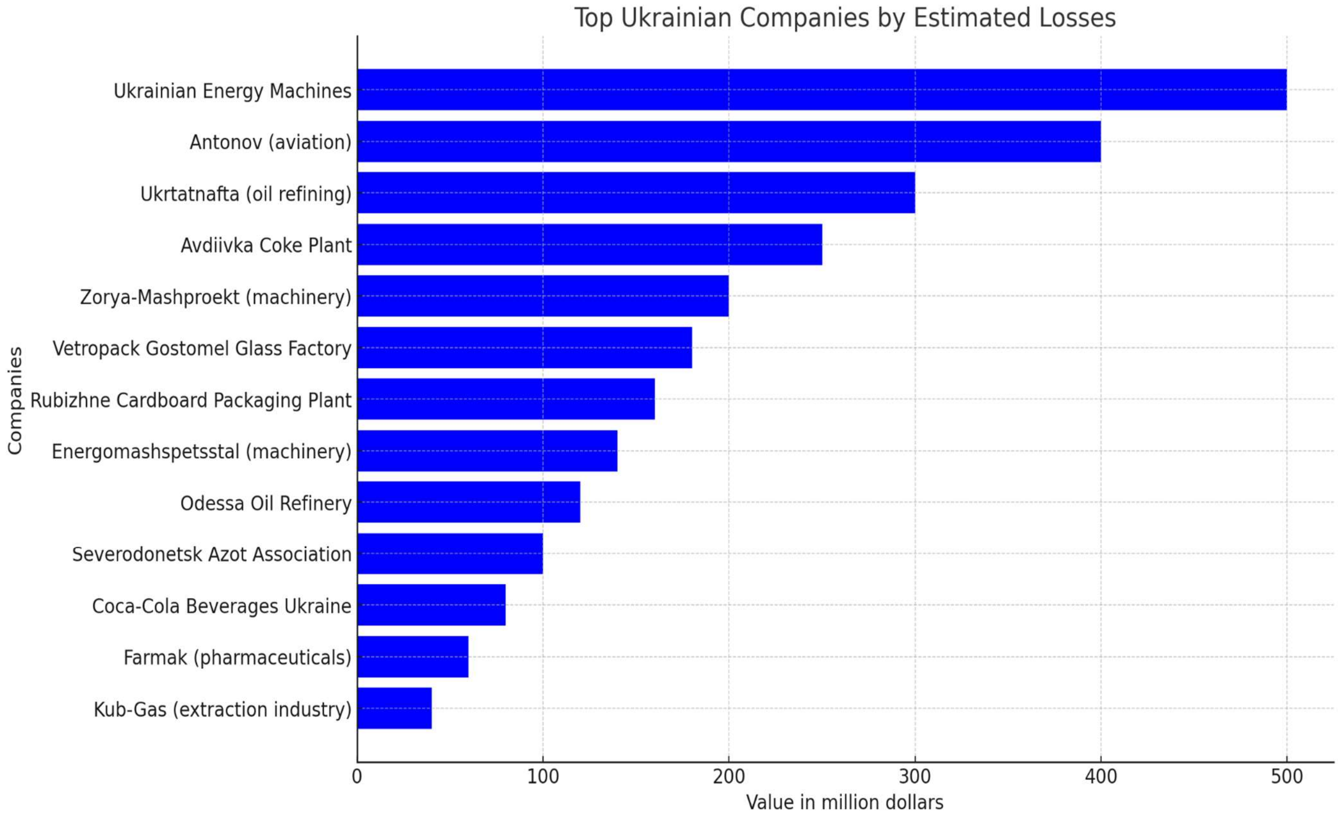

Figure 6.4. Largest affected industrial assets (according to available information on damaged assets)

As of June 13, 2023, the conflict has resulted in damage to 19 airports and civilian airfields, as well as at least 57 railway stations and associated infrastructure. The total damage to infrastructure is estimated at $31.3 billion, with indirect losses accounting for $17.7 billion. Preliminary estimates suggest that the cost of restoring this infrastructure will be approximately $41.8 billion.

The Ukrainian energy sector has also been severely affected. Direct damage to energy infrastructure is estimated at UAH 49.5 billion (USD 1.8 billion).

This damage assessment is based on both direct and indirect valuation methods, including the cost of restoring energy facilities, factoring in the original book value, current repair costs, and replacement costs [23].

The evaluation of damage relies on data from open sources and information provided by business owners within the sector. For large-scale facilities, a tailored approach is used, including financial records to assess damage to power plants, and damage coefficients for power lines and substations based on their location within affected settlements.

Assessment of losses in the energy sector is ongoing due to the challenges of obtaining accurate data on privately-owned facilities, as well as limited access to sites within combat zones and temporarily occupied territories:

- Distribution System Operators: The Ministry of Energy estimates losses for distribution system operators at approximately UAH 15.4 billion. This figure is expected to rise as losses in active combat areas are assessed, along with the costs associated with thorough repairs. Currently, operators have performed only minimal repairs to restore electricity supply, which has significantly impacted supply reliability.
- Generating Capacity: Approximately 4% of Ukraine's generating capacity has been destroyed, with an additional 35% located in occupied territories. Although the loss of assets in occupied areas is not included in direct loss calculations, it significantly contributes to indirect losses, particularly in terms of lost revenue.
- Ukrenergo: The national transmission system operator Ukrenergo reports losses of UAH 7.7 billion, excluding assets in non-controlled territories.
- Gas Distribution System Operators: Losses are estimated at UAH 6.1 billion. Three thermal power plants have been completely destroyed, and five others have sustained damage. Overall, around 50% of Ukraine's thermal generation capacity is either destroyed or situated in occupied areas.
- Zaporizhzhia Nuclear Power Plant (NPP): Europe's largest nuclear facility, located in an occupied area, has limited access for proper maintenance. Despite operating within the Ukrainian power grid, the plant remains under constant pressure from occupying forces.
- Other Major Thermal Power Plants: Facilities such as the Zaporizhzhia TPP and Luhansk TPP are located in occupied regions, while intense fighting continues around the Vuhlehirsk TPP.
- Kakhovka Hydroelectric Power Plant (HPP): Seized by occupying forces, with damage to equipment estimated at UAH 550 million, according to Ukrhydroenergo.
- Solar and Wind Generation: Approximately 30% of Ukraine's solar generation and over 90% of its wind generation capacity are in occupied regions, including Kherson, Zaporizhzhia, and Mykolaiv. Preliminary estimates indicate that assets valued at approximately UAH 870 million have been destroyed.

The cumulative indirect losses for the electricity sector since the conflict's onset are estimated at UAH 340.3 billion. Losses in the gas production, transit, and distribution sectors amount to UAH 61 billion, while the oil production and refining sectors have incurred losses of UAH 64.6 billion.

The methodology for calculating indirect losses in the electricity sector involves projecting a balance of electricity production and consumption post-conflict. Losses are calculated for various producer groups, taking into account changes in tariffs, production, transmission, and distribution volumes.

In the gas sector, losses are driven primarily by reduced production, with output declining by 10-12% since the full-scale invasion began. The gas transmission system operator has experienced losses due to decreased transmission volumes for domestic consumption, reduced revenues from entry fees for imports, and losses of gas for technological purposes.

For the oil refining sector, losses stem from the suspension of operations at the Kremenchuk refinery and the Shebelynka gas processing plant. The shutdown of these facilities has created logistical challenges in supplying petroleum products.

A significant rise in energy and fuel prices has complicated efforts to meet demand and prepare for the autumn and winter seasons. This has also led to increased financial imbalances within the energy system, as energy prices and tariffs for a significant portion of consumers have remained unchanged.

As of June 1, 2022, the projected deficit in the electricity market was approximately UAH 35 billion. This deficit is attributed to reduced payments for electricity and services in conflict zones, as well as lost profits and other losses incurred by market participants due to decisions made by the Ministry of Energy and other government authorities during the war.

Estimating the needs of the electricity and gas supply sectors is an extremely complex task. To determine these needs, it is necessary to develop a new forecast balance for energy consumption and, based on this balance, devise a plan for network development and generation capacity expansion. However, the Ukrainian energy system's reliance on outdated power generation technologies and its lack of flexibility significantly constrain its ability to increase the share of renewable energy sources.

A simplified calculation, focusing solely on losses and liquidity needs for operational restoration without considering the future energy balance, suggests that the total needs of these sectors amount to approximately UAH 103 billion.

To address the industry's need for technological modernization, the cost of physical asset losses has been adjusted by a factor of 1.4. Additionally, financial support equivalent to approximately 10% of lost annual income is required to restore operations [24].

About 242 km of sewerage networks were destroyed, 51 sewage pumping stations were partially damaged or completely destroyed, most of them in Kyiv, Kharkiv and Cherni

13 landfills for household waste, 3 waste sorting lines and 3 biogas plants were destroyed. 172 garbage trucks that provide waste removal were destroyed.

Indirect losses to the economy in terms of heating, water supply and sewage facilities are estimated at $2.3 billion. These are losses to service providers due to reduced payments for services by consumers. The total cost of repair and reconstruction of damaged and destroyed heat supply (excluding CHP), water supply, sewage and household waste management facilities will be at least UAH 45.4 billion ($1.6 billion in equivalent, at the official NBU exchange rate as of June 13, 2022).

6.4 The Significance of Life Cycle Assessment (LCA) in Evaluating the Environmental Consequences of the War

Life Cycle Assessment (LCA) is an essential tool in assessing the comprehensive environmental impacts of any activity, and its significance is particularly pronounced in the context of war. LCA enables the evaluation of the full spectrum of environmental consequences resulting from military activities, from the extraction of raw materials and manufacturing of military equipment to the operational phase, including transportation and use, and finally, to the disposal or decommissioning of military assets.

One critical aspect of LCA is its ability to account for both direct and indirect environmental impacts, offering a holistic view that is essential for understanding the full consequences of warfare. For instance, while the immediate destruction caused by conflict is often the most visible impact, indirect effects such as the carbon footprint of supply chains, the long-term environmental degradation from chemical pollutants, and the disruption of ecosystems must also be considered.

In the military context, supply chains play a significant role in the overall environmental impact. Military operations rely on extensive and complex supply networks, often extending globally. These supply chains contribute to a large proportion of a military's total carbon footprint, as they involve the production, transportation, and logistics of equipment and materials used in military operations.

A study on the UK military's supply chain, for example, found that emissions from supply chain activities far exceeded the operational (Scopes 1 and 2) emissions, with a carbon footprint ratio of approximately 5.8 when correcting for underreporting in the national GHG inventory.

Moreover, the operational phase of military activities includes mobile emissions from land, sea, air, and space vehicles. The life cycle impacts of these operations are highly dependent on factors such as fuel efficiency, vehicle age, and the intensity of use. For militaries with significant air and naval capabilities, such as the United States and the United Kingdom, these operational emissions are substantial and must be thoroughly evaluated using LCA.

Beyond the operational impacts, the end-of-life phase of military equipment also presents significant environmental challenges. The decommissioning of military assets, including the disposal of hazardous materials and the rehabilitation of contaminated land, can have long-lasting environmental consequences. LCA helps in identifying and mitigating these impacts by considering the environmental costs associated with each stage of the equipment’s life cycle.

In summary, LCA is a critical framework for assessing the environmental consequences of war. By providing a comprehensive view of the environmental impacts across the entire life cycle of military operations and equipment, LCA enables more informed decision-making and the development of strategies to mitigate these impacts. The use of LCA in this context highlights the need for a broad perspective when evaluating the environmental costs of conflict, extending beyond immediate destruction to include long-term and indirect consequences.

6.5 Environmental Consequences of the War: An LCA Perspective

The environmental consequences of the war in Ukraine are profound, as illustrated by the detailed Life Cycle Assessment (LCA) provided in the document. LCA is used to comprehensively assess the environmental impact across various stages of the war, from the immediate destruction of infrastructure to the ongoing military operations. This perspective is essential for understanding the war's long-term environmental costs, particularly in terms of greenhouse gas (GHG) emissions and broader ecological degradation.

Infrastructure and Industrial Destruction. The destruction of infrastructure, including residential, industrial, and public buildings, has led to significant releases of GHGs. The embedded carbon in these structures, which includes materials like cement, steel, and other construction elements, is released into the atmosphere upon destruction.

The reconstruction of these facilities, necessary for recovery, further exacerbates emissions due to the high carbon footprint of building materials and processes. The document estimates that the reconstruction could lead to GHG emissions of approximately 54.7 million tCO_2e, indicating the long-term environmental impact of rebuilding efforts.

Military Activities and Their Implications. Military activities have been a substantial source of GHG emissions, with the document estimating that these operations have resulted in 37 million tCO_2e of emissions. These emissions arise from the fuel consumption of military vehicles, the use of explosives, and the construction of defensive structures. The production and eventual destruction of military equipment also contribute significantly to the overall carbon footprint. The ongoing war not only adds to global GHG emissions but also complicates international efforts to combat climate change, underscoring the importance of considering the environmental impacts of warfare in global climate strategies.

The use of LCA in this context allows for a more comprehensive understanding of the war's environmental consequences, extending beyond immediate damage to include long-term and indirect effects. By analyzing the full life cycle of war-related activities—from the destruction of existing infrastructure to the future impacts of reconstruction and military operations—LCA provides critical insights that can inform strategies for minimizing environmental damage and addressing the climate impacts of wars.

6.6 The Impact of Infrastructure and Industrial Destruction on Greenhouse Gas Emissions

The war in Ukraine has led to massive destruction of infrastructure and industrial sites, resulting in significant greenhouse gas (GHG) emissions. These emissions arise from several key activities. Firstly, the destruction of buildings, factories, and other facilities releases large amounts of embedded carbon, particularly carbon dioxide (CO_2), that was previously stored in construction materials such as cement, steel, and insulation. The document estimates that the GHG emissions from the reconstruction phase, including the use of these materials, could reach approximately 54.7 million tons of CO2 equivalent (tCO2e). This substantial carbon footprint is driven by the energy-intensive processes required for producing construction materials, as well as the emissions associated with the demolition, removal, and replacement of destroyed infrastructure.

Furthermore, the destruction of industrial facilities often leads to uncontrolled chemical releases, which contribute to both immediate and long-term environmental degradation.

These chemical releases include volatile organic compounds (VOCs) and other hazardous substances that not only harm the local environment but also contribute to global GHG emissions. This underscores the significant role that infrastructure and industrial destruction play in exacerbating climate change.

6.7 Greenhouse Gas Emissions Resulting from Military Activities and their Implications for Climate Change

Military activities during the war have been a major source of GHG emissions (Figure 6.5), with profound implications for global climate change. The document highlights that emissions from these activities are substantial, totaling 37 million tCO2e. These emissions arise from multiple sources, including the consumption of large quantities of fossil fuels by military vehicles, the use of explosives, and the construction of military fortifications. The continuous operation of military machinery, the transportation of troops and supplies, and the maintenance of wartime infrastructure contribute heavily to the overall carbon footprint of the conflict.

Additionally, the production and destruction of military equipment generate significant emissions. The manufacturing of military hardware is an energy-intensive process, involving the extraction and processing of raw materials, which adds to the war's carbon footprint. The destruction of military assets, followed by the need for replacement, further compounds these emissions. The document notes that the ongoing warfare has disrupted global efforts to mitigate climate change, as the additional emissions from military activities and the destruction of infrastructure undermine progress towards international climate goals.

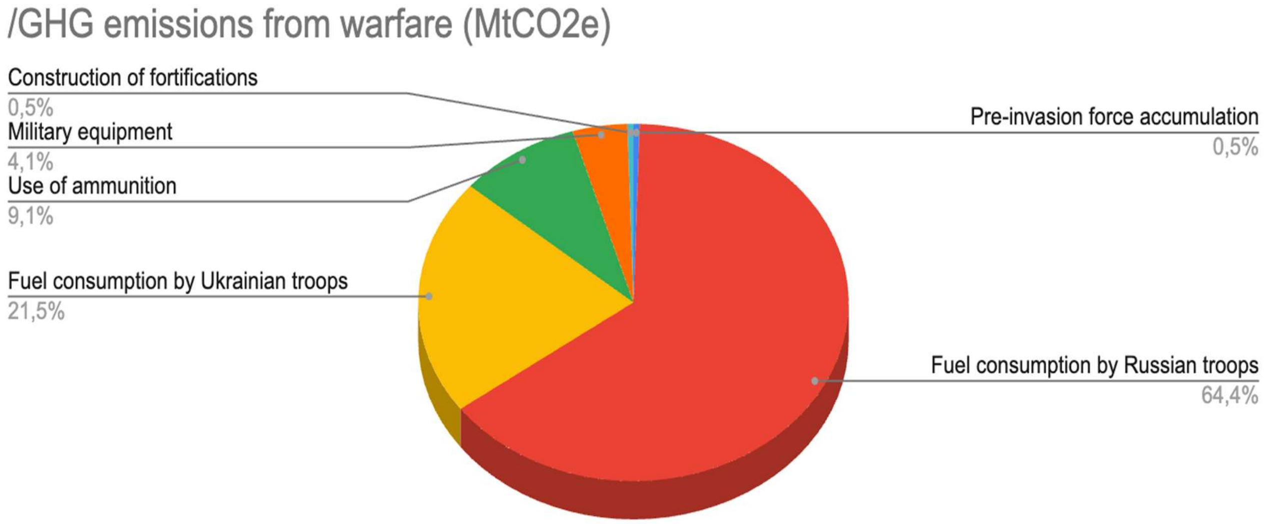

Figure 6.5. GHG emissions from warfare ($MtCO_{2e}$) in Ukraine

The implications of these emissions are far-reaching. Not only do they contribute directly to global warming, but they also have the potential to trigger a cascade of environmental impacts, including more extreme weather events and disruptions to ecosystems. The war in Ukraine thus represents a significant setback in the global fight against climate change, highlighting the urgent need for comprehensive strategies to mitigate the environmental impact of military wars.

These analyses demonstrate the critical importance of integrating LCA methodologies in assessing the environmental consequences of warfare, providing a more complete understanding of the long-term impacts on climate and environmental sustainability.

6.8 LCA as s Tool for Assessing Pollution and Climate Change Methodology of LCA in Evaluating the Environmental Impact of the War

Life Cycle Assessment (LCA) is a critical tool for evaluating the environmental impacts of products, processes, or activities across their entire life cycle. In the context of pollution and climate change, LCA provides a comprehensive approach to assess the cumulative effects of various stages, from raw material extraction to disposal, thus offering insights into how different factors contribute to environmental degradation and greenhouse gas (GHG) emissions.

The methodology of LCA in evaluating the environmental impact of war involves several essential steps, which include:

1. Goal and Scope Definition: The primary goal of applying LCA in the context of war is to assess the environmental impacts of military activities, infrastructure destruction, and subsequent reconstruction efforts. The scope of the analysis typically covers all life cycle stages, from the initial conflict, which causes direct damage, to the long-term environmental consequences of reconstruction.

2. Life Cycle Inventory (LCI): This step involves collecting detailed data on the inputs (e.g., energy, materials) and outputs (e.g., emissions, waste) associated with each phase of the war and its aftermath. The document suggests using tools like One Click LCA, which allows for automated data collection and analysis, ensuring a comprehensive LCI that covers all relevant environmental aspects.

3. Life Cycle Impact Assessment (LCIA): During this phase, the collected data is analyzed to evaluate the potential environmental impacts, such as global warming potential (GWP), acidification, and human toxicity.

The document highlights the use of standardized categories such as those outlined in EN 15804 and ISO 14040/44, which ensure that the impacts are assessed consistently and can be compared across different studies.

4. Interpretation and Improvement: The final phase involves interpreting the results to identify significant environmental impacts and opportunities for improvement. The LCA can reveal which stages of the war and reconstruction process contribute most to pollution and GHG emissions, allowing policymakers to target these areas for mitigation efforts. The document also emphasizes the importance of considering regional factors, as these can influence the environmental impact of specific activities.

6.9 Life Cycle Assessment of the Destroyed Construction Materials and their Environmental Impact

The destruction of construction materials during the war leads to significant environmental impacts, which can be thoroughly assessed using LCA. Here’s a breakdown of the key considerations:

1. Material Characterization: The LCA process begins by identifying the types of materials destroyed, such as concrete, steel, and glass [25]. Each material has its own life cycle profile, including its embodied energy and carbon, which are released into the environment upon destruction. The document suggests that the initial destruction phase releases a substantial amount of CO_2, contributing significantly to GHG emissions [26].

2. Impact of Destruction and Debris Management: The destruction of buildings and infrastructure results in large volumes of debris, which poses a disposal challenge. The document discusses the potential environmental impacts of improper debris management, such as increased emissions from transportation and the release of pollutants if materials are incinerated or improperly disposed of in landfills [27].

3. Reconstruction and Material Production: The need to rebuild destroyed structures further exacerbates environmental impacts. The production of new construction materials is energy-intensive and generates significant GHG emissions. The document outlines how using LCA can help in selecting more sustainable materials and construction methods that minimize environmental damage during the reconstruction phase [28].

4. Recycling Potential: One of the key strategies to mitigate the environmental impact of destroyed construction materials is recycling.

The document suggests that crushed concrete can be reused as aggregate in new construction, which not only reduces the demand for new materials but also lowers the overall carbon footprint of the rebuilding process. LCA helps in quantifying the benefits of recycling and supports decision-making in post-war reconstruction efforts [26].

LCA is an invaluable tool in assessing the environmental consequences of war, particularly in understanding the full scope of pollution and climate change impacts resulting from military activities and the destruction of infrastructure. By applying LCA, decision-makers can identify critical points in the life cycle where interventions can reduce environmental damage, support sustainable reconstruction, and contribute to global climate change mitigation efforts [25, 28, 29].

6.10 Transboundary Pollution Impact and Climate Change

Transboundary pollution refers to pollution that originates in one country but crosses borders and causes harm to the environment or health in another country. In the context of military activities and wars, transboundary pollution can have significant environmental impacts that exacerbate climate change. This pollution includes the release of greenhouse gases (GHGs), toxic chemicals, and particulate matter from military operations, as well as the destruction of industrial facilities and infrastructure during conflicts. These pollutants do not respect national borders and can contribute to global environmental degradation and climate change.

Military operations, particularly those involving large-scale warfare, are significant sources of transboundary pollution. The emissions from the use of military vehicles, aircraft, and naval vessels contribute to GHG emissions, which in turn affect global climate systems. According to the document, the global military carbon footprint is estimated to be around 2,750 MtCO2e, which accounts for approximately 5.5% of global GHG emissions. This figure is larger than the total carbon footprint of some major industrial nations, underscoring the scale of the impact [30].

In addition to GHGs, military activities release other pollutants, such as nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM), which can be transported across borders and contribute to air quality degradation in neighboring countries. These pollutants can lead to acid rain, which damages ecosystems, soils, and water bodies far from the original source of emissions.

The destruction of industrial sites and infrastructure during conflicts, as seen in the Ukraine war, can release vast amounts of pollutants into the environment. For example, the document reports that the Ukraine war resulted in significant emissions from the destruction of industrial facilities, which included 49 $MtCO_{2e}$ from military fuel use, fires, and gas pipeline leaks. These emissions not only contribute to local environmental degradation but also have far-reaching impacts on the global atmosphere [31].

Fires caused by the destruction of oil depots, chemical plants, and other industrial facilities release toxic substances, including volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs), which can travel long distances in the atmosphere. These pollutants contribute to smog formation and have serious health impacts, including respiratory problems and cancer, in regions far from the original site of the conflict.

The transboundary pollution resulting from military activities and infrastructure destruction contributes directly to climate change. The release of GHGs, particularly CO_2, methane (CH_4), and nitrous oxide (N_2O), from these activities increases the concentration of these gases in the atmosphere, enhancing the greenhouse effect and leading to global warming. The document highlights that military emissions including those from conflicts like the Ukraine war, play a significant role in exacerbating climate change by adding substantial amounts of GHGs to the global total [32].

Moreover, the environmental damage caused by transboundary pollution can lead to feedback loops that further accelerate climate change. For instance, the destruction of forests and other carbon sinks during military operations reduces the Earth's capacity to absorb CO_2, while the release of black carbon from fires can decrease the albedo (reflectivity) of snow and ice, leading to faster melting and additional warming.

Transboundary pollution from military activities and wars is a significant contributor to global environmental degradation and climate change. The release of GHGs, toxic chemicals, and particulate matter during conflicts has far-reaching impacts that extend beyond national borders, affecting air quality, ecosystems, and the global climate. Addressing the environmental impacts of military activities requires international cooperation and the integration of environmental considerations into military planning and conflict resolution strategies.

6.11 Assessment of the Spread of Pollutants from Ukraine to EU Countries

The ongoing conflict in Ukraine has resulted in substantial environmental impacts, particularly concerning the spread of pollutants across borders into neighboring EU countries.

This phenomenon is largely due to the release of greenhouse gases (GHGs), particulate matter, and various toxic chemicals as a direct consequence of military activities and the destruction of industrial infrastructure. As noted on page 8 of the document, the war in Ukraine has led to significant emissions, including 49 $MtCO_2e$ from warfighting activities, which encompasses military fuel use, fires, and gas pipeline leaks. These pollutants, once released into the atmosphere, are subject to atmospheric transport mechanisms that can carry them over long distances, crossing international borders into EU countries. The predominant winds in the region facilitate the movement of these airborne pollutants westward, potentially affecting air quality and public health in countries such as Poland, Hungary, Slovakia, and Romania.

The spread of pollutants from Ukraine to neighboring EU countries has raised concerns about the potential impacts on air quality. Increased levels of particulate matter (PM) and other pollutants have been recorded in border regions, particularly during periods of intense military activity or following the destruction of industrial sites. The health implications of this transboundary pollution are significant, as exposure to elevated levels of PM and toxic chemicals is linked to respiratory and cardiovascular diseases, as well as other adverse health outcomes.

In response to these concerns, environmental monitoring networks in EU countries have intensified their efforts to track the levels of pollutants originating from the conflict in Ukraine. Data collected from these monitoring stations are critical for assessing the extent of transboundary pollution and for informing mitigation strategies. The document highlights the need for enhanced international cooperation between Ukraine and EU member states to address the environmental challenges posed by the war, including the development of joint strategies to mitigate the impact of transboundary pollution [33, 34].

The spread of pollutants from Ukraine to EU countries is a significant environmental issue that underscores the broader impacts of military conflicts on regional air quality and public health. The transboundary nature of this pollution necessitates a coordinated response, including robust environmental monitoring and international cooperation, to mitigate its effects and protect the health and well-being of populations in affected regions [35].

6.12 The Role of International Cooperation in Managing Transboundary Pollution

One of the key roles of international cooperation in managing transboundary pollution is the establishment of coordinated monitoring networks. These networks are essential for tracking the movement and concentration of pollutants across borders.

The document highlights the importance of shared data between countries to accurately assess the extent of pollution and its impact on air quality, ecosystems, and human health. For instance, the integration of data from multiple sources, including satellite observations and ground-based sensors, can provide a comprehensive picture of pollution levels and help in predicting its spread.

Moreover, international agreements and frameworks, such as the United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (CLRTAP), play a critical role in facilitating data sharing and joint monitoring efforts. These agreements establish common standards for data collection and reporting, ensuring that all parties have access to reliable information needed to address transboundary pollution effectively.

International cooperation is also crucial for the development and implementation of policies aimed at reducing transboundary pollution. Collaborative policy-making allows countries to align their environmental regulations and standards, making it easier to manage pollution that crosses borders. The document points out that joint policy initiatives, such as emissions reduction targets and the adoption of best practices for pollution control, are more effective when implemented across multiple countries, as they create a level playing field and prevent pollution leakage (where pollution is simply shifted from one country to another).

In the context of military-related pollution, international agreements that regulate the environmental impact of military activities are particularly important. For example, the Geneva Conventions and their Additional Protocols include provisions that prohibit unnecessary environmental damage during armed conflicts. Strengthening these international legal frameworks and ensuring their enforcement can help reduce the environmental footprint of military operations and mitigate transboundary pollution.

Another important aspect of international cooperation is the promotion of technological innovation and capacity building. The document emphasizes the need for countries to work together in developing and deploying new technologies that can reduce pollution and mitigate its impacts. This includes advancements in monitoring technologies, pollution control equipment, and cleaner energy sources that can be used in military operations. Capacity building initiatives, such as training programs and technical assistance, are also vital in helping countries, particularly those with limited resources, to manage transboundary pollution more effectively. By sharing expertise and providing support, developed countries can assist their neighbors in implementing more effective pollution control measures and in building the necessary infrastructure for environmental protection.

International cooperation is indispensable in managing transboundary pollution, especially in the context of military activities and conflicts. Through coordinated monitoring, collaborative policy-making, and the promotion of technological innovation, countries can work together to mitigate the environmental impacts of pollution that crosses borders.

Strengthening international legal frameworks and ensuring that all nations have the capacity to manage pollution effectively are key to protecting both the environment and public health in an increasingly interconnected world [36].

6.13 Post-War Ecosystem Restoration: Assessing the War's Impact on Global Climate Processes

Investments needed for Ukraine's transition to a low-carbon economy, aligned with its Nationally Determined Contribution (NDC), are projected at approximately €102 billion by 2030. However, the direct infrastructure damage due to the ongoing war has already reached $63 billion by the end of March 2023. When considering the broader economic losses, which include a decline in GDP, halted investments, labor force displacement, and increased costs for defense and social support, Ukraine's total economic losses are estimated to be between $543 billion and $600 billion. These figures highlight the severe diversion of financial resources that could have otherwise been allocated towards reducing greenhouse gas (GHG) emissions by millions of tons of CO_2 equivalent (tCO_{2e}), which will now be required for post-war reconstruction to restore pre-war economic activity levels.

The Russian Federation's full-scale invasion of Ukraine, now well into its second year, has led to extensive damage or destruction of residential areas and industrial sectors. Russia's continuous targeting of civilian infrastructure, particularly energy and water facilities since October, was intended to make life untenable for Ukrainians during the winter – an effort that ultimately failed. The consequences of this conflict are most profound in Ukraine, but they also reverberate beyond its borders, from the millions of Ukrainian refugees in Europe to Russia's attempts to wield gas supplies as a geopolitical weapon. This energy crisis has exacerbated the existing cost-of-living crisis in Europe and has even led to power blackouts in some Asian nations.

The global economy, still largely dependent on fossil fuels, is highly susceptible to such disturbances, which have a direct impact on GHG emissions. Our initial assessment focused on the most immediate GHG emission impacts, including those from warfare, wildfires, refugee movements, and post-war reconstruction efforts.

Due to the harsh winter conditions (which reduced the occurrence of wildfires) and limited movement of the front line (resulting in lower rates of destruction), the rate of carbon emissions has been lower than during the early stages of the conflict. Despite some adjustments and corrections to the data, emissions from warfare have continued unabated.

In this subsequent assessment, we examined two additional impact sectors, neither of which are geographically located within Ukraine. We assessed the war's impact on the European energy sector, particularly gas and power, where it was found that some impacts led to increased emissions while others resulted in decreases, effectively canceling each other out (i.e., a negligible net impact on emissions). Additionally, the closure of Ukrainian and Russian airspace has resulted in longer flight routes between European and Asian cities, contributing to increased emissions.

The war's toll on Ukraine’s economy has been devastating, particularly in regions near the front lines. With 30% of the population displaced, a significant portion of the workforce engaged in military defense, and widespread power outages, the economy has been severely crippled, especially during the winter months. A shrinking economy typically results in reduced emissions; however, as argued in the relevant section, a substantial portion of these emissions has merely been transferred abroad. This occurs either directly through the relocation of Ukrainians, indirectly through the takeover of Ukraine's steel production by other countries, or through the increased import of goods such as humanitarian aid and food into Ukraine.

A comprehensive overview of GHG emissions across four updated sectors and two new sectors is provided in the table below. Similar to our initial report, we have included the one-time emissions resulting from the sabotage of the Nord Stream 1 & 2 pipelines. The reconstruction of civilian infrastructure accounts for the largest share of emissions, nearly half of the total. Warfare, along with fires in forests, agricultural lands, and urban areas, contributes nearly 20% and 15% of the total emissions, respectively. Notably, the leakage from the Nord Stream 1 & 2 pipelines released large quantities of methane – a potent GHG – resulting in emissions nearly equivalent to those caused by fires [34].

After twelve months of full-scale conflict, the total emissions from the war have already reached levels comparable to Belgium’s annual GHG emissions. The ongoing Russian invasion of Ukraine will have enduring effects on climate change and global GHG emissions. The conflict has accelerated Europe's transition to renewable energy and prompted a reevaluation of the role of natural gas as a transitional fuel. Consequently, the war in Ukraine is likely to lead to significant policy changes not only in Europe but globally.

Ukraine is eager to engage in the green transition during its post-war reconstruction. Such a transition is essential for Ukraine’s aspirations to join the European Union. Beyond environmental benefits, Ukrainians have recognized that a fossil-free energy system enhances national security—a powerful incentive for shaping future Ukrainian policies.

This transition, however, can only occur once Ukraine’s territorial integrity is restored and the country is securely integrated into the European security architecture. Long-term stability is a prerequisite for investing in a green transition. While a cessation of hostilities might temporarily reduce carbon emissions, prolonging the conflict or freezing it into a prolonged stalemate could ultimately harm the climate by forcing Ukraine to prioritize militarization over sustainable development [33].

6.14 Strategies for Rehabilitating polluted Areas Using LCA

The scope and comprehensiveness of the climate impact assessment have been expanded compared to the initial report. However, several sources of greenhouse gas (GHG) emissions resulting from Russia's war in Ukraine have yet to be fully accounted for. Some of these additional emission sources include:

1. Destruction of Carbon Reservoirs: Beyond the large fires, the unsustainable use and destruction of biomass resources, such as forests and shelterbelts, have contributed significantly to GHG emissions. These resources have been exploited for heating, construction of fortifications, and other needs. Additionally, explosions and other forms of environmental degradation have damaged trees and vegetation, which has facilitated the spread of pests and further compromised these carbon reservoirs.

2. Combustion of Industrial Goods: The shelling of industrial facilities and logistics centers has led to the combustion of a wide variety of goods, including food products, chemicals, and construction materials like fiberglass composites. The emissions resulting from attacks on agro-industrial facilities, including the destruction of nitrogen-based fertilizers, represent another significant source of GHG emissions.

3. Infrastructure-Related Emissions: The destruction of infrastructure has also led to the release of other GHGs, such as sulfur hexafluoride (SF_6) from damaged and destroyed electric transformers, and hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) from fire extinguishing systems.

4. Carbon Footprint of Humanitarian Operations: The operations related to the supply and distribution of humanitarian aid also contribute to the overall carbon footprint, which needs to be accounted for in the broader assessment of the war's environmental impact.

To date, the assessment of military emissions has concentrated on those directly associated with Russia's aggression and Ukraine's defensive actions. However, the impacts of GHG emissions extend beyond Ukraine's geographical borders.

For instance, the rerouting of civil aviation due to the conflict has increased emissions. Additionally, heightened military aviation activities have been observed outside of Ukraine, particularly with NATO increasing surveillance flights along its eastern borders. Furthermore, heavy military equipment transported to Ukraine from across the Atlantic has contributed to additional GHG emissions.

Russia's invasion has also triggered a rearmament process across Europe, underscoring that peace on the continent cannot be taken for granted. Even after the war ends, Europe is likely to face a deteriorated security environment, requiring sustained military preparedness. Increased military spending has already been documented, which will likely lead to higher fuel demand and increased GHG emissions due to the expanded number of military platforms and intensified training, exercising, and patrolling activities.

This assessment emphasizes the necessity of incorporating military emissions into international climate accounting frameworks. NATO's Climate Change & Security Impact Assessment underscores that climate change is already a "threat multiplier," exacerbating strategic competition and triggering new conflicts over resource access. While there is potential for improving energy efficiency and integrating renewable energy in military operations, the primary focus will remain on military effectiveness. Thus, tracking and managing GHG emissions from military activities is crucial for achieving climate goals, especially as Europe aims for a net-zero carbon world by 2050.

The assessment indicates that post-war reconstruction activities will generate substantial GHG emissions. However, this also presents an opportunity to minimize climate damage by applying sustainable and low-carbon technologies and materials in the reconstruction efforts.

1. Embodied Carbon: A significant source of emissions in the building sector is embodied carbon—GHG emissions released during the extraction, manufacturing, transportation, and

assembly of construction materials. These emissions occur at the time of construction or renovation and cannot be reduced afterward, emphasizing the importance of selecting low-carbon materials and technologies at the design stage.

Comparative data for apartment buildings constructed using typical practices in Central and Eastern Europe (emitting approximately 575 kg CO_2/m^2) with those built using modern technologies shows a significant potential for emission reductions. For example, France plans to reduce embodied carbon emissions in construction to 490 kg CO_{2eq}/m^2 by 2031. Given the scale of Ukraine's reconstruction, implementing low-carbon technologies could result in emission reductions measured in millions of tCO_{2e}.

2. Local Materials and Economic Recovery: The use of local materials and the development of local supply chains for construction materials not only reduce the carbon footprint but also contribute to economic recovery and job creation.

3. Climate Finance and Market Instruments: Market-based mechanisms, such as those outlined in Article 6 of the Paris Agreement, could channel additional international support for reconstruction through climate finance. Designing such programs would require stakeholder engagement, establishing appropriate monitoring, reporting, and verification (MRV) systems, and leveraging existing methodologies for carbon emission reductions in the building sector. City or regional-scale programs, developed in consultation with stakeholders, could also support the establishment of local supply chains, further reducing climate impact and promoting economic recovery.

Ukraine, with the support of its international partners, seeks to hold Russia accountable for its aggression, including the environmental damages caused. Historical precedents, such as the compensation paid by Iraq for environmental damage following its invasion of Kuwait, highlight the importance of thorough documentation and evidence collection. Litigation related to climate damage, especially from military conflicts, is a relatively new area, but there is an increasing body of international law addressing such issues. Future updates will explore mechanisms within peace treaties and the practice of the International Court of Justice, the UN Compensation Commission, and national jurisdictions to determine potential claims related to Russia's aggression and its global climate impact.

6.15 Ukraine's Involvement in International Climate Initiatives Post-War and Importance of Ukraine's Participation in Global Environmental Initiatives

A systematic plan for determining and assessing the extent of damage caused by military operations. Tasks include analyzing, classifying and documenting the damage caused, as well as identifying recovery and compensation strategies.

The plan envisages a phased implementation of measures, starting with a preliminary analysis and ending with the final determination of total losses. Only some of the strategic goals related to the post-war reconstruction of Ukraine were selected for presentation.

Strategic Objective 1

At the first stage of the implementation of the post-war recovery strategy, which lasted from June 2022 to the end of 2022, the main goal was to determine methodological approaches to recording and assessing the total amount of damage and losses caused by the war, as well as to determine the recovery needs. However, in order to achieve this goal, it was necessary to address some key issues, such as the inconsistency of policies of different bodies and incomplete information on damaged property and other objects due to the escalation of hostilities in certain areas. Qualitative indicators of achievement are following:

1. Unified approaches to the methodology for assessing and determining the total amount of damage to physical infrastructure caused by the armed aggression of the Russian Federation were defined.

2. The total amount of lost profits and environmental damage caused by the armed aggression was determined.

3. The overall need for the restoration of the country as a result of armed aggression is established.

4. The amount of damage was verified with international partners.

Tasks to achieve the objective are:

1. Analyze approaches and select the optimal methodology for determining the amount of damage and losses.

2. Regularly update and refine the analytical calculations to determine the amount of damage and losses.

3. Coordinate the amount of damage and recovery needs with international partners.

Strategic Objective 2

The second stage, which lasts from January 2023 to December 2025, aims to determine the total amount of damage and losses incurred as a result of the war, as well as the needs for reconstruction. At the same time, the damage and losses are being recorded on a site-by-site basis, and the corresponding assessment of losses is being carried out. These tasks are expected to be completed by the end of hostilities and de-occupation.

However, there are risks that may complicate the achievement of the goals, such as limited access to the areas where hostilities or temporary occupation are ongoing, insufficient human resources for prompt recording due to the large volume of damaged objects within individual cities and communities, and lack of funding for technical surveys and assessments.

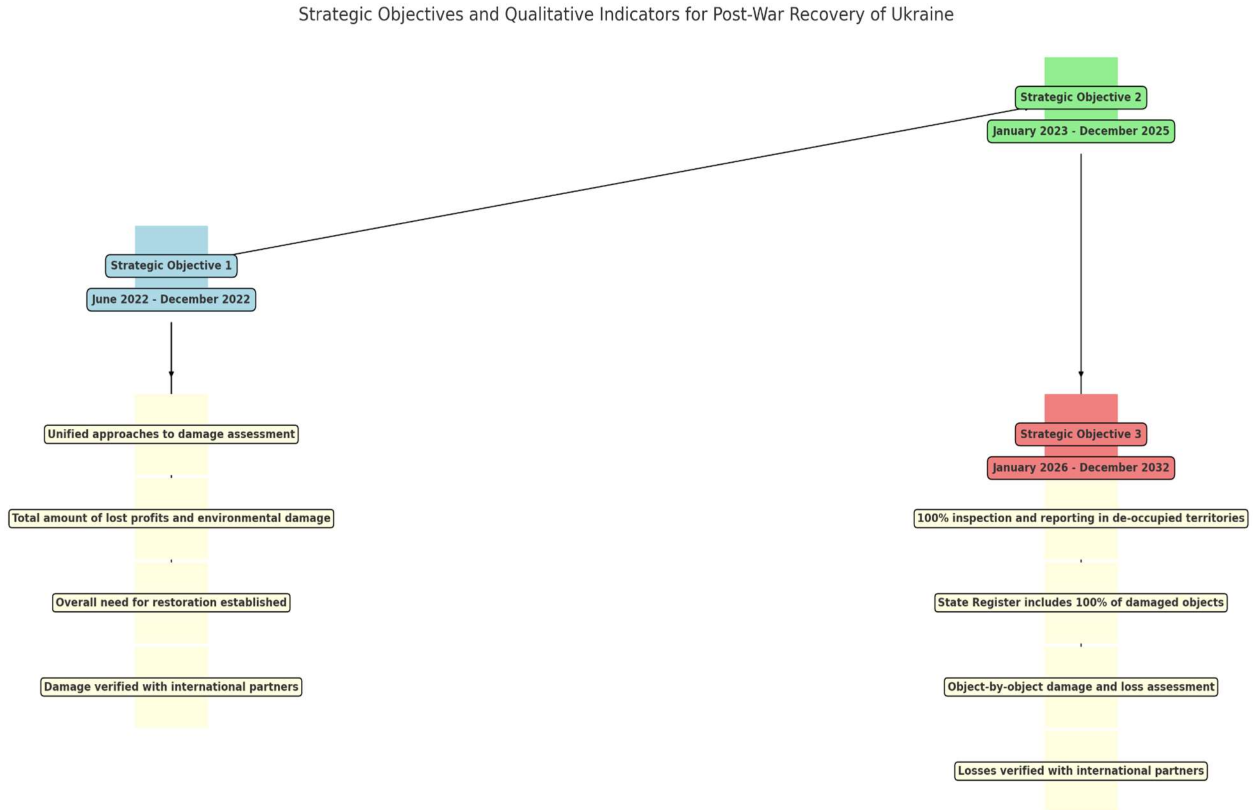

Figure 6.6. Strategic Objectives and Qualitative Indicators for Post-War Recovery of Ukraine

Qualitative Indicators of Achievement:

- 100% of the objects that were destroyed or damaged as a result of the armed aggression of the Russian Federation in the de-occupied territories were inspected and a corresponding report was drawn up;
- The State Register of Property Damaged and Destroyed as a Result of Hostilities, Terrorist Acts, Sabotage Caused by the Military Aggression of the Russian Federation includes 100% of the objects that were destroyed or damaged as a result of the armed aggression;
- An object-by-object assessment of damage and losses was made at 100% of the facilities that were destroyed or damaged, and the total amount of losses was determined;
- Verify the amount of losses with international partners.

These goals and objectives (Figure 6.6) are also directly related to various areas of recovery and development, including infrastructure restoration and development, economic development, energy security, construction and urban planning, digitalization, justice, environmental safety and social protection.

Strategic Objective 3

In the third stage, which will last from January 2026 to December 2032, the main goal will be to continue to record the damage and losses incurred as a result of the war, as well as to conduct an appropriate assessment of losses. These tasks are expected to be completed within five years after the full cessation of hostilities and de-occupation. However, there are risks, such as lack of access to a significant part of the territories where hostilities or temporary occupation continue, lack of human resources to conduct operational recording due to the large amount of destroyed and damaged facilities within one city or community, and lack of funding for technical surveys and independent assessment.

Qualitative indicators of achievement of the objective will be the same as in strategic objective 2. These goals and objectives are also directly related to various areas of recovery and development, including infrastructure restoration and development, economic development, energy security, construction and urban planning, digitalization, justice, environmental safety, and social protection.

Ukrainian legislation provides for the creation and operation of a unified register that will store complete information on damage caused by armed aggression. The regulatory framework in this regard includes the Procedure for Maintaining the State Register of Property Damaged and Destroyed as a Result of Hostilities, Terrorist Acts, and Sabotage, which was made possible by Resolution No. 380 of 26.03.2022.

The development and adoption of legislative acts, such as the Law of Ukraine on Amendments to the Laws of Ukraine "On Management of State Property Objects" and "On Local Self-Government", as well as amendments to the Code of Ukraine on Administrative Offenses and the Criminal Procedure Code of Ukraine, is aimed at improving the state policy of managing state and municipal property.

In addition, resolutions of the Cabinet of Ministers of Ukraine are being developed and adopted on the procedure for maintaining the Unified Register of State and Communal Property. This register is created to systematize information and provide access to it.

The Ministry of Infrastructure, the Ministry of Regional Development, the Ministry of Reintegration and Temporarily Occupied Territories, the Ministry of Digital Transformation, the Ministry of Justice, the Ministry of Culture, the State Property Fund, the Ministry of Internal Affairs, the State Emergency Service, as well as local governments, military administrations, and other agencies are responsible for conducting the inventory and maintaining the register.

The damage caused by Russia's armed aggression is a serious problem for Ukraine. Recording all these losses is critical to ensuring the realization of the right to compensation and reparations. The process of recording damages enables the Ukrainian government to collect objective data on the extent and scope of the damage caused, which is necessary for further negotiations with Russia on compensation. Russia should be held accountable for the damage caused, and this can be achieved through legal measures at the international level. For this purpose, it is necessary to have clear documentation of all losses and damages suffered by Ukraine as a result of the aggression. With reliable data and documents, Ukraine will have strong grounds to demand compensation from Russia for the damage caused. The position of the European Union (EU) on this issue is key to a successful resolution of the situation. The EU should show solidarity with Ukraine and support its efforts to demand compensation from Russia. This could include diplomatic pressure, economic sanctions, and other measures aimed at making Russia take responsibility for its actions. The Ukrainian government and EU countries should work together to address this issue by ensuring that all losses are recorded and by putting legal and political pressure on Russia to provide compensation for the damage caused. This is the only way to achieve justice and restore Ukraine's rights and interests.

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Chapter 07

Calculation Model for Building Energy Simulation

Martin Kováč[1], Veronika Merjavá[1]

[1] Faculty of Civil Engineering, Technical University of Košice, 042 00 Košice, Slovakia

martin.kovac@tuke.sk, veronika.merjava@tuke.sk

To assess the environmental impact from the operation of the proposed office building as accurately as possible we used the progressive approach to calculate the energy consumption of the building that uses algorithms for dynamic solution of heat flows in the building. To solve heat flows in the building we used the commercial simulation tool DesignBUILDER version 7, that uses worldwide known solver EnergyPlus version 9.4. In this simulation tool the whole calculation model of the proposed office building was created. In the phase of so-called pre-pre-processing the geometric model of the building was created with defining the location (Country: Slovak republic, City: Bratislava) and all climatic data (file in the format of IWEC – international weather for energy calculation).

The calculation model includes boundary conditions for all building elements (opaque and transparent), for all activities in the office building (occupancy, internal heat gains), for HVAC (heating, ventilation, and air conditioning) systems, for preparation of DHW (domestic hot water) and for the artificial lighting. The next phase so-called the processing we used the engine of EnergyPlus integrated in the simulation tool of DesignBUILDER where all equations for the transfer of heat and matter are solving. In the last step so-called post-processing we analysed the hourly and yearly data of the fuel consumption for heating, cooling, mechanical ventilation, domestic hot water preparation and for the artificial lighting in the office building.

7.1 Geometry

The geometry of the office building was directly created in the used simulation software DesignBUILDER on the base of the project of the architectural design of the building. The office building has two main parts. The one part is the Building A with 7 floors and the second part is the Building B with 4 floors. The proposed office building is situated in the specific location of Bratislava the capital city of the Slovak republic. The geometry model of the office building also includes surrounded buildings in order to simulate energy demands for heating, cooling and artificial lighting as accurately as possible.

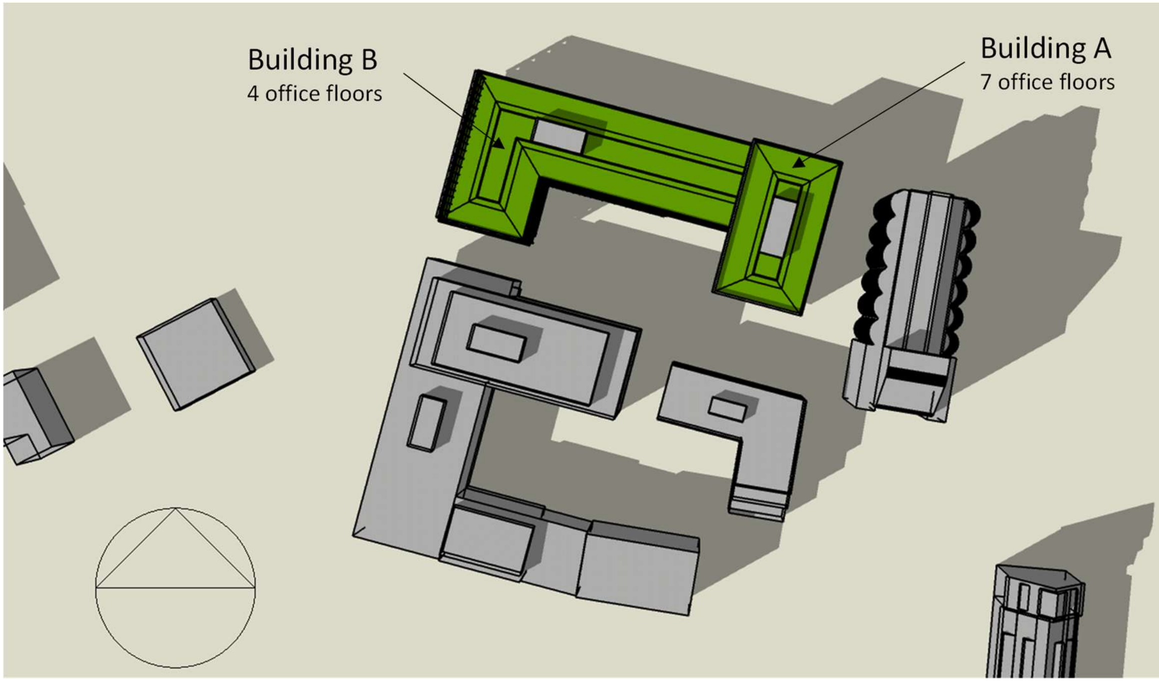


Figure 7.1 Building orientation towards North and surrounded buildings – geometry of the calculation model

Generally, we can create the geometry model of the building in the used simulation tool by three different approaches. The first approach works with the so-called paper model where all building elements have the zero thickness. The second one creates the geometry model of the building with the real thickness of all building elements. The third one is something like a hybrid approach. It is a combination of previous two where we can define building elements with zero and real thickness. Our calculation model uses the second approach to create geometry model of the building in order to simulate solar heat gains during winter and also solar heat loads during summer as accurately as possible. The thickness of building elements significantly influences the transfer of solar radiation into the indoor environment of the building in comparison to the so-called paper model (building elements with the zero thickness). Also, the advantage of this used approach is that we accurately can analyse the demand of using the artificial lighting on the base of level of daylighting in the interior of the building. All transparent building elements have their frames in the geometry model because we want to calculate the energy demand for the artificial lighting, solar heat gains during heating season and solar heat loads in summer as accurately as possible.

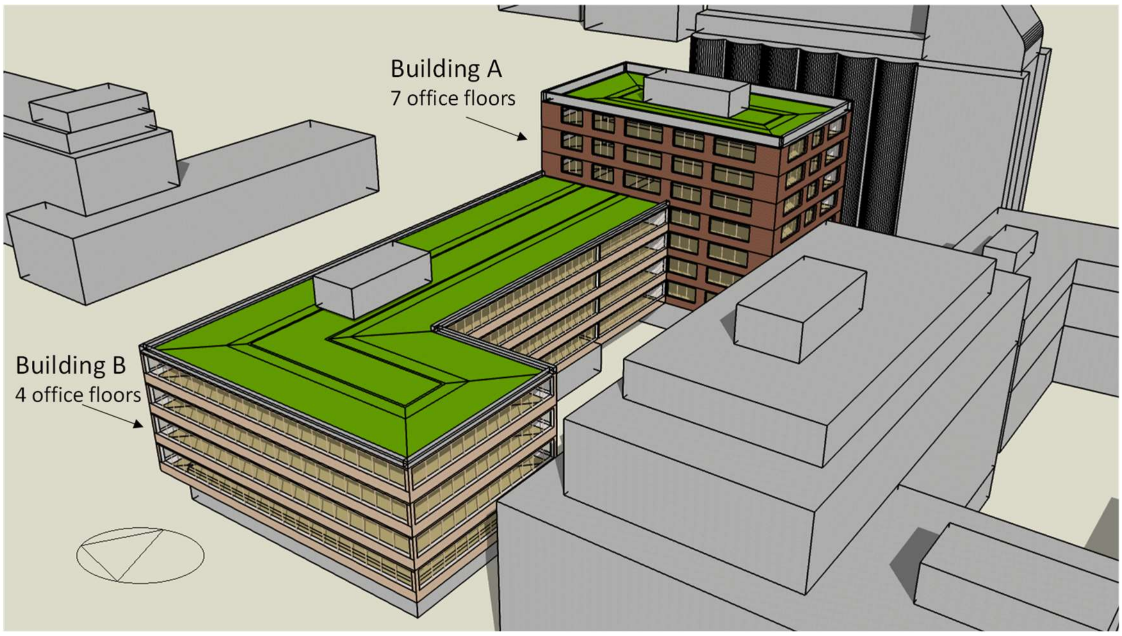


Figura 7.2 The view of the office building – geometry of the calculation model

In the interior of the Building A and Building B the office open spaces are in the perimeter of each floor. The employees have direct access to corridors, kitchens, meeting rooms, toilets, stairs, and lifts located in the centre part of the Building A and Building B. The proposed internal disposition of the floor is involved to the whole geometry model of the office building. All internal building elements that physically separate the rooms was created in the simulation tool like a standard internal partition with all thermal-technical properties. In the situation where the rooms have different number of employees or electric appliances or there is different request on the daylight, we used so-called virtual internal partition to separate these rooms. This approach created the detailed geometry model of the office building, that is very similar to the real building and operation inside the building as accurately as possible.

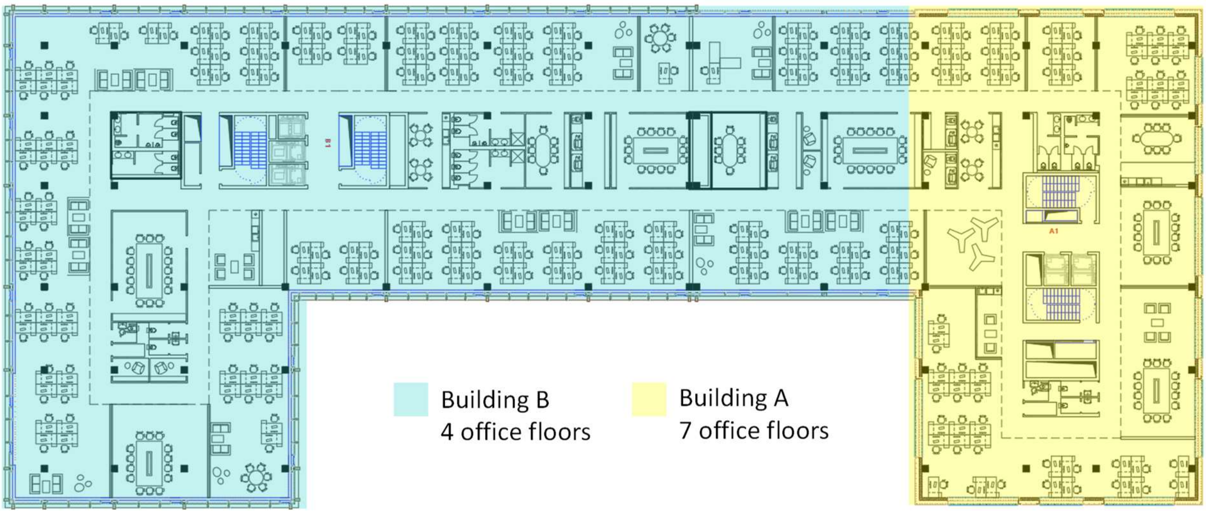


Figure 7.3 Typical floor of the office building

The next picture (Figure 5.4) X shows the geometry model of the interior of each floor for the Building A and Building B. The virtual internal partitions were used to separate the office open spaces from the corridors and all other internal walls are modelled like a standard internal partition. In the next step were added the boundary conditions for occupancy, electric appliances, artificial lighting, heating, cooling, mechanical ventilation, and domestic hot water preparation.

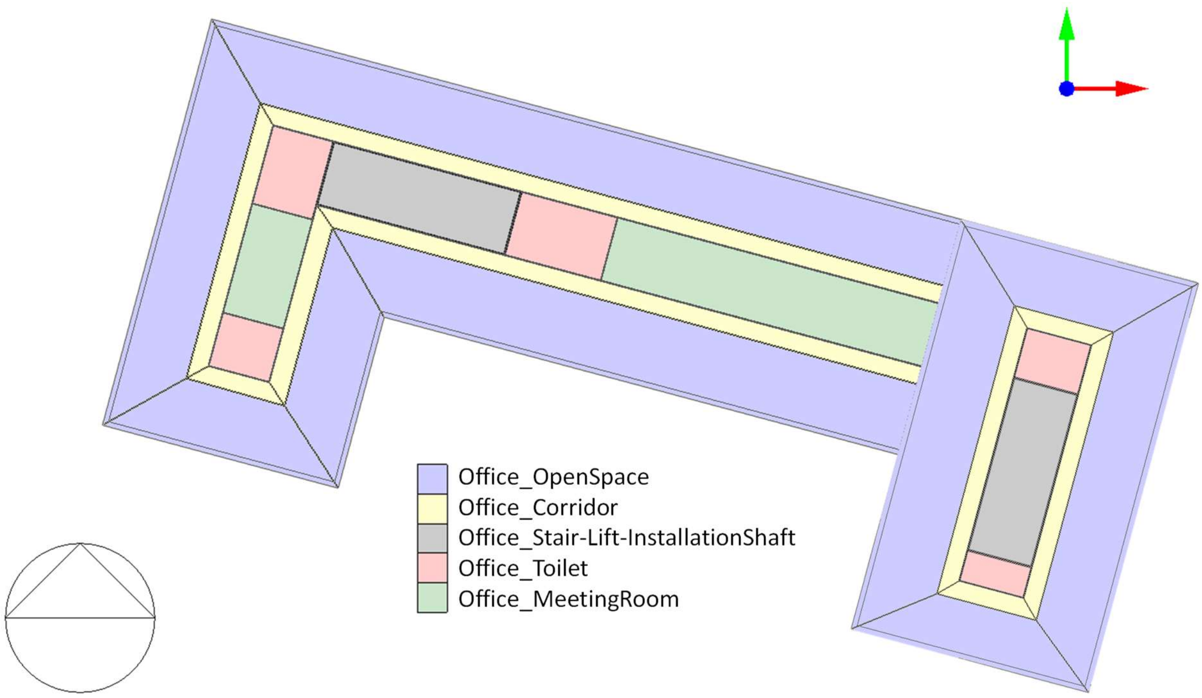


Figure 7.4 Internal zones – geometry of the calculation model

7.2 Opaque and Transparent Building Elements

After completing the whole geometry model of the office building, the thermal-technical parameters of opaque building elements and the thermal-optical properties of transparent building elements were defined. Each layer of the opaque building element has its value of thickness, thermal conductivity, specific heat, and density. All these parameters influence the heat flows in the building. The building structure of the office building is assessed like a heavyweight because there are the reinforced concrete ceilings, columns and external walls used. This kind of building structure mitigates the amplitude of the internal air temperature in the building during hot summer days. External constructions like a flat roof or wall contains the layer of the thermal insulation to achieve the required U-value. From the point of view the heat accumulation all internal walls are poor because they are made of aluminium frames with gypsum plasterboards and closed air gap between them. The internal floors contain the air layer with the thickness of 110 mm to put the electric infrastructure there.

The next Table 7.1 describes thermal-technical parameters of each layer for all building opaque elements used in the calculation model.

Table 7.1. The properties of opaque building elements – calculation model

External wall

Layer	Thickness (mm)	Thermal conductivity (W/(m.K))	Specific heat (J/(kg.K))	Density (kg/m^3)
Gypsum plasterboard	12.5	0.150	1060	750
Reinforced concrete	200.0	1.500	1000	2400
Thermal insulation	240.0	0.040	840	30
U value (W/(m^2.K))	0.157			
Flat roof				
Layer	Thickness (mm)	Thermal conductivity (W/(m.K))	Specific heat (J/(kg.K))	Density (kg/m^3)
Gypsum plasterboard	12.5	0.250	1000	900
Reinforced concrete	250.0	1.500	1000	2400
Thermal insulation	250.0	0.034	1400	35
U value (W/(m2.K))	0.130			

Floor above the exterior				
Layer	Thickness (mm)	Thermal conductivity (W/(m.K))	Specific heat (J/(kg.K))	Density (kg/m³)
Carpet	6.0	0.060	1300	200
Wood board	38.0	0.120	1340	880
Closed air gap	110.0	0.733	1010	1.188
Reinforced concrete	250.0	1.500	1000	2400
Thermal insulation	240.0	0.036	840	20
U value (W/(m2.K))	0.130			
Internal floor				
Layer	Thickness (mm)	Thermal conductivity (W/(m.K))	Specific heat (J/(kg.K))	Density (kg/m³)
Carpet	6.0	0.060	1300	200
Wood board	38.0	0.120	1340	880
Closed air gap	110.0	0.733	1010	1.188
Reinforced concrete	250.0	1.500	1000	2400
U value (W/(m2.K))	0.997			
Internal wall between office rooms				
Layer	Thickness (mm)	Thermal conductivity (W/(m.K))	Specific heat (J/(kg.K))	Density (kg/m3)
Gypsum plasterboard	25.0	0.150	1060	750
Closed air gap	50.0	0.208	1010	1.188
Gypsum plasterboard	25.0	0.150	1060	750
U value (W/(m2.K))	1.200			
Internal wall around the concrete building core				
Layer	Thickness (mm)	Thermal conductivity (W/(m.K))	Specific heat (J/(kg.K))	Density (kg/m3)
Reinforced concrete	200.0	1.500	1000	2400
U value (W/(m2.K))	2.542			

The thermal-technical parameters of the opaque building elements and the thermal-optical parameters of the transparent building elements influence the amount of solar heat gains during winter season and solar heat loads during summer days. In other words, they influence the energy demand for heating and cooling. The amount of heat gain or heat load from the sun radiation for the building depends on the size of transparent surfaces and their thermal-optical parameter SHGC (solar heat gain coefficient). This calculation model for the office building considers with the value of 0.35 for SHGC and with the value of 0.624 for light transmission (LT).

The transmission of daylight through the window glazing influences the energy demand for the artificial lighting, that is also assessed in this energy analysis. Windows with triple glazing are used on the building façade.

Table 7.2. The properties of transparent building elements – calculation model.

Window	
Glazing	Triple
Solar heat gain coefficient (SHGC)	0.350
Light transmission (LT)	0.624
U value (W/(m2.K))	0.600
Frame	Wood
Frame width	150 mm
U value (W/(m2.K))	1.100

7.3 Internal Heat Gain During Winter and Heat Load During Summer

The heat gain/load from the sun for the internal space of the building is so-called external heat gain or load. But there is also so-called internal heat gain (in winter) or heat load (in summer) from the people, electric appliances, and artificial lighting. The calculation model considers with the office work (sitting, writing, partly standing and walking), where the reference value of the metabolic rate is at the value of 120 Watts per one person. This value includes both sensible and latent part. The conditions of surrounded environment (air temperature, relative humidity of air, radiant temperature of internal surfaces, air velocity), the type of activity of people they are doing, and the clothing (thermal resistance of winter and summer clothes) influence the ratio between the sensible and latent part. The used calculation model does not consider with the fix ratio between these two parts, but there the dynamic algorithm is used. The employees are at the work only during workdays in time from 7.00 AM to 6.00 PM and the occupancy density in the building A is at the value of 0.1063 People/m^2 (9.4 m2/people) and 0.1616 People/m^2 (6.2 m^2/people) in the building B.

Table 7.3. The overview of internal heat gain (load) from occupancy – calculation model.

Internal heat gain (winter) / load (summer)	
Occupancy	
Number of people for open space Building A	57 people/floor Occupancy density: 0.1063 People/m2 Occupancy density: 9.4 m2/people
Number of people for open space and meeting rooms Building B	172 people/floor Occupancy density: 0.1616 People/m2 Occupancy density: 6.2 m2/people
Operation time	7.00 AM – 6.00 PM (workdays)
Metabolic rate (sensible + latent heat)	120 W/person (light office work)
Clothing	Winter clothing: 1.0 Summer clothing: 0.5

The electric appliances such as computers, monitors, copiers, and other produce heat during their operation time. This energy makes heat gain for the internal space of the building during winter season and so decreases the energy demand for heating. Vice versa this thermal energy causes the heat load in the interior of the building during summer days and so increases the energy demand for cooling. Our calculation model considers with the number of electric appliances (desktop computers) equal to the number of employees. The reference power density of electric appliances is from 11 to 16 Watts per square meter of floor area. The operation time is the same as the work time of employees, so from 7.00 AM to 6.00 PM only during workdays. The heat that the electric appliances generate during their operation time is transferred into surrounded environment by convection. This transfer of energy influences directly the internal air temperature in the building.

Table 7.4. The overview of internal heat gain (load) from electric appliances – calculation model

Internal heat gain (winter) / load (summer)	
Electric appliances	
Number - Building A	57 appliances/floor Power density: 11 W/m^2
Number - Building B	172 appliances/floor Power density: 16 W/m2
Operation time	7.00 AM – 6.00 PM (workdays)
Radiant fraction (heat to the space)	0.000
Convective fraction (heat to the space)	1.000

The LED luminaires are used in the calculation model due to their low electric power and their high illuminance 1.5 – 2.0 W/(m^2.100lx). The significant part of their electric power is transferred into the light (visible fraction 0.8) and the rest is the heat transferring into surrounded space by convection (convection fraction 0.1) and radiation (radiation fraction 0.1). This heat energy from the artificial lighting causes the heat gain for the interior of the building during heating season (lower energy demand for heating) on the one hand side. On the other hand, this same heat energy causes the heat load for the interior of the building during summer months. This increases the require on the cooling power of the used cooling system. The convective part of heat from the artificial lighting influences the surrounded air temperature and the radiant part influences the internal surface temperature of the room. The level of illumination for the office room is 500 lx and it is measured in the plane that is 0.80 m above the floor. It is so-called the working plane height and this value is for the corridor 0.0 m. The target illumination in corridors is only 100 lx. In our calculation model the artificial lighting is in operation only during workdays in time from 7.00 AM to 6.00 PM. It uses the simple lighting control where if the target illuminance in the space is achieved by the daylighting the artificial lighting switches off.

Table 7.5. The overview of internal heat gain (load) from artificial lighting – calculation model

Internal heat gain (winter) / load (summer)	
Artificial lighting	
Type	LED luminaire
Target illuminance – open space, meeting rooms Target illuminance – corridors	500 lx 100 lx
Working plane height – open space, meeting rooms Working plane height – corridors	0.80 m 0.00 m
Lighting control	Simple 1 stepped control strategy (If the target illuminance is achieved the lighting is switched off)
Power density	1.5 – 2.0 W/(m2.100lx)
Visible fraction	0.800
Radiant fraction (heat to the space)	0.100
Convective fraction (heat to the space)	0.100
Operation time	7.00 AM – 6.00 PM (workdays)

7.4 Heating, Ventilating and Air Conditioning

When employees are in the office building the operative temperature in winter is set up on 20 °C. In other time (workday: 6.00 PM – 7.00 AM, weekend: 24 hours) the heating system uses heating set back when the operative temperature is only 17 °C. The operative temperature includes the air temperature and the mean radiant temperature of the space. The cooling system covers the heat load of the internal spaces from the external and internal heat sources. The cooling system is provided only during the working time, so only in workdays from 7.00 AM to 6.00 PM, when the operative temperature is set up on 26 °C. In other time during summer months the cooling system is completely deactivated.

Table 7.6. The overview of the base information about heating and cooling – calculation model.

HVAC	
Heating	
Operation time – heating	7.00 AM – 6.00 PM (workdays)
Operation time – heating set back	6.00 PM – 7.00 AM (workdays) 0.00 AM – 12.00 PM (weekend)
Setpoint temperature – heating	20 °C
Setpoint temperature – heating set back	17 °C
Cooling	
Operation time – cooling	7.00 AM – 6.00 PM (workdays)
Operation time – cooling set back	N/A
Setpoint temperature – cooling	26 °C
Setpoint temperature – cooling set back	N/A

The indoor air quality is provided by the system of mechanical ventilation with heat recovery from the extract air. The air handling units are located on the flat roof of the office building, and they are in operation only in workdays from 7.00 AM to 6.00 PM. This time is the same as the working time of employees. In other time the mechanical ventilation is switched off. Only infiltration of air through the air tightness of the building facade provides the air change in the building. The air tightness of the façade is very low, so the air change in the building when the air handling units do not work is very low (0.05 1/h).

The volume flow of fresh air through the air handling units was calculated on the base of technical standard STN EN 16798-1. The calculation model conders with the second category of indoor environmental quality (IEQ) where the required flow of fresh air is 7.0 l/(s.person) and 0.7 l/(s.m2) of the floor area. So, the final volume flow of fresh air includes both these values. Each air handling unit uses the crossflow heat exchanger with the efficiency of heat recovery at the value of 60 %.

Table 7.7. The overview of the base information about the mechanical ventilaton – calculation model.

HVAC	
Ventilation	
Ventilation strategy	Mechanical ventilation with heat recovery
Type of heat exchanger	Crossflow heat exchanger
Category of indoor environmental quality	II. category (STN EN 16798-1)
Airflow per person	7.0 l/(s.person)
Airflow per square meter of low polluting building	0.7 l/(s.m^2)
Calculated total airflow	Airflow per person + airflow per square meter
Efficiency of heat recovery	60 %
Operation time of mechanical ventilation	7.00 AM – 6.00 PM (workdays)
Infiltration	0.05 (1/h)
Operation time of infiltration	24/7

The next figure shows that the operation time of mechanical ventilation in the building is the same as the working time of employees. The air change covers the infiltration of air through the building façade and calculated volume flow of fresh air according to STN EN 16798-1. In other time we can only see the air change due to infiltration of air.

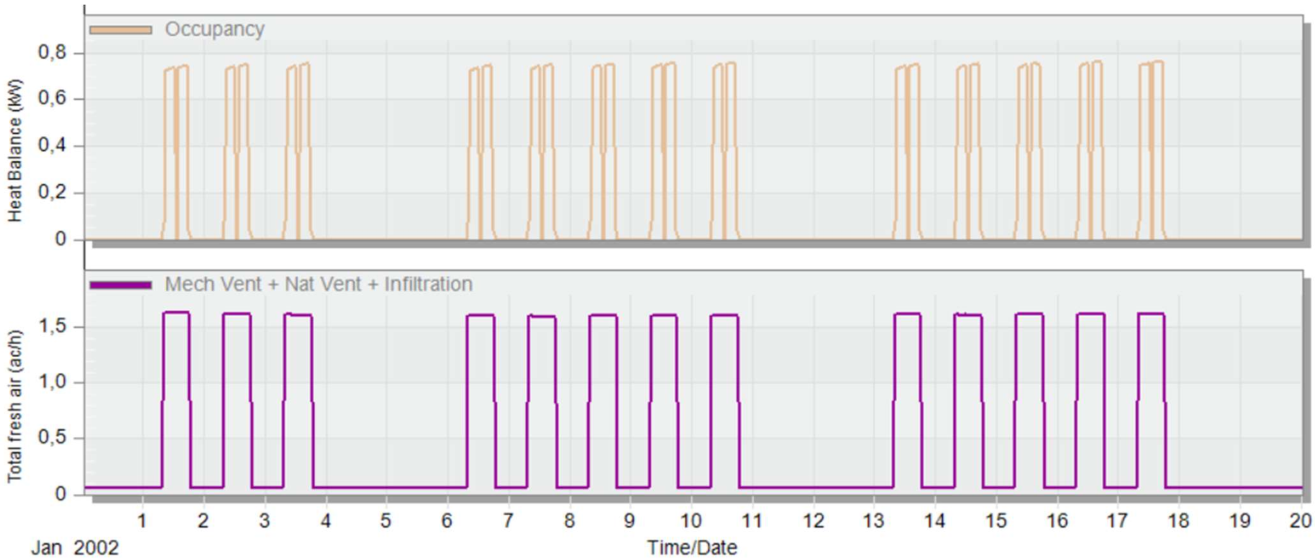


Figure 7.5 Trend of total fresh air – calculation model

7.5 Dew Hot Water Preparation

In the part of domestic hot water preparation, the calculation model is simple because we only need to calculate the energy demand. This only depends on the hot water consumption and its temperature. The cold water with 10 °C is heated to 40 °C and the daily specific hot water consumption is 5 litres per person. For the number of employees in the building A the daily hot water consumption is at the value of 1995 litres and for building B is the daily hot water consumption 3440 litres.

Table 7.8. The overview of daily hot water consumption – calculation model

Domestic hot water (DHW)	
Daily specific hot water consumption per person	5 l/(person. day)
Daily hot water consumption Building A Building B	 1995 l/day 3440 l/day
Cold water temperature	10 °C
Hot water temperature	40 °C

7.6 Baseline and Alternative Solution of HVAC and DHW System

Baseline solution of HVAC with DHW preparation uses natural gas and electricity like a fuel for the system of heating, cooling, mechanical ventilation, and domestic hot water preparation. The heat source for the heating system are natural gas condensing boilers with efficiency of 95 % in combination with panel radiators. To achieve the highest efficiency from the operation of condensing boilers the design water temperature of heating system is only 55 °C in combination with equithermal regulation of water temperature on the base of outdoor air temperature. During hot summer days the electric heat pump (air/air) in combination with ceiling cassette units provide the operative temperature of 26 °C in the interior of the office building in time when employees are in the office. The average value of energy efficiency ratio (EER) for the cooling system achieves the value of 4.0 during the cooling season. The system of mechanical ventilation provides the supply of fresh air in the office building. There are used two air handling units (AHUs) at the roof of the building A and the same number of AHUs is also used for the building B. Supply air inlets of mechanical ventilation are situated in the perimeter of the external wall under the ceiling. Then the air from the office space is extract through the extract inlets of mechanical ventilation localized in corridors in the core of the office building.

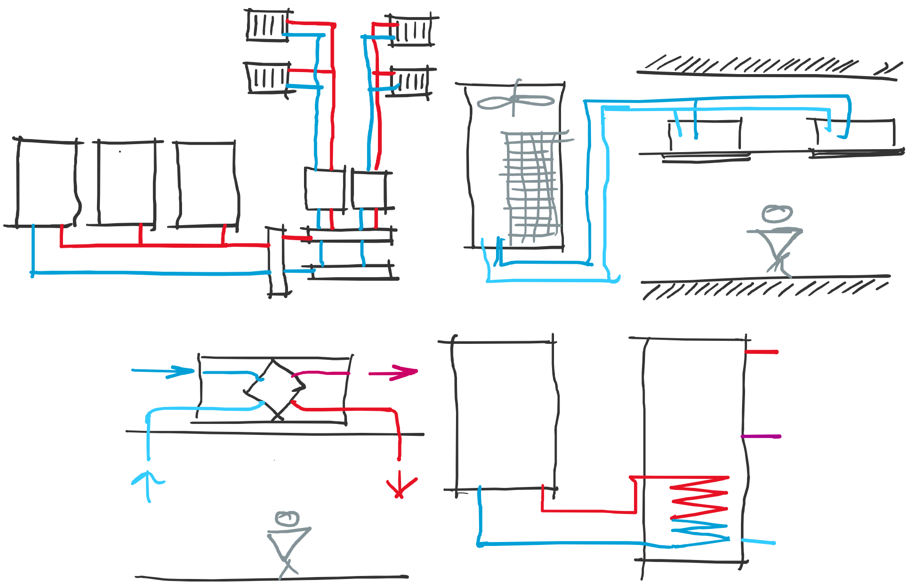


Figure 7.6 Scheme of HVAC with DHW preparation – baseline solution

This kind of air distribution scheme we can call as a cross-displacement ventilation. So, there are not used any swirling air inlets (intensive mixing of indoor air) to decrease the spread diseases. The air handling units use crossflow heat recovery with the efficiency of 60 %. The domestic hot water preparation is central with DHW vessels localized in the boiler room.

The heat source to prepare the hot water is the same as the heat source for the heating system. There are used natural gas condensing boilers.

Table 7.9 Properties for the baseline solution – calculation model

Baseline solution	
Heating	
Type of heat source	Natural gas condensing boilers
Efficiency of heat source	95 %
Type of emitters	Water panel radiators
Design temperature of water system	55 °C
Cooling	
Type of cool source	Electric heat pumps (VRV system)
Energy efficiency ratio (EER)	4.0
Type of emitters	Cassette indoor units
Ventilation	
Type of air handling unit (AHU)	Rooftop AHUs
Ventilation strategy	Mechanical ventilation with heat recovery
Efficiency of heat recovery	60 %
Specific fan power (SFP)	< 0.449 Wh/m3
Calculated total airflow	Airflow per person + airflow per square meter
Domestic hot water	
Type of heat source	Natural gas condensing boilers
Efficiency of heat source	95 %
Domestic hot water preparing	Central water tank with hot potable water
Hot water temperature	40 – 50 °C

Alternative solution of HVAC with DHW preparation only uses electricity like a fuel for the system of heating, cooling, mechanical ventilation, and domestic hot water preparation. This solution only uses heat and cool sources based on the using of renewable energy sources.

There is very important to use the proper emission subsystem for heating and cooling to achieve the highest energy efficiency of heat and cool source. The heating system uses electric heat pumps (air/water) in combination with low temperature of hydro boxes. The ceiling radiant heating system (gypsum plasterboard with integrated pipes under the ceiling) is used in the building. There is used the water system with design water temperature only 35 °C in combination with equithermal regulation of water temperature on the base of outdoor air temperature. The low water temperature in heating system and using of heat pump is the best combination because the heat pump can achieve the highest value of COP (coefficient of performance).

This calculation model considers with COP of 3.0. The advantage of ceiling radiant heating system is the improvement of thermal comfort of people in the office spaces because this system increases the internal surface temperature of surrounded surfaces in the room (external and internal walls, floor, windows). So, the temperature difference between the surface temperature of person and surrounded internal surfaces is diminishing and so the heat loss from the person body decreases. During the summer months these electric heat pumps (air/water) work in the reverse regime and provide cool for the cooling system. Cooling system use the same low temperature hydro boxes that were used during winter for the heating of the building. When the employees are in the building the operative temperature is set on 26 °C. The cooling of the office rooms is provided by the ceiling radiant cooling system (gypsum plasterboard with integrated pipes under the ceiling). It is a water system with design water temperature of 19 °C when the electric heat pumps can work with higher efficiency. The reference value for so-called energy efficiency ratio of heat pumps (EER) is 5.0. The advantage of ceiling radiant cooling system is the improvement of thermal comfort of people in the office spaces because this system decreases the internal surface temperature of surrounded surfaces in the room (external and internal walls, floor, windows). This state we could compare with the visit of old castle. The using of radiant cooling eliminates the noise in the office room in comparison with using of ceiling cassette cooling units (integrated fans). The ventilation system in the office building is completely the same as the ventilation system in so-called baseline solution of HVAC with DHW preparation. The domestic hot water preparation remains central with DHW vessels localized in the technical room. In this case the heat source to prepare the hot water are electric heat pumps (air/water) in combination with high temperature hydro boxes that can heat the potable water at 40 – 50 °C. In this regime the electric heat pumps work with COP of 2.9.

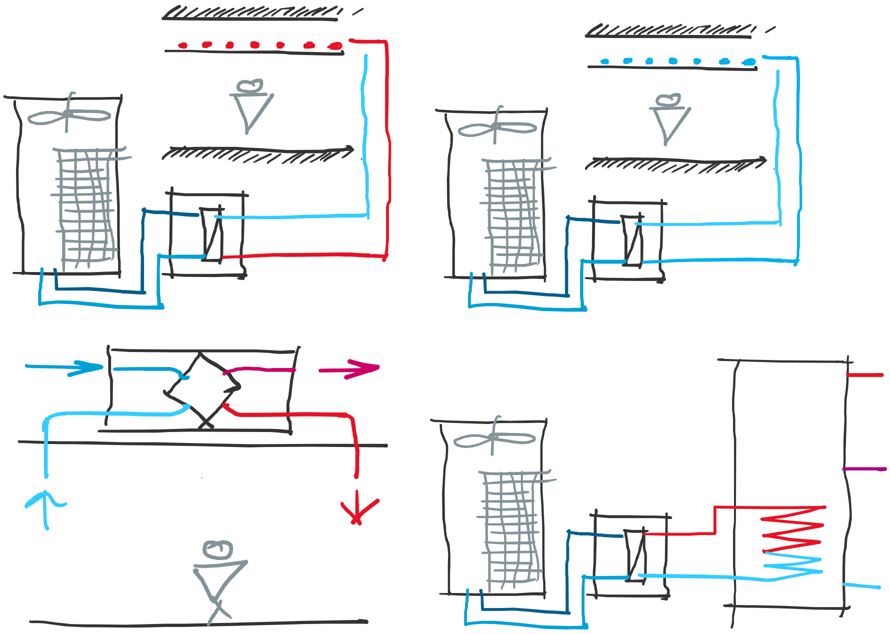


Figure 7.7 Scheme of HVAC with DHW preparation – alternative solution

Table 7.10 Properties for the alternative solution – calculation model

Alternative solution	
Heating	
Type of heat source	Electric heat pumps (VRV) with low temperature hydro boxes
Coefficient of performance (COP)	3.0
Type of emitters	Ceiling gypsum plasterboard with integrated pipes
Design temperature of water system	35 °C
Cooling	
Type of cool source	Electric heat pumps (VRV) with low temperature hydro boxes
Energy efficiency ratio (EER)	5.0

Type of emitters	Ceiling gypsum plasterboard with integrated pipes
Design temperature of water system	19 °C
Ventilation	
Type of air handling unit (AHU)	Rooftop AHUs
Ventilation strategy	Mechanical ventilation with heat recovery
Efficiency of heat recovery	60 %
Specific fan power (SFP)	< 0.449 Wh/m3
Calculated total airflow	Airflow per person + airflow per square meter
Domestic hot water	
Type of heat source	Electric heat pumps (VRV) with high temperature hydro boxes
Coefficient of performance (COP)	2.9
Domestic hot water preparing	Central water tank with hot potable water
Hot water temperature	40 – 50 °C

7.7 Results from Building Energy Simulation

The primary goal of the building energy simulation (BES) is to compare the energy performance of proposed office building between the baseline and alternative solution of HVAC with DHW preparation.

The alternative solution of HVAC with DHW preparation significantly uses renewable energy sources (electric heat pump air/water) and radiant subsystem for emission of heat or cool into the surrounded space. By improving the energy performance of building (lower consumption of fuels) we decrease the amount of so-called operation carbon that is assessed in the process of WBLCA (whole building life cycle assessment). Five partial cases C1 – C5 were simulated for both baseline and alternative solution of HVAC with DHW preparation to decrease the fuel consumption of the office building.

Table 7.11 Changes in cases C2 - C5 from the default case C1 for the building A and building B

Case (C1)
Reinforced concrete building construction - ceilings and columns
Double floor
Without passive shading elements / active shading devices
Without night pre-cooling (night ventilation) during summer period
Artificial lighting with simple control strategy (ON/OFF) (if the target illuminance of the space is achieved by the daylight the lighting is switched off)
Case (C2)
With passive shading elements (vertical and horizontal overhangs) – only for building B
Case (C3)
With passive shading elements (vertical and horizontal overhangs) – only for building B
With night pre-cooling (night ventilation 1:00 AM - 4:00 AM) from May to August
Case (C4)
With passive shading elements (vertical and horizontal overhangs) – only for building B
With night pre-cooling (night ventilation 1:00 AM - 4:00 AM) from May to August
Reinforced concrete building construction - ceilings and columns (with suspended plasterboard ceiling)
Case (C5)
With passive shading elements (vertical and horizontal overhangs) – only for building B
With night pre-cooling (night ventilation 1:00 AM - 4:00 AM) from May to August
Reinforced concrete building construction - ceilings and columns (with suspended plasterboard ceiling)
Artificial lighting with advanced control strategy (linear regulation of power density) (with the change of space illuminance by the daylight the power density of LED luminaires is linearly regulated)

The case C1 is the default state and the case C2 is different from C1 in the using of passive shading elements on the façade of the building B. This building has large transparent surfaces on the façade. There is used the horizontal and vertical overhangs decreasing the energy demand for cooling in summer (shading of windows) and improving the architecture of the building façade. These passive shading elements are not use on the façade of the building A because there are not so large windows.

In the case C3 the passive shading elements on the façade of the building B were used again and the night mechanical ventilation for both buildings (A, B) was added. This ventilation is in operation in time from 1.00 AM to 4.00 AM during May and August. By using of the night ventilation, we can pre-cool the building construction by cooler outdoor air in the nighttime. In the next hot sunny day, the building construction can absorb more heat from the heat load of the space in the building and so decreases the energy demand for cooling.

The case C4 is the same as the case C3, but there are added the gypsum plasterboards to improve interior acoustic in the office rooms. These building elements could be used for ceiling radiant heating and cooling.

The last case C5 is the combination of case C4 and using of advanced control strategy for artificial lighting. The electric power for LED luminaires is linearly regulated on the base of daylighting level in the interior of the building. If the target illuminance by the daylight in the space is reached the artificial lighting is completely deactivated.

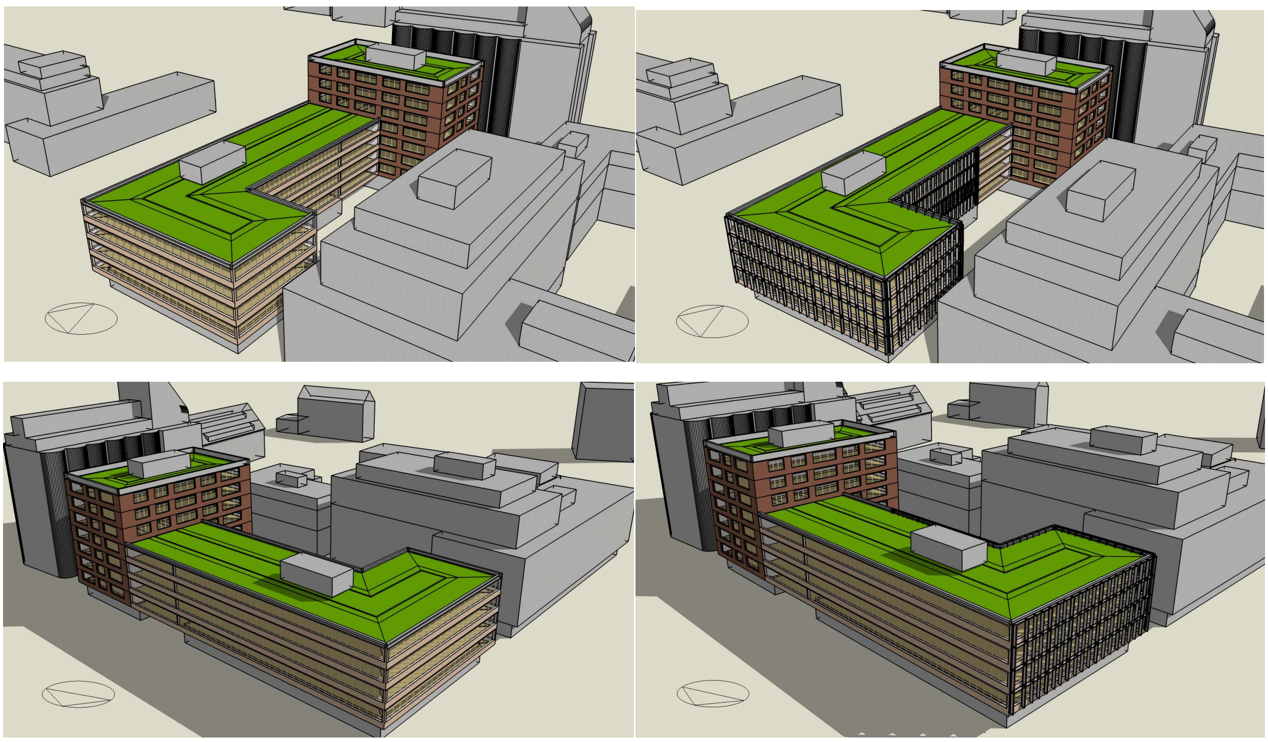


Figure 7.8 View of the building B without passive shading elements (left) and with passive shading elements (right) – geometry of the calculation model.

The figure 7.8 left shows the building B without passive shading elements on the façade. This situation causes more heat load in the building from the solar radiation. In the figure 5.8 right and the figure 7.9 is the same building B but with application of passive shading elements (horizontal and vertical overhangs) that reduce the heat load from the sun inside the building during the hot summer days. These shading elements are only used on the south and west façade of the building B.

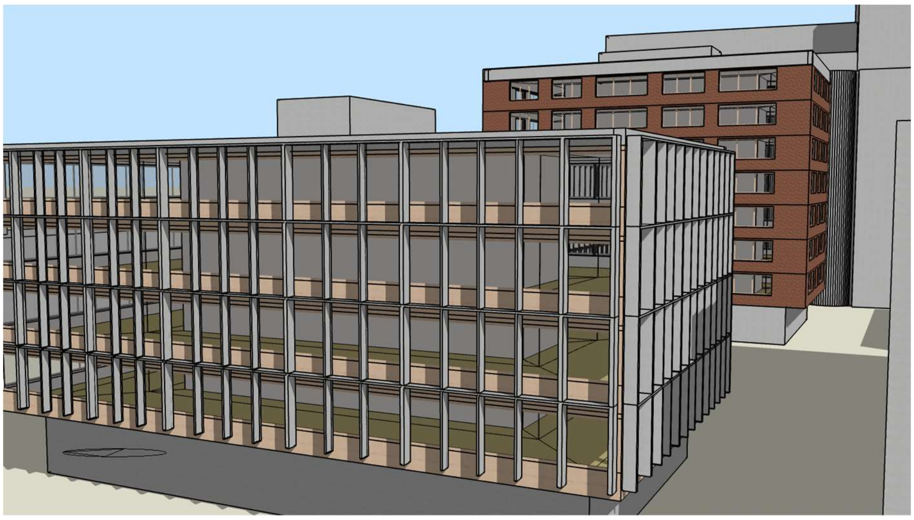


Figure 7.9 Detailed view of the used passive shading elements (horizontal and vertical overhangs) at the building B – geometry of the calculation model.

The graph in the figure 5.10 shows the comparison the energy consumption for the operation of the building A (left) and building B (right) by the application the partial cases C1 – C5. This energy covers the energy for the system of heating, cooling, mechanical ventilation, domestic hot water preparation and artificial lighting. The graph presents the results of cases C1 – C5 for the baseline solution of HVAC and DHW preparation where natural gas and electricity are used like a fuel. The lowest energy consumption for both buildings is in the case C5. The results from the energy simulation showed that the use of passive shading elements for the building B (case C2) the energy consumption for heating increases by 6.7 %, but the energy consumption decreases by 13.2 %. If we add night ventilation in time from 1.00 AM to 4.00 AM during the May and August, we can decrease the energy consumption for cooling by 22.3 % for the building B and by 11.9 % for building A in comparison with the case C1. The replacing of simple control strategy of the artificial lighting with the advanced control strategy brings the energy saving for artificial lighting by 27.3 % for the building B and by 37.6 % for the building A in comparison with the default state (case C1). The simple control works in two stepped regime (ON/OFF) what means that the artificial lighting is switched off when the target illuminance by daylight in the space is reached (500 lx at working plane 0.80 m – office, 100 lx at working plane 0.00 m - corridor). The advanced control strategy is more intelligent approach because the electric power input for LED luminaires is linearly regulated on the base of actual daylight level in the interior of the building. More daylight means less electric power input for LED luminaires. This fact also influences the energy consumption for heating and cooling what can we see in the graph for case C5 for both buildings. The energy consumption for heating increased (lower heat gains from artificial lighting) and the energy consumption for cooling decreased due to lower heat load from the artificial lighting.

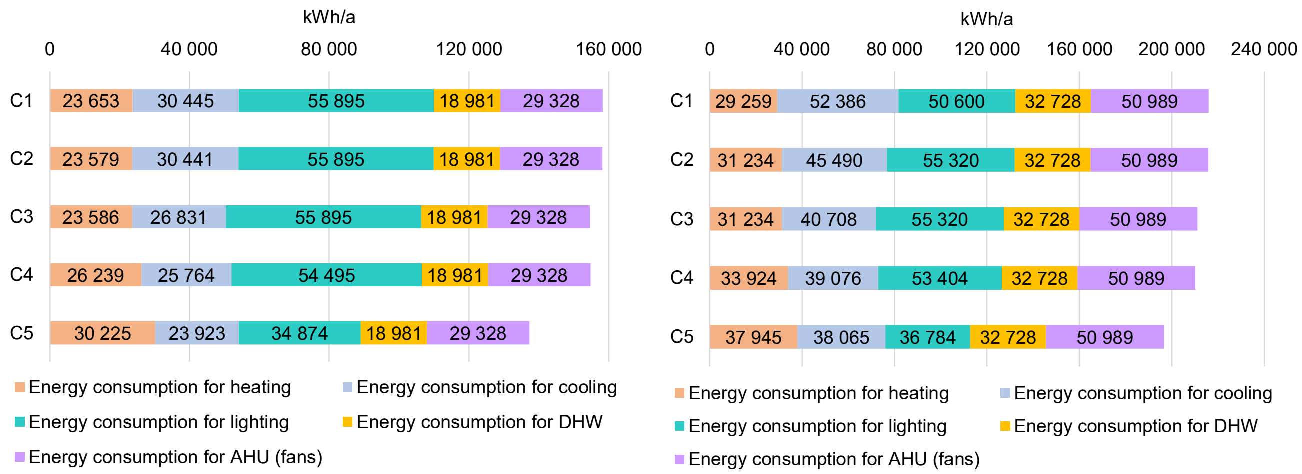


Figure 7.10 Comparison of energy consumption for HVAC, DHW, lighting among analysed cases C1-C5 – building A (left) and building B (right)

Generally, the most important is to decrease the energy consumption for operation of HVAC systems, DHW preparation and artificial lighting together (case C5). The next graph in the Pic X. shows the percentage savings on the energy consumption by the application of partial cases C2 – C5 in comparison with the case C1. The potential of energy savings is in the range of 2 to 13 % for the building A and from 0.1 to 9 % in the case of building B.

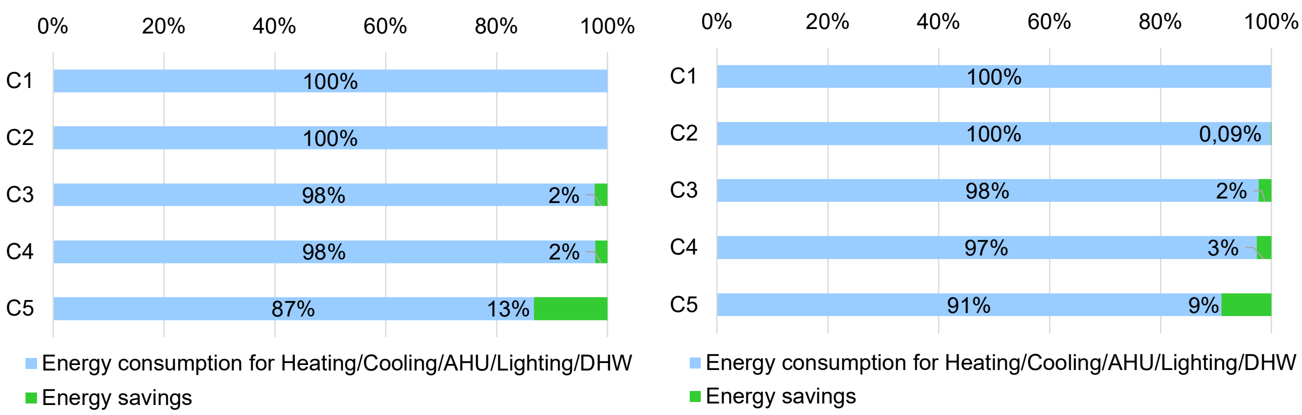


Figure 7.11 The potential of energy savings for cases C2-C5 in comparison with the case C1 - building A (left) and building B (right)

The most effective variant is the case C5 and not only for the baseline solution of HVAC and DHW preparation but also for the alternative solution of HVAC and DHW preparation. By the application of the case C5 we can decrease the energy consumption for heating, cooling, mechanical ventilation, DHW preparation and artificial lighting in the range of 9 to 13 % for both buildings in the comparison with the default state C1. This is the baseline solution where natural gas and electricity are used like a fuel.

The renewable energy source (electric heat pump) is only used in cooling system for both buildings. In the case of alternative solution of HVAC and DHW preparation where only electricity like a fuel and only renewable energy sources are used (electric heat pumps in heating, cooling and DHW preparation) the energy savings are in the range of 14 to 20 % for both buildings.

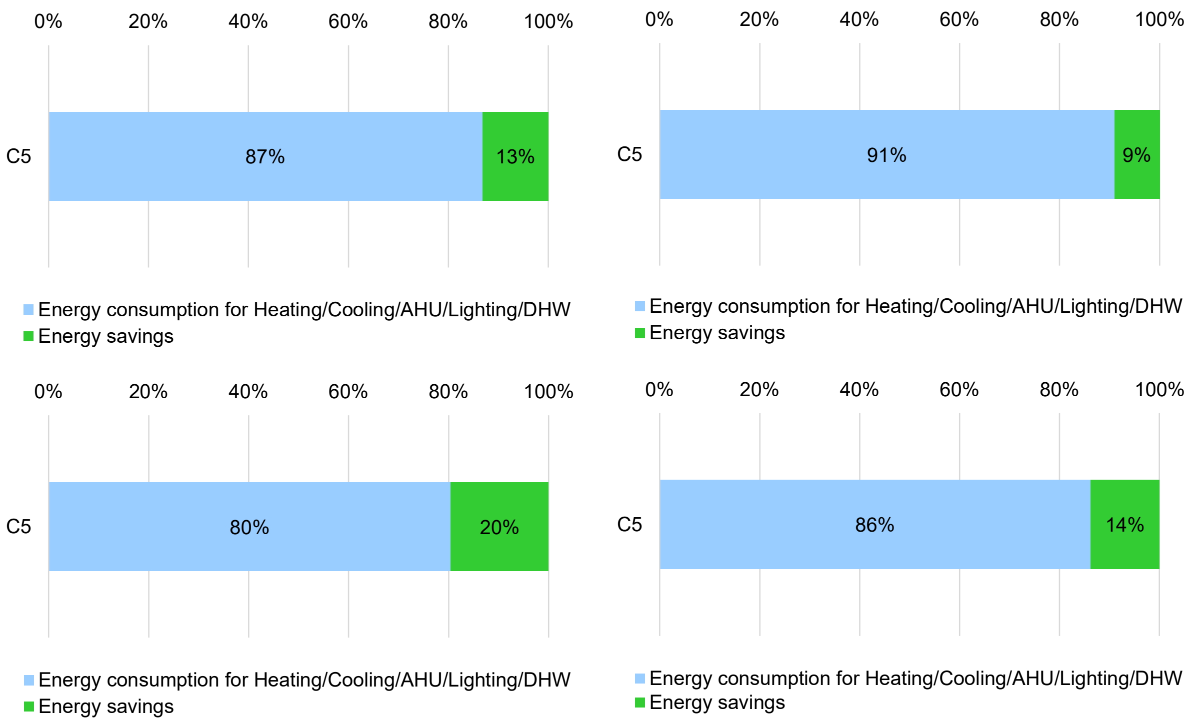


Figure 7.12 The energy saving for the case C5 in comparison with the case C1 for the baseline solution (above) and the alternative solution (below) - building A (left) and building B (right)

If we use the alternative solution of HVAC and DHW preparation by the application of case C5 we can decrease the energy consumption for heating, cooling, mechanical ventilation, DHW preparation and artificial lighting in the range of 27.8 to 28.3 % for both buildings (Pic X.) in comparison to the baseline solution of HVAC and DHW preparation. So, if we want to design energy efficient buildings we must take the attention not only for the shape of the building, used building materials, size of the transparent surfaces on the building façade but also to the proper selection and combination of HVAC systems and DHW preparation. And not only in terms of used heat source (heating and DHW: condensing natural gas boiler vs. electric heat pump with low-temperature hydro box for heating and high-temperature hydro box for DHW, cooling: electric heat pump with indoor cassette units vs. electric heat pump with hydro box and ceiling cooling) but also in terms of used subsystems for emission of heat and cool into the surrounded space (heating: convection heating by using hot water radiators vs. radiant heating by using plasterboard ceiling with integrated pipes, cooling: indoor cassette air units vs. ceiling cooling by using plasterboard ceiling with integrated pipes).

The using of renewable energy sources (electric heat pumps in heating, cooling system and DHW preparation) brings the interested energy savings in consumption of fuel. For our office building it is about 28 %. Here it important to note that we used electric heat pumps (air/water) with worse energy parameters generally (lower COP in heating and DHW preparation, lower EER in cooling) in comparison with electric heat pumps water/water or earth/water. There the energy savings for the operation this office building would be higher.

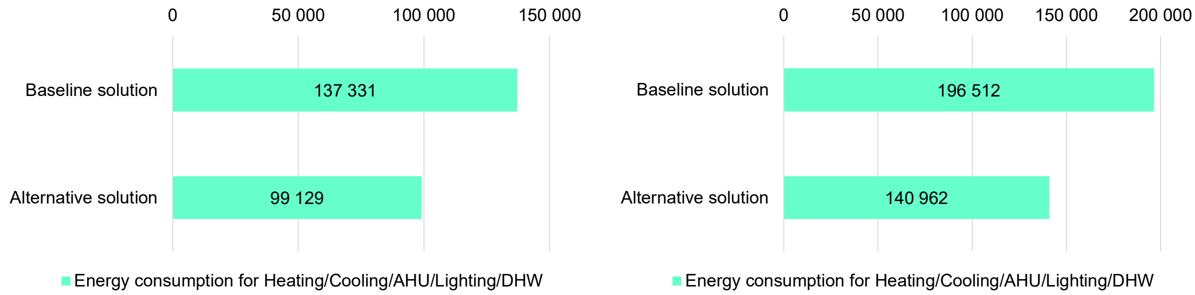


Figure 7.13 The comparison of energy consumption between the baseline and alternative solution - building A (left) and building B (right)

Chapter 08

Equivalent CO2 Emissions of the Irrigation System at the University of Alicante

Pardo, M.A.[1], Benalcázar, D.[1], Vilcekova, S.[2]

[1] Department of Civil Engineering, University of Alicante, Carretera de San Vicent del Raspeig s/n, 03690 Alicante, Spain.

[2] Institute for Sustainable and Circular Construction, Faculty of Civil Engineering, Technical University of Košice, Vysokoškolská 4, 04200 Košice, Slovakia

Reducing emissions is one of society's greatest challenges. The continual use of resources and ongoing urban expansion leads to pollution and disrupts the environmental equilibrium. The construction industry and its supply chains manage resource allocation and energy use, leading to a steady escalation in greenhouse gas (GHG) emissions.

8.1 Introduction

The European Commission has identified it as one of its fundamental objectives, proposing greenhouse gases (GHG) reduction by 2050 with strategies for the economic and social transition [1]. The European Union is working on "Pathways for the transition to a net-zero greenhouse gas emissions economy and strategic priorities" [2], highlighting in a sub-section "Maximize the deployment of renewables and electricity to fully decarbonize Europe's energy supply", which underlines Europe's dependence on oil and gas (accounting for 55% of energy demand in 2018). Faced with this problem, the EU aims to reduce the total energy demand by 20% by 2050 [3].

The Intergovernmental Panel on Climate Change (IPCC) studies climate and assesses scientific, technological, and socio-economic knowledge on the risk of climate change forced by entropic activities. It also studies its environmental and socio-economic impacts [4]. The IPCC established in its fifth report four climate change scenarios or RCPs (Representative

Concentration Pathways) with four levels of GHG emissions [5] for the near future and up to the end of the 21st century. These RCPs estimate different GHG concentrations by considering different increases in radiative forcing or climate forcing by 2100 [6] — the difference between the insolation (sunlight) absorbed by the Earth and the energy radiated back to space—. These scenarios are ranged between RCP2.6, RCP4.5, RCP6.0 and RCP8.5 (the latter being the most pessimistic scenario, with large GHG releases and consequent impacts, considering an increase of 8.5 W/m2), with the laissez-faire (do nothing) scenario being a case between RCP6.0 and RCP8.5 [5,7,8]. The production and release of GHGs into the atmosphere depends on several factors, such as population size, economic activity, lifestyle, energy use, land use, technology, and climate policy.

Spain's commitments, within the Europe 2020 objectives, are to reduce GHG emissions by up to 10% in 2020 compared to 2005 (because of the 52.88% increase in emissions compared to 1990) [9]. The consumption of natural gas as an energy source in Spain leads to a 13% increase in GHG emissions because of fossil fuels [10]. According to the European Union [11], expected that, although Spain will have met its emissions targets by 2020, this will not be the case by 2030. So, we must make first efforts to meet the emission reduction targets.

With implementing targets for diminishing these gases by the European Union, compared to 1990 according to the Kyoto protocol [12], renewable energies [13–15] are one policy that allows the reduction of emissions by reducing fossil fuel consumption. On a global scale, emissions are because of industrial activities (around 35% of total annual emissions)[16,17], and agriculture (between 15 and 20%) [18,19]. This figure is higher than the figure given by the US Environmental Protection Agency (EPA), which quantifies it at 11% [20]. On a Spanish scale, these numbers are different, with 20% of emissions coming from industry, 25% from road traffic and 15% from agriculture and livestock [21].

Life Cycle Assessment (LCA) is a systematic and comprehensive method for evaluating the environmental impacts of a product, process, or service throughout its entire life cycle [22,23]. The life cycle considers the extraction of raw materials, production, transportation, use, and end-of-life disposal or recycling. LCAs include (i) defining the objectives of the assessment and the boundaries of the system, (ii) compiling a detailed inventory of all inputs (e.g., raw materials, energy) and outputs (e.g., emissions, waste) associated with each stage of the product's life cycle, (iii) assessing the potential environmental impacts of the inputs and outputs, and (iv) interpreting the results of the life cycle inventory and impact assessment to draw conclusions and identify areas for improvement. Researchers employ the LCA approach to delve deeper into the environmental impact of buildings and the built environment. It examines various aspects such as the environment, energy consumption, waste disposal, and the associated environmental consequences when buildings reach the end of their useful life. This approach serves as a valuable tool for identifying areas of improvement to reduce GHG emissions. By considering different shapes, window sizes, or orientations, we can make improvements in building design [24]. The impact of improving buildings to achieve higher energy standards is evaluated in terms of life cycle [25–28]. Many studies focus on assessing different material options in buildings [29]. Kazemi and Zardari, (2020) [30] show that materials have an important influence on Global Warming Potential (GWP). A different approach was taken with the primary emphasis of the study being on the life span of the building [31]. The next study [32] is centred on the recycling potential of building material at the end of the building's life cycle. Some studies focus on one building and its embodied energy [33], while others compare representative building types for a region [34]. Most studies point to the share of life cycle phases on the equivalent amount of CO2 emissions. Targeting life stages with high emissions, the goal is to reduce global GHG emissions. Transportation by traffic road produces the largest emissions [35,36], materials including manufacturing and processing (81%) [37], and installation, considering the layout of the structure [38,39] and considering recycling materials [40,41], being a workable choice for diminishing emissions produced in this life stage (22–58% reduction) [42]. So, this highlights how important these stages are in the life cycle analysis of any infrastructure. The landscape character assessment is a helpful tool in landscape planning and policy management [41]. It encompasses both environmental and societal initiatives, making it applicable in a wide range of contexts. The study by Nguyen et al. (2017) [40] presents an LCA model that evaluates the trade-offs and synergies between intensification and carbon-sequestering conservation measures in annual crop production landscapes to assess local climate mitigation potential. The development of the Swiss Agricultural Life Cycle Assessment (SALCA) as an LCA tool to estimate and compare the impacts of specific land uses and management options is introduced [30]. Recently, LCA has also been used to quantify the environmental impacts of engineering constructions and networks. Besides the creation of GHG emissions, irrigation is a major consumer of water and energy in southwestern Europe [43–45].

The primary sources of greenhouse gas emissions by the economic sector in the United States are transportation (29%), industry (30%), commercial and residential (30%), and agriculture (11%) [46]. Other approaches have showed the potential to elevate this figure by as much as 20% [47], while others have reported comparable findings (10%) [48] on a global scale.

Emissions stemming from energy activities associated with irrigation, which encompass activities like water pumping and conveyance, constitute a substantial share, ranging from 50% to 70%, of the overall emissions originating from energy-related activities within the agriculture sector [49]. Soil use and crop types, traditional or modern [50], condition the irrigation (sprinklers, flooding, etc.) and the machinery used.

The life cycle analysis of an irrigation network is a common approach used to compare different irrigation methods. For example, using smart sprinklers reduces 38% of water and energy consumption [51,52]. Similarly, systems based on decision support systems (DSSs) have shown a 42% reduction in resource usage [48]. Using reclaimed water reduces freshwater consumption, energy usage, and fertilizer needs, leading to a 23.8% decrease in emissions [53,54]. Some other techniques for measuring GHGs in agriculture are chamber-based techniques (open and closed) [55] and irrigation management practices (flood irrigation versus drip and sprinkler irrigation) also influence the GHG emissions as the rate of CO2 increases under low irrigation [56]. Based on a review of research papers focusing on LCAs, it can be concluded that a lack of studies focused on the analysis of environmental impacts during the life cycle of irrigation systems. Therefore, the primary outcome of this study involves evaluating the CO2 equivalent emissions for the selected irrigation system and pipe materials.

The University of Alicante’s irrigation network was selected for developing this study. Using GWP, carbon dioxide equivalent (CO2-e) emissions can be quantified within cradle-to-gate and cradle-to-grave boundaries over a 25-year period to achieve the 2030 Sustainable Development Goals (SDGs), goal 13 [57]. But the lack of a database that collects all the information on the materials used makes it difficult to quantify the emissions produced. For this reason, analyses of emissions from product life cycles are difficult [58,59]. The study outlines the analysis, data collection, methodologies, software, results, and interpretation. Furthermore, the aim is to answer a series of questions: the stage in the system’s life that produces the most emissions (I), the proportion between the different life stages (II), the decisions and policies to be adopted to reduce emissions (III), the influence of the different materials in the useful life of the infrastructure (IV), and the emissions derived from its manufacture and commissioning (V). The analysis yielded essential data to make environmental decisions about the infrastructure, and to evaluate the system's operability in water, energy, and carbon flow [60]. It can also be utilised in research quantifying the emissions of the life cycles of these networks or any considered infrastructure. The method described allows for export to other locations, with few limitations in its universal application. However, as seen, most of the parameters are imposed by the geographical location of the installation, and we can change a few.

The analysis focuses on managing irrigation networks and provides fundamental data for decision-making from an environmental perspective on the installations of this infrastructure. It can also be used in research that quantifies the emissions of the life cycles of these networks or any infrastructure considered. The method described above can export to other locations, with few limitations in its universal application. But, as seen, most of the parameters are imposed by the installation location, and few can be changed.

The data necessary to carry out this analysis and the software used for quantifying global emissions are determined. Subsequently, they are shown in a general summary. The irrigation network of the University of Alicante is selected as a real case study and the results are discussed with earlier research and conclusions are shown where the questions previously asked are answered.

8.2 Materials and Methods

The following describes the data required to do the life cycle analysis, describes the software used, and presents the results obtained.

8.2.1 Data Required

Calculating the carbon footprint emitted by the campus irrigation network has been obtained from a series of data displayed in Table 8.6. For each of the materials that make up the network itself, manufacturing and transport data must be added to the site where the installation has been carried out. The rows referring to the material are inserted as data after the rows showed, for successive materials.

Table 8.6. Data required in an irrigation network.

	Parameter	Units
	Irrigation water	m^3/year
	Irrigation surface	m^2
	The total length of the irrigation network	m
	Operating energy	kWh/year
Material i	Length	m
	Operation energy	kWh
	Transport	km
	Repairs	%
	Losses	%

8.2.2 Calculation Software

Based on the data described above, the carbon footprint of the life cycle of the civil works and the products used in the works, known as environmental product declaration and under the ISO 14 021 standard, is obtained. Software One Click LCA was selected for determining CO2e emissions. The GWP of the life cycle of civil works comes from environmental product declarations and meets requirements stated by ISO 14025 standard. The One Click LCA software provides environmental impact data according to quality standards, which can help reduce costs [61]. In pursuit of this objective, five rationalization methodologies are implemented, as elucidated [61]

These methodologies encompass excluding specific life cycle stages, processes, or impact categories, thereby streamlining the analysis. Furthermore, they involve substituting conventional inventory data with quality assessments of outcomes or quantified information, enhancing the precision of the evaluation. Additionally, methodological standardisation is implemented through adopting established assessment tools and standards, ensuring consistency in the analytical process. Finally, automation plays a pivotal role in this endeavour, as life cycle analyses are conducted with the assistance of software that seamlessly integrates essential product information, thereby enhancing efficiency and accuracy in the assessment process elucidated [61]. It also reports the GHG emissions produced throughout the life of the infrastructure

Calculating Life Cycle Assessment (LCA) analysis following the normative ISO 21930, ISO 14040, ISO 14044, ISO 14021, ISO 14025, EN 15804, and EN 15978 is important for many reasons:

- Standardisation. These ISO and EN norms provide a standardised framework for conducting LCA, ensuring consistency and comparability of results across different products, processes, or services. Adhering to these standards allows for meaningful and accurate comparisons between different life cycle stages and different products or systems.
- Environmental Performance Evaluation: LCA analysis helps evaluate the environmental performance of products, processes, or services throughout their entire life cycle.
- Product Improvement: LCA analysis helps find areas for product or process improvement. By quantifying the environmental effects and identifying the principal contributors, it becomes easier to target specific areas for optimization, such as material selection, production processes, packaging, transportation, and end-of-life management. This leads to more sustainable design choices and helps drive continuous improvement.
- Communication and Transparency: The ISO and EN norms provide guidelines for preparing Environmental Product Declarations (EPDs) and Environmental Product Information (EPI), which enhance transparency and ease communication of environmental performance with stakeholders.
- Regulatory Compliance: Following these norms ensures compliance with international standards and regulations for LCA and environmental labelling.
- International Acceptance: ISO and EN norms are recognised and accepted standards for LCA analysis. By adhering to these norms, LCA results are more likely to be accepted and understood by stakeholders worldwide, including customers, investors, government agencies, and environmental organizations. It enhances the credibility of your analysis and allows for meaningful comparisons across regions and industries.

Adhering to the normative ISO 21930, ISO 14021, ISO 14025, EN 15804, and EN 15978 when conducting LCA analysis ensures standardisation, enables comprehensive environmental performance evaluation, facilitates product and process improvement, enhances communication and transparency, supports regulatory compliance, and ensures international acceptance and credibility of LCA results.

Carbon footprint calculations performed by the software follow the methodologies described in the following regulations:

- ISO 21 930. Sustainability in building construction. Environmental declaration of construction products.
- Standard ISO 14 021. Environmental labels and declarations. Self-declared environmental claims (Environmental labelling II).
- Standard EN 15 804. Sustainability in construction. Environmental product declarations. Basic product category rules for construction products.
- Standard EN 15 978. Sustainability in construction. Assessment of the environmental performance of buildings.

Global Warming Potential (GWP) expressed per declared unit (kg CO2e/DU) and energy rating meet the requirements according to EN 15804, ISO 14021 and ISO 21930. A second result refers to the same parameter, GWP expressed per functional unit (kg CO2e/FU) and energy rating, but following the EN 15978 standard. The primary goal is to consider the entire infrastructure and its operation until the end of its life, 25 years. This concept includes a "cradle-to-grave" system boundary and for this One Click LCA Levels are used.

8.2.3 Software Outputs

The software returns, as a result, the overall emissions, embodied carbon, and energy rating according to EN 15 804 and ISO 14 021 and 21 930. It shows the total impact produced only by the materials used in the irrigation network, from manufacturing raw materials to their transport and processing in the factory. In Saxon terminology, these results are defined as "cradle to gate" as they refer from the manufacture of the material to the instant of use.

A second result refers to the same terms (overall emissions, embodied carbon, and energy rating) but follows the ISO 15 978 standards. The difference is that the complete infrastructure and its operation until the end of its life are considered. This concept is known as "cradle to grave" because it considers the entire life cycle of the product.

The results are shown in Table 7. The carbon emissions produced for each material are added as data following the rows shown, for the various materials that make up the irrigation network.

Table 7 Results of the global and partial emissions of the irrigation network.

	Parameter	Units
	Global emissions	kg CO_2e
	Embodied carbon	kg CO_2e/m^2
	Energy rating	-
Material i	Percentage in irrigation network	%
	Partial emissions	kg CO_2e
	Partial embodied carbon	kg CO_2e/m^2

8.2.4 Flowchart

The procedure for performing this analysis and quantifying carbon footprint follows this process (Chyba! Nenašiel sa žiaden zdroj odkazov.). Data collection is a determination of the materials' mass and their characteristics. The first analysis ("cradle-to-gate") considers raw materials extraction (A1), their transport to the factory (A2), and their manufacture (A3). The second analysis ("cradle-to-grave") includes the product stage (A1–A3), transport to the construction point (A4), and installation (A5). Other stages included are related to the operation, such as re-pairs (B3) and energy consumption (B6). Finally, it includes the stages after the useful life of the infrastructure, such as waste transportation (C2) and disposal (C4).

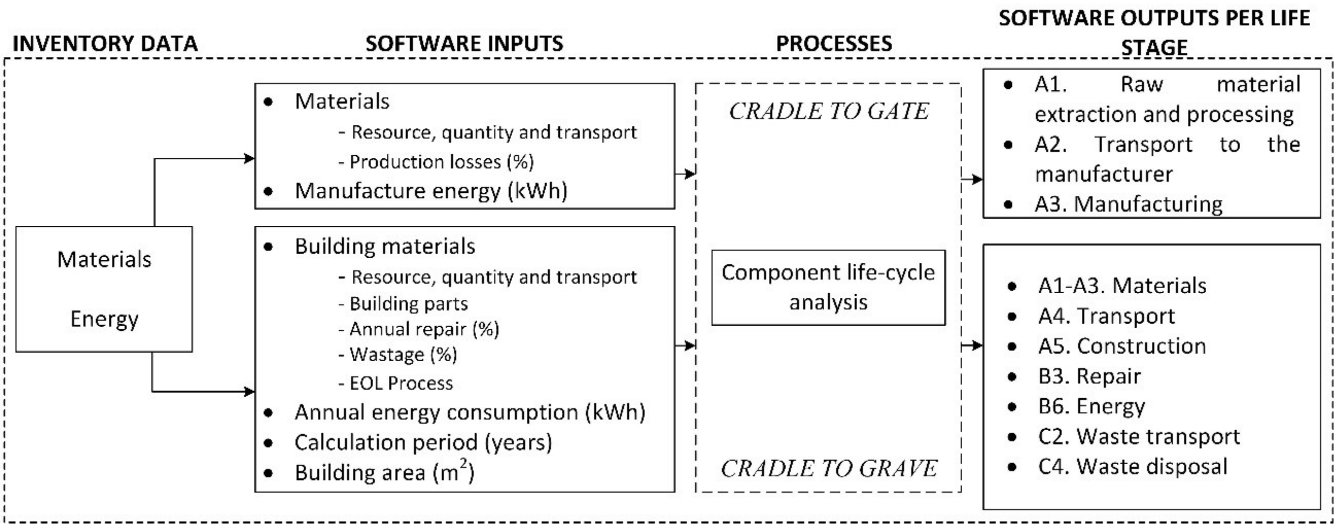


Figure 8.10. Cradle to gate and cradle to grave stages flowcharts

8.3 Case Study

8.3.1 Irrigation Network of the University of Alicante

The case study site is on the campus of the University of Alicante (Figure 8.2), in the municipality of San Vicent del Raspeig, Alicante. The University occupies an area of 805 874 m2, of which 329 271 m2 (40.86%) are green areas on campus. These areas are irrigated with brackish water obtained from the aquifer [62] on which the University of Alicante is located.

This water undergoes an inverse osmosis desalination treatment because of its high salinity [63,64]. Later, transported to a lake, from where water is collected and used to irrigate the university's parks and gardens, as well as being used as a decorative element in the forest itself.

Water is distributed throughout the University campus along the pressurised irrigation network (partially buried in the ground). Pumping devices distribute water to the existing vegetation by sprinkling for the irrigation of lawns and gardens and by drip irrigation for trees. The pressurised network is a looped network (Figure 8.11) covering the entire length of the campus, with a total length of 23 009 metres from the regulation lake to the south-eastern end of the University.

Total length of the irrigation network comprises 70% polyvinyl chloride (PVC) pipes and the remaining 30% of asbestos cement pipes. These pipes were installed when building the University and have been maintained in areas with minimal maintenance and without renovation. However, when the campus was extended, PVC was installed, as produced far fewer negative effects on both the environment and human beings.

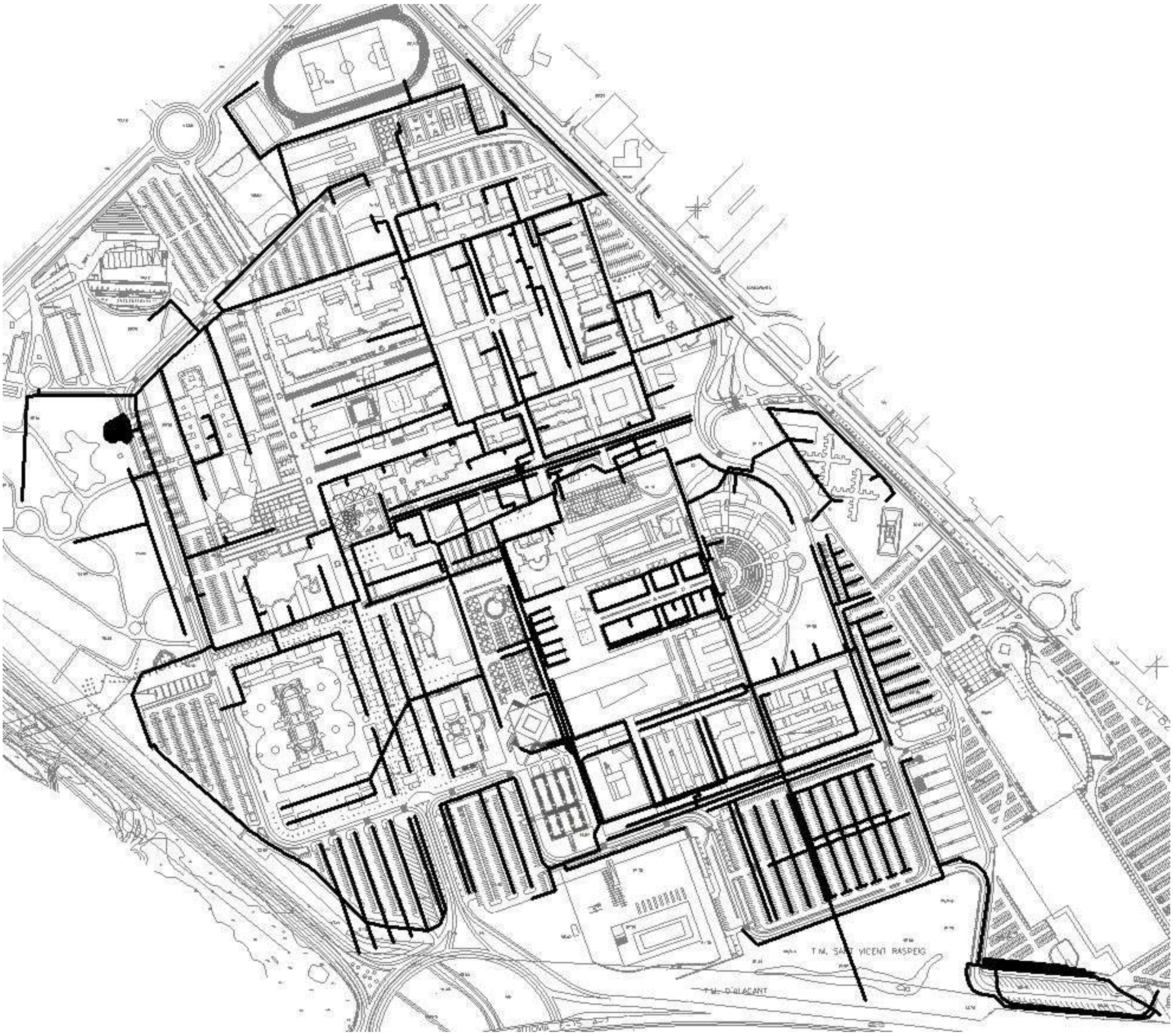


Figure 8.11. Looped irrigation network of the University of Alicante.

8.3.2 Actual Data in the Alicante Network

We gathered data on the material used to build the network to calculate GHG emissions, as we expected it would be the primary factor in emissions because of its manufacture and transport [65]. The construction processes carried out when installing the irrigation network have hardly any significant emissions. Therefore, the software used does not take them into account in determining the GHG emitted during installation (Chyba! Nenašiel sa žiaden zdroj odkazov.).

Table 8.1 Software input data

Analysis	Material	Mod.	Parameter	Unit	Quantity	Observations
Cradle-to-Grave Analysis	PVC	A1	Material supply	m	16,106.3	Life stage PVC length of the irrigation network
		A2	Transport	km	1611	Distance from raw material extraction to the manufacturer
		A3	Energy	kWh	38,694	Energy used in material production
	AC	A1	Material supply	m	6902.7	Life stage asbestos cement length of the irrigation network
		A2	Transport	km	1511	Total distance from leaving the factory to the construction site
		A3	Energy	kWh	60,136	Energy used in material production
Cradle-to-Grave Analysis		A1–A3	Products	m	23,009	Total network length
		A5	Construction	m^2	11,504.5	Building surface
		B6	Operational energy	$kWh \cdot year^{-1}$	14,366	Energy consumed (pumping and distribution equipment)
	PVC	B3	Repairs	%	2	Annual repair rate
		A1–A3	Loses	%	5	Percentage of losses in production
	AC	B3	Repairs	%	0	Annual repair rate
		A1–A3	Loses	%	5	Percentage of losses in production

Note there is no repair percentage for asbestos cement material, as replaced by PVC if any faults. PVC material is brought from Gaillon, France, and high-density polyethene (HDPE) is brought from L'Hospitalet de Llobregat, Barcelona. From their factories, the material is transported to be installed at the University of Alicante.

8.3.3 Study Cases

The study aims to focus on the analysis of the CO2e emissions produced during the life cycle of the current irrigation network. Two variants with different materials are compared to the current network. So, it is possible to obtain which materials are more suitable in terms of CO2e emissions. The three variants studied are:

- Case 0. The current situation of the network comprises PVC (70% of the network) and asbestos cement (the remaining 30%).
- Case 1. The irrigation network comprises PVC.
- Case 2. The irrigation network is studied and comprises a different material to the earlier ones, high-density polyethylene (HDPE), the material studied.

8.4 Results

8.4.1 Global Results

Results returned by the software are the overall greenhouse gas emission and the embodied carbon emission. First values refer to the gases emitted during the construction and demolition of the infrastructure and the supply chain of all the materials used from its manufacture to their end of life. While the second value (10-20% of the total carbon footprint emitted) is obtained by calculating the emissions per unit of surface area and determining the energy rating based on the total embodied carbon emitted. The above-mentioned standards present several impact category indicators, such as ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), and others. In this study, our em-phasis centered on the GWP indicator in connection with the European Green Deal goals and the European climate law. The latter sets the goal of reducing net greenhouse gas emissions by at least -55% by 2030 compared to 1990 levels [66]. Thus, the GWP indicator is the primary focus of our study. For the case study, the overall and embodied GHG emissions for a calendar year based on the above norms and standards are shown in Table 8.

Table 8 Total emissions and classification of the irrigation network of the University of Alicante according to the standards followed.

Outcome 1		
Global emissions	320 383	kg CO_2e
Embodied carbon	1	kg CO_2e / m^2
Energy rating	A (<220)	-
Outcome 2		
Global emissions	449 709,3	kg CO_2e
Embodied carbon	1	kg CO_2e / m^2
Energy rating	A (<220)	-

The emissions generated in outcome 1 ("cradle to gate") account for 71% of the overall impact achieved in outcome 2 ("cradle to grave"), based on ISO 15 978. These are the operation and demolition/valorisation stages, which account for almost three-quarters of the emissions performance.

8.4.2 The Impact of Products on GWP within "Cradle-to-Gate" Analysis

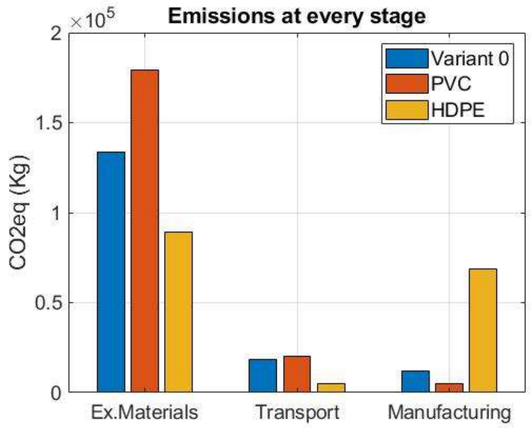
In the following, the aim is to find how the material affects emissions, in kg CO2e, over the 'cradle to gate' system boundary for the three3 defined cases. The results are presented in Table 8.9.

Table 8.9 Cradle-to-gate emissions of the cases on display

Module	Stage	Case 0	Case 1	Case 2
A1	Ex. materials	133507.8 (81.4%)	179021.5 (87.8%)	89333.2 (54.6%)
A2	Transport	18315.5 (11.2%)	19996.1 (9.8%)	5215.8 (3.2%)
A3	Manufacturing	12172.9 (7.4%)	4765.9 (2.4%)	68934.8 (42.2%)
	TOTAL	163996.2	203783.5	163483.9

The irrigation network comprises sections with different diameters. To take into account the emissions associated with each diameter, the total lengths for each diameter shall be entered. Emissions based on diameter, production process, material, and energy consumption shall be considered. Recording pipe lengths can make sure emissions calculations consider different diameters. Emissions vary with the material used and manufacturing processes.

The data show that raw material extraction (A1) is the process with the greatest influence on the GHG emissions of the product used. PVC and HDPE have different impacts on manufacturing processes, even though they are both petroleum products. This A1 module is the largest contributor to emissions (80–55%) for the variants analysed. Variant 2 (HDPE) involves a higher energy consumption and higher CO2e emissions during the pipe manufacturing phase (A3, 42,2%). The comparison of the results for the total values of CO2e is shown in Figure 8.3.



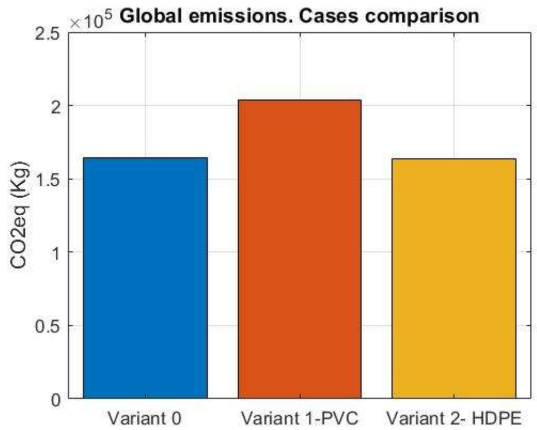


Figure 8.12. Global emissions from the "cradle to gate" stage. Comparison of cases

8.4.3 The Effect of Materials in Cradle-to-Grave Analysis

The different cases in the “cradle-to-grave” stage are analysed for the different materials, and the emissions produced, in kg CO2e, are summarised in Table 8.10. In this table, the results are failed for the one-year study and the useful life of the installation is equal to 25 years.

Table 8.10 Cradle-to-grave emissions of the exposed cases.

	Module	Stage	Case 0	Case 1	Case 2
Analysis 1 year	A1-A3	Materials	230 280,6 (51%)	172 527,1 (40%)	192 609,9 (45%)
	A4	Transport	29 201,2 (6%)	4 598,9 (1%)	1 768,1 (0%)
	A5	Construction	39 563,6 (9%)	43 585,6 (10%)	51 940,0 (12%)
	B3	Repairs	12 835,1 (3%)	18 271,3 (4%)	17 706,9 (4%)
	B6	Energy	5 818,9 (1%)	5 818,9 (1%)	5 818,9 (1%)
	C1-C4	End of life	132 010,0 (30%)	188 300,3 (43%)	159 760,3 (37%)
		TOTAL	449 709,4	433 102,1	429 601,0
Analysis 25 years	Module	Stage	Case 0	Case 1	Case 3
	A1–A3	Product	127934.1 (37%)	255598.8 (47%)	102809.5 (34%)
	A4	Transport	3533.7 (1%)	2481.0 (0%)	943.7 (0%)
	A5	Construction	6274.5 (2%)	12934.4 (2%)	5197.0 (2%)
	B3	Repairs	61994.1 (18%)	129343.9 (24%)	51969.9 (17%)
	B6	Operational energy	145474.2 (42%)	145474.2 (27%)	145474.2 (47%)
	C2	Waste transport	15.9 (0%)	321.9 (0%)	98.8 (0%)
	C4	Waste disposal	14.1 (0%)	286.0 (0%)	87.8 (0%)
		TOTAL	345240.6	546440.2	306580.9

Analysis over a 1-year life cycle

Through an LCA analysis over a life cycle of one year, we have obtained information about each stage of the process.

- Case 0. The emissions of the 1-year analysis of the current network are higher than the 'cradle to gate' stage, since the construction, operation, and end of life of the infrastructure are considered. But, the emissions produced indicate a clear dominance of the materials and end-of-life of the system, and the emissions derived from these contribute 81% of the overall emissions of the current infrastructure.

- Case 1. A PVC network generates emissions like those produced by the existing network (433 102,1 kg CO2e of the PVC network compared to 449 709,4 kg CO2e of the current network). The main difference lies in the influence of the materials, with the current network being 11% higher, as made up of asbestos cement.
- Case 2. The HDPE network also presents similar results to the current case in terms of emissions generated by the materials and end of life of the infrastructure. Table 6 shows that the reduction in overall emissions lies in transport, because of the shorter distance between the origin of the material and its final location.

In a summary, the overall infrastructure data for the 1-year analysis is shown in Figure 8.13.

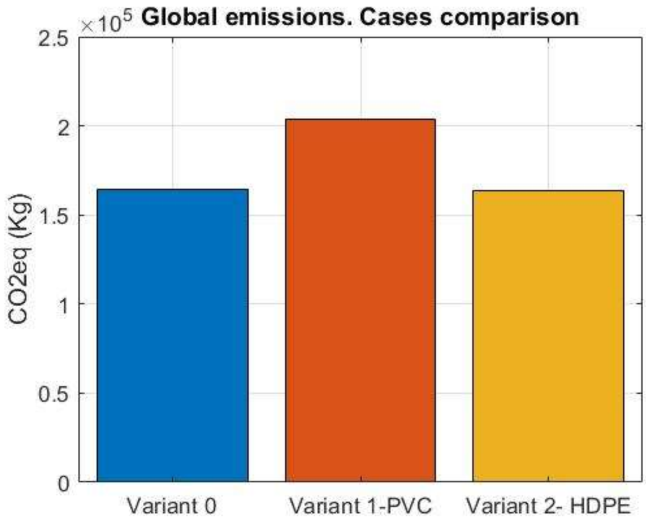


Figure 8.13. Global emissions from cases analysed. (1-year life cycle)

Analysis over a 25-years life cycle

The analysed variants in terms of materials for the "cradle-to-grave" system boundary expressed in kg CO2e are summarised in Table 8.10. In the table, the results are broken down for a reference service life of 25 years. In the following, the results in Table 8.10 are discussed for the different cases.

Case 0. In the current irrigation network, the stages corresponding to products (A1–A3) and energy consumption (B6) have a significant influence on overall emissions (37% and 42%). The GWP of transport (A4, 1%), construction (A5, 2%) and end-of-life (C2, C4; 0%) is reduced as they are stages that occur at specific times, causing environmental impacts only once during the life cycle.

Case 1. Network repairs produce high emissions (24%), while energy consumption has a 27% contribution. However, the influence of the network materials (A1–A3) is the highest in this variant (47%), being this life stage as the principal contributor to GWP.

Case 2. The stages in the life cycle that contribute the most to high GHG emissions are energy consumption (47%), materials manufacturing and transport (34%), and repairs (17%). Energy consumption is consistent across all variants, but the second variant has the highest emission ratio.

Even though PVC and HDPE are materials derived from petroleum, the results show that the effect of repairs on the pipe shows a significant difference between the two materials. The emissions of PVC (129,343.9 kg CO2e) are 2.5 times higher than those produced by HDPE (51,969.9 kg CO2e). In every variant, energy consumption remains unchanged despite having different percentage contributions.

Case 1. Network repairs produce high emissions (24%), while energy consumption has a 27% contribution. However, the influence of the network materials (A1–A3) is the highest in this variant (47%), being this life stage as the principal contributor to GWP.

Case 2. The stages in the life cycle that contribute the most to high GHG emissions are energy consumption (47%), materials manufacturing and transport (34%), and repairs (17%). Energy consumption is consistent across all variants, but the second variant has the highest emission ratio.

Even though PVC and HDPE are materials derived from petroleum, the results show that the effect of repairs on the pipe shows a significant difference between the two materials. The emissions of PVC (129,343.9 kg CO2e) are 2.5 times higher than those produced by HDPE (51,969.9 kg CO2e). In every variant, energy consumption remains unchanged despite having different percentage contributions. As a summary, the overall infrastructure data for the 25-year analysis is Figure 8.14.

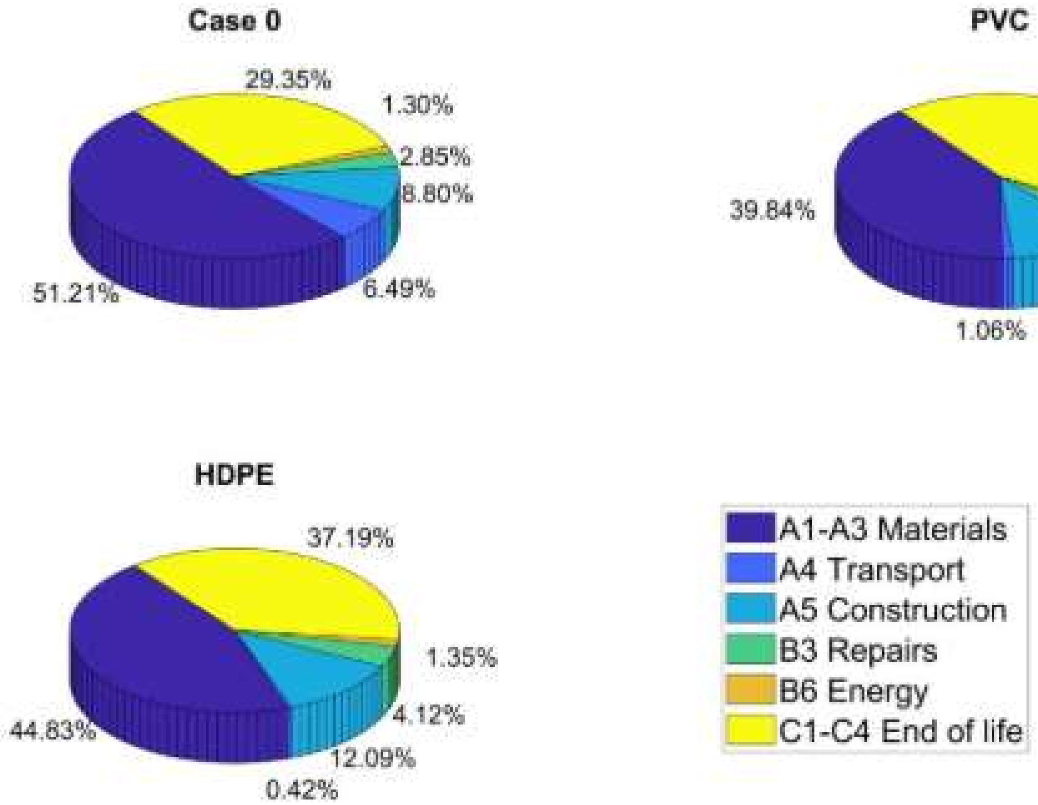


Figure 8.14. Percentage share of life cycle stages on total CO2e emissions for 25 years.

8.4.4 Sensitivity Analysis

Under ISO 14044, a sensitivity analysis is imperative for evaluating results and conclusion reliability. The primary aim of this analysis is to ascertain the extent to which uncertainties in data and allocation methods, among other factors, impact the results and conclusions. It is strongly advised to conduct sensitivity analysis for variations in input raw materials, including secondary materials, alterations in transportation distances, modifications in the production process, changes in energy mix, and adjustments in end-of-life scenarios.

This study examined how the pipes would be affected by a 10% increase in length. Table 8.11 points out that, within the system boundary 'cradle-to-grave,' the percentage reduction in GWP for module A1 amounts to 6.81%, 3.48%, and 6.31% for variants 0, 1, and 2, respectively.

Table 8.11 GHG emission distribution with alternative options for pipe length.

Case	% Share of A1 on the GWP Total	% Reduction
Case 0	38.67	-6.81
Case 1	32.76	-3.48
Case 2	29.1	-6 31

Expanding the irrigation network by 10% allows for more plots to be irrigated on campus. The extension has the potential to make the network more efficient and cover more areas for irrigation. Variant 1 has a higher environmental impact in terms of Global Warming Potential (GWP) for module A1 compared to other variants. Variant 1 has higher emissions in the A1–A3 module, as shown in Table 8.10. This is because of the material supply aspect (A1), which has higher values (Table 8.9).

8.5 Discussion

Upon scrutinizing around 200 articles, only a select few were found suitable to include in the discussion section. Most of these articles centre their attention on Life Cycle Assessment (LCA) concerning building materials and complete structures, spanning diverse categories like residential and commercial buildings. Their primary focus revolves around the attributes of materials and various phases of the life cycle. This research, however, distinguishes itself by delving into the intricacies of the irrigation system, a subject relatively unexplored in existing literature. Hence, it is apt to regard this study as a valuable contribution and a pioneering pilot investigation in this specific domain.

This study determines the emissions produced in an irrigation network and irrigated fields. During the 1-year analysis of the network materials, they produce a considerable amount of GHGs (81%) from the overall irrigation system, besides those produced by the existing vegetation. This study determines the CO_2e emissions produced in an irrigation network and irrigated fields. The network produced 37% of GHGs from the irrigation system, besides those produced by the existing vegetation. It has been determined that a network comprising HDPE pipes (case 2) was found to have lower total GWPs emitted into the atmosphere. The study [67] has also reached this conclusion. HDPE accounts for 68% of the PVC material’s carbon emissions (215 $kgCO_2e/m$ out of 315 $kgCO_2e/m$) when considering production, transport, and installation

(Table 8.12). In this study, the transport emissions (A2) are like the actual irrigation network (Case 0) and the PVC and HDPE variants are exposed. The distance varied depending on the case in the study by [67] than in the university's network.

Other approaches [68] quantified an increase in GWP expressed as CO2e for one meter of HDPE pipes (25.5 kgCO2e/m) compared to the PVC material (21.1 kgCO2e/m). The results are shown in Table 8.12.

Table 8.12. Comparison of pipe materials

GWP ($kgCO_{2e}/m$)	University Network			Du et al. (2013) [66]		Hajibabaei et al. (2018), [67]	
	Actual	PVC	HDPE	PVC	HDPE	PVC	HDPE
Production	5.6 (93%)	11.1 (94%)	4.5 (91%)	315 (99%)	215 (99%)	21.1 (63%)	25.5 (67%)
Installation	0.27 (5%)	0.56 (5%)	0.23 (5%)	2.8 (1%)	2.8 (1%)	3.8 (11%)	3.8 (10%)
Transport	0.15 (2%)	0.11 (1%)	0.23 (4%)	0.26 (0%)	0.17 (0%)	8.8 (26%)	8.8 (23%)

In Table 8.12, the authors presented emission results from different irrigation systems. Various factors contribute to the differences in emission results obtained across different irrigation systems. Drip irrigation emits less water than flood irrigation because of its efficient delivery. Technology and design differences caused this. Water management practices play a significant role where well-executed practices lead to reduced emissions. The choice of energy source influences emissions, as systems powered by renewable energy emit less than those reliant on fossil fuels.

Furthermore, the specific soil can also impact emissions, with flood irrigation potentially causing higher emissions in certain anaerobic soil conditions. Maintaining and operating systems properly can improve performance and may reduce emissions. Emissions can be affected by regional climate, soil characteristics, and water availability. To fully understand emission variations among different irrigation systems, all these elements must be considered [68]. Notably, greenhouse gas emissions from HDPE production account for 16%, slightly exceeding those from PVC production at 14%, when considering pipelines of similar size in drinking water transport and distribution networks. This study [68] highlighted the crucial role of the operational stage, which influences GWP and involves the highest energy consumption. Analyses of various pipeline networks emphasized carbon steel pipelines contribute more to GWP compared to those made from alternative materials. Manufacturing emerges as the second most impactful stage in terms of GWP. In terms of materials, this study show that carbon steel pipes exhibit higher GWP than pipes made from other materials, while manufacturing concrete pipes contributes less to GWP than other materials. The study observes that, owing to the weight of concrete, the transportation of concrete pipelines results in the highest GWP. Conversely, the lightweight nature of HDPE translates to a lower environmental impact during transportation compared to other pipeline materials. Other approaches [56] focused on urban agriculture, conducted an LCA of urban farms and community gardens in several locations. The findings reveal that the primary sources of environmental impacts were attributed to infrastructure elements such as irrigation pipes and hydroponics structures, as well as factors like irrigation, compost, and peat used for seedlings. Water scarcity impacts were predominantly influenced by irrigation (90% to 99%). Among the various contributors to energy use, irrigation emerged as the largest, contributing an average of 19% to climate change impacts and 27% to energy resource use.

Given that electricity contributes to environmental impacts, it is noteworthy that the study [68] underscores the scenario investigated for 2019 as having the highest impact on climate change, totalling 57 Mt. of CO2e*year-1, attributed to coal and natural gas technologies. Although the emissions are expected to be eliminated by 2050, there will still be a climate change impact from other energy plant life cycle processes, amounting to 12 Mt. of CO2e*year-1 in 2050, reflecting an 80% reduction from the 2019 levels. The intermediate scenario for 2030 shows a moderate reduction of 47% compared to the 2019 impact. The study [68] advocates integrating Life Cycle Assessment (LCA) methods in future-oriented low-carbon building design and global urban planning to discuss anthropogenic climate change.

The variation in emissions produced by the type of irrigation used has been shown in multiple studies. Canaj et al. (2022) [69] showed that implementing smart sprinkler irrigation results in a 38% decrease in water and energy consumption compared to conventional irrigation. Compared to the results obtained, the emissions produced per hectare of both traditional and smart irrigation are 33.8% of those emitted by the current study (18 484,68 kg CO2e ha-1 per year for both types of irrigation compared to 13 657,7 kg CO2e ha-1 for the university network). It should be noted that the overall water and energy consumption in reference [69] are much lower than the study carried out given the water needs of the vegetation considered, stating that, despite the high-water consumption of the study, emissions are not only caused by water consumption, but also by the geometry, materials, and layout of the pipes in the irrigation network.

Since drip irrigation saves water and energy, Eranki et al. (2017) [70] quantified the different emissions in drip and flood irrigation. It indicated the influence on the total system impact of the two irrigation systems studied (50% of the overall impact for drip and 92% for flood irrigation). The pumping machinery for drip irrigation accounts for higher emissions (25% vs. 13%), considering the emissions generated by the materials and equipment used to run the network. Jamali et al. (2021) [71] quantify emissions from localised irrigation systems (sprinkler and drip irrigation) and find that they have lower emissions than flood irrigation. Flood irrigation generates 10 000 kg CO_2 ha^{-1}, while sprinkler irrigation emits 8 000 kg CO_2 ha^{-1}. These results are lower than the 'cradle to grave' result of the University's irrigation network, quantified at 13 657,7 kg CO_2 ha^{-1}. Drip irrigation — the only considering plastic materials (polyethene, 5% of total emissions for both cases) — produces 9 000 kg CO_2 ha^{-1}.

In this study, we verified that localised irrigation network produces the least impact on the environment, despite the similarity between the flood irrigation of Jamali et al. (2021) and the study of the irrigation network of the University. However, Kazemi and Zardani (2020) [72] opposite, considering the same factors. They obtained drip irrigation emissions (1 284,2 kg CO_2 ha^{-1}) are higher than flood irrigation (764,3 kg CO_2 ha^{-1}). This is due to two differential factors in drip irrigation, pumping equipment is used and it consumes fuel [71,72]. Acharya et al. (2015) [73] obtain similar conclusions, the emissions produced by sprinkler and drip irrigation systems (23 228.5 kg CO_2 ha^{-1} and 33 400 kg CO_2 ha^{-1}) are significantly higher than those obtained from blanket irrigation (10 114.3 kg CO_2 ha^{-1} and 16 000 kg CO_2 ha^{-1}). The latter values are closer to the result in this study.

Table 8.9 shows that the transport of materials and equipment to the installation site is a relevant parameter, as a direct source of emissions because of fossil fuels. Acharya et al. (2015) [37] presents the influence of materials manufacturing and transportation for both sites (approximately 83% and 17% versus 81.4% and 11.2% for the 'cradle to gate' result) were found to be factors to be taken into consideration for their contribution to overall emissions. Therefore, logistics produces a high percentage of carbon footprint by companies (up to 75%) [74]. It is therefore a term to reduce along with that related to end-of-life treatments.

8.6 Conclusions

The total CO_2e emissions produced by the irrigation network of the University of Alicante in every stage of its useful life have been quantified. The proposed calculation meth-od responds to the questions planned before.

- During the reference service life (25 years) 345 tonnes of CO_2e are emitted. Materials (127.9 Tn CO_2e; 37%) and energy (145.5 Tn CO_2e; 42%) are the stages where the highest GWP is produced and where action should be taken.
- Apart from these high percentages for materials and energy, repairs also stand out, with 18% (62 tonnes of CO_2e) of the emissions produced. Construction (6.3 tonnes of CO_2e) and transport of materials (3.5 tonnes of CO_2e) account for approximately 1%. These figures for transport, although they seem small compared to other stages, occur at a single point in time (during manufacture). It is possible to reduce the impact produced by this factor by using local suppliers.
- Following the results obtained, a potential solution to reduce emissions is to reduce operational energy in the use stage (B6). Renewable energy sources emerge as a workable choice considering the climate conditions in the region (solar, wind, etc.). Another potential choice (in the infrastructure design phase) would use materials with lower emissions as HDPE. This material (HDPE) has 11% fewer emissions compared to the current case (PVC and asbestos cement). This solution reduces modules A1 and B3.
- We can see the influence of materials at the product stage (A1–A3) and in the stage of repairs (B3). The current network (PVC and asbestos cement) and a network comprising PVC pipes (Cases 0 and 1) show higher GHG emissions. Therefore, the network comprising HDPE pipes (Case 2) results as the best choice for emission reduction in the product stage (A1–A3) as seen in Table 8.9.
- Manufacturing of the materials contributes to one-third (for PVC) to one-half (for HDPE) of the total emissions from the irrigation network's life cycle. HDPE has a lower impact in the production stage (A1–A3) but contributes more emissions in the repair and end-of-life stages (C2–C4) based on EN 15978 standards.

It has been proved that by replacing the current network with one made of HDPE pipes, a reduction is obtained in all stages. The reduction in this context can be observed in specific stages that have a onetime contribution rather than a cumulative effect. Shorter distances between suppliers and installation sites have led to a 73.3% decrease in transport emissions. Installing the network also leads to reducing 17.2% in emissions. The results obtained allow us to find materials (40%) and energy (42%) are the key stages with the greatest effects and, therefore, the ones to be acted upon first. Nearby suppliers can help reduce emissions by using eco-friendly materials. Furthermore, adopting renewable energy sources such as solar and wind power can serve as a sustainable alternative to conventional electricity, significant given that energy consumption is identified as a primary factor responsible for 42% of emissions. In terms of irrigation methods, drip irrigation is a more contemporary and efficient approach compared to flood or sprinkler systems. Additionally, the use of materials with lower environmental footprints and the implementation of water-conservation policies plays pivotal roles in curtailing emissions.

The present work has emphasized identifying the stages of the life cycle of an irrigation network and the corresponding emissions. Undoubtedly, this study identifies materials manufacturing and energy consumption during operation as the primary producers of emissions. Therefore, the results can be extrapolated to other similar facilities, as these life cycle stages should be addressed, as they are the most significant sources of emissions.

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Chapter 09

Environmental Impact Assessment of Multistorey Residential Buildings

Silvia Vilčeková, Eva Krídlová Burdová, Jana Budajová, Katarína Harčárová, Adriana Eštoková

Faculty of Civil Engineering, Technical University of Košice, 042 00 Košice, Slovakia

Building materials and used technologies in buildings can have negative influence on the environment and climate change through the life cycle of buildings. For this purpose, an assessment of the environmental impacts and circularity of 11 residential buildings was carried out using the LCA methodology. The buildings were assessed within a moderate climate zone and "Cradle to Cradle" system boundaries over a lifetime of 60 years. In general, product phase and operational energy contributed most to the high GHG emissions. Materials such as aerated concrete (up to 89.4%), concrete (20-51%) and clay brick (38-47%) caused the highest values of GWP. End-of-life phase including incineration, landfilling and reuse of materials was quantified in the range of 0.1-74%. Circularity scores, representing materials recovery, have reached values ranging from 23% to 48%. The best circularity score was due to downcycling (45.8%) and use as energy (32.1%) of applied materials. Using multicriteria analysis, the most suitable building in terms of environmental impact and circularity was identified.

9.1 Introduction

According to 2020 Global status report for buildings and construction, building sector was in 2019 responsible for 35% of total energy consumption and it stayed on the same level in 2019, compared to previous year. However, carbon dioxide (CO_2) emissions associated with operation of buildings, are increased and reached their highest values in 2019. In addition, operational energy was responsible for 28% of total global energy-related CO_2 (around 10 $GtCO_2$). Together with building construction industry it counts 38% of total global energy-related CO_2 emissions, of which 17% is directly or indirectly linked to residential buildings (United Nations

Environment Programme, 2020). The main goal in reduction of negative environmental impact is directed to reducing the energy for building operation. Over the years this strategy was implemented in the European Union (EU) by many directives. EU requirements are implemented in Slovak standard STN 73 0540-2 which lays down thermal technical requirements for building structures and buildings, which ensure the fulfillment of the basic requirements for buildings, in particular the fulfillment of the basic requirement for energy efficiency and heat recovery and the provision of hygiene, health and environmental protection. Buildings built after 1.1.2021 have to meet the requirements of nearly zero-energy buildings. Operational energy can be reduced by implementing more materials and different solutions. If more materials are built in, embodied energy rises, thus optimalisation in material and construction stage of life cycle could help and prevent shifting the burden from one stage to another. As mentioned in work of Sartori and Hestnes, the operational energy appears to be the most important aspect, but also embodied energy should be addressed as second instance (Sartori and Hestnes, 2007).

Reduction of energy demand and environmental impacts became priority in environmental policies in European countries as mentioned above. Life cycle assessment as an analytical tool is used for determining the environmental impacts and finding measure for improvements. The most suitable phase is pre-design and design stage, considering different building shapes, window sizes or orientation as studied in work of Monteiro et al. (2021). Impact of improving buildings to achieve higher energy standards is investigated in many studies (Blengini and Di Carlo, 2010; Citherlet and Defaux, 2007; Dahlstrøm et al., 2012; Lewandowska et al., 2013). Some of them deal with building materials and their proportion to the environmental impacts of buildings (Chen et al., 2020; Monahan and Powell, 2011). Different approach was taken with life span of the building as the main focus of the study (Mequignon et al., 2013). Improvements were also analyzed using different methods on the same case study (Din and Brotas, 2016). LCA is also used for the investigation of EoL, mainly for recycling potential of building materials (Thormark, 2002). Another study is focused on one building analyzing the major contributors as embodied energy (Asif et al., 2007). Comparison of representative building types for region is also the one of he main objective of the studies (Bastos et al., 2014). Such analysis highlights the importance of setting the functional units for the comparison of different building types. Other aspects have to be considered, such as regional data due to different climates and different energy sources for the electricity grid (Morales et al., 2019).

9.2 Goal and Scope

The aim of this study is to analyse multistorey residential buildings from environmental impacts indicators and circularity score. For the analysis OneClickLCA software was used. This is based on the international standards EN 15804, EN 15978, ISO 14040 and ISO 14044. Functional unit (FU) was set as one square meter (m2) of usable floor area and estimated design life is 60 yearsSystem boundary were set to ''Cradle to Cradle'' and life cycle stages included are shown in Figure 9.1. Circularity relates to the end of life phase C1-C4 (EoL). Finally, the buildings were subjected to multicriteria analysis for which MCA7 software was used. The decision methods, namely weighted sum method (WSA), ideal point method (IPA), concordance and disagreement method (CDA) and TOPSIS method (Korvin; 2010) were applied.

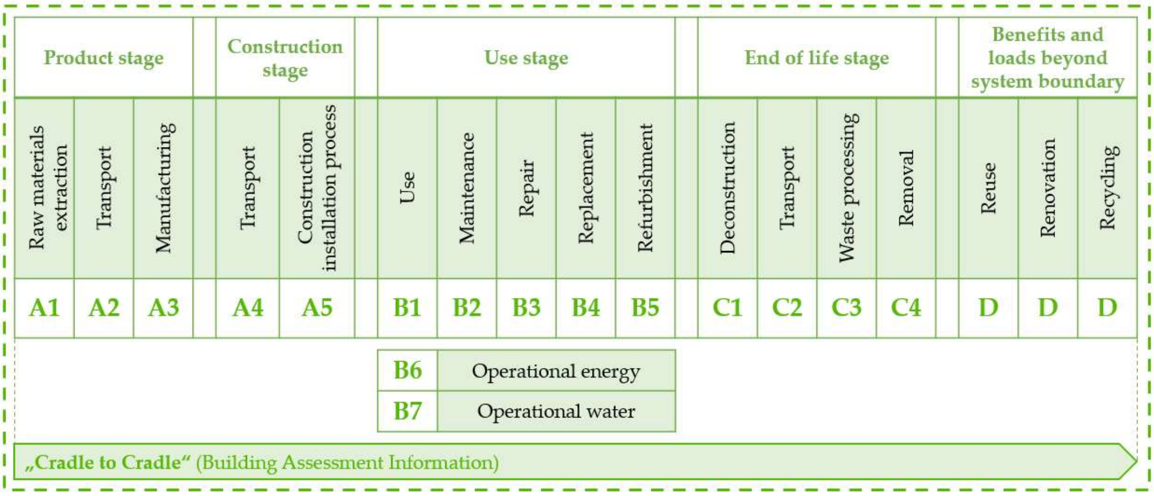

Figure 9.1. System boundaries in LCA

9.3 Life Cycle Inventory Analysis

Life cycle inventory analysis (LCI) was used to calculate the environmental impacts. Evaluated 11 residential buildings were built or undertook construction in years from 2017 to 2023. Basic characteristics of the buildings are presented in table 9.1.

Table 9.1. Basic characteristics of buildings marked as A - K

	Building A	Building B	Building C	Building D	Building E	Building F
Location	Trnkov	Košice	Bratislava	Bratislava	Humenné	Košice
Build-up area	330.1 m²	1 286 m²	2 477.6 m²	4 957 m²	297 m²	1 866.3 m²
Usable floor area	1 166.1 m²	4 608.1 m²	11 721 m²	3 607 m²	1 177.8 m²	7 981.4 m²
Number of apartments	12	50	123	89	11	134
Number of polyfunctional spaces	0	2	0	0	0	0
Number of floors	4	7	8	8	4	7
Elevator	1	1	2	2	2	2
Construction year	2022	2020	2019	2021	2017	2019
	Building G	Building H	Building I	Building J	Building K	
Location	Poprad	Poprad	Raslavice	Košice	Trenčín	
Build-up area	271.4 m²	437.6 m²	170.3 m²	5 500 m²	348.3 m²	
Usable floor area	849.4 m²	5 059 m²	418.1 m²	42 000 m²	1 266 m²	
Number of apartments	14	45	6	350	9	
Number of polyfunctional spaces	0	0	0	0	2	
Number of floors	4	13	8	10	3	
Elevator	0	1	0	9	1	
Construction year	2009	2020	2019	2021	2022	

The residential buildings have already been constructed and meet the thermal technical requirements for buildings according to the applicable international standards. All the materials used, and their quantities are determined and used in the analysis. In all buildings a reinforced concrete frame (columns and beams) supplemented with fill masonry was used. The roofs of the selected buildings were conventional flat roofs. The energy supply was provided by gas condensing boilers or district heating. The water for drinking, sanitary facilities and for the building fire safety system is provided by the public water supply. Public grid was used as electricity source. Information about operational energy was obtained from project documentation and energy performance report or from technical report. The results of the environmental assessment of residential buildings were expressed per 1 m^2 FU for the comparison. The OCL software followed the CML and PEF methodology as well as the European approach to level(s) assessment. Various databases and data sources such as Ecoinvent, OneClickLCA, GaBi, Okobaudat and EPD were used in the analysis. For materials without declared environmental information, average valus of environmental indicators are considered. The OCL software was used to conduct an environmental evaluation of the buildings' life cycle and their circularity, following LCA principles. The buildings were assessed within the boundary of the "Cradle to Cradle" system for a building lifetime of 60 years. Building circularity was assessed using the Building Circularity Indicator (BCI).

9.4 Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) is a method used to assess the potential environmental impacts of a product or service throughout its entire life cycle, from raw material extraction to disposal. LCIA helps to quantify and understand the environmental burdens associated with a product or service, enabling informed decision making and sustainable practices. LCA categories refer to different impact categories that are considered when assessing the life cycle of a product or service. These categories typically include factors such as greenhouse gas emissions, energy consumption, water consumption, land use and toxicity. By analysing these categories, researchers can assess the environmental impacts of a product or service throughout its life cycle. They use a variety of indicators at different levels such as global, regional, and local impact categories (Hauschild et al., 2018).

Global environmental indicators monitor the state of the environment at a worldwide level, including greenhouse gas emissions, air and water quality, biodiversity, and deforestation, such as GWP potential for climate change, ODP potential for ozone depletion and ADP-E. Regional indicators target a specific region, monitoring air and water quality, land use, biodiversity, waste, and energy consumption such as AP, EP and POCP. These measurements help identify environmental problems and shape strategies for conservation and sustainable development. Local indicators measure the state of the environment in the local area, and include air and water quality, waste management, green spaces, noise pollution, and community involvement in environmental initiatives such as ADP-FF and WD. Impact category indicators included in the calculation are shown in Figure 9.2.

Impacts categories indicators	Abbreviation	Unit
Global Warming Potential total	GWP total	kg CO_{2e}
Global Warming Potential fossil	GWP fossil	kg CO_{2e}
Global Warming Potential biogenic	GWP bio	kg $CO_{2e\ bio}$
Global Warming Potential, LULUC	GWP LULUC	kg CO_{2e}
Depletion potential of the stratospheric ozone layer	ODP	kg $CFC11_e$
Acidification potential	AP	mol H+ eq.
Eutrophication aquatic freshwater	EP-AF	kg Pe
Eutrophication aquatic marine	EP-AM	kg $N_{eq.}$
Eutrophication terrestrial	EP-T	mol $N_{eq.}$
Formation potential of tropospheric ozone	POCP	kg $NMVOC_{eq.}$
Abiotic depletion potential for non-fossil resources	ADP-E	kg Sb_e
Abiotic depletion potential for fossil resources	ADP-FF	MJ
Water use m^3 deprived	WD	m^3

Figure 9.2. Parameters describing the main environmental impacts

9.5 Results and Discussion

The life cycle assessment of residential buildings was divided into three impact categories, namely global, regional, and local. *Global indicators* are presented in Figure 9.3 for each stage of the life cycle. The study evaluated the global indicators and found that in terms of total GWP, building K causes the largest CO_{2e} emissions, 3 576.81 kg CO_{2e}/m^2. Among the materials that contribute the most to the negative environmental impact of building K includes autoclaved aerated concrete, which accounts for up to 89.4%. The A1-A3 phase of products contributed a large share to the GWP category, namely 2 474.45 kg CO_{2e}/m^2. This was followed by the operational energy (B6) with 673.96 kg CO_{2e}/m^2. Transport (A4) and EoL (C1-C4) had the lowest environmental impacts. The benefits and loads from incineration, landfilling and reuse under Module D for the global indicators are 5.42%.

A study from New Zealand that evaluated 2 two-storey buildings within the syste mboundary "Cradle to Cradle" found that the lightweight timber building emitted 13.7 kg CO_{2e}/m^2/year while the lightweight steel building emitted 15.4 kg CO_{2e}/m^2/year. Operating energy in both buildings was the most significant contributor to carbon emissions at 49.5 to 57.6%, over the entire life cycle of the building, followed by the A1-A3 product phase. The estimated lifetime of these buildings was 90 years which required more operational energy compared to the other phases of the building life cycle (Dani et al.; 2022). Petrovic et al. in a study from Sweden found a very similar result. The authors evaluated a smaller residential building made of wood with a 100-year lifetime where the "Cradle to Grave" system boundary was used. The production phase contributed 30%, the maintenance phase 37%, contributing the most to the total carbon emissions up to 67%, while the operational energy contributed only 21%. The EoL phase was the least represented with only 2%. In terms of materials, concrete contributed the most with 6.1 t CO_{2e} which made up 19% of the total emissions (Petrovic et al.; 2019). Chandrakumar et al. analysed the total carbon emissions of a residential building in New Zealand with a 90-year lifetime in the "Cradle to Grave" system boundary. Their research determined that the building emitted 16 kg CO_{2e}/m^2/year. Results of CO_{2e} for residential buildings in other countries ranged between 10 and 90 kg CO_{2e}/m^2/year. Operational energy (60%), maintenance and replacement (13%) and product phase (12%) contributed the most to climate impacts (Chandrakumar et al.; 2020). A study from Canada examined a two-storey residential building in terms of environmental impacts over a 60-year lifetime within the system boundary of the "Cradle to Grave". The study determined that operational energy caused almost half of the total environmental impacts, followed by the production phase with a share of 7 to 51% for all indicators evaluated (Zhang er al.; 2013). According to Rashid et al. in the pre-use phase, concrete in foundations was identified as the largest contributor to GWP, acidification and eutrophication (Rashid et al.; 2017). According to Vitale et al. in assessment of a residential building in Italy, they found that the use phase had the largest contribution to total emissions at 77% and 84% for the global warming and non-renewable energy indicators, respectively (Vitale et al.; 2017). A study in China showed that a residential building emitted 2993 kg CO2e/m^2 over its estimated 50-year lifetime. The operational energy contributes 68.9% of the total GHG emissions and the product phase contributes 23.9%. In terms of materials, concrete is the most widely used building material and contributes 44% of the total GHG emissions (Yang et al.; 2018). In a study from Saudi Arabia, an LCA was performed to analyse the life cycle environmental impacts of a typical residential building within the boundary system "Cradle to Grave". The authors found that operational energy had the most significant impact on GWP over the 50-year life cycle. By applying renewable energy sources, it would be possible to reduce CO_2

emissions from electricity by 53%, but this remains negligible when considering the overall environmental impact of the building (Alhazmi et al.; 2021). A study from Brazil examined residential buildings in terms of their environmental impacts within the boundary of the "Cradle to Grave" system over a 50-year lifespan. According to the results, operational energy is the most critical, and in terms of construction, foundations, masonry and coatings have the greatest impact. In terms of materials, concrete, ceramic tiles and steel contributed the most (Evangelista et al.; 2018). A life cycle energy analysis was performed in a study of eight residential buildings from Australia. Embedded energy was found to account for 10 to 30%, while operational energy accounted for 65 to 90%. Demolition energy was less than 4% of life cycle energy (Guan et al.; 2015).

In terms of the ADP-E category, building C is the largest contributor with 30.09 kg Sbe/m^2. For almost all the buildings assessed (buildings A-K), the largest emissions were caused by the operational energy (B6) required for heating and hot water preparation in the range of 37-72% and in the product phase (A1-A3) in the range of 37-70%. The materials with the highest CO_{2e} emissions are concrete at 20-51 %, clay bricks at 38-47 % and aerated concrete at 89.4 %.

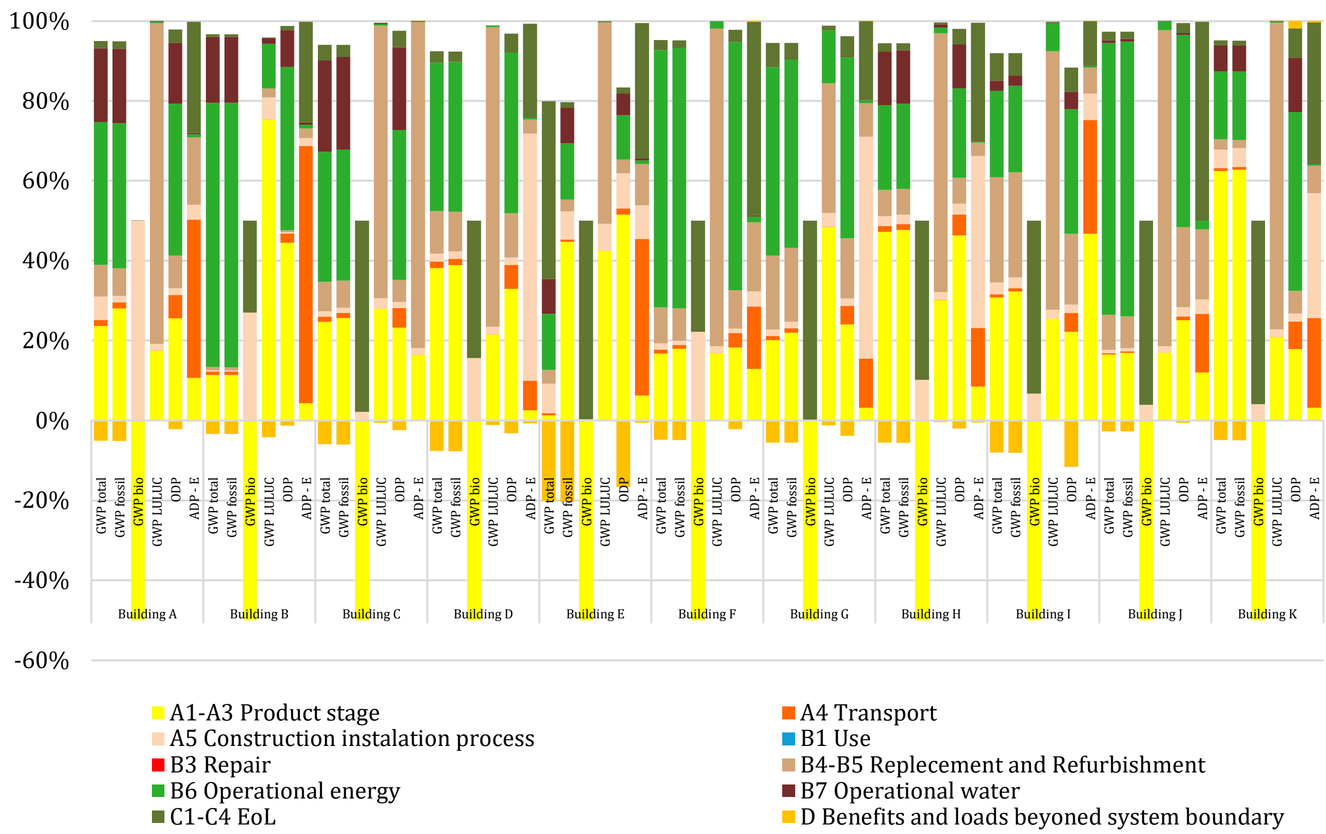

Figure 9.3. Global indicators expressed for each life cycle phases in percentages

Considering ***regional indicators***, building B caused emissions of 14.89 mol H+ eq./m² for the AP category and 31.38 mol Neq./m² for the EP-T category. The energy consumption phase (B6) was the worst in terms of these indicators and had a portion of 65-89%. Building E caused emissions of 1.65 kg Pe/m² in the EP-AF category, 2.29 kg N eq./m2 in the EP-AM category and 7.32 kg NMVOC eq./m² in the POCP category. The product phase (A1-A3) was also the worst in terms of these indicators, accounting for 63-85% of the total emissions. The EoL phase (C1-C4) had the lowest impact. Module D representing potential of benefits and loads beyond the system boundary range from 0.1-37%. Materials with the highest contribution for building B were precast concrete slab (34.2 - 42.91%), transport concrete (25.5 - 29.2%) and clay bricks (4.7 - 6.5%). In building E, materials with the highest contribution were multi-layered hardwood floors (85.1-90%) and concrete (3.01-4.4%).

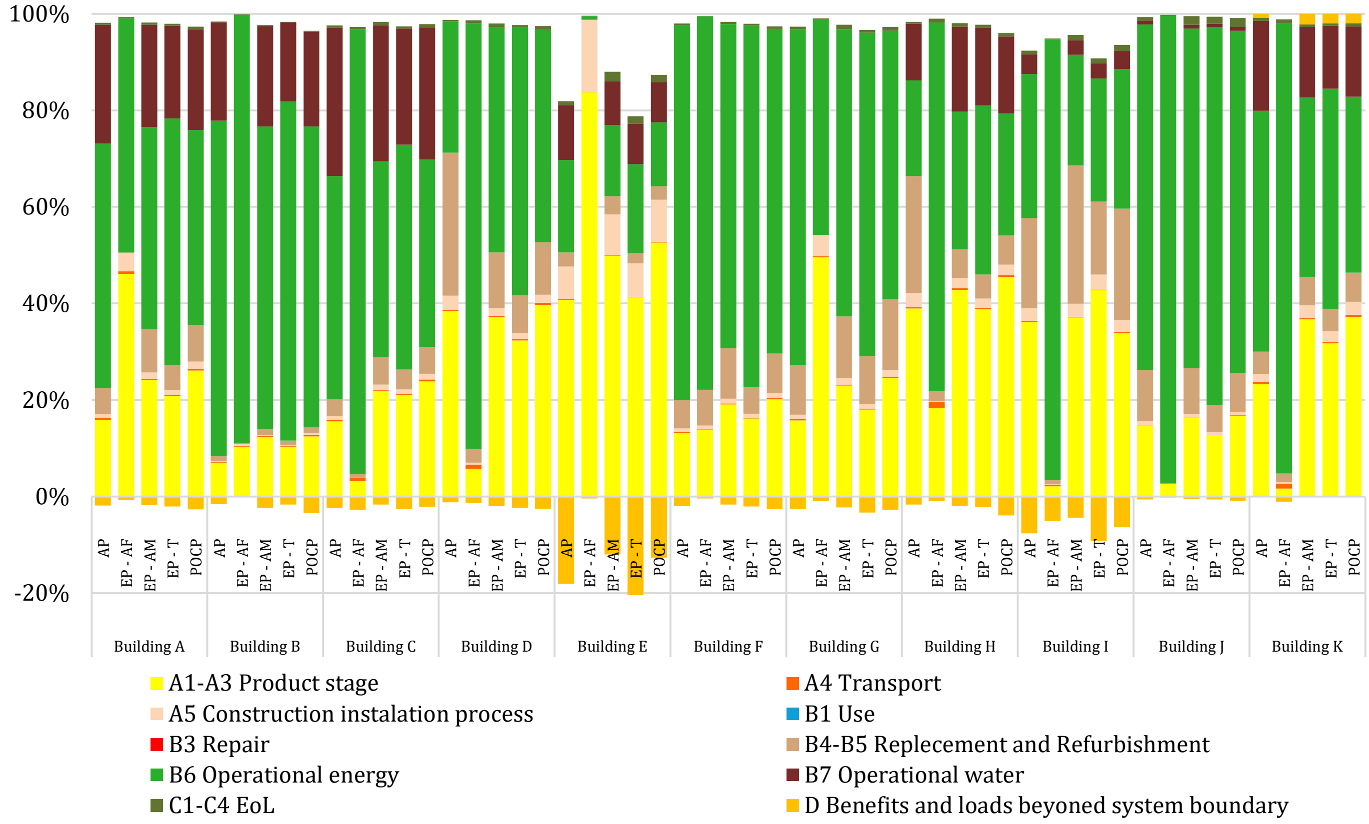

Figure 9.4. Regional indicators expressed for each life cycle phase in percentages

In terms of *local indicators*, building F achieved values of 44,610.58 MJ/m² and 5,693.46 m³/m² for ADP-FF and WD, respectively. Building K achieved also the worst results for ADP-FF and WD with values of 39,797.21 MJ/m² and 7,118.72 m³/m², respectively. On the other hand, building D (20,991.6 MJ/m²; 2,146.8 m³/m²) reached the lowest values. Operational energy B6 contributed the most to local indicators, with a range of 42.6-92.5% for all buildings. The EoL indicator (C1-C4) had the lowest impact. For Module D, the benefits and loads beyond the system for local indicators range from 0.07-29.3% for all buildings. Regarding building F, the three materials with the highest contribution were concrete (22.9% and 71.9%), reinforcement (1.2% and 16.3%), and EPS insulation (20.5% and 0.6%). Related to the building K, concrete (34.3% and 97%), reinforcement (16.3% and 1%) and EPS insulation (21.6% and 0.6%) contributed mostly to the local impacts.

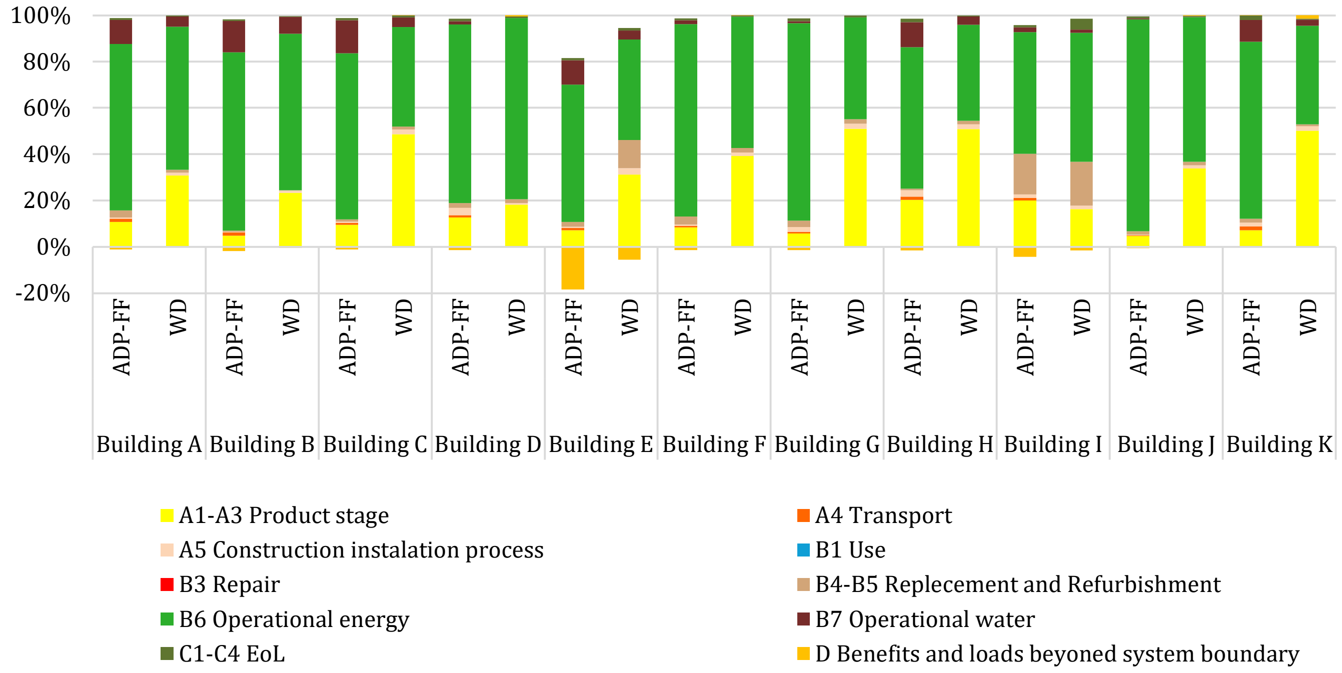

Figure 9.5. Local indicators expressed for each life cycle phase in percentages

Table 9.2 listed the materials that contribute most to GWP in the product phase (A1-A3) and their percentage in buildings. Aerated concrete caused 0.42 kg CO2e/kg (166 kg CO2e/m3) with with a share of up to 89.4% of the total emissions caused by the materials. They are followed by clay brick with a share of 78%, reinforcement steel with a share of 59.2%, concrete with a share of 50.9%. Higher values were also achieved by PVC frame window, lime-cement plaster, cement screed and precast concrete.

Table 9.2. Most contributed materials to GWP. Total value in t CO2e / percentage.

	Building t CO2e / %									
Material	A	B	C	D	E	F	G	H	I	J	K
Clay brick, CO_2	114	92	335	80	32	170	70	1 568		339	
	39	7.3	9.7	6.7	78	6.2	39	47		3.5	
Ready-mix concrete, normal strength, generic, C25/30, with CEM I, 0% recycled binders	71		1 751		61	565		608		2 025	125
	24.1		50.9		20	20.7		18.2		20.7	4
Ready-mix concrete, normal-strength, generic, C30/37, 0% recycled binders in cement (300 kg/m³)		179		560		413		241			
		14.2		46.5		15.2		7.2			
Autoclaved aerated concrete blocks, 388 kg/m³ CO_2		82 t							38		2 800
		6.5							13.1		89.4
Reinforcement steel (rebar), generic, 97% recycled content (typical), A615 CO_2			240	107		345			171	877	
			7	8.9		12.7			59.2	9.0	
PVC frame window, double-leaf, triple-glazed, per m², U= 0.76 W/m²K, 76mm, 43.658			127	142			28	219		1 471	
			3.7	11.8			15.7	6.6		15	
Lime-cement plaster, L = 0.8-0.9 W/mK, 1800 kg/m3, EN15804+A2							16		7.5		
							8.9		2.6		
Cement based self-levelling screed, 1600 kg/m³ CO_2	6.3				24			156			53
	2.2				2.4			4.7			1.7
Precast concrete cover slab, C30/37, 50 mm, XC1-XC4 CO_2		604									
		47.7									

Top materials: first (orange); second (orange); third (orange); fourth (orange)

Table 9.3 showed the materials that are the most wastage. Wood-based materials such as softwood lath (17.9%), structural timber (17.9%), medium density fibreboard MDF (16.7%) or oriented strand board OSB (16.7%) were in the top ranks. Wood-based waste is generated in large quantities in construction activities. Such waste is a renewable resource that can be recycled and used to produce eco-friendly products and renewable energy (Hossain et al.; 2018). Waste wood was used for wood incineration or reuse of the material. Materials with a higher share of waste included gypsum plaster, cement mortar, PVC-P roofing membrane, gypsum plaster board, geotextile, dry mortar or polyethylene vapor barrier membrane.

Table 9.3. Most wastage materials

Material	A	B	C	D	E	F	G	H	I	J	K
Softwood lath (stud), kiln dried, planed, 440 kg/m^3, 10% moisture content, coniferous wood	17.9%										17.9%
Gypsum plaster, from 100% natural gypsum, in powder form	13%	13%	13%	13%							
Cement mortar (One Click LCA)	13%	13%				13%					
Gypsum lime plaster, 900 kg/m^3, EN15804+A2	13%										
PVC-P roofing membrane reinforced with glass fibre fleece, 3.1 kg/m2, FATRAFOL 814 (Fatra a.s.)	10%			10%	10%	10%			10%		
Woven polypropylene geotextile, 0.11 kg/m^2	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Gypsum plaster board, regular, 10% recycled gypsum, 6.5-25 mm (0.25-0.98 in), 10.725 kg/m_2 (2.20 lbs/ft^2)		12.5%				12.5%				12.5%	
Lime cement plaster		13%	13%					13%			13%
Ceramic glazed tile, 20 kg/m^2 (One Click LCA)		10%	10%	10%		10%	10%				
Rock wool (mineral wool) insulation without facing, L=0.036 W/mK, R=0.83 m^2K/W, 150 mm, 4.5 kg/m^2, 150 kg/m^3, PTS, TPE (Knauf Insulation)		8%		8%		8%		8%		8%	8%
Polyethylene vapour barrier membrane, 0.15 mm, 0.14			10%			10%		10%			
EPDM waterproofing membrane, 1.5 mm, 1.95 kg/m^2			10%		10%		10%				
Autoclaved aerated concrete solid blocks, 100x150x300 mm (4x6x12 in), 600 kg/m3, 2.83 kg/unit, fly ash content 70%			7.5%						7.5%	7.5%	
Gypsum plaster board, regular, 10% recycled gypsum, 6.5-25 mm (0.25-0.98 in), 10.725 kg/m^2 (2.20 lbs/ft2) (for 12.5 mm/0.49 in), 858 kg/m3 (53.6 lbs/ft^3)			12.5%						12.5%		12.5%
Dry mortar, 35/65/650(MC2.5) (Dan-Grit A/S)				13%				13%	13%		
Medium density fibreboard (MDF), 19 mm, 760 kg/m^3					16.7%						
Oriented strand board (OSB), 613 kg/m3, 3% moisture content					16.7%	16.7%	16.7%				
Structural timber, spruce, 450 kg/m3, 15% moisture content, KVH® structural timber (Stora Enso)					17.9%				17.9%		

first (orange); second (orange); third (orange); fourth (orange)

Based on multicriteria analysis, the most optimal building was found. According to the CDA evaluation criteria, building D achieved best value and ranked second according to all other evaluation criteria (IPA, WSA, TOPSIS). Based on the IPA and WSA, the most optimal building is A, and TOPSIS, building C. Building G was ranked second (CDA) and third (IPA, WSA and TOPSIS). Building K ranked worst according to all evaluation criteria. Materials such as aerated concrete

(2 799.6 t CO_{2e}) and reinforced concrete (124.8 t CO_{2e}) belong to the largest contributors. Results of the multicriteria analysis are presented in Table 9.4.

Table 9.4. Results of multicriteria analysis.

	Building	CDA	Building	IPA	Building	WSA	Building	TOPSIS
1	Building D	4.2051	Building A	0.2063	Building A	0.7937	Building C	0.7054
2	Building G	4.6376	Building D	0.2312	Building D	0.7688	Building D	0.6851
3	Building A	4.8072	Building G	0.2563	Building G	0.7437	Building G	0.6814
4	Building H	6.2326	Building H	0.3365	Building H	0.6635	Building H	0.6442
5	Building J	6.6161	Building C	0.3427	Building C	0.6573	Building J	0.6224
6	Building C	7.3376	Building J	0.3864	Building J	0.6136	Building E	0.6146
7	Building E	7.5859	Building E	0.3963	Building E	0.6037	Building I	0.5648
8	Building I	9.8051	Building I	0.4745	Building I	0.5255	Building B	0.5049
9	Building F	9.8467	Building F	0.5714	Building F	0.4286	Building F	0.504
10	Building B	10.358	Building B	0.6046	Building B	0.3954	Building A	0.4956
11	Building K	10.8917	Building K	0.6844	Building K	0.3156	Building K	0.4533

9.6 Conclusion

This research focused on the life cycle assessment of 11 residential buildings in terms of their environmental impacts. The data obtained from these assessments were subjected to a multi-criteria analysis to produce a ranking of the residential buildings with the highest and lowest environmental burdens. Results of the multicriteria analysis show that building D scored the best according to the CDA evaluation criterion. According to the other evaluation criteria (IPA, WSA, TOPSIS) this building ranked second. The building A received the best ratings according to IPA and WSA evaluation criteria and building C according to TOPSIS. The worst ranked building according to all evaluation criteria is building K. Within the assessed residential buildings, the operational energy (B6) caused significant emissions for all assessed indicators. This was followed by the product phase (A1-A3). The transport phase (A4) had the least impacts. Materials with the largest contribution to GWP were aerated concrete, concrete, clay bricks and reinforcing steel.

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Chapter 10

LCA and Emissions Analysis of the University of Alicante Business Creation Centre

Fuster-Casas., S.C. [a], Galao, O. [a], and Pardo, M. A.[a]

a Department of Civil Engineering, University of Alicante, 03690 Alicante, Spain

The transition to renewable energy sources and improving energy efficiency are crucial factors in reducing carbon emissions in the construction sector. In the future, clean energy technologies like solar and wind power will be crucial for sustainability goals. Implementing zero or positive-energy buildings, which generate more energy than they consume, will also be necessary. LCA methodologies need an upgrade to include considerations of the entire life cycle of renewable energy technologies, from producing equipment to its decommissioning and recycling. The ability to adapt to new technologies and energy sources will be key to minimising the environmental impact of construction projects in the future.

10.1 Introduction

As part of its European Green Deal, the EU has set ambitious goals to reduce CO2 emissions (Commission et al., 2021). This policy framework aims for a climate-neutral EU by 2050, with interim goals of reducing greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels (EU, 2018). To achieve these targets, the EU is focusing on decarbonising key sectors, including energy, transportation, and industry. By motivating renewable energy sources, encouraging energy efficiency, and promoting sustainable practices in industries, the EU aims to lower emissions across the continent. By implementing carbon pricing through the Emissions Trading System (ETS), businesses are encouraged to move toward cleaner energy sources. This is because they are directly confronted with the cost of carbon emissions, which motivates them to reduce their environmental impact.

The Intergovernmental Panel on Climate Change (IPCC) created four climate change scenarios, called Representative Concentration Pathways (RCPs). These scenarios predict different levels of greenhouse gas (GHG) emissions through 2100. These scenarios range from RCP2.6, the most hopeful, to RCP8.5, the most concerning, which assumes an increase in radiative forcing of 8.5 W/m^2. Radiative forcing reflects the difference between solar energy absorbed by Earth and the energy it radiates back into space (Shindell et al., 2013).

Many scientific frameworks are trying to find critical thresholds in Earth's biogeochemical and ecological processes that keep the planet's stability and resilience. The nine key "Planetary Boundaries" established by the Stockholm Resilience Centre show that some have already been exceeded (like climate change and biodiversity loss), while others are in danger zones. Exceeding any of these boundaries may lead to abrupt, catastrophic changes, threatening the stability and resilience of the global systems that support life (see Figure 10.15). The aim is to raise awareness among governments, businesses, and citizens to operate within these boundaries to secure a sustainable future for the coming generations.

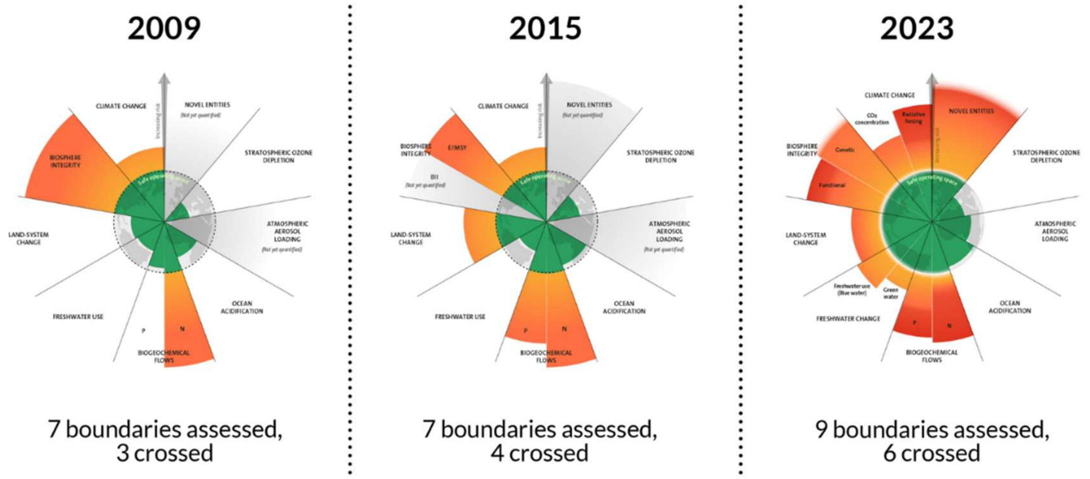


Figure 10.15. The evolution of the planetary boundaries' framework. Azote for Stockholm Resilience Centre, Stockholm University
(Richardson et al., 2023; Rockström et al., 2009; Steffen et al., 2015)

GHG emissions vary by industry sector, with energy production and consumption being the largest contributor, responsible for 80% of global emissions in the US and Europe (Pavel and Polina, 2024). This includes emissions from electricity generation, heat production, and transportation, with fossil fuel combustion as the primary source. The industrial sector accounts for 19% of global emissions (Moscoso, 2018; Worrell et al., 2018), because of energy use and high-emission processes like steel and concrete production. Agriculture, forestry, and land use contribute around 14% (Domen, 2009), through methane from livestock, nitrous oxide from fertilisers, and deforestation. Other sectors, such as buildings —23%; (Huang et al., 2018) — also contribute but to general emissions. Efforts to reduce emissions across these sectors are critical to meeting international climate goals, as each sector has unique challenges and opportunities for sustainable transformation.

In construction, Life Cycle Assessment (LCA) is a systematic method for evaluating the environmental impacts of a product, process, or service (Eštoková et al., 2023; Häfliger et al., 2017) throughout its life cycle, from raw material extraction to disposal. LCA aims to offer a comprehensive view of these effects, identifying opportunities for sustainability improvements. This analysis covers impact categories such as greenhouse gas emissions, resource depletion, energy use, water consumption, and waste generation(Nwodo and Anumba, 2019).

Building Information Modelling (BIM) is a digital process for planning, designing, constructing, and managing buildings (Hosseini et al., 2018). It involves creating a 3D model that integrates data on structural, mechanical, electrical, and plumbing elements.

Combining BIM and LCA is crucial for making construction more sustainable (Vilutiene et al., 2019). BIM creates detailed digital models, and LCA assesses environmental impacts. Together, they offer an effective framework for addressing the environmental footprint of construction projects. Several studies have applied BIM and LCA to residential buildings (Yang et al., 2018), illustrating carbon footprint calculations for a building. Other research has focused on assessing embodied carbon and environmental impacts in high-rise buildings, identifying materials and processes with significant effects (Ma et al., 2024). Other works utilised BIM-LCA for large-scale public buildings, managing emissions in complex projects (Cheng et al., 2020). Challenges appear when considering interoperability and data complexity, highlighting the lack of standardisation as a significant barrier and reviewing BIM-LCA methods and recommended standardisation and enhanced interoperability (Soust-Verdaguer et al., 2017). Recent advancements in BIM-LCA, including emerging technologies like AI and machine learning were explored (Chen et al., 2024), which promise to improve accuracy and efficiency. A review of the BIM-LCA literature, emphasising trends and future research needs was conducted (Obrecht et al., 2020), identifying developing common standards and improved LCA databases. The methodologies for integrating BIM and LCA methodologies for integrating BIM and LCA to enhance information management throughout the construction process were evaluated

(Guignone et al., 2023) to enhance information management throughout the construction process.

This study examines the Business Creation Centre Building at the University of Alicante, constructed with reinforced concrete. Through cradle-to-gate simulation, it quantifies carbon dioxide equivalent (CO_2-eq) emissions using Global Warming Potential (GWP). First, a 3D model of the Business Creation Centre building at the University of Alicante was created using Autodesk's Revit software. The official project documentation served as a reference and guide for starting the model, provided by the Business Creation Centre management office. Because the original construction materials, including their manufacturers and countries of origin, were not available, standard materials like concrete, aluminium, and glass (similar to those specified in the project) were used for the modelling. The research details the analysis process, data collection, methodologies, software used, results, and interpretations. The main aim of the present study was to measure CO_2 emissions of the materials used in the building's construction, considering the concrete's major structure (including foundation), external steel service structure, enclosures and main finishes.

In this study, the researchers aimed to answer the following key questions.

1. Which life cycle materials contribute the most to emissions?
2. How do emissions compare to locally sourced and distant materials?
3. What is the best approach for conducting an LCA analysis?
4. How can LCA support more sustainable construction practices?
5. What is the influence of energy in future cases?

The described method could be applied to other locations, with few limitations, making it universally applicable. However, as seen, the geographical location of the installation imposes most of the parameters, but a few can be changed. This study determined the data and software necessary to analyse equivalent CO_2 emissions. After obtaining the results, a general summary of the calculations performed was created, and then the findings from this building were analysed and compared with earlier research. Finally, conclusions that answer the questions were drawn. This helped extract relevant conclusions to contribute to the goal of reducing emissions in the construction sector. Some pictures of the actual state of the building are shown in Figure 10.16.

10.2 Methods and Procedures

In this work, interoperable BIM and LCA software were used, generating a constant and fluid workflow, resulting in considerable time savings. The focus was set in a concrete structure building that includes curtain walls and an external auxiliary steel structure.

Initially, we only had access to the construction project documentation for the Business Creation Center at the University of Alicante. This documentation was in pdf format and provided by the Centre's Management Office. This was a major drawback because we needed to spend hundreds of hours developing the model, even checking the accuracy of the plans against reality. This is a lesson learned that Public Administrations should have etched into their memory.

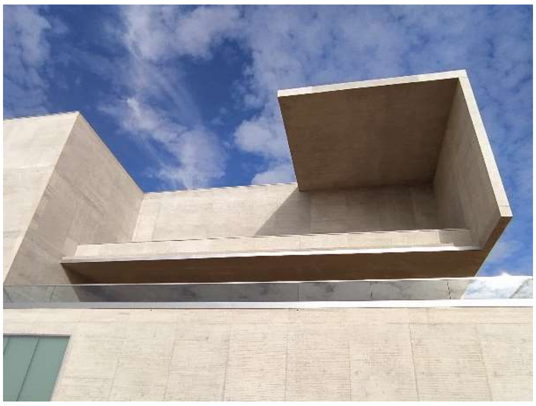


Figure 10.16. Current pictures of the building (Nov. 2024)

10.3 BIM Methodology

BIM methodology makes up an environment where collaborative work predominates in the creation and management of a construction project. Its goal is to centralise all project information in digital information models. Using this shared information, different programs can collaborate, which allows the construction project to progress and improve, encompassing more areas than a single program could manage.

The interoperability between Autodesk Revit and ONE CLICK LCA was key to this project. In addition, a series of programs and plugins facilitated and enhanced workflow efficiency. Revit helped to create the 3D model, which sent all relevant information to ONE CLICK LCA. The "LCA in Autodesk Revit" plugin allows integrating ONE CLICK LCA and Revit. This speeds up the data entry process into the "construction material" database of ONE CLICK LCA software. Users can conduct complete life cycle assessments (LCA) on the construction materials of their designs directly from Revit. The plugin enables users to perform quick analyses to decide the best material options (i.e., the most sustainable) while designing their models in Revit.

10.4 CDE

As Common Data Environment (CDE), the Open BIM - Revit plugin (from CYPE Ingenieros, SA) allows any Autodesk Revit user to integrate their model into the BIMserver. Centre platform and take advantage of all the platform’s features: representing BIM models in augmented and virtual reality; update control and issue management; participant management in the project; and connection with various Open BIM applications, including CYPE tools (Figure 10.17).

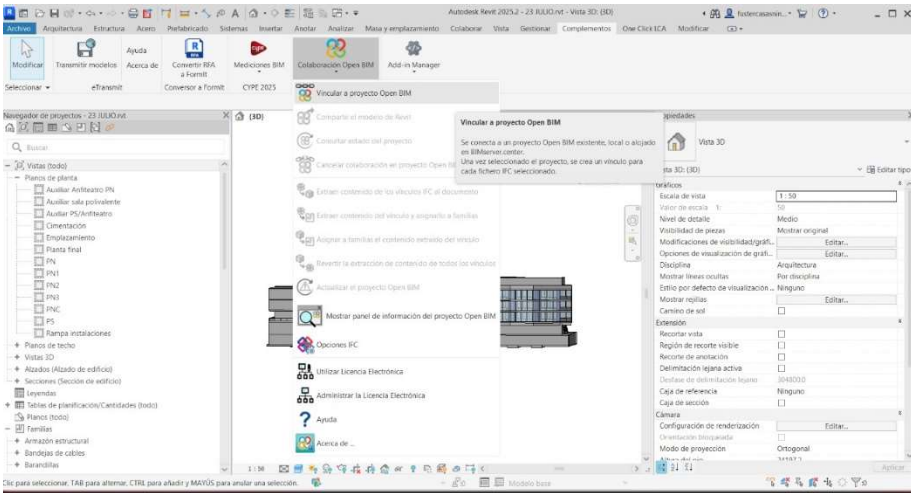


Figure 10.17. The main menu of the OpenBIM-Revit plugin (CYPE company).

With the "Open BIM - Revit" plugin, users can start an Open BIM project from Revit. This allows the Revit model to communicate with CYPE models, enabling real-time bidirectional collaboration between the different project disciplines and Revit through the exchange of IFC files. This improves communication between Revit and the specialised CYPE toolset, optimizing the BIM workflow.

In this study, the "Open BIM - Revit" plugin will be essential as a communication tool for the BIMserver. Centre platform, allowing all project collaborators to access the updated 3D Revit model.

10.5 BIM 3D Model Software

The main software used was the well-known Autodesk Revit tool, a BIM design tool used in architecture but also in civil engineering to create 3D models of various types of structures and buildings, facilitating their construction by providing correct representations through integrating user-generated sketches.

Using this software, a 3D model of the building under analysis was created, focusing solely on its architectural aspects and incorporating structural elements without achieving a high level of detail. Figure 10.18 shows the program’s framework and interface with the building under study modelled in 3D. This figure presents the Revit interface, which shows the modelling toolbar, views, and other options at the top. On the left side, the Project Browser includes Views, Schedules/Quantities, Sheets, Families, etc. On the right side, the Properties panel is for the selected object or view (a 3D view, in this case).

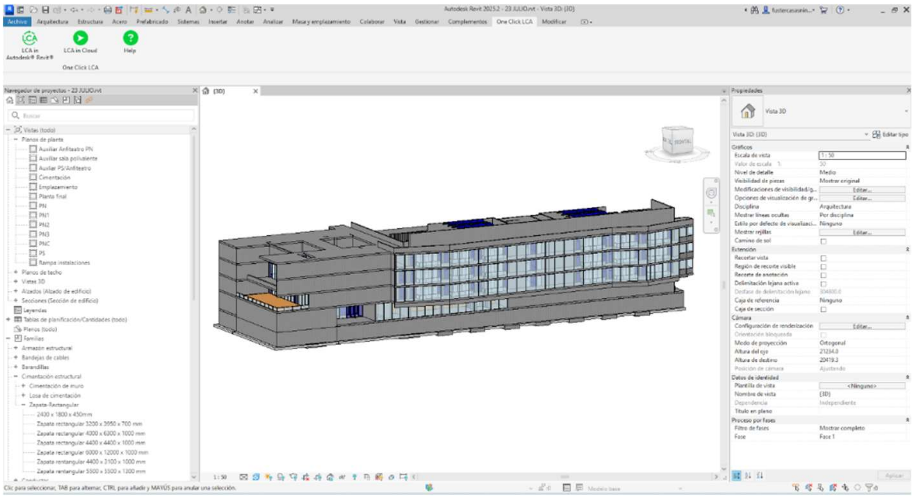


Figure 10.18. Revit program interface. Model of the Business Creation Center.

10.6 Life Cycle Assessment (LCA) Software

Life Cycle Assessment (LCA) has been developed employing the OneClick LCA software. One Click LCA is a leading software that automates the LCA process, integrating with BIM platforms like Revit and ArchiCAD. It facilitates sustainability analysis and environmental performance evaluation of buildings, allowing for efficient resource management and reduction of emissions.

The software returns information related to global warming potential (GWP), GWP per functional unit, and energy rating, based on the standards EN 15804, ISO 14021, and ISO 21930. Therefore, it shows the total impact produced only by the materials used, from the raw materials to their transport and processing in the factory. We define these results as "cradle to gate" because they encompass the process from material manufacture to the moment of use. We used the OneClick LCA Zero software for these results.

A second result refers to the same terms (GWP, GWP per functional unit and energy rating) but following the ISO 15 978 standards. This difference considers the complete infrastructure and its operation until the end of its life. The software OneClick LCA Levels uses this concept, known as "cradle to grave," because it considers the entire life cycle of the product.

The next step in this study, after modelling the structure in BIM using Revit, is to perform the life cycle analysis. For this step, the online program ONE CLICK LCA was used. Figure 10.19 shows the program's first interface.

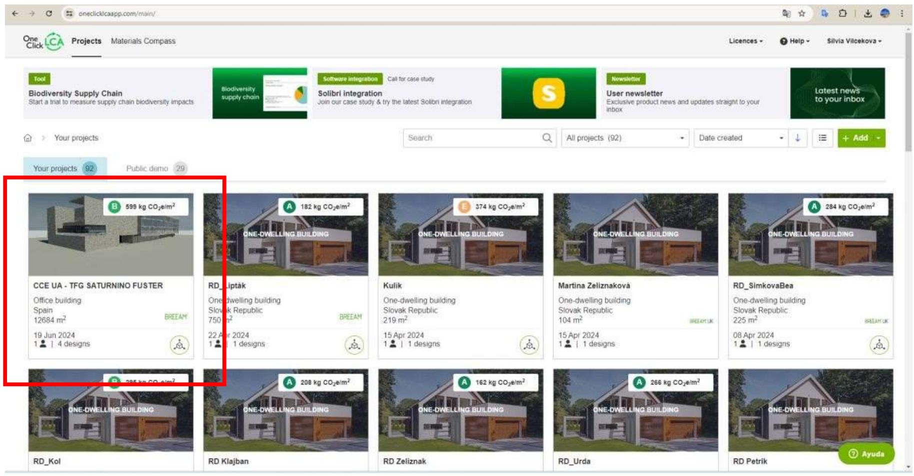


Figure 10.19. View of the ONE CLICK LCA software with this study highlighted in red

The ONE CLICK LCA workflow involves creating building designs and constructions where users enter various parameters, such as materials, building type, and surface area. The next step is to create a project design, in which you must enter various parameters, as shown in Figure 10.20. This will distinguish your design from the others. Users can create original designs within the same project and compare them. This project includes one major study and two variants, which we will explore further in future sections.

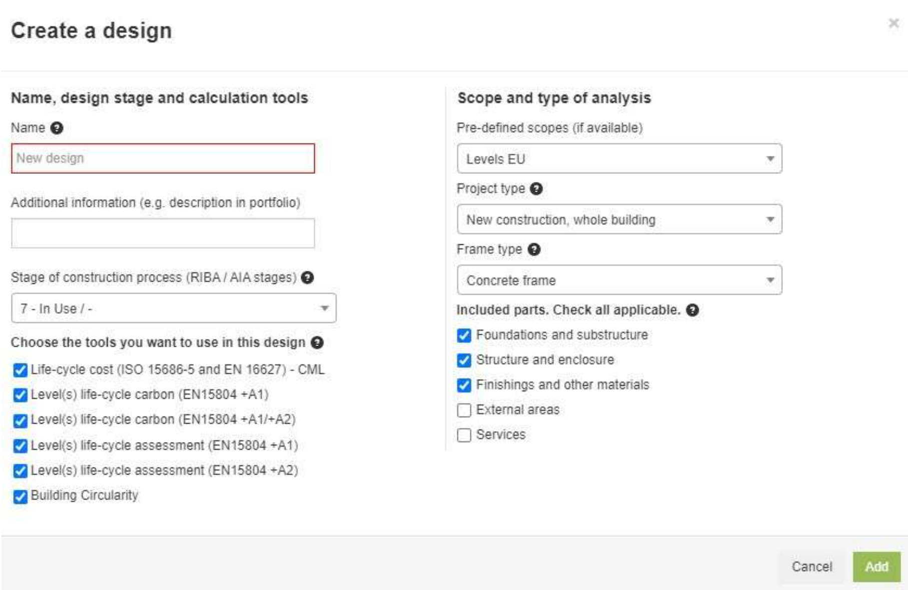


Figure 10.20. Data inserted for a project design.

As seen in Figure 10.20, this study considers the structure to be concrete, and includes the following tools:

Life-cycle cost (ISO 15686-5 and EN 16627),

Life-cycle carbon levels (EN15804 +A1) [Level(s) life-cycle carbon (EN15804 +A1)],

Life-cycle carbon levels (EN15804 +A1/+A2) [Level(s) life-cycle carbon (EN15804 +A1/+A2)],

Life-cycle assessment levels (EN15804 +A1) [Level(s) life-cycle assessment (EN15804 +A1)],

Life-cycle assessment levels (EN15804 +A2) [Level(s) life-cycle assessment (EN15804 +A2)], and

Building Circularity. The study also considered the structure, enclosures, finishes, and foundation.

Table 10.13 outlines specific concepts associated with Standard EN 15804:2012+A2:2019, categorising different lifecycle stages of a building. The product stage, encompassing stages A1 to A3, includes raw material supply, transport, and manufacturing. Stages A4 and A5 correspond to the construction process stage, which involves transportation to the construction site and assembly operations. Importantly, A4 and A5 also account for impacts from previous product stages (A1 to A3). In the use stage, the standard continues to track the impact of A-stages where applicable. For the end-of-life stage, the standard defines "C" stages to cover processes such as deconstruction, transport, waste processing, and disposal. Finally, the "D" stage is potential benefits and loads from reuse, recycling, and recovery beyond the building's lifecycle. This stage calculates the impacts avoided by reusing materials or products from the building after its end-of-life, promoting sustainable practices and circularity.

Table 10.13. Types of EPD concerning life cycle stages covered and life cycle stages and modules for the construction works assessment, in EN 15804:2012+A2:2019

EPD Type	Product Stage	Construction Stage	Use Stage	End of Life Stage	Beyond System Boundary
	A1 – Raw material supply	A4 – Transport	B1 – Use	C1 – Deconstruction	D – Reuse, recovery, recycling
	A2 – Transport	A5 – Installation	B2 – Maintenance	C2 – Transport	
	A3 – Manufacturing		B3 – Repair	C3 – Waste processing	
			B4 – Replacement	C4 – Disposal	
			B5 – Refurbishment		
			B6 – Operational energy use		
			B7 – Operational water use		
I					
II					
III					

Finally, after entering the data for a specific design into the project, the design requests the parameters shown in Figure 10.21.

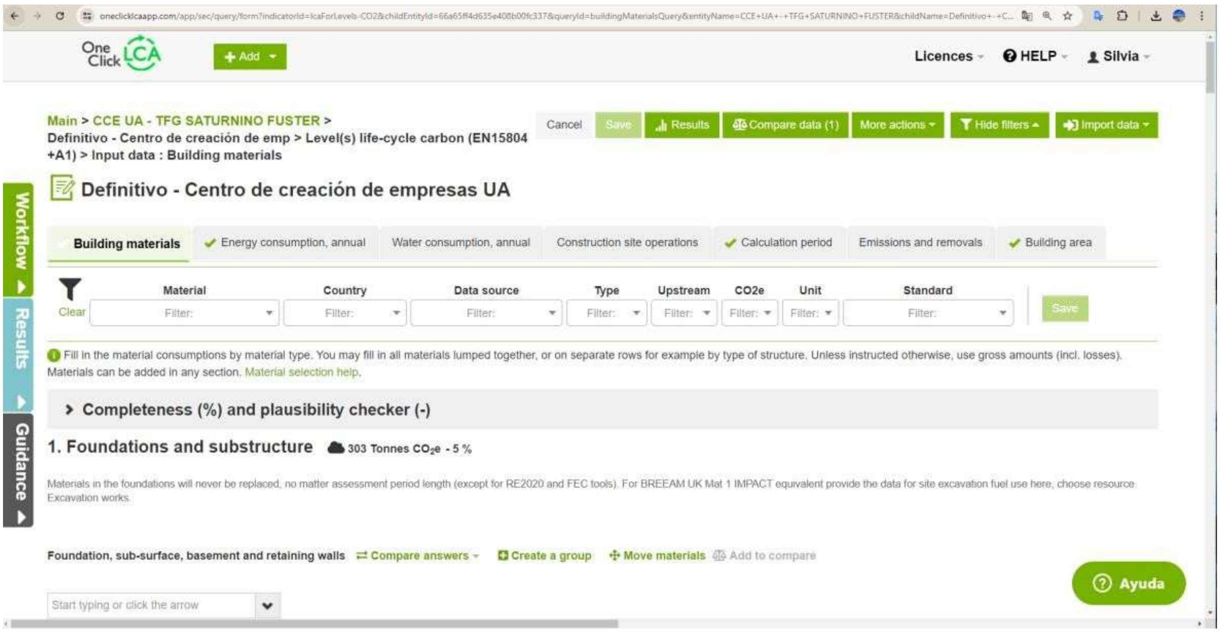


Figure 10.21. Final Design – Business Creation Centre UA. Introduction of analysis parameters for each design, including Materials, Energy consumption, Calculation Period, and Construction Area.

After completing the steps, it will be possible to quantify the kg CO_2-eq/m^2 of the materials used in construction, as well as their cost. The results are discussed and analysed in the results section.

10.7 Plug-In LCA in Autodesk Revit

The "LCA in Autodesk Revit" plugin connects ONE CLICK LCA with Revit. This allows users to extract crucial data from their Revit models, including material names, categories/classes, geometric data, and units. These features accelerate data entry in the main ONE CLICK LCA software's construction material data query. This allows users to conduct complete life cycle assessments (LCA) from Revit on their designs' building materials.

The plugin allows users to perform quick analyses to find the best material options (i.e., the most sustainable) while designing their models in Revit. This is crucial because it eliminates the need for a time-consuming process to gather information on environmental sustainability. No changes are required in the Revit model as the plugin operates directly within it. Figure 10.22 shows the plugin’s interface, highlighting its two key features: LCA in Autodesk Revit and working in the ONE CLICK LCA cloud. In this study, both functionalities were used.

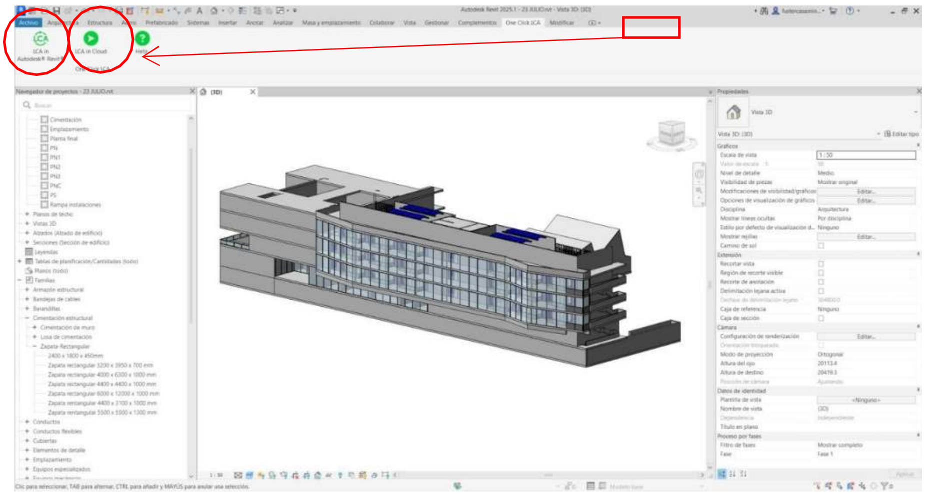


Figure 10.22. Plugin 'LCA in Autodesk Revit’.

Autodesk Revit's LCA functionality was initially used to map and estimate materials, as illustrated in Figure 10.22. In the 3D representation of the Revit model, a colour scale can show signifying each structural element in terms of embodied CO_2, based on the mapped material, as shown in Figure 10.23.

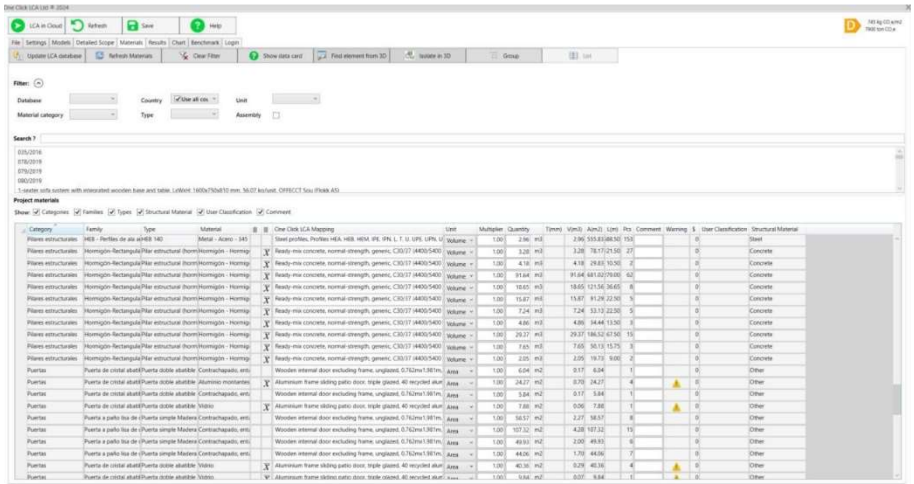


Figure 10.23. List of materials for Plugin LCA in Autodesk REVIT. Option to list materials mapped.

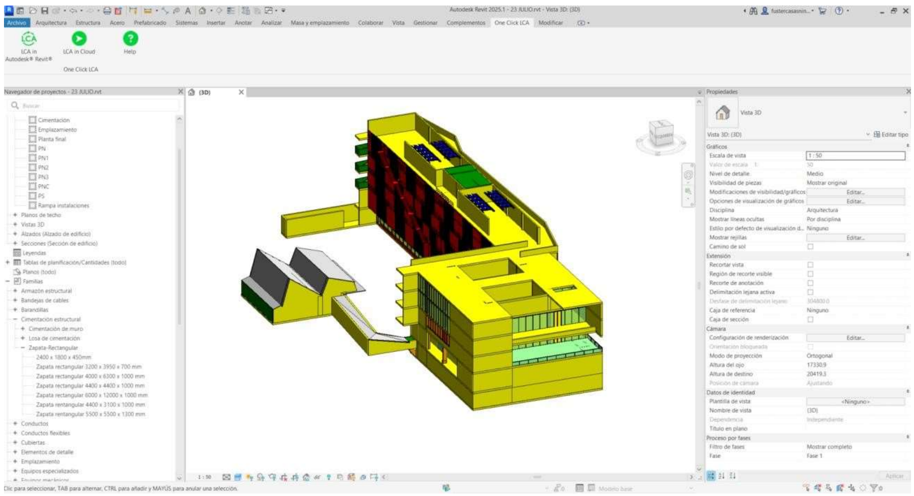


Figure 10.24. Graphical representation using a colour scale on the modelled elements.

Following this first estimation and graphical representation, the second functionality, LCA in Cloud, was used. This feature of the plugin allows for the direct insertion of materials into a selected design within the main ONE CLICK LCA project, as shown in Figure 10.25. The last design, chosen for the ONE CLICK LCA project result, included an exported Excel sheet. This sheet documented the mapping done using the plugin's first functionality. The plugin's second functionality allows users to download this Excel sheet before configuring the mapping.

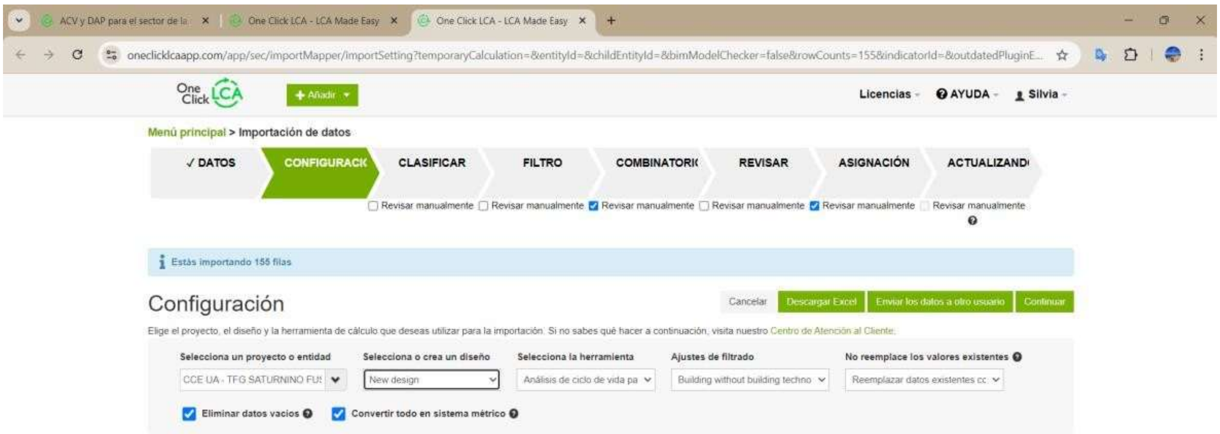


Figure 10.25. ONE CLICK LCA interface, after using the "LCA in Autodesk Revit" plugin's cloud functionality. The first step is now identical to working directly in the program.

10.8 Carbon Designer 3D

Carbon Designer 3D is a proprietary application of ONE CLICK LCA, which operates independently. This application allows for the rapid creation of a reference building with minimal project knowledge. Carbon Designer 3D enables quick life cycle analysis and allows for design variations by switching between predefined building structures or selecting relevant materials. Carbon Designer 3D includes model visualisation, which helps improve understanding the proportions of the design. Carbon Designer 3D works outside of a specific design but allows saving various design options for later consultations.

Users can use the tool in the early stages of design, but it also supports detailed options and creation. You can compare modelled designs or save them within the project for later comparisons with other designs (Figure 10.26 and Figure 10.27).

The application produces a less detailed version of the embodied carbon of the materials in the building under study, which forms a design for comparison with others. The application quantifies the design with the materials, using the least project parameters entered before achieving the result, as described earlier.

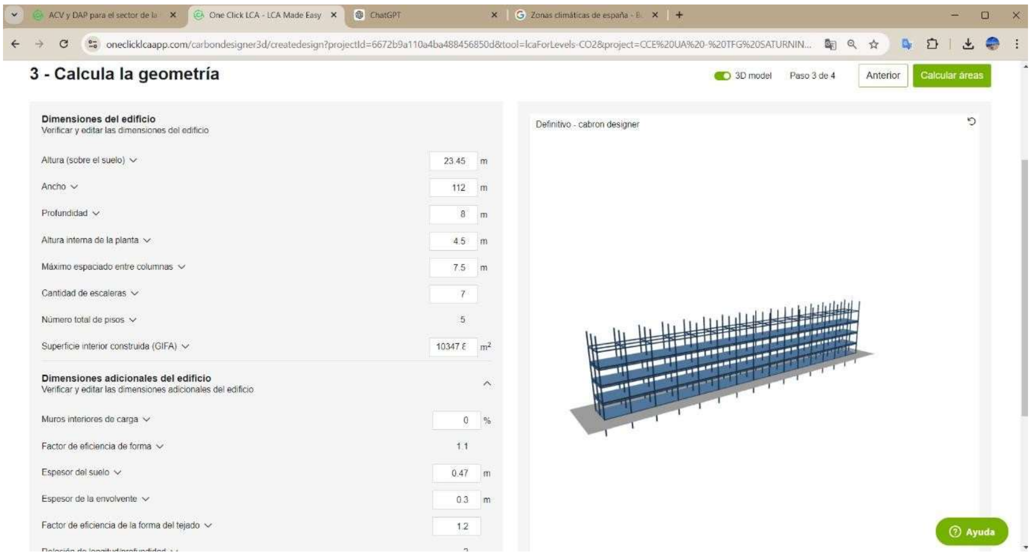


Figure 10.26. Carbon designer interface. Geometry parameters and visualisation of the building.

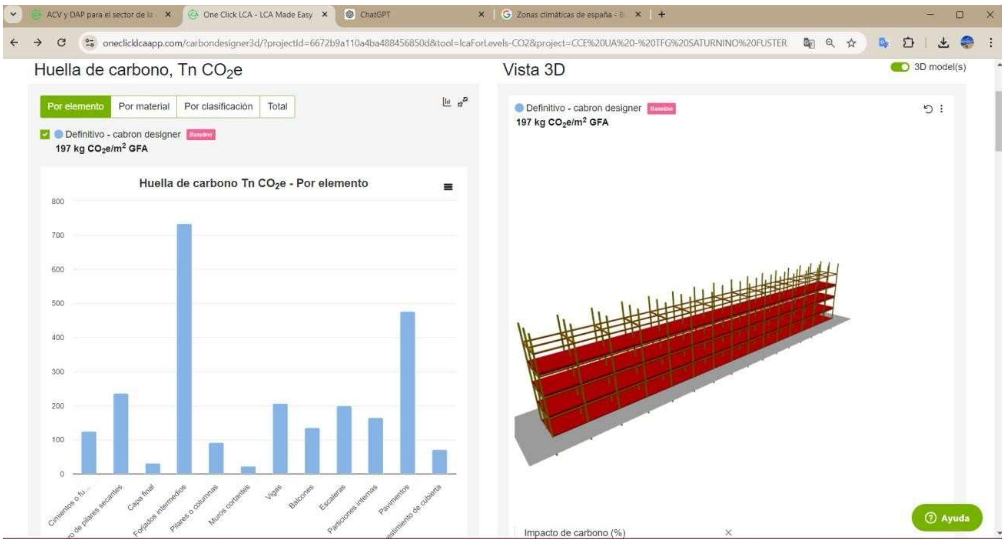


Figure 10.27. Final Results for Carbon Designer 3D.

10.9 Working Flow

First, we created a 3D model of the Business Creation Centre building at the University of Alicante using Autodesk's Revit software. The official project documentation — which were pdf files (represented by red arrow in Figure 10.28)— served as a reference and guide for initiating the model, provided by managing the Business Creation Centre. Standard materials (like those in the original project) such as concrete, aluminium, and glass were used, as the actual construction materials, including manufacturer and country of origin, were unavailable.

The next step involves using the "LCA in Autodesk Revit" plugin to transfer the previously mentioned standard materials through an initial mapping (represented by the yellow arrow connecting BIM MODEL and LCA, Figure 10.28). This plugin can generate an Excel sheet of each structural element and its assigned material, divided by Revit's IFC categories. If the "LCA in Autodesk Revit" plugin is not used, the materials must be manually entered into an Excel sheet, with 147 rows of elements and their classification characteristics across 31 columns. Using the plugin provides significant time savings. This plugin saves significant time by avoiding manual data entry.

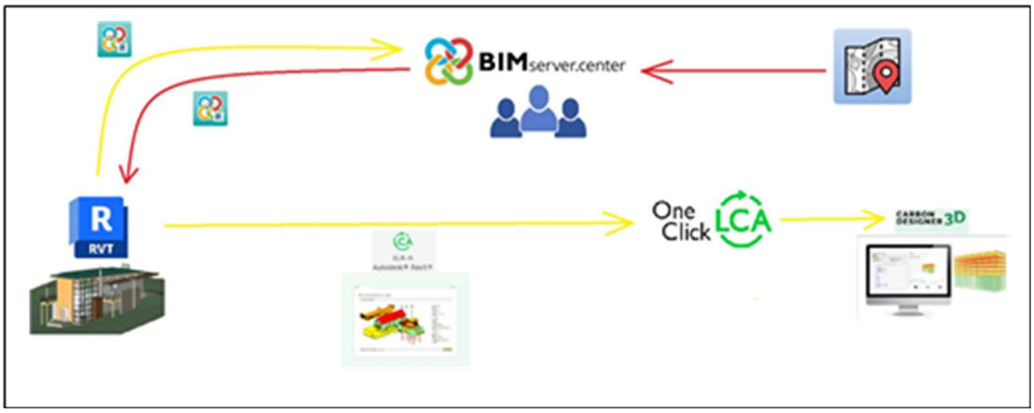


Figure 10.28. Workflow

Following this, the online software ONE CLICK LCA (Software logo, Figure 10.28) was used to perform the LCA analysis. Following the input of the project's overall and detailed design parameters, a life cycle analysis was performed on six tools and three designs. Minor modifications were made throughout the analysis.

One of the design variants used the ONE CLICK LCA's Carbon Designer 3D module independently (Carbon Designer 3D logo on the right-down side in Figure 10.28). This design included only essential project parameters and an optimised distribution of structural materials, with no additional modifications, unlike the other two designs. The Revit 3D model was then exported using the "Open BIM - Revit" plugin, which allows Revit models or models from any software that exports to IFC to be uploaded to the BIMserver. Centre cloud platform. Once in the cloud, platform users who are part of the project team can view, share, and contribute to the project without requiring additional user access.

To complete the workflow, the CYPE software suite's OpenBIM Site program generates the 3D model's site and topography, which will then be exported to BIMserver. Centre and re-imported into Revit via the "Open BIM - Revit" plugin. This results in a unified Revit model and LCA analysis outcomes with various design options in ONE CLICK LCA. Figure 26 shows the entire process.

Next, the ONE CLICK LCA software performed a life cycle analysis (LCA) for six tools and three different designs with minor changes. One of these designs used Carbon Designer 3D, an independent ONE CLICK LCA tool, with optimised material mapping and minimal project parameters.

The "Open BIM - Revit" plugin, from CYPE, exported the Revit model to BIMserver. centre, enabling team members to collaborate on the project via the cloud. Lastly, the CYPE software suite's OpenBIM Site generated the model's site and topography, exporting it back into Revit for a unified final model (federated model) and analysis results with different variants (Figure 10.28).

10.10 Case Study

The site of this case study is at the campus of the University of Alicante (Figure 10.29). Specifying the location is crucial. This area of the University falls within Alicante municipality, while the rest of the campus is part of San Vicente del Raspeig (Alicante) municipality. The proposed building is the Business Creation Centre of the University of Alicante. The present study focuses on one of the most emblematic buildings of the University of Alicante. A detailed LCA study was performed to find the stages and materials with the highest emissions. The University of Alicante inaugurated the building on October 16, 2023. The infrastructure, spanning over 10,350 square meters, is part of a larger 21,000 square meter complex. It's designed to support scientific and technological entrepreneurship, providing space for knowledge-intensive companies that collaborate with the university's research and talent.

The building has a ground floor, a first floor, and three upper floors, divided into two functional parts. To manage the shared spaces of the program is the primary role. The second part contains two parallel sections that enclose a courtyard, which has been excavated and landscaped. The Business Creation Centre is located in this courtyard. This area includes offices and laboratories for companies focused on science and technology. Four pilot buildings on two levels within the complex link to the main building. The courtyard is a key part of the project. It was dug out long ago to bring light and air into the lower levels. Now, it's used for installations starting from the second floor. Both technical facades include all the special installations of the building related to the laboratories. They comprise pre-fabricated concrete panels designed for future connections. The stairs that link the pathways for maintenance access distinguish the courtyard (Marcos Vazquez Consuegra, 2024). The building has a total constructed area of 12683.25 m² and a gross usable area of 10347.86 m².

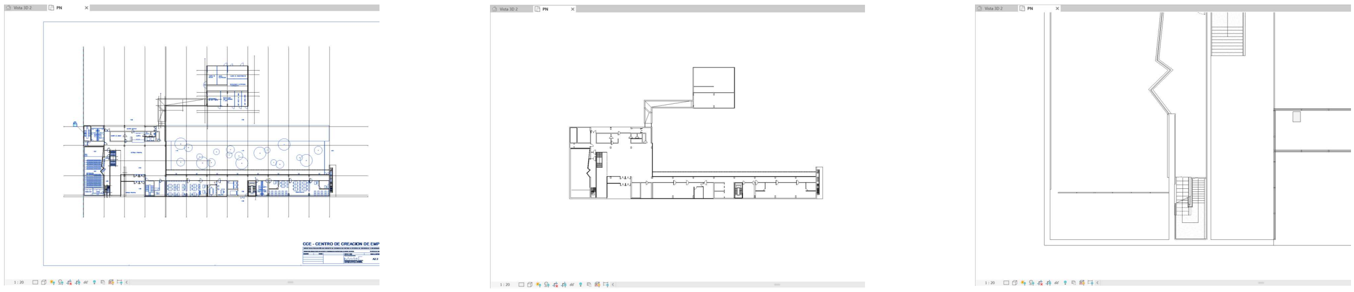
The building's primary structure is made of reinforced concrete, complemented by secondary materials like glass and aluminum, particularly evident on the exterior.

Figure 10.29. Location of the building in the University of Alicante campus.

10.10.1 Input Data

The only initial information available was PDF files, including sheets and budget descriptions, supplied by the University of Alicante's Business Creation Centre. On-site visits were crucial to verify the accuracy of the data. Using floor plans, elevation plans and section plans, we built the 3D model in Revit. We then scaled and placed the pdf plans properly.

The following figures (Figure 10.30 to Figure 33) show the workflow in Revit. The process begins with the insertion, placement, and scaling of the Level 0 plan. This is followed by the design of grids and culminates in 3D modelling of elements, primarily the structural ones. As observed, walls, enclosures, stairs, ramps, columns, doors, windows, railings, and curtain walls with their respective mullions and glass panels have been modelled. Likewise, important to highlight that the dimensions and characteristics of each architectural or structural element in elevation were obtained from the project documentation.



a) PDF level 0 file inserted in Revit, Grids and 3D model.

b) 3D model (Level 0 top view).

c) 3D model detail (Level 0 top view).

Figure 10.30. Revit Input data for the study.

Figure 10.31. 3D view (East)

Figure 10.32. 3D view (North-West)

Figure 33. 3D view (West)

10.10.2 Variants

Two different variants were proposed to compare and decide if the differences that may arise compared to the main design are negative or positive.

The effect of the transport (variant 1)

Variant 1 differs from the main design in its choice of galvanised steel, switching from locally sourced galvanised steel to that imported from France. The Environmental Product Declarations (EPD) for both the original and substitute materials are shown in Figure 10.34 (right).

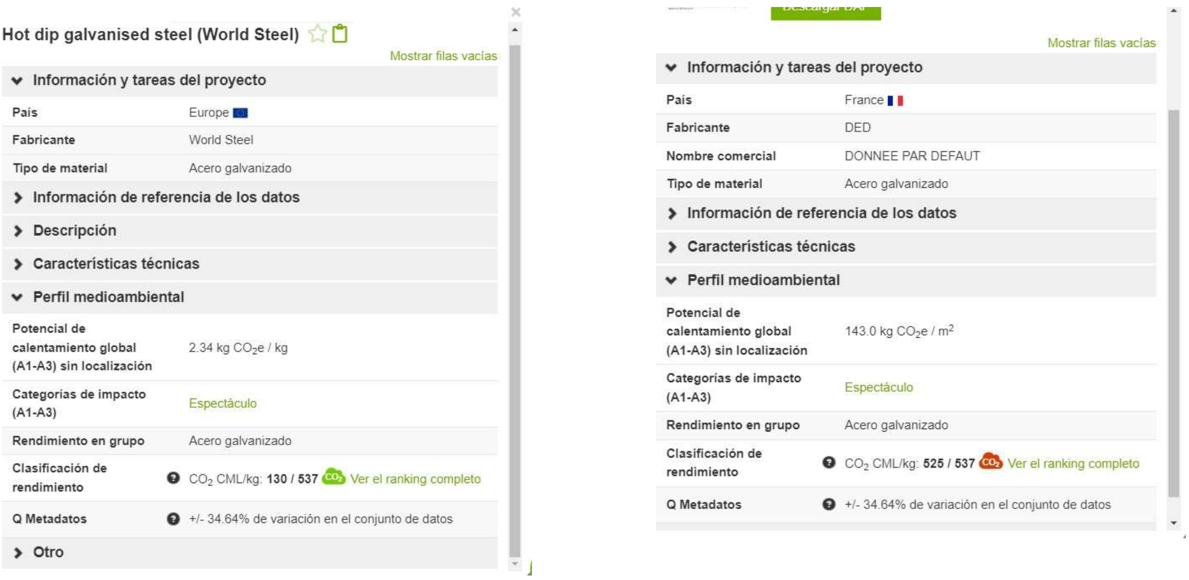


Figure 10.34. Left-Galvanised steel for calculating the GWP for the UA business creation centre. Right- French galvanised steel for Variant 1.

Comparison with the reference model (variant 2)

Variant 2 employs the Carbon Designer 3D program to generate a design based on given parameters. This enables the configuration of a model building that resembles, but does not perfectly match, the one under study. This variant serves as an idealised example or reference model.

Figure 10.35. Carbon designer 3D for variant 2.

10.11 RESULTS

10.11.1 Embebbed carbon for each element

The first approach involved creating a BIM model of the building and using the ONE CLICK LCA plugin to estimate the embodied carbon in the different structural elements. This provided a convenient initial visual representation, as shown in Figure 10.36.

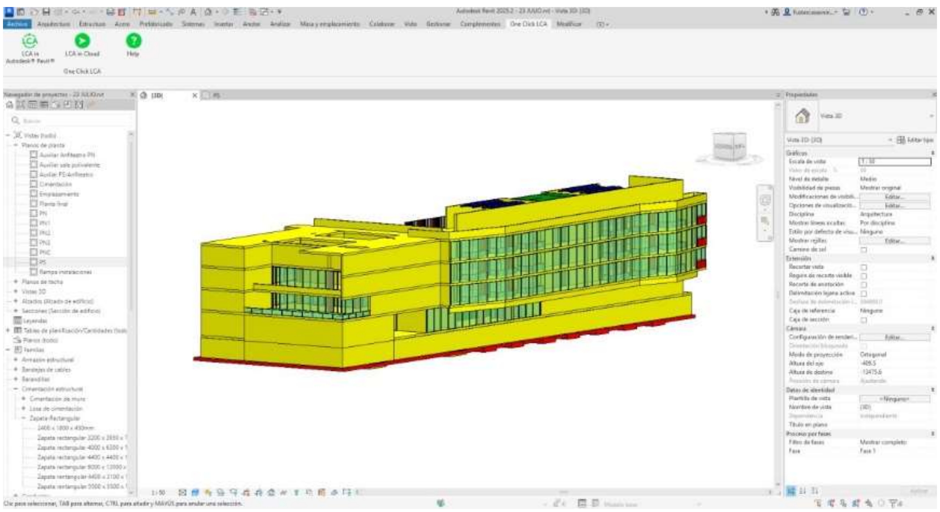


Figure 10.36. Southeast of the Business Creation Centre.

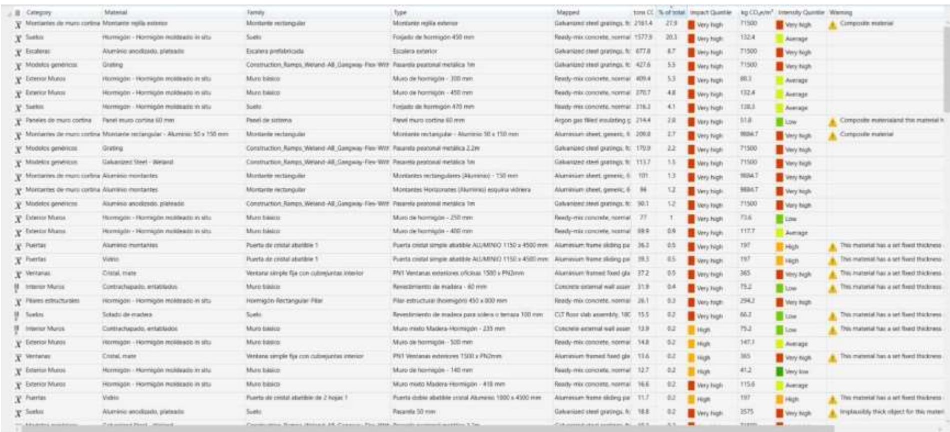


Figure 10.37. List of materials after plugging mapping.

The elements with the highest impact are the metallic components. In the figures, these elements, coloured in the most "polluting" shade (red), are identified as the most harmful in the entire building. The "metallic mullions" of the curtain walls, also coloured red, contribute to the amount of embodied carbon. Additionally, it's worth noting that although not shown in red, concrete makes up the largest part of the project and is coloured in a medium to high tone (yellow). Concrete includes elements such as slabs, walls, columns, and stairs. Therefore, based on this first visualisation and given that concrete accounts for 60% of the entire structure, it can be determined that the most harmful material is concrete.

10.11.2 One-click LCA software results

Life-cycle cost (ISO 15686-5 and EN 16627) – CML

This tool is based on "Life Cycle Costing" (LCC), which is a method used to assess the total ownership cost of an asset over its useful life. In Table 10.14, and

Table 10.15, stages present the results and by materials.

Table 10.14. Results of the UA Business Creation Centre by stages.

Stage	Value (€)	Percentage %
A0-A5 Construction	11000000	99.75
B4-B5 Replacement/Renovation	3200	0.03
B6 Energy	370	0

C1-C4 End of life	23000	0.22

As observed, for this tool, the most significant and decisive stage is the one between A0-A5 (Construction). This figure is 99% of the total life cycle cost. Based on the earlier results, we determined that the life cycle cost for the main Definitive Design - UA Business Creation Centre is entirely concentrated in the early phases of the life cycle.

Table 10.15 presents the Life Cycle Costing (LCC) and its section: Life Cycle Cost, adjusted for inflation. The ONE CLICK software produced these results.

Table 10.15. Results of the UA Business Creation Centre by materials.

Material	Value (€)	Percentage %
Glass glazing and facades	5300000	49.34
Ready-mix concrete for external walls and floors	3800000	35.55
Aluminium	990000	9.26
Galvanised steel	480000	4.53
Cross-laminated timber (CLT), glued laminated timber, and laminated veneer lumber (LVL)	40000	0.37
Wood (softwood and hardwood)	27000	0.25
Structural steel profiles and steel	22000	0.2
Glass wool insulation	17000	0.16
Concrete reinforcement (rebar)	10000	0.1
Others	25000	0.23

After analysing the results related to materials, this tool concludes that the most expensive materials are: 50% of the total life cycle cost because of glass material. Concrete accounts for 36%, reasonable considering the most used material in construction. Finally, metals—steel and aluminium—represent 15%. We've analysed the calculation method and results. The initial cost of the materials is the most impactful factor in the life cycle cost analysis. Notably, glass makes up 50% of this cost. The estimated glass measurement is 3838.04 m^2 with a unit cost of 1372.5 EUR. This results in a final LCC of 5267710 EUR for the glass components, which is half of the building's total cost.

Level(s) Life-Cycle Carbon (EN 15804 +A1)

In the life-cycle carbon for Level(s), the primary aim is to quantify greenhouse gas emissions throughout the life cycle of buildings. This calculation tool only accepts Environmental Product Declarations (EPD) under the EN 15804:2013+A1 standard.

Table10. 16 presents the results for the main Definitive Design - UA Business Creation Center in this study. To the earlier tool, and despite calculating different parameters, they resemble each other in that the results show that the most impactful stage in terms of CO_2 emissions is within the A1-A3 materials stages. This phase handles 90% of the total emissions.

Table10. 16. Results of the UA Business Creation Center for the EN (15804+A1) analysis.

Stage	Value (Tons CO_2-eq)	Value (Kg CO2-eq/ m^2)	Percentage %
A1-A3·Materials	5800	560.5	89.44
A4 Transport	240	23.19	3.65
A5 Construction	300	28.99	4.66
B4-B5 Replacement/Renovation	12	1.16	0.19
B6 Energy	3.3	0.32	0.05
C2 Waste Transport	120	11.60	1.82
C3 Waste process	12	1.16	0.19

Table 10.17 presents the global warming per material. These results show that 60% of the total emissions measured in this tool are because of concrete. This is because concrete is the most widely used material throughout the entire project, making its presence the most significant and its contribution to total emissions the highest. Concrete is the most polluting material because of its Global Warming Potential (GWP) with 293.41 kg CO2-eq.

Table 10.17. Results of the global warming in Kg CO2-eq

Material	Value (Tons CO2-eq)	Percentage %
Pre-mixed concrete for external walls and floors	4000	60.86
Aluminium	1100	16.24
Galvanised steel	1000	16.02
Glass glazing and facades	190	2.95
Glass doors with aluminium frames	130	2.00
Windows with aluminium frames	41	0.63
Structural steel profiles and steel	14	0.21
Glass wool insulation	13	0.20
Cross-laminated timber (CLT), glued laminated timber, and laminated veneer lumber (LVL)	12	0.18
Others	46	0.71

Below, we present a calculation for an isolated structural element, specifically a rectangular footing, to determine the CO_2 emissions (kg CO2-eq) generated. This calculation utilizes data from the ONE CLICK program. The material specified is pre-mixed, normal-strength concrete (C30/37, 4400/5400 PSI) with no recycled binders in the cement (300 kg/m^3 or 18.72 lbs/ft^3). The user-entered quantity is 288.0 m^3, with a thickness of 0.0 mm. The default functional unit is 1 m^3, with a resource mass of 2400.0 kg/m^3. Using the default unit, this results in a total volume of 288 cubic meters. Before applying localisation, we calculated the emissions impact at 294.23 kg CO2-eq, with a maximum allowable localisation change of 5.21. Applying a localisation factor of -0.82 kg CO2-eq reduces the impact to 293.41 kg CO2-eq. Consequently, the total Global Warming Potential (GWP) for the material amounts to 84502.92 kg CO2-eq.

To compare, we analyse an isolated element: a sliding patio door with an aluminium frame, the second most carbon-intensive material according to the tool, contributing 16% of total emissions. This door is triple-glazed, constructed with 40% recycled aluminium, and measures 3 m x 2.18 m with a mass of 51.76 kg/m^2. The user-entered area is 6.89 m^2, with a functional unit of 1 m^2. The resource mass per unit is 51.76 kg/m^2, totalling 6.89 m^2.

Before applying localisation adjustments, the emissions impact is 195.0 kg CO2-eq. After accounting for localisation (-26.89 kg CO2-eq), the impact factor decreases to 168.11 kg CO2-eq. This results in a total Global Warming Potential (GWP) of 1158.28 kg CO2-eq for the door (6.89 m^2 × 168.11 kg CO2-eq). Notably, aluminium, while the second most polluting material, has a GWP that is 0.9 times lower than concrete.

Level(S) Life-Cycle Carbon (EN 15804 +A1/+A2)

This tool provides a solid foundation for life cycle carbon assessment, with EN15804 +A1/A2 offering a more advanced and comprehensive method. It covers all stages of the life cycle in greater detail, from production to end-of-life of the building, providing a more complete picture of the environmental impact.

Figure 10.38 shows that the overall result of the structure in terms of kg CO2/m^2, obtained through ONE CLICK LCA software was 626.92 kg CO2/m^2, which gives it a C rating, the third most positive on the emissions classification scale. The C rating shows high emissions within positive ratings, suggesting suboptimal environmental performance for the building in terms of greenhouse gas emissions per unit of surface area. This classification highlights the need to implement significant improvements in the building's design and construction to achieve more sustainable standards and reduce its environmental impact. This positive result stems that this work only accounts for the building's structure and doesn't consider emissions associated with operations like water and energy use, repairs, and so on.

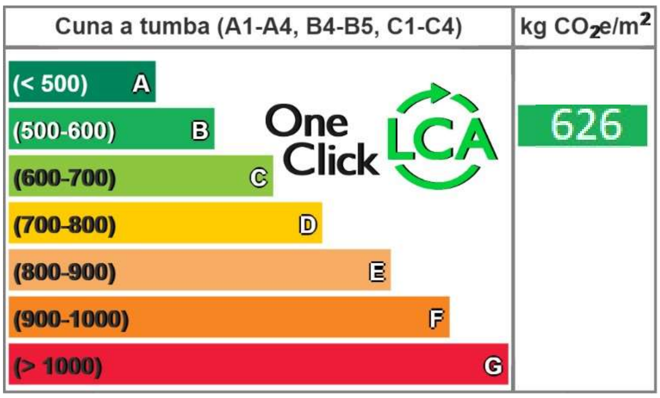


Figure 10.38. The result was obtained with the Carbon Lifecycle tool, according to Level(s) (EN15804 +A1/+A2).

This tool covers all stages of the life cycle in greater detail, from production to the end of the building's life. It provides a more comprehensive view of the environmental impact. After reviewing the results, the ones achieved here are the same as those presented in Table 10.17. We understand that they are like the previous section because the GWP calculation in both tools is comparable.

Building Circularity

Building circularity in a Life Cycle Assessment (LCA) refers to the extent to which a building or construction project follows principles of the circular economy. This means reducing the use of virgin materials, maximising the reuse, refurbishment, and recycling of building materials, and minimising waste generated throughout the building's life cycle. Circularity aims to create a closed-loop system where we continually reuse resources instead of discarding them. In an LCA, evaluating can assess building circularity:

Material efficiency: Assessing the use of sustainable, reusable, or recyclable materials, and minimising material consumption and waste production throughout the building's design, construction, and operational phases.

Design for Disassembly: Considering how easy it will be to disassemble the building at the end of its life and recover materials for reuse or recycling.

Durability and Longevity: Evaluating the life span of materials and building components to ensure that they are durable and require less frequent replacement, thus reducing the need for new resources.

Reuse and Recycling: Determining how much of the building's materials can be reused in future construction projects or recycled, thus reducing the need for new raw materials.

Waste Reduction: Calculate how much construction waste we can avoid or divert from landfills, including material reuse and efficient waste management practices.

By integrating these principles into an LCA, building circularity helps to reduce the overall environmental impact, lower carbon emissions, and conserve natural resources, contributing to a more sustainable construction industry.

The "Circularity" indicator score represents the total circularity of the materials, considering both the use of materials in the project and their end-of-life. The indicator is calculated as the average of "Recovered Materials" (which represents the use of materials in the project) and "Returned Materials" (which represents the effectiveness of materials that are returned, rather than being discarded or degraded in value). The calculation is based on mass without any weighting and is presented in Figure 10.39.

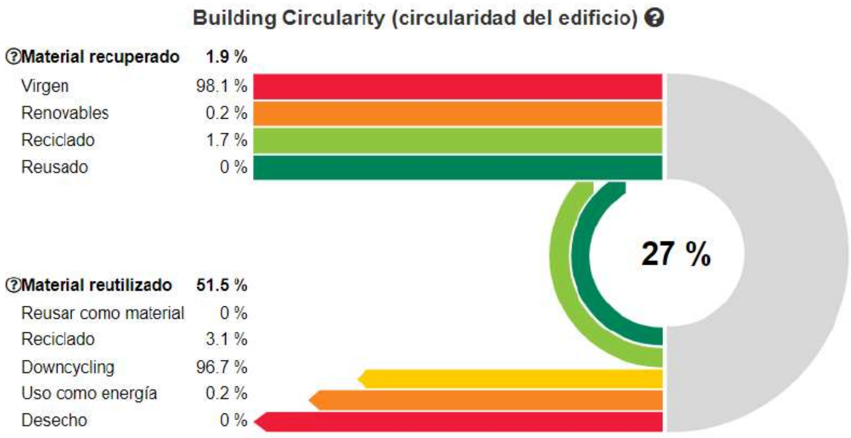


Figure 10.39. Circularity building for the Business Creation Centre.

A building circularity score of 27% means that only 27% of the building materials used, or the processes involved, follow principles of the circular economy. This score reflects the extent to which the project incorporates material reuse, recycling, and sustainability, both during the construction phase and at the end of the building's life cycle. This value suggests that a small proportion of the materials used in the construction project were recovered, reused, or made from recycled content. Furthermore, the design does not prioritize easy disassembly, reuse, or recycling of materials at the end of the building's life. There is significant room for improvement to reduce waste, extend the life cycle of materials, and increase the recycling and reuse of materials. In short, while 27% shows some efforts toward sustainability, it also suggests that the building is still heavily reliant on linear processes (i.e., using new materials that are eventually discarded) rather than adopting a fully circular approach to material management.

Table 10.18 presents the graphical results of the design. The recovered materials for this project include approximately 1 million kilograms of concrete, 52000 kilograms of recycled metals, and 7400 kilograms of wood used for energy recovery. These values reflect the efforts made to integrate circularity into the building's material use, emphasising the reuse and recycling of materials to reduce waste and environmental impact.

Table 10.18. Results of the design when calculating building circularity

Category	Mass (Kg)	Primary Materials (%)	Recycled (Kg)	Material recovery (Kg)	Energy recovery (kg)	Non-hazardous disposal (Kg)
Concrete, brick, tile, ceramic	28592092	100		1143684		
Wood	43510	100			7433	
Glass	127944	100	19			
Metals	717853	33	52440			
Insulation	9545	88				764
Gypsum-based	12262	83	1533			
Mixed	56488	93	0		7	14
TOTAL	29559694		53992	1143684	7440	778

10.11.3 Variants

VARIANT 1

In Figure 10.34 (left), the Global Warming Potential (GWP) of galvanised steel used in the building's first calculation is shown as 2.34 kg CO_2-eq/m^2. For Variant 1, Figure 10.34 (right) shows a higher GWP for galvanised steel at 143.00 kg CO_2-eq/m^2, over 60 times higher than the first steel calculation. Despite this increase, galvanised steel remains more sustainable than concrete, which has a GWP of 234 kg CO_2-eq/m^2. Table 10.19 presents the results for Variant 1, showing that the major design achieves 42% lower emissions by sourcing materials differently than in Variant 1.

Table 10.19. GWP of Variant 1

Results	Tons CO2-eq
A1-A3 Materials	8352.91 | +44 %
A4 Transport	222.60 | -7.25 %
A5 Construction	502.51 | +67.5 %
B4-B5 Replacement/ renovation	12.22 | 0 %
B6 Energy	3.37 | +1.81 %
End of life	130.15 | -1.4 %
Total	9223.75

VARIANT 2

The second variant created for this project involves a design through the Carbon Designer 3D program. Using the parameters, this program allows for the configuration of a model building similar, though not identical, to the building under study. This variant is a great example and reference point, but it can't be directly compared to the main design. The optimization process is so advanced that achieving the same CO2 emissions is very difficult. Figure 10.40 displays two parts from a carbon footprint analysis in a building model. The bar chart illustrates the carbon footprint of different building components, measured in tons of CO2 equivalent per element. The components include foundation and slab, exterior wall panels, roof, internal facades, internal partitions, beams, and stairs. The right side (3D Model View) presents a 3D model of a structural element, likely part of the building's frame or exterior wall system and the label indicates that carbon emissions are equal to 181 kg CO2-eq/m². This is a optimised design that serves as a reference model, showcasing ideal performance in terms of CO2 emissions. However, because of its advanced optimisation, difficult to match the levels of CO2 emissions achieved in this variant with the actual building's design.

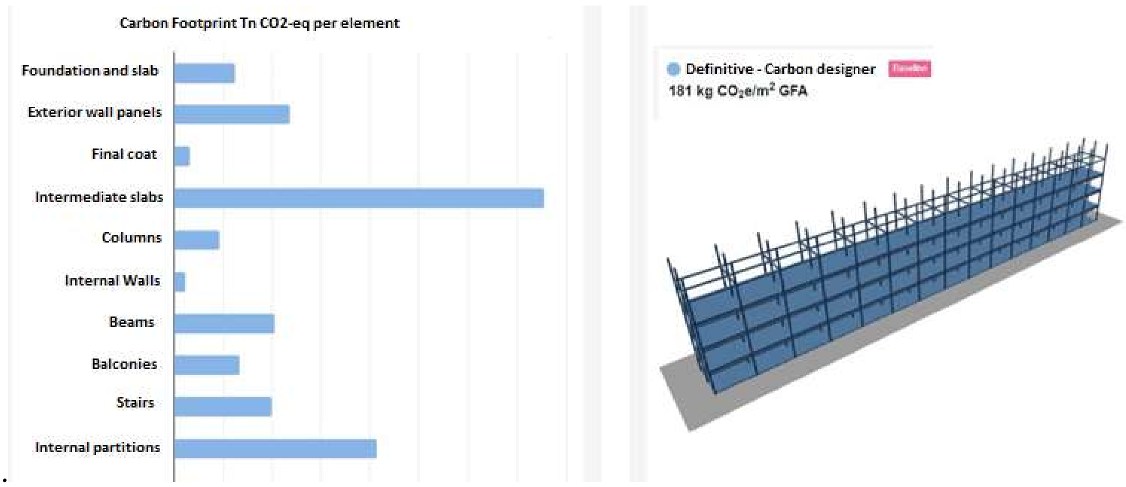


Figure 10.40. Carbon Designer 3D with final results of Variant 2.

So, variant 2 is not a direct comparison because of because both the major design and Variant 2 are at different scales. Through optimization, focusing solely on the building's skeleton, this variant achieves an A rating (181 kg CO_2-eq/m²). These results are very positive and difficult to achieve for a building of the magnitude of the one studied in this project.

10.12 DISCUSSION

The Life Cycle Carbon for Level(s) (EN15804 +A1) tool presents a summary of results as follows (Table10. 16). The total equivalent carbon dioxide emissions of the project for the scope are calculated in this tool. (6187.3 Tons of CO_2-eq), and the total equivalent carbon dioxide emissions of the project for the calculated scope in this tool, divided by the evaluation period (50 years) and the gross internal area in m² (10347.86). This value is equal to 12.57 Kg CO_2-eq/m2/year. The pre-mixed concrete is the primary contributor (Table 10.17) at 4000 Tons CO_2e (60.86%), the same results as found in other approaches which identify concrete as the principal contributor to these emissions (Hottle et al., 2022). Aluminium continued to be a significant part (16.24%), while the sourced galvanised steel was then only 16.02% of the total. This design received a Crating of 626.92 kg CO_2-eq/m², highlighting the positive impact of choosing local and less polluting materials (Figure 10.38). This value of 626.92 kg CO_2-eq/m² aligns with the emission reduction efforts highlighted in the study by Cheng et al. (Cheng et al., 2020), demonstrating consistency with recommended practices to reduce carbon footprints.

By averaging the data from 161 global studies, the median carbon emissions for various stages of the process were found to be the values of carbon emission values for each life-cycle stage. These emissions in stages A1–A3, A4–A5, B1–B5, B6–B7, C1–C4, and D were 321.2, 32.2, 114.9, 20.9, 1515.0, and -188.6 kgCO_2eq/m2 (Huang et al., 2024). These values expressed as kgCO_2eq/m2/year are presented in (Table 10.17). Table 10.20 also includes other values.

Table 10.20. Comparison of results for the emissions achieved in several studies

Stage	Value (Kg CO2-eq/ m2 /year)				
	UA business Creation Centre	V1	(Huang et al., 2024).	(Monahan and Powell, 2011)	(Seo et al., 2016)
A1-A3·Materials	11.21	16.14	6.42	6.51	15.19
A4 Tansport	0.46	0.43	0.64	0.16	0.39
A5 Construction	0.58	0.97		1.43	0.67
B1-B3 Use, Maintenance and Repairs	-	-	2.30		
B4-B5 Replacement/ Renovation	0.02	0.02			
B6 Energy	0.01	0.01	0.42		
B7 Water	-	-			
C1 De-construction demolition	-	-	30.30		
C2 Waste transport	0.23	0.23			
C3 Waste process	0.02	0.02			
C4 Waste disposal	-	-			
D Benefits and loads	-	-	-3.77		
	Cradle To Grave			Cradle To Gate	
Total	12.54	17.83	36.31	8.1	16.25

The carbon emissions on the "UA Business Creation Centre" (Kg CO2-eq/m² per year) compared to other approaches shows that the values achieved here (11.21 CO2-eq/m² per year) are considerably high compared to the others (6.42 and 6.51). On the other hand, Seo et. al., (2016) reported an even higher value of 15.19 Kg CO2-eq /m² year. This suggests that the UA Business Creation Centre might use materials with a higher carbon footprint, indicating a need for improved material selection or efficiency in material use. About the transport (A4) the value 0.46 Kg CO2-eq /m² year shows efficient transportation but shows room for optimization, perhaps through local sourcing or reduced transport distances. With regard to construction (A5; 0.58 Kg CO2-eq /m² year), lower emissions here suggest more efficient construction practices at the UA Business Creation Centre, potentially because of advanced construction techniques or prefabrication.

The value for Replacement / Renovation (B4-B5; 0.02 Kg CO_2-eq /m² year) is very low, which suggests minimal expected renovations or replacements, showing durable materials. The waste transport values (C2) for the UA Business Creation Centre account for 0.23 Kg CO_2-eq /m² year, representing a small but notable impact. The low emissions in this phase indicate minimal waste processing requirements or efficient waste management.

The UA Business Creation Centre seems to have a higher impact in areas like materials and transportation, but a low impact in maintenance and replacement. This suggests opportunities for reducing emissions through better sourcing and material selection. In contrast, Monahan and Powell's data implies a more comprehensive approach to lifecycle benefits, especially through recycling or reuse at the end of life, which could inspire further reductions in the UA Business Creation Centre's lifecycle impact.

Variant 1 showed a carbon rating of 891.37 kg CO_2-eq/m² (Table 10.19). This variant presents high emissions as it considers the effect of the transport of imported galvanised steel. These emissions totalise 9223.75 Tons CO_2-eq/m², a value 29.69% higher than those emissions quantified in the building (687.3 Tons CO_2-eq/m²). This transport contributed 4100 Tons of CO_2-eq (44.02%, Table 10.19) to the total. Variant 1 is 17.83 Kg CO_2-eq/m² per year (Table 10.20).

Variant 2 optimised using the Carbon Designer 3D, stands out for its innovative approach to emission reduction. The value achieved here is 181 kg CO_2-eq/m², representing the minimum emissions required for the UA business creation centre. This is 28.87% of the total amount. Variant 2 demonstrated a notable decrease in emissions, in line with the recommended best practices outlined (Ma et al., 2024). The total amount of emissions is 1872.96 Tons CO_2-eq, 626.92 kg CO_2-eq/m², representing 3.62 Kg CO_2-eq/ m2 /year. So, we can consider 6487.3-1872.96= 4614.33 Tons CO_2-eq are emitted because of this design. That design showed a more sustainable strategy, with pre-mixed concrete for walls and floors accounting for 33.43% of total emissions, at 770,000 kg CO_2-eq. Replacing traditional materials with more sustainable options was clear, with a significant reduction in using steel and concrete. Materials like cross-laminated timber and other wood products total 360000 kg CO_2-eq (15.46%), and concrete reinforcement contributed 350000 kg CO_2-eq (15.20%). Using partition systems and glass wool insulation also reduced emissions. Selecting construction materials required careful consideration. The decision to use a large amount of galvanised steel for the exterior grid, despite its high Global Warming Potential (GWP), increased the project's carbon footprint by

3000 Tons CO_2-eq. This steel is used to create shading for the building. Recycled materials also played a crucial role, in reducing GWP and lowering emissions.

Hollberg et al. (2021) evaluated BIM-based LCA results for building design, finding that integrating these technologies allowed for a detailed assessment of environmental impact. The results showed that advanced tools and sustainable materials could reduce emissions.

Looking ahead, both the BIM method and LCA analysis will continue to develop and solidify as essential tools for sustainable design and management of buildings. The trend toward digitalisation and sustainability in the construction sector will further drive adopting these technologies. Continuous improvements in software interoperability and functionality will lead to deeper integration of data, enabling projects with lower environmental impact and greater energy efficiency. In addition, crucial for new public buildings to be designed, constructed, and monitored using Building Information Modeling (BIM) methodology. This approach facilitates creating federated "as built" models, which integrate data from various disciplines into a single coherent representation of the building. By employing BIM, stakeholders can make sure better coordination, enhance collaboration among architects, engineers, and contractors, and improve the accuracy of the final construction. This not only streamlines the project lifecycle but also provides a valuable resource for future maintenance and management, contributing to the long-term sustainability and efficiency of public infrastructure.

10.13 CONCLUSIONS

The present manuscript answered the following questions:

Which life cycle material produces the most emissions?

Concrete is one of the most widely used construction materials globally because of its durability, versatility, and low cost. However, this material is also one of the largest contributors to CO_2 emissions, a fact that has raised significant concerns about environmental sustainability. Cement production, the key part of concrete, handles 8% of global carbon dioxide emissions (Cheng et al., 2020). This impact is because of the calcination process of limestone, which releases large amounts of CO_2. The extraction and transportation of the materials required for concrete production also contribute to the high level of emissions. Therefore, reducing reliance on concrete or improving its production processes is crucial to mitigating its environmental impact. The results of the present study showed that concrete was the major contributor to pollution, accordingly as being the higher in quantity per cubic meter in the building. So, reducing this material was expected to decrease the overall pollution of a project.

What is the influence of using materials sourced from great distances compared to using local materials?

Using imported construction materials instead of those locally available can increase the carbon footprint of a project. The increase is mainly because of emissions associated with transporting materials over long distances and potential differences in the environmental regulations and industrial practices of the countries of origin. As an example, in this study, French-imported galvanised steel may have a higher carbon footprint than locally-produced steel. The LCA analysis, in Variant 1, showed this result, where French imported galvanised steel resulted in higher total emissions. Using local materials not only reduces transportation emissions but also supports local economies and can offer greater transparency about the environmental practices of suppliers (Hollberg et al., 2021).

Which is the best case to perform an LCA Analysis?

To achieve the best possible scenario in a life cycle assessment (LCA), adopting combined sustainable strategies from design through construction is a must. This includes selecting materials with a low carbon footprint, those that are recyclable or come from renewable sources, and using construction techniques that minimise waste and optimise energy efficiency. Implementing advanced design and simulation tools, such as BIM, can help find opportunities for sustainability improvements (Ma et al., 2024). A holistic approach that considers the entire building life cycle—from raw material extraction to demolition and recycling— is crucial to raise awareness to minimise environmental impact. To achieve or approach this scenario, tools like Carbon Designer 3D can be used. The present study utilised this tool in Variant 2. While achieving zero emissions is complex, such tools can be crucial in optimizing materials and resources to minimise emissions.

Can we support buildings with more sustainable LCA-based construction?

Governments and international organisations recognise prising sustainability in construction and are offering various aids and grants to promote more eco-friendly building practices. Some support may include tax incentives, grants for projects that reduce CO2 emissions, and financial help to develop sustainable materials and technologies. For example, in the European Union, programs like Horizon 2020 have allocated significant funds to sustainable construction projects that use LCA to improve their environmental performance. These aids not only encourage adopting sustainable practices but can also reduce the first costs associated with implementing advanced technologies and eco-friendly materials.

What is the influence of energy in future cases?

The transition to renewable energy sources and improving energy efficiency are crucial factors in reducing carbon emissions in the construction sector. In the future, clean energy technologies like solar and wind power will be crucial for sustainability goals. Implementing zero or positive-energy buildings, which generate more energy than they consume, will also be necessary. LCA methodologies need an upgrade to include considerations of the entire life cycle of renewable energy technologies, from producing equipment to its decommissioning and recycling. The ability to adapt to new technologies and energy sources will be key to minimising the environmental impact of construction projects in the future.

The integration between REVIT and ONE CLICK LCA using the LCA in the Autodesk Revit plugin was positive. Importing the BIM model from REVIT to ONE CLICK LCA simplified the analysis, and saved time and effort in data collection. This seamless integration ensured the right information transfer, reduced errors, and improved analysis efficiency. The results showed the greenhouse gas emissions for each stage of the building's lifecycle, from raw material extraction to construction and use. We proved that the interoperability between different software was a valuable tool in LCA analysis. Linking BIM model data with analysis software allows for a more detailed assessment of environmental impacts. This interconnection facilitated real-time data updates and revisions, allowing, in this case, and other contexts, professionals to make continuous and efficient adjustments and improvements. Integrating these two tools proved beneficial in terms of accuracy and efficiency, justifying their use in life cycle analysis projects. In the construction sector, public administration utilizes LCA (Life Cycle Assessment) to gauge environmental impacts, identify crucial areas, comply with regulations, and achieve green building certifications.

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