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LIFE CYCLE ENVIRONMENTAL IMPACT OF BUILDINGS

LECTURE NOTES

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The textbook examines modern approaches to assessing the environmental impact of buildings throughout their life cycle. It presents an analysis of global environmental challenges and international programs and strategies for mitigating them, highlighting the role of the construction sector in reducing its carbon footprint. The publication outlines the main stages of the building life cycle, including methods for assessing environmental impacts at each stage, the regulatory framework, the specifics of using environmentally friendly materials, and the standards of ecological certification (LEED, BREEAM, DGNB), along with practical examples of their implementation. Special attention is devoted to BIM-integrated life cycle analysis technologies and digital tools such as OneClickLCA for modeling embodied emissions. The textbook is intended for students of architecture and construction specialties, researchers, and professionals in the fields of architecture, civil engineering, and building materials production.

The textbook was prepared as part of the International Project under the Erasmus programme 101127884 — The Bridge — ERASMUS-EDU-2023-CBHE «Bridging the gap between university and industry: Master Curricular Supporting the Development of Green Jobs and Digital Skills in the Ukrainian Building Sector»

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CONTENT

INTRODUCTION

The modern world is undergoing a stage of profound transformation linked to global environmental challenges, including climate change, depletion of natural resources, ecosystem degradation, urbanization pressure, and increasing energy consumption. The response to these challenges is the search for paths of sustainable development, which implies a balance between the economic, social, and environmental aspects of human activity. One of the key industries capable of significantly influencing this balance is the construction sector, as it consumes over 40% of the world's energy resources and generates approximately one-third of global greenhouse gas emissions.

In the 21st century, the construction industry is acquiring new meaning -moving from the traditional erection of structures to the creation of an energy-efficient, environmentally balanced, and comfortable living environment. In view of this, understanding the environmental impact of buildings throughout their entire life cycle—from raw material extraction and material production to operation and demolition—becomes extremely important. The Life Cycle Assessment (LCA) approach enables an objective evaluation of a building's total environmental impact and the development of strategies to mitigate negative consequences.

A comprehensive system of regulatory, methodological, and software tools for assessing the environmental performance of buildings has been established worldwide. International ecological certification standards, such as LEED (USA), BREEAM (UK), and DGNB (Germany), set high requirements for energy efficiency, indoor environmental quality, the rational use of resources, and waste management. They stimulate designers and developers to focus on the principles of "green" building, which today is not only a manifestation of social responsibility but also an essential competitive factor in the global economy.

At the same time, the development of digital technologies has opened up new possibilities for modeling the environmental parameters of buildings. Integrating the Life Cycle Assessment (LCA) methodology into the Building Information Modeling (BIM) environment enables the analysis of environmental impact already at the design stage, allowing for quick adjustments to decisions and optimization of material and structural choices. Digital tools enable the automated calculation of embodied carbon, analysis of the impact of various design options, and the generation of reports in accordance with international standards.

The Ukrainian construction sector, as it integrates into the European space, is actively implementing the principles of sustainable development and environmental management. The relevance of implementing LCA approaches, "green" standards, and digital technologies in domestic practice is driven by the need to modernize the construction industry, increase its energy efficiency, and reduce the carbon footprint of the national economy. This, in turn, requires the training of a new generation of specialists—engineers, architects, and designers—capable of thinking systemically, understanding the relationship between technical solutions and environmental consequences, and utilizing modern digital tools to make sustainable design decisions.

The purpose of this textbook is to provide a holistic understanding of the environmental aspects of construction activities among higher education students, from the concept of sustainable development to practical methods for assessing the environmental impact of buildings. The textbook aims to provide theoretical knowledge and practical skills in applying modern tools of environmental analysis, while also familiarizing students with international approaches to environmental certification, regulatory requirements, and methods for assessing the life cycle of buildings and building materials.

This textbook has been prepared as part of the implementation of the International Project under the program 101127884 — The Bridge — ERASMUS-EDU-2023-CBHE «Bridging the gap between university and industry: Master Curricular Supporting the Development of Green Jobs and Digital Skills in the Ukrainian Building Sector»

CHAPTER 1. GLOBAL ENVIRONMENTAL THREATS AND INTERNATIONAL APPROACHES TO THEIR SOLUTION

1.1. Global Environmental Threats

Contemporary urban planning faces unprecedented challenges caused by global risks. Climate change, economic crises, technological threats, pandemics, and social instability have a profound impact on the planning, construction, and management of urban territories. Rapid urbanization and population growth necessitate new approaches to creating safe, resilient, and adaptable cities that can withstand contemporary threats.

Global warming and extreme weather events are compelling architects and engineers to reconsider design and construction principles by implementing innovative solutions, energy-efficient technologies, and environmentally friendly materials.

Since the mid-20th century, humanity has begun to recognize the large-scale environmental threats caused by technological progress and intensive economic activity. The first scientific studies, particularly the landmark report by the Club of Rome, "The Limits to Growth" (1972), which was prepared by specialists from the Massachusetts Institute of Technology, warned that without a change in the consumption model, the planet faces an ecological collapse [1].

In addition to the problems of overconsumption, scientists identified another critical threat in 1987 – climate change, singling it out as one of the most dangerous challenges to humanity's future [2].

The World Economic Forum's "Global Risks Report 2006" was the first systematic study dedicated to the comprehensive analysis of global risks in both the short and long term, and has since become a permanent research tool for monitoring these risks. [3]. Its methodological foundation consisted of identifying and assessing current and emerging threats, studying their interconnections, analyzing the potential impact on various economic sectors, and establishing a basis for developing preventive strategies to mitigate them. Issues of global concern are categorized into five key areas: economic, geopolitical, environmental, social, and technological.

"Global risk" is defined as the possibility of an occurrence or condition that, if it were to happen, would negatively impact a significant portion of the global GDP, population, or natural resources [4].

Contemporary analysis of global risks confirms their systemic nature and the non-isolated character of their manifestation. The cascading interaction of diverse risks is capable of generating cumulative phenomena, so-called "perfect storms" – synergistic events where the total destructive effect significantly exceeds the additive sum of the consequences of individual risks. All risk categories are interconnected, and this interconnection can lead to a "domino effect," where the emergence of one risk triggers the cascading development of others, amplifying their overall negative impact on society, the economy, and the environment [5].

Global risks differ not only in their nature and consequences but also in their speed of development. Some unfold gradually over an extended period and may remain unnoticed until their impact becomes irreversible. A prime example is climate change, which has been occurring for decades, causing rising temperatures, extreme weather events, biodiversity loss, and ecosystem degradation. Although this process is slow, its consequences are catastrophic and have a global scale.

The perception of global risks evolves with the progress of human society. Shifts in priorities, evident in both the long term and especially in the short term, demonstrate the highly dynamic nature of the risk landscape. Over 20 years of researching global risks, not only has the perception of risks within the global impact rankings changed, but the very content of risk categories has also evolved, continuously being updated with new threats (Table 1.1).

According to the analysis presented in the Global Risks Report 2025 on the evolution of key risks and risk categories over the last two decades, the most stable threats, which have consistently topped the rankings throughout this period, are those related to climate change. These include: critical changes to Earth systems, extreme weather events, biodiversity loss and ecosystem collapse, natural resource shortages, and pollution, among others [4, 5].

Table 1.1

The Evolution of Global Risk Categories Over Time:
A Case Study of Environmental Threats [3, 4, 6]

Global risk	Global Risk Categories		
	2006	2015	2025
Environmental	- Tropical Cyclones; - Earthquakes; - Climate Change; - Environmental Degradation.	- Extreme weather events (e.g., floods, storms, etc.); - Failure of climate-change adaptation; - Major biodiversity loss and ecosystem collapse (land or ocean); - Major natural catastrophes (e.g., earthquake, tsunami, volcanic eruption, geomagnetic storms); - Man-made environmental catastrophes (e.g., oil spills, radioactive contamination, etc.).	- Biodiversity loss and ecosystem collapse; - Critical change to Earth systems; - Extreme weather events (floods, heatwaves, etc.); - Natural resource shortages (food, water); - Non-weather-related natural disasters (earthquakes, volcanoes, tsunamis, solar flares, etc.); - Pollution (air, soil, water, etc.).

The primary factors leading to these threats include: air, soil, and water pollution; greenhouse gas emissions (CO_2, CH_4, N_2O) from burning fossil fuels for energy production, transportation, and the manufacturing of various food and non-food goods; deforestation; industry; the construction and operation of buildings; and agriculture. This is far from a complete list of factors, but those listed are among the most influential. The consequences of processes associated with climate change, like other global threats, can be both direct and indirect, with the latter triggering secondary effects. Direct consequences include rising temperatures, extreme weather events (such as tsunamis, droughts, and floods), sea-level rise, and species depletion, among others. Indirect consequences include the depletion of natural resources, food and water scarcity in certain regions, energy crises, poverty, migration, and social instability.

According to the Global Risks Report 2025, environmental risks are now represented by six categories (Table 1.2). Five of these rank among the top ten most serious threats over the next decade, with the top four leading the ranking: extreme weather events, biodiversity loss and ecosystem collapse, critical changes to Earth systems, natural resource shortages, and pollution (Fig. 1.1) [4].

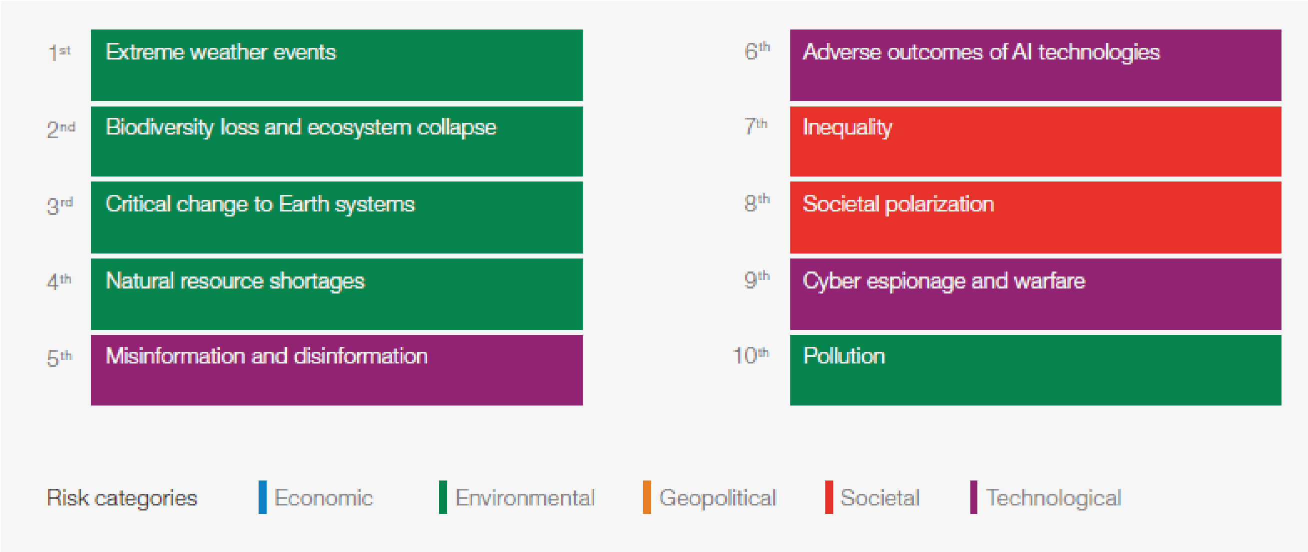


Fig. 1.1 – Ranking of Global Risks over the Long Term (10 years), Ranked by Severity. Source: World Economic Forum Global Risks Perception Survey 2024-2025 [4].

Climate change and natural disasters pose a serious threat to all human settlements; however, their most significant impact is precisely on urban ecosystems. Cities, as hubs of population concentration, economic activity, and critical infrastructure, demonstrate heightened vulnerability to climate change, which directly threatens their stability and long-term development.

According to World Bank data, one in six people on the planet lives in cities, and according to UN projections, the share of the urban population is expected to increase to 70% by 2050. At the same time, cities occupy only 2% of the total land area. Yet, they generate 70% of the gross domestic product (GDP), over 60% of global energy consumption, 70% of greenhouse gas emissions, and 70% of global waste (Fig. 1.2).

Table 1.2

Categories and Definitions of Global Environmental Threats [4]

Environmental Threats	***Biodiversity loss and ecosystem collapse***	Severe consequences for the environment, humankind, and economic activity due to the destruction of natural capital stemming from species extinction or reduction, spanning both terrestrial and marine ecosystems.
	Critical change to Earth systems	Long-term, potentially irreversible and self-perpetuating changes to critical planetary systems, as a result of breaching a critical climatic or ecological threshold or 'tipping point', at a regional or global level. Includes, but is not limited to: sea level rise from collapsing ice sheets, carbon release from thawing permafrost, and disruption of ocean or atmospheric currents.
	Extreme weather events (floods, heatwaves, etc.)	Loss of human life, damage to ecosystems, destruction of property, and/or financial loss due to extreme weather events. Includes, but is not limited to: land-based (e.g. wildfires), water-based (e.g. floods), and atmospheric and temperature-related (e.g. heat-waves) events, including those exacerbated by climate change.
	Natural resource shortages (food, water)	Supply shortages of food or water for human, industry, or ecosystem use, manifesting as food and water insecurity at a local, regional, or global level, stemming from, but not limited to: human overexploitation and mismanagement of critical natural resources, climate change (including drought and desertification), and/or a lack of suitable infrastructure.
	Non-weather-related natural disasters (Earthquakes, volcanoes, tsunamis, solar flares, etc.)	Loss of human life, damage to ecosystems, destruction of property, and/or financial loss due to non-weather-related natural disasters. Includes, but is not limited to: land-based (e.g. earthquakes, volcanoes), water-based (e.g. tsunamis) and extra-terrestrial-based (e.g., asteroid strikes and geomagnetic storms) events.
	Pollution (air, soil, water, etc.)	Introduction of harmful materials into the air, water, and soil stemming from human activity, resulting in impacts to and loss of human life, financial loss, and/or damage to ecosystems. Includes, but is not limited to: household and industrial activities; environmental accidents, such as oil spills; and radioactive contamination.

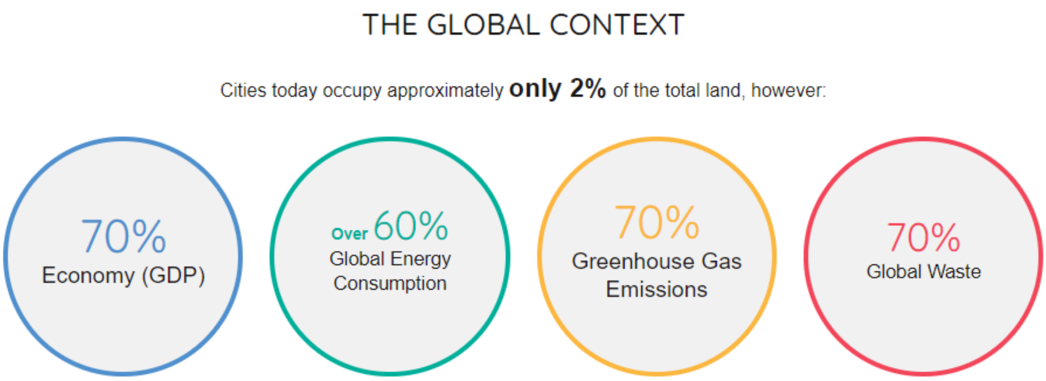


Fig. 1.2 - Urbanization: A Transformative Force and New Challenges for Humanity [8]

The main consequences of climate change and natural disasters for the urban environment include:

- *Rising temperatures and the urban heat island effect*. Climate change contributes to an increase in average annual temperatures in cities, which is further intensified by the Urban Heat Island Effect. This leads to higher loads on energy systems, increased mortality due to heat waves, and deterioration of air quality;

- *Changing weather patterns, droughts, and water scarcity.* The increase in extreme precipitation events leads to more frequent and severe floods, which damage roads, buildings, and transportation networks, resulting in significant destruction. Water scarcity caused by climate change threatens urban water supply and wastewater systems;

- *Increased frequency of natural disasters*. Climate change leads to more frequent and intense hurricanes, typhoons, wildfires, and earthquakes. These events destroy infrastructure, damage buildings and utilities, cause loss of human lives, and result in growing economic losses, especially in urban environments.;

- *Deterioration of environmental conditions and urban ecosystems.* Air pollution, exacerbated by high temperatures, hurts the health of urban populations. Harmful emissions from transportation and industry can significantly alter meteorological conditions, leading to the formation of fog, which in turn produces acid rain and smog [6].

Global environmental threats, including climate change, biodiversity loss, and extreme weather events, pose unprecedented challenges to humanity's stability and future existence. Addressing these global challenges requires a systemic and interdisciplinary approach, in which the architecture and construction sector plays a pivotal role. Decisions made in the design, construction, and operation of buildings and structures directly determine the level of energy consumption, greenhouse gas emissions, resource efficiency, and the adaptive capacity of cities to climate change.

Given the global nature of environmental threats, overcoming them necessitates consolidated international efforts, which are reflected in intergovernmental programs and strategic initiatives aimed at creating a sustainable and safe environment for present and future generations.

1.2. International Strategies and Programs for Addressing Environmental Threats

In response to the growing scale of environmental threats, the global community has developed different concepts, strategies, and programs aimed at ensuring a harmonious balance between societal development, economic growth, and environmental preservation. These frameworks reflect the evolution of human thought — from recognizing environmental problems to pursuing systemic solutions that integrate innovation, social responsibility, and a nature-centered approach. Among the most influential international concepts shaping modern environmental policy are the Sustainable Development, the Circular Economy, Regenerative Design, the Energy–Water–Food Nexus, and the Green Deal — initiatives that have become the foundation of a new global ecological paradigm.

The first international environmental initiatives emerged in the mid-20th century, when the consequences of technological growth and industrialization began to threaten the stability of natural systems. A milestone in the transition to a new stage of global environmental awareness was the United Nations Conference on the Human Environment (Stockholm, 1972) [9], which, for the first time at the intergovernmental level, recognized environmental protection as an integral part of human development. It was at that time that the United Nations Environment Programme (UNEP) was established — one of the key institutions coordinating international environmental policy and initiating global sustainable development programs [10].

The further development of international environmental initiatives took place through the gradual formation of a normative and contractual framework. Significant contributions to this process were made by such documents as the World Conservation Strategy (1980) [11], the Rio de Janeiro Declaration (1992), which contains 27 fundamental principles of environmental law and sustainable development [12], Agenda 21, the Kyoto Protocol (1997) [13], and the Paris Climate Agreement (2015) [14]. Each of these milestones reflects the evolution of international approaches — from localized responses to individual environmental problems toward the recognition of the need for comprehensive, systemic solutions integrated into the socio-economic policies of states.

At the present stage, international environmental cooperation is based on the principles of sustainable development, which combine economic efficiency, social equity, and ecological balance. This approach implies that no aspect of development can be achieved at the expense of environmental degradation. In this context, other concepts, such as the Circular Economy, Regenerative Design, the Energy–Water–Food Nexus, and the European Green Deal, also play an essential role in shaping new models of interaction between society and nature.

The concept of sustainable development occupies a central place in the modern system of international environmental strategies, serving as the theoretical and methodological foundation of global policy in the field of sustainable development. Its essence lies in ensuring the harmonious coexistence of humans, society, and nature based on the principles of rational resource use, social justice, and the preservation of ecosystems for future generations.

The ideas of sustainable development emerged as a result of the growing awareness of the limited nature of natural resources and the negative consequences of industrial growth. A turning point in the development of this concept was the publication of the report of the World Commission on Environment and Development of the United Nations, chaired by Gro Harlem Brundtland, entitled "Our Common Future" (1987) [15, 16]. This report provided the classical definition: "*Sustainable development is* *development that meets the needs of the present without compromising the ability of future generations to meet their own needs*".

This definition laid the foundation for shaping international policy aimed at achieving a balance between economic growth, social well-being, and environmental preservation. The theory of sustainable development has emerged as an alternative to the traditional paradigm of purely economic growth, which overlooks the environmental risks associated with extensive development models.

An important stage in the institutionalization of sustainable development was the United Nations Conference on Environment and Development held in Rio de Janeiro (1992), where the Rio Declaration and Agenda 21 were adopted. These documents defined strategic directions for national policies, emphasizing that economic progress cannot occur at the expense of environmental degradation [12].

The concept of sustainable development is based on the integration of three fundamental dimensions — economic, social, and environmental (Fig. 1.3).

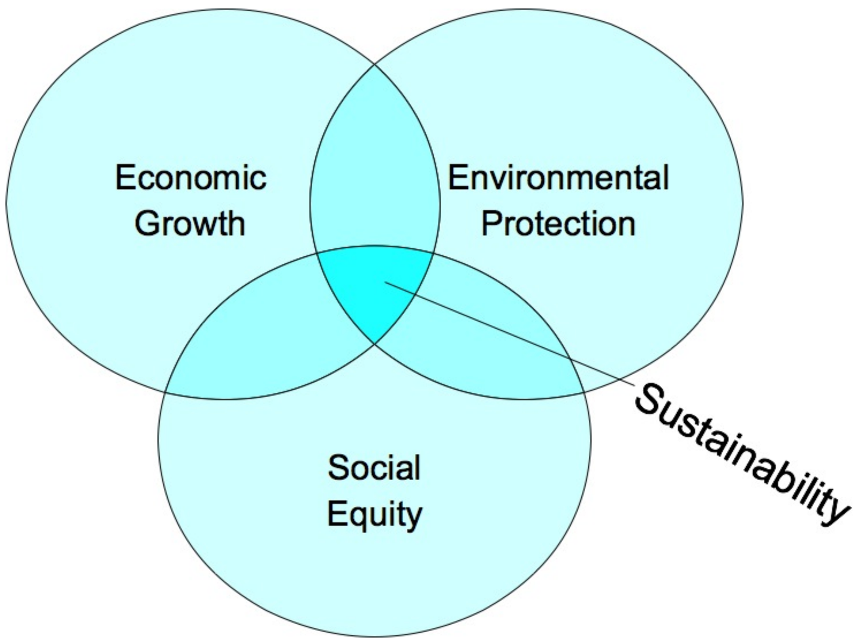


Fig. 1.3 – Sustainable Development Theory

The economic dimension of the sustainable development concept is based on the principles of rational and optimal use of limited resources. This is implemented through the introduction of resource- and energy-efficient, environmentally safe technologies at all stages of the product life cycle — from the extraction and processing of raw materials to the creation of environmentally sound products, as well as the minimization, recycling, and safe disposal of waste.

The social dimension focuses on a human-centered approach aimed at maintaining the stability of socio-cultural systems. The key objectives of this component are to prevent destructive social conflicts and to ensure a fair distribution of material and non-material benefits.

The environmental dimension seeks to preserve the integrity and functional stability of biological and physical natural systems. Priority is given to maintaining ecosystem viability, since the overall stability of the biosphere depends on its condition. It is important to note that, within this framework, both natural and anthropogenic environments — including urbanized areas such as cities — are considered objects of protection.

The further development of the concept was marked by the establishment of the Sustainable Development Goals (SDGs), adopted by the United Nations in 2015 as the foundation of the 2030 Agenda for Sustainable Development (Fig. 1.4). This program comprises 17 goals and 169 targets, addressing issues such as poverty eradication, gender equality, access to clean energy, responsible consumption, climate action, and the conservation of marine and terrestrial ecosystems [17].

Thus, sustainable development has acquired a global dimension, integrating economic, social, and environmental priorities into a unified framework for achieving long-term planetary well-being.

An essential aspect of the modern understanding of sustainable development lies in its practical implementation at various levels of governance — from international agreements to local initiatives. Governments, enterprises, research institutions, and civil society organizations develop their own strategies to achieve specific Sustainable Development Goals. In this context, the role of corporate social responsibility, green investment, environmental management, and sustainable urban policies continues to grow. Today, sustainable development is no longer a declarative objective but rather the foundation of a global survival strategy, combining scientific, economic, and ethical principles to create a safe and equitable world for all generations.

Fig. 1.4 – 17 Goals of Sustainable Development [17]

The Circular Economy is one of the leading concepts of the modern ecological transformation, further developing and operationalizing the principles of sustainable development. Its essence lies in creating an economic system based not on the linear model “produce–consume–dispose,” but on closed-loop resource cycles, in which products, materials, and energy retain their value for as long as possible (Fig. 1.5) [20].

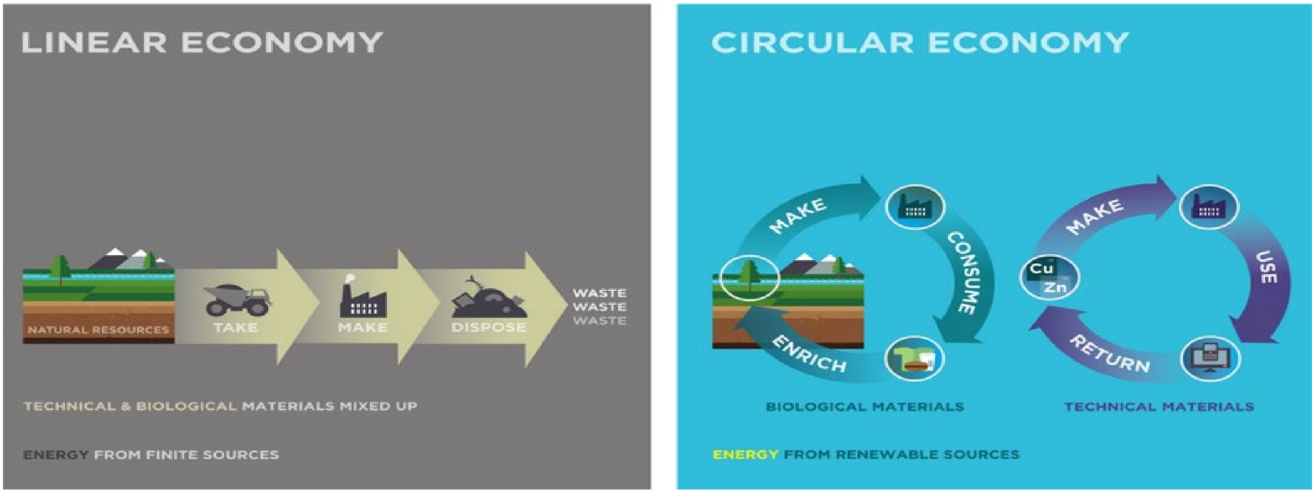


Fig. 1.5 – Linear and Circular Economic Models [18, 19]

The key principles of this model include:

- the production of materials and goods with the maximum use of renewable resources;
- the organization of product use in repeated cycles, ensuring the extension of their life span.

This concept represents an organic continuation and an instrument for implementing the principles of sustainable development. Its fundamental goal is to achieve ecological balance under conditions of sustainable economic growth and social progress. This is accomplished through the maximization of resource efficiency at all stages of the life cycle of goods and services.

The work of architect William McDonough, a leading global expert in sustainable development and design, largely shaped the concept of the circular economy. In collaboration with German chemist Michael Braungart, he developed the "Cradle to Cradle" design principle, which became the conceptual foundation of the circular economy [21, 22]. McDonough emphasizes the need to rethink industrial processes to improve environmental quality. He proposes an innovative, anthropocentric approach to design, advocating the creation of chemically safe products manufactured in accordance with high ethical standards. Their ideas were presented in the book "Cradle to Cradle: Remaking the Way We Make Things", where the authors describe design as "*a restorative, generous force that seeks to leave behind an ecological footprint that inspires delight rather than regret*" [23].

The conceptual framework of the circular economy has been practically implemented through the so-called R-imperatives (from English words beginning with "R"). Initially, the model was based on the classic triad: Reduce (reduce consumption), Reuse (reuse products), and Recycle (recycle materials). However, the evolution of the concept has significantly expanded this list. The modern comprehensive model, presented by Jacqueline Cramer in Vancouver on May 15, 2017, includes ten imperatives (10R) that encompass a broader spectrum of actions — from product design to changes in consumption patterns (Fig. 1.6).

Within the system of international environmental strategies, the circular economy is regarded as a key tool for achieving the Sustainable Development Goals (SDGs), particularly in the areas of responsible consumption and production (SDG 12), climate action (SDG 13), and conservation of natural ecosystems (SDGs 14–15). Its practical implementation enables the transition from quantitative to qualitative growth, where efficiency is defined not by production volumes but by the economy's ability to function without depleting natural systems.

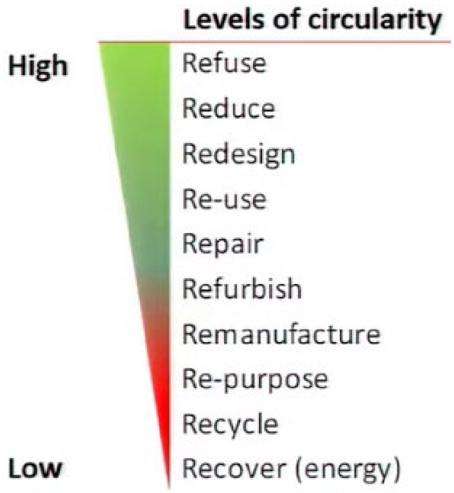


Fig. 1.6 – Levels of Circularity (R-Imperatives) in Jacqueline Cramer's Model

The circular economy implies a profound structural transformation of production and consumption systems, encompassing the following key directions:

- the transition to eco-design and modular manufacturing, which ensures easy repair, disassembly, and recycling of products;
- the development of new business models such as sharing economy, service-based economy, leasing, upcycling, and remanufacturing;
- the application of digital technologies — including artificial intelligence, blockchain, and the Internet of Things (IoT) — to optimize supply chains and track material flows;
- the formation of a culture of conscious consumption and the implementation of educational programs aimed at enhancing environmental literacy and competence in society.

The construction sector occupies a key position within the framework of the circular economy, shaping the concept of circular construction or the circular built environment. This is because the building industry is one of the largest consumers of material resources, the main generator of waste, and a significant source of greenhouse gas emissions. At the same time, it also holds the most important potential for implementing circularity principles.

Adherence to these principles not only reduces the environmental footprint but also extends the life cycle of buildings and materials, decreases dependency on extractive resources, and contributes to the creation of sustainable urban environments.

Regenerative Design represents a new paradigm in the evolution of ecological thinking, one that transcends the traditional framework of sustainable development. While sustainable development focuses on reducing negative environmental impacts and maintaining balance between natural and anthropogenic systems, the regenerative approach actively aims to restore natural processes and enhance the vitality of ecosystems. Its core idea is that human activity can become not merely "less harmful," but a positive and restorative force, capable of strengthening ecological resilience and biodiversity (Fig. 1.7) [24].

The concept of regenerative design was introduced by John T. Lyle, an American architect and theorist, in the 1990s. Lyle conceived the regenerative approach as a design system in which human-made environments are integrated into the natural cycles of energy, water, nutrients, and biomass. Unlike the sustainable design model, which primarily seeks to minimize damage, the regenerative design approach strives to generate clean energy, purify water, restore soils, improve air quality, and enhance the bioproductivity of landscapes. His vision of regenerative systems was articulated in his seminal works Regenerative Design for Sustainable Development and Design for Human Ecosystems.

The key principles of the regenerative approach include:

- System wholeness — considering any object or site not in isolation but as an integral component of the ecosystem within which it operates;

- Positive ecological balance — ensuring that human activity contributes to the renewal and enrichment of natural resources;
- Interaction and self-regulation — employing natural mechanisms to maintain system stability and resilience;
- Community engagement — emphasizing social participation, education, and co-creation with local communities;
- Adaptability — enabling flexible responses to climate change, urban transformation, and technological evolution.

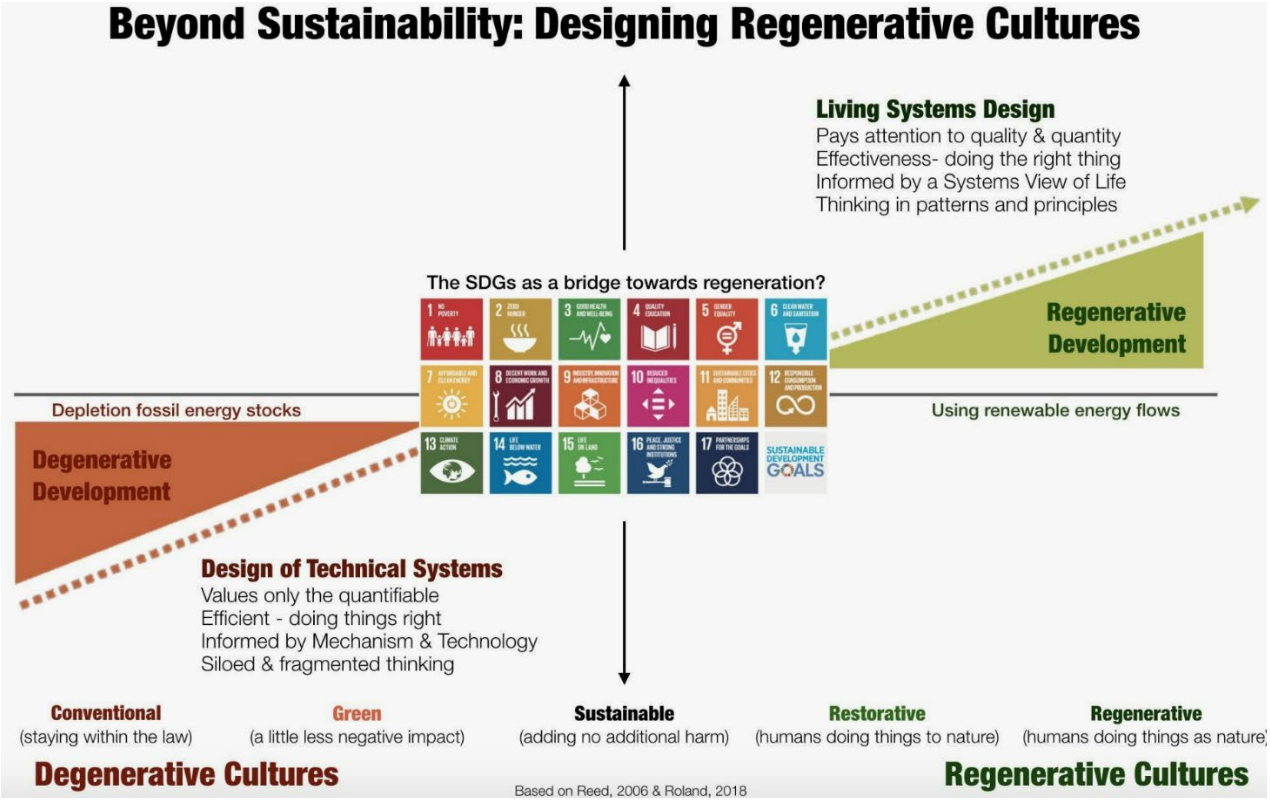


Рис. 1.7 – Regenerative Design: Beyond Sustainable Development towards Designing Regenerative Cultures [25]

The regenerative approach has found particular application in architecture, urban planning, and construction, where it shapes a new generation of environmentally active buildings and structures—those that not only minimize energy consumption but also generate their own resources. Examples include “energy-plus” buildings, air-purifying building materials, rainwater harvesting systems, and waste recycling technologies. The concepts of net-positive energy, Living Buildings, and Biophilic Design have become integral elements of the regenerative approach, combining technological innovation with nature-centered design principles.

In a broader context, regenerative design is perceived as a philosophy of human–nature interaction based on the ethics of coexistence and co-creation. It challenges the anthropocentric model of development, offering instead an ecocentric worldview in which humans act as active participants in ecological processes rather than their disruptors. Thus, the regenerative approach represents not merely a technical strategy but a worldview that shapes a new culture of design, management, and thinking.

International practice demonstrates that regenerative design is gradually being integrated into sustainable urban and territorial policies, green building standards (such as LEED, BREEAM, and the Living Building Challenge), and corporate environmental responsibility strategies. The advancement of this concept is supported by global initiatives, particularly the Regenerative Communities Network and The Capital Institute, which promote the restoration of socio-ecological systems on a global scale.

Consequently, regenerative design represents the next stage in the evolution of ecological thought, combining scientific achievements, innovative technologies, and ethical principles of human–nature coexistence.

Global risks — such as climate change, population growth, and uncontrolled technological expansion — create a complex of interrelated crises: food, water, and energy security. The awareness of this interdependence has led to the development of the *Water–Energy–Food Nexus (WEF Nexus) concept*, which has become a key framework in international environmental strategies and a tool for achieving the UN Sustainable Development Goals (Fig. 1.8).

The WEF Nexus concept is grounded in a systems approach, viewing water, energy, and food not as separate sectors but as interconnected components of a single socio-ecological and economic system. Any policy or management decision in one domain has a direct impact on the other two. For instance, energy production requires water for cooling power plants or producing biofuels; food production consumes significant quantities of both water and energy; and water extraction and purification depend on energy resources. Hence, inefficiency in any element of the "water–energy–food" triad leads to an imbalance across the entire system, creating risks of food insecurity, resource scarcity, and ecosystem degradation.

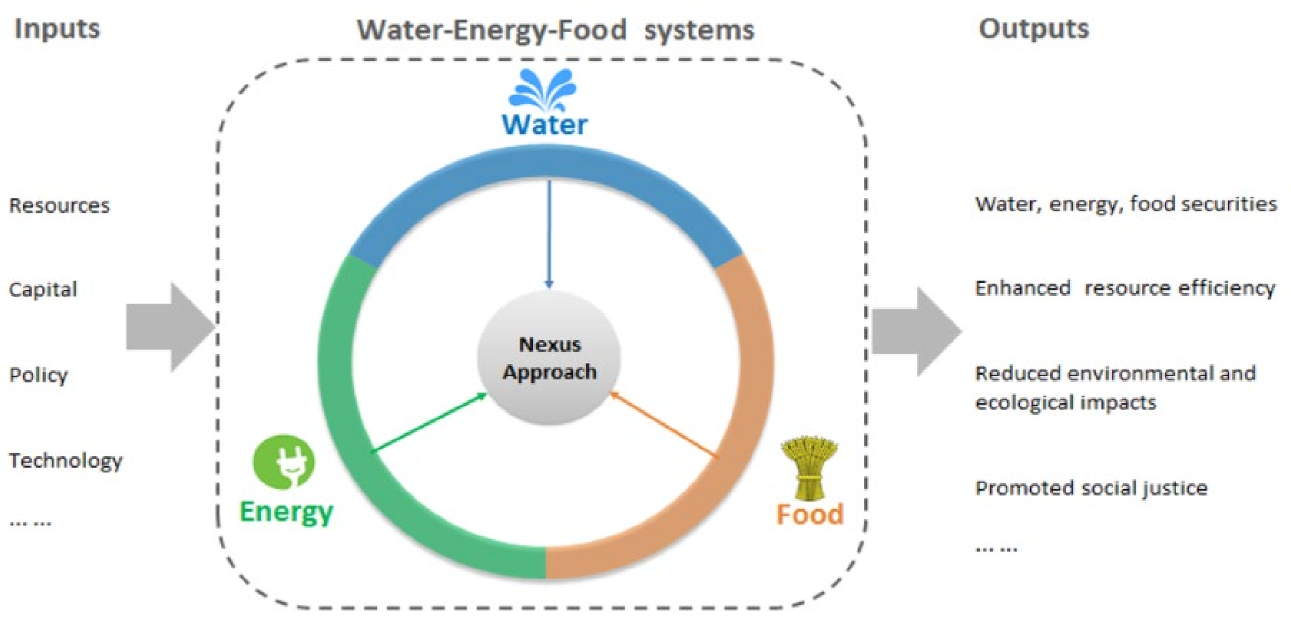


Fig. 1.8 - Water–Energy–Food Nexus (WEF Nexus) concept [24]

The idea of an integrated approach to natural resource management was further developed at the World Economic Forum in Davos (2011), where the systemic Water–Energy–Food (WEF) Nexus model was first presented. Its subsequent institutional consolidation occurred through the initiatives of FAO, UNESCO, UN-Water, GIZ, and the International Food Policy Research Institute (IFPRI). Since then, the concept has become an integral part of global resource governance, as it enables the following: the integration of Sustainable Development Goals (SDG 2 – Zero Hunger, SDG 6 – Clean Water, SDG 7 – Affordable and Clean Energy, SDG 13 – Climate Action); the avoidance of intersectoral conflicts; and the ensuring of long-term resource security.

A notable outcome of the practical implementation of the WEF Nexus approach was the development of the Global WEF Nexus Index [26, 27]. This index serves as a crucial analytical tool for evaluating WEF security at the national level and for monitoring progress toward achieving the SDGs related to water, energy, and food. Table 1.3 presents the top five countries in the Global WEF Nexus Index ranking [24].

Table 1.3

The top five countries in the WEF Nexus Index ranking

Country	Global ranking	Index evaluation	Water	Energy	Food
Norway	1	80.9	79.1	93	70.5
New Zealand	2	77.3	79.1	74.6	78.2
Sweden	3	76.9	78.2	82.3	70.1
Iceland	4	76.6	79.4	93.2	57.2
Canada	5	75.5	68.5	84.8	73.2

The European Green Deal is a comprehensive strategic initiative of the European Union, aimed at achieving climate neutrality by 2050 and transitioning toward a model of sustainable, resource-efficient, and competitive development. Presented by the European Commission in December 2019, this document marked a turning point in both European and global environmental policy, as it integrated environmental priorities into all spheres of the EU's socio-economic agenda.

The European Green Deal is not merely an environmental program but a new economic model of development that combines economic growth with environmental protection, energy decarbonization, and the improvement of citizens' well-being. The primary objective of this initiative is to transform the European Union into the first climate-neutral continent.

The key strategic objectives of the European Green Deal (Fig. 1.9) [28, 29] include:

1. Achieving climate neutrality by 2050 — reducing greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels and reaching net-zero emissions by 2050 (the goal of the "Fit for 55" package).

2. Transition to clean energy — promoting the development of renewable energy sources, improving energy efficiency, and phasing out fossil fuels.

3. Sustainable economy — implementing the updated Circular Economy Action Plan (2020), which aims to reduce waste, extend product life cycles, and enhance resource reuse.

4. Sustainable agriculture — realizing the Farm to Fork Strategy, designed to establish a healthy, environmentally friendly, and fair food system.

5. Biodiversity conservation — implementing the EU Biodiversity Strategy for 2030, which provides for the restoration of degraded ecosystems and the expansion of protected natural areas.

6. Greening industry and transport — fostering the development of green infrastructure, the decarbonization of heavy industry, and the broader adoption of electric transport.

7. Financing the green transition — establishing the Just Transition Mechanism and the Sustainable Europe Investment Plan to support a fair and inclusive transformation toward sustainability.

Fig. 1.9 - The key strategic objectives of the European Green Deal [24]

The construction sector is one of the key areas for implementing the European Green Deal, as buildings account for approximately 40% of energy consumption and more than one-third of CO_2 emissions in the EU. A central component of this policy is the Renovation Wave Initiative (2020), which aims to enhance energy efficiency and decarbonize the building stock.

According to the revised Energy Performance of Buildings Directive (EPBD), all new buildings must be zero-emission by 2030. The European Green Deal also integrates circular economy principles through the reuse of materials and life-cycle-based design. The promotion of regenerative and biophilic design supports the creation of buildings that not only minimize environmental harm but also contribute to the restoration of ecosystems.

Through financial mechanisms such as the Just Transition Mechanism and the Next Generation EU Fund, the construction industry is becoming a driving force of the green transformation, combining technological innovation, social responsibility, and environmental performance.

International programs and concepts aimed at overcoming environmental threats form a global platform for transitioning toward a sustainable development model. The concepts of sustainable development, the circular economy, regenerative design, and the Water–Energy–Food (WEF) Nexus define a new logic of interaction between society and nature — one focused on reducing environmental pressure and restoring natural systems.

The European Green Deal serves as a practical instrument for implementing these ideas at the policy level, integrating environmental, economic, and social objectives. Within this strategy, the construction sector plays a particularly significant role as a driver of decarbonization, energy efficiency, and circular design principles. Collectively, these initiatives demonstrate the global transition toward a new development paradigm — one that is ecologically oriented, technologically innovative, and socially responsible.

1.3. Carbon Footprint. The Role of the Construction Industry in Reducing the Carbon Footprint

The carbon footprint is the amount of greenhouse gases (primarily carbon dioxide - CO_2, but also methane, nitrous oxide, etc.) emitted into the atmosphere as a result of human activities, organizational operations, product manufacturing, or event hosting. These gases trap heat in the atmosphere, and their accumulation intensifies the greenhouse effect, leading to an increase in the Earth's average temperature, glacier melting, sea-level rise, extreme weather events, and other consequences for the climate and life on the planet.

The carbon footprint is measured in tons of carbon dioxide equivalent (CO_2-eq.), which allows for accounting for the different climate impacts of various greenhouse gases.

The construction industry is one of the largest sources of greenhouse gas emissions. According to various estimates, it accounts for 37% to 40% of global CO_2 emissions (fig. 1.10).

Fig. 1.10 - Factors determining the carbon footprint of construction products

The main sources of emissions are operational carbon and embodied carbon.

The operational carbon footprint refers to the greenhouse gas emissions associated with the direct operation and maintenance of a building. That is, these are CO_2 emissions from the energy the building consumes daily to maintain the comfort of its occupants.

Almost all emissions in this category are generated through energy consumption, the main types of which are listed in Table 1.4.

Table 1.4

Sources of Operational Emissions

Type of Energy Consumption	Example of Emission Generation
1. Heating	Burning natural gas, liquid fuel, or coal; using electricity (if generated from fossil fuels) for an electric boiler or convectors.
2. Cooling	Operation of air conditioners powered by the electrical grid.
3. Hot Water Supply	Water heating using a gas boiler or water heater.
4. Ventilation	Operation of supply and exhaust ventilation systems and heat recovery ventilators.
5. Lighting	Electricity consumption by incandescent, LED, and fluorescent lamps (the latter two are significantly more efficient).
6. Household appliances and equipment	Operation of computers, servers, refrigerators, stoves, televisions, and other electronic devices.

Historically, operational carbon constituted 75-90% of a building's total footprint over a 50-year lifespan. Therefore, the fight against climate change in the construction industry has for decades focused precisely on it. A key point in this case is the direct dependence of the magnitude of operational emissions on the energy source. For example, if a building is powered by **solar panels or wind turbines**, its operational footprint will be close to zero. Conversely, if a building is heated by **natural gas**, its operational footprint will be very high.

Accordingly, strategies for reducing operational emissions from buildings include:

1. **Improving the energy efficiency of the building envelope:**

- High-quality thermal insulation of walls, roofs, floors, and foundations.
- Installation of energy-efficient glazing units (with low-emissivity coating and argon) and high-quality frames.
- Elimination of thermal bridges through the appropriate design of joints to prevent heat loss.

2. **Installing innovative engineering systems and equipment:**

- **Heat Recovery Ventilators (HRVs)** -- a ventilation device that serves for energy conservation and creating a comfortable indoor microclimate. Its main task is to exchange heat between the exhaust air being removed from the room and the fresh air coming from outside, without mixing them.
- **Heat Pumps for home heating** - devices that use heat from the environment (air, ground, or water) to heat a house and provide hot water, operating on the reverse refrigeration principle. They do not generate heat but transfer it from one environment to another, making them energy-efficient and environmentally friendly.
- Modern energy-efficient equipment, for example, condensing boilers, LED lighting, and equipment with a high energy efficiency class (A+++).

3. **Using Renewable Energy Sources (RES)**

- Involves installing solar panels, wind turbines, heat pumps, and solar thermal collectors to generate own electricity and heat, which helps reduce dependence on fossil fuels, increase autonomy in conditions of external energy grid instability, lower costs, and reduce harmful emissions into the environment.

4. **"Smart" Control and Management**

- Involves implementing Building Management Systems (BMS) or Building Automation Systems (BAS), which are computerized systems for controlling and managing building equipment such as heating, ventilation, and air conditioning, lighting, security systems, and elevators, to optimize comfort, energy efficiency, and operational costs. The system collects data from sensors and provides a centralized user interface for remote control, and can trigger maintenance alarms and security alerts. BMS technology enhances building safety, improves occupant comfort, and significantly reduces energy consumption by automating system operation based on real-time conditions and predefined parameters.

Previously, operational emissions were the dominant source of emissions throughout a building's life cycle. However, due to strict energy efficiency standards, buildings now consume much less energy. As buildings become more energy-efficient, approaching the Nearly Zero-Energy Buildings (NZEB) standard, the share of *embodied carbon* in the building's total emission balance increases sharply.

Embodied Carbon is the total greenhouse gas emissions associated with all stages of the life cycle **up to the point of handing over the building for operation**. In other words, it is the "amount of carbon" that was "spent" or "emitted" to create the object itself.

In modern energy-efficient homes, embodied carbon can account for 50% to 70% of total emissions over the entire life cycle.

Embodied carbon is associated with processes that occur during:

- Extraction of raw materials, processing, and manufacturing of materials such as cement, steel, wood, etc.
- Transportation (shipping materials to construction sites);
- Construction (emissions arising directly during the building erection process);
- Maintenance and repairs, during which materials or structural elements may be replaced.
- Building demolition and disposal of relevant waste.

Some examples of such emission generation are given in Table 1.5.

Table 1.5

Examples of Embodied Carbon Generation

Process	Content	Example
Material Production	Raw material extraction, transportation to the plant, and direct production (firing, smelting, etc.).	Firing clinker for cement, steel smelting, and glass production.
Transportation & Construction	Transporting materials from the plant to the construction site and the installation process (emissions from construction machinery operation).	Emissions from a truck delivering concrete, or from the operation of a tower crane.

Since embodied carbon is largely determined by processes related to construction materials, strategies for reducing emissions involve finding low-carbon alternatives.

Low-carbon building materials are materials whose production, transportation, installation, and disposal are associated with significantly lower greenhouse gas emissions (carbon footprint) compared to conventional traditional counterparts. This is not one specific type of material, but rather a characteristic or approach to their selection based on an analysis of their life cycle. Such materials typically correspond to one or more of the following principles:

- Low energy intensity of production, meaning less energy (especially from fossil fuels) is required for their creation;
- Use of natural renewable resources;
- Recyclability, ease of disassembly, and reuse;
- Local production to reduce transportation emissions;
- Durability and repairability, which postpones the need for replacement and disposal;
- Ability to absorb and retain carbon from the atmosphere.

To reduce embodied carbon, it is extremely important to make low-carbon choices already at the design stage, to plan for adaptability and flexibility of design solutions. Choosing local materials and suppliers helps reduce carbon emissions from transportation while stimulating the local economy. Examples of local materials include wood and wood products (such as cross-laminated timber, glued laminated timber, and LVL), as well as agricultural waste (straw and hemp).

Applying design for disassembly principles, primarily using prefabricated construction technologies, enables the building to be disassembled at the end of its life cycle, minimizing waste and promoting the reuse of individual elements and materials. This enables the application of circularity principles, which will contribute to achieving the Sustainable Development Goals and mitigating the effects of climate change.

Another fundamental design strategy is the application of circular economy principles during construction and at the disposal stage, which involves choosing recycled and recyclable materials.

Related to the principles of the circular economy is the sorting of waste generated from building demolition. This provides valuable resources for creating new components and materials suitable for reuse. Recycling construction debris saves energy by reducing the need to extract new raw materials and produce new elements, thereby reducing overall emissions. Secondary materials include recycled concrete rubble for aggregate, recycled plastics for producing plastic blocks, construction panels, pipes, waterproofing membranes, window profiles, and insulation, and wood waste for producing particle boards, plywood, etc.

CHAPTER 2. BUILDING LIFE CYCLE AND ITS ASSESSMENT METHODS

2.1. Building Life Cycle Stages

Construction is one of the most important sectors of human activity, shaping living conditions and accounting for about 13% of global GDP, while providing employment for a significant part of the world's population. A key characteristic of the traditional construction industry is its excessive energy consumption, which contributes to global warming and climate change. Energy is used in all stages — from the extraction of raw materials to the production and transportation of materials, construction processes, operation, maintenance, and demolition of buildings. It is well known that the construction sector accounts for approximately 40% of total energy consumption and 36% of CO_2 emissions worldwide [30].

However, this very sector has one of the greatest potentials for contributing to sustainable development and achieving climate neutrality. The implementation of sustainability criteria in construction can be achieved through innovative technologies aimed at the rational and efficient use of natural resources — transitioning from non-renewable raw materials and primary products to those created using recycling technologies and "green" engineering solutions, as well as through the use of renewable energy sources and energy-efficient approaches.

The transition to carbon-neutral construction necessitates a comprehensive approach to design development, encompassing the life cycle of all building elements — from material production to construction, operation, and disposal at the end of service life, including all energy and resource expenditures, as well as the environmental impact of each stage. This assessment serves as a key tool for scientifically substantiated determination of the sustainability degree of any building project.

It is important to note that the choice of design solutions should be guided by the evolution of environmental awareness and the shift from the traditional ex post assessment (aimed at mitigating harm and environmental risks of existing activities) to the ***ex ante*** approach — preventive research and analysis of concepts and strategies before construction begins, to design ecologically efficient or low-impact systems [31].

Environmentally responsible design is becoming increasingly popular and necessary in architectural and construction practice. Today, it focuses on two key directions: developing strategies for “green” design of buildings and settlements, and analyzing the environmental impact of building materials, structures, and facilities to create effective design solutions. This shift transforms traditional design principles, necessitating their reevaluation and adaptation to new conditions and scenarios that encompass the entire life cycle of buildings. The emphasis is placed not only on the architectural form, but also on the building's functioning throughout its whole operational period, where temporal and spatial aspects become crucial. This applies to all levels of the built environment — from individual buildings to entire urban spaces.

The importance of building lifespan and maintenance planning becomes critical at the early stages of design. These aspects are closely linked to technological choices, which, in turn, depend on the ecological context. Therefore, environmentally responsible design necessitates a holistic approach that encompasses all stages of a building’s life cycle, from creation to disposal.

The life cycle of a building is the period encompassing all stages of its creation, operation, and disposal — from the architect’s initial idea to demolition, recycling, and reuse. At each stage, the building interacts with the environment by consuming natural resources, energy, and water, and by generating greenhouse gas emissions and other pollutants.

The main stages of a building’s life cycle include: conception and design, extraction of raw materials and production of building materials, construction, operation and maintenance, demolition, followed by recycling or reuse (Fig. 2.1). Each of these stages is associated with intensive consumption of natural, energy, water, and material resources.

Energy consumption accompanies all stages of a building’s life cycle — from the extraction and processing of raw materials for construction products to the assembly of structures, operation of buildings (heating, lighting, ventilation, etc.), and finally demolition, waste recycling, or disposal.

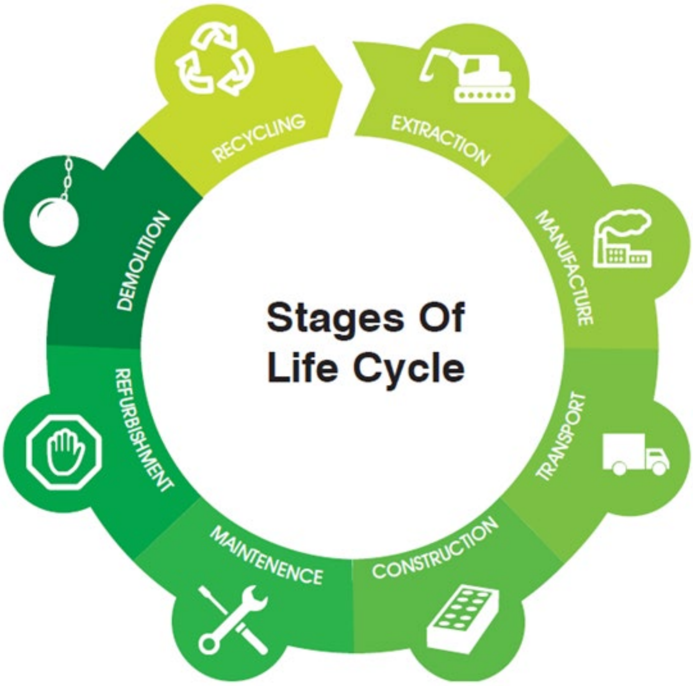


Рис. 2.1 – Building Life Cycle Stages [32]

The design stage is a determining phase in the building life cycle, as it shapes the fundamental decisions that define not only the functional and aesthetic characteristics of a construction object but also its long-term environmental impact. It is at this stage that strategic decisions are made regarding energy efficiency, resource conservation, the use of environmentally safe materials, and the optimization of operational regimes. The chosen structural solutions, engineering systems, and applied technologies directly determine the intensity of future greenhouse gas emissions, the consumption of energy carriers and water resources, as well as the overall degree of environmental impact throughout the building's lifespan.

A key tool for ensuring sustainability at the design stage is the Life Cycle Thinking (LCT) methodology, which involves decision-making that accounts for all phases of a building's or product's existence. Conceptually, LCT can be defined as an approach that views a product or process analogously to a living organism, passing through successive stages of birth, growth, maturity, and end of life [31].

Extraction of Raw Materials and Production of Building Materials. Even before construction begins, a building has already exerted an environmental impact. The production of construction materials and components is closely linked to the extraction and processing of natural raw materials, a process characterized by high energy intensity. The extraction of resources such as sand, clay, iron ore, limestone, timber, bauxite, and gravel requires significant amounts of energy and water while generating substantial waste — including spoil heaps, toxic compounds, and heavy metals that contaminate soils and water bodies.

Beyond the depletion of non-renewable resources, raw material extraction causes severe ecosystem disturbances: landscape transformation, destruction of vegetation cover, soil degradation, biodiversity loss, and disruption of ecological balance.

The extractive industry relies heavily on fossil-fuel-powered equipment and transportation infrastructure to move raw materials to processing sites. In today's globalized economy, transportation-related environmental impacts are especially significant. Since a large share of building materials is not locally produced, their long-distance transportation adds considerable environmental load even before construction begins.

Studies show that the embodied energy of materials accounts for 15% to 60% of total energy consumption over a building's life cycle [33]. Moreover, the cement industry alone is responsible for approximately 5% of global CO_2 emissions [34].

The material production phase generates the highest pollution levels in the supply chain and building life cycle, primarily due to intensive energy consumption and associated emissions of pollutants. The high environmental footprint of this stage necessitates the introduction of resource-efficient technologies that aim to reduce production energy demand, utilize industrial by-products, and integrate secondary raw materials into manufacturing cycles.

Construction Phase. The construction phase is a key stage in the building life cycle, during which design solutions are materialized into a physical structure. This process encompasses a wide range of activities — from site preparation and the erection of structures to the installation of engineering systems and finishing works. These operations are accompanied by intensive consumption of materials (concrete, steel, wood) and energy resources, generating both direct and indirect greenhouse gas emissions.

Anthropogenic impacts at this stage manifest through:

- air pollution (dust particles, emissions from construction machinery);
- water pollution (contamination of surface and groundwater);
- noise generation from mechanical equipment;
- waste accumulation and landfill use.

A significant contributor to environmental pressure remains material logistics, which relies on carbon-intensive transport. Suboptimal technological decisions and inefficient process management exacerbate the negative effects on ecosystems.

Operation Phase. The operational phase is the longest in a building's life cycle, typically lasting more than 50 years. During this period, the structure requires continuous resource input — energy and water for the operation of engineering systems, as well as materials for maintenance and repairs. This phase is characterized by cumulative environmental impacts, manifested in:

- generation of household and wastewater;
- CO_2 emissions resulting from energy consumption;
- construction waste during renovations and refurbishments.

The intensity of these impacts is directly determined by design decisions — particularly, the energy efficiency of architectural and structural solutions, the quality of building envelopes, the performance of construction works, the optimization of facility management systems, and the environmental awareness of occupants.

During major renovation or reconstruction, resource consumption increases again due to the production of new materials and accompanying waste generation. The scale of these material flows depends on the adaptive potential of the building, predetermined at the design stage — the greater the flexibility of architectural and structural solutions, the fewer resources are required during reconstruction.

Demolition Stage. The demolition stage completes the building's life cycle, involving the dismantling of structures, sorting of components, and disposal of materials. The need for demolition arises from technical aging (physical deterioration of structures) and moral obsolescence, defined by noncompliance with contemporary comfort standards. Comfort criteria, which include sanitary-hygienic parameters and functional characteristics, constantly evolve under the influence of technological progress.

Demolition generates significant amounts of construction waste, often containing hazardous substances that require specialized disposal methods. The problem is aggravated by the lack of a systematic approach to the final stage of a building's life cycle during the design phase. The solution lies in the implementation of reversible design, where design decisions facilitate dismantling and selective demolition of building parts, enabling, where possible, recycling operations and the reintegration of materials into the production cycle.

Recycling or Reuse Stage. Given the large amount of waste generated at the final stage of a building's life cycle, the recycling and reuse of materials become critically important for reducing the environmental footprint of construction. Today, architects are increasingly interested in evaluating and minimizing the environmental impact of the buildings they design. Tools such as energy modeling help predict and, through quality design, reduce operational energy consumption. However, this is not sufficient when it comes to the building's end-of-life stage.

To determine what to do with a building at the end of its life cycle, it is necessary to incorporate strategies and principles during the design phase that ensure the architectural object retains its value once it reaches the end of its service life. These principles are embodied in the Design for Disassembly (DfD) paradigm.

This methodology involves:

- creating buildings designed for future disassembly and component recovery;
- using modular structures and environmentally safe materials;
- applying technologies that enable materials to be returned to the production cycle.

DfD requires rethinking the entire life cycle of a building—from selecting materials with known durability to planning scenarios for their future reuse. Such an approach not only reduces waste volumes but also promotes the improvement of production processes and construction technologies [35].

2.2. Life Cycle Assessment (LCA).

Life Cycle Assessment (LCA) is a tool developed to determine the overall environmental impact of a product, service, activity, or process. LCA evaluates the environmental effects of a given product throughout its entire lifespan — from "cradle to grave," that is, from raw material extraction to final disposal. The concept of "cradle to grave" is known as Life Cycle Assessment (LCA). It is a systematic method that assesses the environmental impact of any product throughout its entire life cycle — from raw material extraction ("cradle") to disposal ("grave").

The purpose of LCA is to help reduce harmful environmental impacts. By analyzing all stages of a product's life comprehensively, we gain a clear picture of how much energy and resources are consumed and what pollutants are released into the air, water, and soil. This information enables the comparison of materials and technologies, allowing for the identification of better alternatives for creating products with minimal environmental impact.

The application of Life Cycle Assessment (LCA) in the construction sector is a key instrument for achieving sustainability. The LCA methodology enables accurate measurement and reduction of a building's environmental impact at all stages — from material extraction to disposal. This directly contributes to minimizing harm to ecosystems and human health. In the modern context, tools such as LCA are essential for implementing the concept of sustainable development in construction, ensuring the creation of buildings with minimal environmental footprints and long-term efficiency.

There are many types of Life Cycle Assessment (LCA). The main rule is that the level of detail in the study determines its depth: the more specific the data required, the more comprehensive the assessment must be. For instance, a report prepared for internal company use will have less stringent requirements than a report intended for publication or environmental product labelling.

In addition to classical LCA, there is a range of related assessment tools based on its principles, including:

- Environmental Product Declarations (EPD) developed using LCA results;

- Industry-specific studies adapted to the standards of particular product categories;
- Targeted analyses such as carbon or water footprint assessments;
- Social Life Cycle Assessment (s-LCA), which considers the social aspects of production;
- Long-term monitoring studies aimed at assessing dynamic changes in impacts over time.

The uniqueness of the LCA methodology lies in its flexibility — it allows for the implementation of diverse specialized assessments while relying on a unified, systematic, and scientifically grounded framework.

Life Cycle Assessment research involves a detailed inventory of the energy and materials required across the entire value chain of a product, process, or service, as well as the calculation of associated environmental emissions. Thus, LCA evaluates the cumulative potential environmental impact to document and improve the overall environmental profile of a product.

The methodological foundations of Life Cycle Assessment (LCA) are defined by the international standards ISO 14040 and ISO 14044, developed by the International Organization for Standardization (ISO).

ISO 14040:2006 "Environmental management — Life cycle assessment — Principles and framework" establishes the fundamental principles, structure, and stages of LCA, including goal and scope definition, inventory analysis of inputs and outputs, impact assessment, and interpretation of results [36].

ISO 14044:2006 "Environmental management — Life cycle assessment — Requirements and guidelines" provides detailed requirements for data collection, calculations, sensitivity analysis, verification of result validity, and report documentation [37].

According to these standards, the Life Cycle Assessment (LCA) process consists of four interrelated stages (Fig. 2.2):

1. ***Goal and Scope Definition*** — defining the purpose and boundaries of the study;

2. ***Life Cycle Inventory (LCI)*** — compiling an inventory of inputs and outputs throughout the product's life cycle;

3. ***Life Cycle Impact Assessment (LCIA)*** — evaluating the potential environmental impacts associated with those inputs and outputs;

4. ***Interpretation*** — analysing and interpreting the results to draw conclusions and support decision-making.

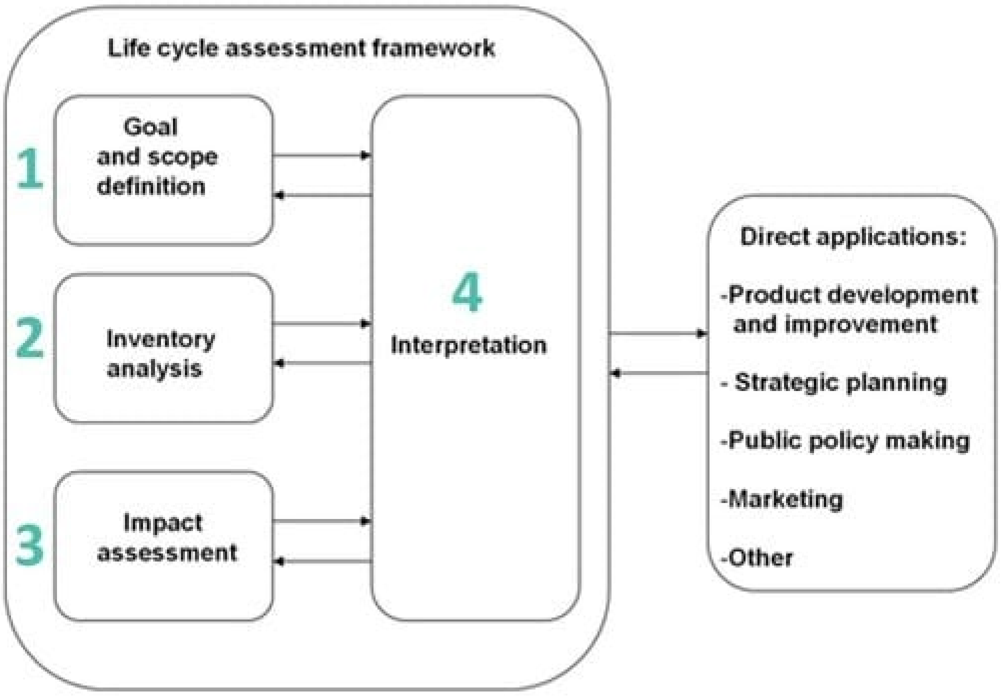


Fig. 2.2 – Life Cycle Assessment (LCA) Stages [36]

The use of ISO standards ensures the comparability, scientific validity, and transparency of LCA results, making them suitable for international application, environmental product labeling, and the development of sustainable strategies in the construction sector. The stages of the process are often interdependent, meaning that the outcome of one stage may influence the completion of others. Therefore, none of the stages can be considered complete until the entire assessment has been finalized.

Step 1. *Goal and Scope Definition.*

The first stage of conducting a Life Cycle Assessment (LCA), in accordance with the ISO 14040 and ISO 14044 standards, is the definition of Goal and Scope. At this stage, the main parameters of the study are established, setting the direction for the entire assessment. These parameters are often referred to as Study Design Parameters (SDP) and include defining the objectives, system boundaries, the object of study, the functional unit, and the level of analytical detail.

The goal of an LCA may include, for example:

- assessing the environmental impact of a building throughout its entire life cycle;
- comparing two building materials or technologies (e.g., traditional concrete and eco-concrete);
- developing an Environmental Product Declaration (EPD);
- optimizing design solutions to reduce the carbon footprint.

The scope defines the system boundaries, which means that it determines which life cycle stages are included in the analysis.

For buildings or construction products, the goal and scope definition stage is critical because it determines:

- which life cycle phases will be considered (production, operation, maintenance, end-of-life);
- which environmental indicators will be assessed (CO_2 emissions, energy consumption, waste generation, etc.);
- what data must be collected (material flows, resource consumption, energy sources).

Thus, a clearly defined goal and scope ensure the scientific credibility and comparability of LCA results. In the context of the construction industry, this means that all subsequent calculations must be based on a transparent and consistent logic, from material selection to the end-of-life and recycling scenarios of the building.

Step 2. *Life Cycle Inventory (LCI)*

At the second stage of the Life Cycle Assessment (LCA), a Life Cycle Inventory (LCI) analysis is carried out. Its purpose is to collect, systematize, and quantify all input and output resource flows associated with the life cycle of a product, building, or service.

During the LCI process, the following are considered:

- ***Inputs*** — natural resources, materials, energy, water, auxiliary substances that enter from the environment or other production processes;
- ***Outputs*** — all types of emissions to air, water, or soil, waste, by-products, noise, or thermal pollution, etc.

The result of this stage is a detailed material and energy flow balance within the defined system boundaries.

For buildings or construction products, the LCI typically includes:

- Material extraction and production stage — the amount of raw materials used (cement, steel, timber, insulation materials), energy consumption, and associated CO_2 emissions;
- Transportation stage — distances, type of transport, fuel consumption, and emissions;
- Construction stage — energy use of equipment, water consumption, waste generation;
- Operation stage — electricity, heat, and water consumption, and emissions from heating, ventilation, and air-conditioning systems;
- Demolition and disposal stage — demolition waste, potential for reuse or recycling of materials.

The LCI forms the foundation for the next phase — Life Cycle Impact Assessment (LCIA). The accuracy and reliability of LCA results directly depend on the completeness and quality of the data collected at this stage.

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

At the third stage of the LCA methodology, the Life Cycle Impact Assessment (LCIA) is conducted. Its purpose is to convert the quantitative data obtained during the LCI phase into comprehensible indicators of environmental impact, enabling informed environmental and managerial decisions.

According to ISO 14040 and ISO 14044 standards, the main LCIA phases include:

1. *Selection of impact categories, indicators, and characterization models.*

At this stage, specific environmental aspects to be analyzed are determined, such as global warming potential, ozone layer depletion, acidification, eutrophication, human toxicity, or freshwater consumption.

ISO standards require that the selected set of categories comprehensively reflect the relevant environmental issues for the geographical and industrial context in which they are applied.

Commonly used assessment methodologies include TRACI (USA), ReCiPe (EU), CML, AWARE, and others, which provide standardized impact factors.

2. *Classification of inventory results*.

Results from the LCI phase (lists of all emissions and resource uses) are allocated to the selected impact categories.

For instance, CO_2, CH_4, and N_2O emissions are classified under global warming; NO_x and SO_2 under acidification; heavy metals or organic compounds under human toxicity.

This classification is typically performed using specialized databases and software, such as SimaPro, GaBi, or OpenLCA.

3. *Characterization*.

In this step, quantitative conversion of the data is performed — each impact flow is expressed in a common measurement unit within its category. Characterization factors (equivalency factors) are applied. For example, for global warming potential (GWP), results are expressed in CO_2-equivalents (CO_2-eq):

1 kg CO_2 = 1 CO_2-eq

1 kg $CH_4 \approx 28$ CO_2-eq

1 kg $N_2O \approx 265$ CO_2-eq

Thus, emissions of different greenhouse gases are translated into a unified scale, allowing for a comparison of their contributions to climate change.

Step 4. *Life Cycle Interpretation*

The Interpretation phase is the final stage of the Life Cycle Assessment (LCA). Its main goal is to transform the obtained results into scientifically grounded conclusions and practical recommendations that can guide environmentally sound decision-making.

According to ISO 14044, this stage involves:

- Completeness check — verifying whether all relevant life cycle stages have been included;
- Sensitivity analysis — assessing how variations in input data affect the final results;
- Consistency analysis — ensuring that the methods used align with the initially defined goals and scope.

The objective of the interpretation phase is to identify the alternative with the lowest overall environmental burden — i.e., the option that minimizes impacts on air, water, and land ecosystems throughout the entire life cycle, from resource extraction to end-of-life disposal.

In the context of buildings or construction products, life cycle interpretation enables:

- identification of materials, design solutions, or technologies with the least environmental impact;
- justification of energy-efficient or low-carbon design decisions;
- development of recommendations to optimize the operational phase (e.g., improving thermal efficiency or selecting materials with lower global warming potential);
- ensuring compliance with environmental standards and green building certification systems such as LEED, BREEAM, DGNB, or EDGE.

2.3. Software for Building Life Cycle Analysis

Life Cycle Assessment (LCA) is a scientific method used to evaluate the environmental impact of a product or service throughout its entire life cycle, from raw material extraction and manufacturing to use and disposal. Life Cycle Assessment (LCA) software tools are designed to support this process. They provide a comprehensive view of a product's environmental impact, helping to inform decisions in the field of sustainable development.

Conducting a life cycle assessment helps identify areas for improvement, reduce environmental impact, and achieve sustainability goals. These tools enable the evaluation of the environmental performance of products and services, ensuring that the most environmentally sound choices are made at every stage of the life cycle.

In the past, conducting a detailed Life Cycle Assessment (LCA) for buildings involved extensive manual calculations and laborious data collection, making the process resource-intensive and inaccessible for many projects. Today, innovative LCA software in architecture is fundamentally changing this assessment, significantly increasing accuracy, efficiency, and reducing complexity.

Digital LCA solutions for construction, such as Athena Impact Estimator, Tally, and One-Click LCA, simplify the assessment of building materials and processes. These tools feature an intuitive, user-friendly interface that allows sustainability specialists, construction and civil engineering professionals, and project managers to model various construction scenarios and assess their environmental impact quickly. Thanks to built-in scenario analysis capabilities, stakeholders can easily compare design options, material choices, and construction methods to identify alternatives with the lowest impact.

The main strength of eco-efficiency modeling tools lies in their powerful databases. These platforms integrate large, pre-populated databases containing accurate information on the environmental impact of various building products, materials, and systems. By automating data collection processes, software solutions eliminate the need for manual searching and verification of environmental data, significantly reducing the time required for a full building assessment.

Modern LCA software also seamlessly integrates project-specific data, such as Bills of Materials (BOM), energy efficiency calculations, and local site characteristics. This automation ensures accuracy and consistency in LCA results, closely aligning with actual project conditions. By simplifying data integration, these tools enable teams to quickly create comprehensive and transparent sustainability assessments that comply with widely recognized standards and certifications, such as LEED and BREEAM.

Innovative LCA software for construction projects lowers the barriers to sustainable construction, popularizing access to detailed sustainability assessments. Due to increased accessibility and ease of use, more construction projects can effectively implement LCA methodologies, ensuring significant improvements in environmental performance across the built environment.

The main categories of life cycle assessment software include:

1. Specialized Software for in-depth analysis.
2. BIM-integrated Software for practical applications.

2.3.1. Specialized Life Cycle Assessment Software

These programs are the most powerful tools used by professionals to conduct detailed studies in accordance with the requirements of international standards ISO 14040, which contains the principles and framework for life cycle assessments, and ISO 14044, which outlines the requirements for conducting the assessment.

The most popular in this group are **SimaPro**, **Sphera's LCA for Experts**, and **openLCA**.

SimaPro

SimaPro – is a life cycle assessment (LCA) software chosen by research institutes and consultants.

https://simapro.com/

SimaPro is one of the most popular and authoritative tools among LCA practitioners. It offers a very flexible platform with a large number of databases (e.g., ecoinvent) and assessment methods. SimaPro is a tool that provides a comprehensive framework for conducting life cycle analysis. It has a large Life Cycle Inventory (LCI) database containing information on thousands of materials and processes. This significantly facilitates data collection and analysis at all stages of a product's life cycle.

SimaPro allows users to customize LCA modeling by adjusting parameters and input data to reflect specific industry or regional characteristics. This feature makes conducting analysis tailored to specific needs simpler and more effective.

Furthermore, SimaPro enables the creation of custom reports that clearly and concisely summarize LCA results. This simplifies the process for stakeholders to understand the study's results and make informed decisions.

SimaPro is used by businesses, government agencies, and research institutes to conduct life cycle analysis of products and processes in various industries, including construction, energy, and the food industry. It is a powerful and flexible tool that helps organizations make informed decisions about their environmental impact and improve sustainability performance.

Sphera's LCA for Experts (formerly GaBi) combines life cycle assessment (LCA) modeling and reporting software with reliable and consistent environmental data.

https://sphera.com/

Sphera is another popular tool for conducting life cycle assessment (LCA), widely used worldwide. It is known for its extensive environmental database, covering a wide range of industries and geographical regions. With over 20 industry databases, Sphera's analytics allow for assessing environmental impact at every stage of a product's life cycle and making evidence-based decisions.

Sphera allows users to customize LCA modeling by changing parameters and input data to reflect specific industry or regional characteristics. This feature enables the conduct of analysis tailored to specific needs. Furthermore, Sphera/GaBi enables the creation of custom reports that clearly and concisely summarize LCA results. This simplifies the process for stakeholders to understand the analysis results and make informed decisions.

Sphera can be integrated with other sustainability tools, such as carbon footprint calculation software, to provide a more comprehensive overview of environmental impact.

Sphera/GaBi is used by businesses, government agencies, and research institutes to conduct LCA of products and processes in various industries, including construction, transportation, and consumer goods. It is a powerful and flexible tool that helps organizations make informed decisions about their environmental impact and improve sustainability performance. GaBi is often sold as part of the 'Sphera Sustainability Solutions' product suite, which also includes other software tools related to sustainability.

OpenLCA is a unique free and open-source software for professional environmental, social, and economic life cycle assessment.

www.openlca.org/

It is a powerful alternative to commercial solutions. It has an active community and supports various databases and plugins. Ideally suited for learning LCA and for organizations with limited budgets.

Among its capabilities are conducting LCA, calculating carbon footprint, eco-design, creating Environmental Product Declarations (EPD), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA).

OpenLCA is designed to be flexible and adaptable, allowing users to customize the software according to their specific needs and conduct a wide range of sustainability studies. OpenLCA supports a wide range of impact assessment methods, enabling users to select the method most suitable for their specific study.

The software enables the analysis of inventory for products or services, including data on raw materials, energy consumption, and emissions. Overall, OpenLCA is a powerful and flexible tool for conducting LCA, accessible to a wide range of users, offering a set of features for conducting detailed sustainability analyses and communicating results to stakeholders.

2.3.2. BIM-integrated Life Cycle Assessment Software

This category is most relevant for architects and engineers, as it allows analysis to be conducted directly within the BIM environment (Revit, ArchiCAD, etc.). Let's consider the most popular software products.

https://oneclicklca.com/

One Click LCA is software for conducting life cycle assessment (LCA) and creating Environmental Product Declarations (EPD), developed specifically for the construction industry.

One Click LCA is a cloud-based software tool for conducting life cycle assessments (LCAs) and evaluating the environmental impact of buildings, infrastructure, and other construction projects. It is a web platform that integrates with primary BIM tools (Revit, ArchiCAD), as well as with Excel. It automates the export of material quantities from the model and automatically determines the environmental impact. Widely used for building certification (LEED, BREEAM, DGNB).

This software suite supports working with various types of objects and materials, including:

- Buildings (new construction and existing structures).
- Infrastructure (transport, utilities, engineering networks).
- Renovation and retrofit objects.
- Building materials and products.
- Building portfolios (comprehensive assessment of building groups).

The program contains a large database of building materials, including data on embodied carbon and other environmental impact indicators. This database allows users to calculate the environmental impact of a building's materials and find more environmentally friendly alternatives.

The software can also be used to analyze the energy and water consumption of buildings and identify opportunities for improving energy efficiency and water use efficiency.

Tally Life Cycle Assessment (tallyLCA) is a plugin for Autodesk Revit for conducting life cycle assessment (LCA) and evaluating embodied carbon in construction projects.

https://choosetally.com/

Tally Life Cycle Assessment works directly within the BIM model environment, automatically analyzing data on materials, volumes, and properties of building elements. The tool enables a detailed assessment of the environmental impact of materials at all stages of the life cycle, from production to disposal. It uses verified databases, such as EC3 and GaBi, providing access to reliable information on the carbon footprint of various materials and helping to compare alternative solutions.

TallyLCA enables the visualization of analysis results through clear charts and diagrams, highlighting elements with the most significant environmental impact. It supports LEED, BREEAM, and LBC certification standards, generating reports required for certification submission. Furthermore, users can model different project scenarios, comparing design options, materials, and structures to optimize environmental performance.

The tool is designed for architects, BIM managers, structural engineers, and sustainability consultants who work in Revit and need to integrate environmental analysis into the design process. Results can be exported to PDF, Excel, or HTML for further use and reference.

The main advantage of TallyLCA is its focus on embodied carbon and deep integration with Revit, which avoids data import and allows for continuous analysis during project development. The tool is particularly effective for projects oriented towards international standards and certification.

Embodied Carbon in Construction Calculator (EC3) is a free, open-access tool and supporting EPD database that stimulates the selection of low-carbon products to achieve the sustainability goals of construction projects.

www.buildingtransparency.org/tools/ec3/

EC3 Tool – Embodied Carbon in Construction Calculator is a free cloud platform that helps the construction industry conduct benchmarking, assess, and reduce embodied carbon in construction projects by using Environmental Product Declarations (EPD). Developed with partners such as the Carbon Leadership Forum and Building Transparency, the tool integrates material quantities from projects or BIM models with a large EPD database, enabling the selection of low-carbon alternatives.

The tool's functionality allows users to establish a baseline for embodied carbon for materials and projects. It helps identify opportunities for reducing embodied carbon by comparing materials and selecting alternatives with lower environmental impact. The tool integrates with BIM, using data from building information models or construction estimates to calculate embodied carbon at the project level. Calculations use a comprehensive database of digital, independently verified Environmental Product Declarations (EPD) to provide carbon footprint data.

Users of the EC3 Tool can include architects and contractors for creating low-carbon designs and selecting materials during procurement. At the same time, project owners can use it to set requirements and limits on embodied carbon for future buildings.

Overall, the importance of the considered tools lies in stimulating demand for low-carbon solutions, facilitating the assessment and comparison of materials, which creates a market for sustainable construction, promotes transparency, encourages manufacturers to disclose the environmental impact of their products, and stimulates innovation in the field of low-carbon materials.

2.4. Green Building Certification Systems.

To promote the widespread adoption of environmentally sustainable building design and construction practices worldwide, the World Green Building Council (WorldGBC) was established in 2002. It is a global non-profit network of national Green Building Councils [38].

The Council's mission is to transform the building and construction sector in three key areas:

- reduction of the negative impact on the climate;
- improvement of the health and well-being of occupants;
- efficient use and circularity of resources.

The organization operates through an extensive network of approximately 75 national councils worldwide. Through a systems-based approach to transformation, this network leads the building sector toward a clean, equitable, and sustainable built environment with net-zero carbon emissions.

One of the primary tools for implementing sustainable technologies in construction is the green certification system — a framework for evaluating buildings based on sustainability and environmental performance criteria.

Green building certification is a system for assessing the sustainability level and environmental efficiency of construction projects throughout all stages of their life cycle — from design and construction to operation, renovation, and end-of-life management.

It is based on a comprehensive analysis of a building's impact on the environment, human health, and economy, to minimize negative effects and enhance the quality of the living environment.

The primary objective of environmental certification is to reduce the ecological footprint of the construction sector and to promote the transition toward sustainable development.

The key principles of green building certification include:

- energy efficiency and the use of renewable energy sources;
- rational use of water and materials;
- reduction of CO_2 emissions and waste generation;
- indoor environmental quality (lighting, ventilation, comfort, acoustics);
- life cycle consideration (LCA — Life Cycle Assessment);
- social sustainability — safety, inclusiveness, and accessibility.

There are several internationally recognized green building certification systems applied in most countries worldwide. The most well-known and influential are: **BREEAM** (Building Research Establishment Environmental Assessment Method, United Kingdom); **LEED** (Leadership in Energy and Environmental Design, United

States); as well as other regional standards, such as: **HQE** (Haute Qualité Environnementale, France); **CASBEE** (Comprehensive Assessment System for Built Environment Efficiency, Japan); **Green Star** (Australia, New Zealand); **DGNB** (Deutsche Gesellschaft für Nachhaltiges Bauen, Germany); and others.

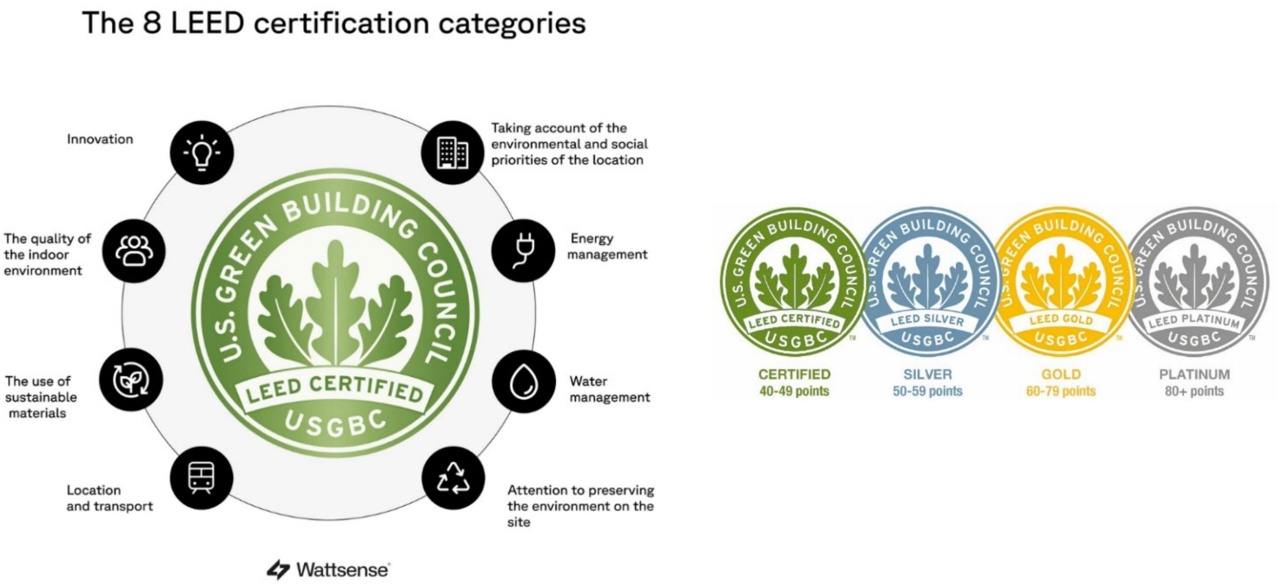
The **LEED (Leadership in Energy and Environmental Design)** standard, developed in the United States in 1998, is the national standard for designing high-performance sustainable buildings [39].

LEED employs a 100-point rating system that evaluates buildings according to the following categories (Fig. 2.3a):

- *Location and Site Selection*: involves choosing appropriate construction sites that preserve or even restore existing natural habitats and wildlife areas.
- *Location and Transportation*: transportation choices have a significant impact on CO_2 emissions and climate change; therefore, proximity to public transport and promotion of sustainable mobility options are encouraged.
- *Water Efficiency*: building design and engineering systems should minimize water consumption, enable rainwater harvesting, and optimize wastewater recycling.
- *Energy and Atmosphere*: energy efficiency is a cornerstone of LEED certification. Passive design strategies adapted to climatic conditions, use of renewable energy sources, and advanced energy management systems are key evaluation criteria.
- *Indoor Environmental Quality*: continuous monitoring of indoor air quality and effective ventilation are essential for ensuring healthy indoor environments.
- *Materials and Resources*: LEED promotes the use of locally sourced, environmentally certified, and low-impact materials that reduce environmental burdens.
- *Innovation in Design*: this category rewards innovative and creative approaches that go beyond standard certification requirements.
- *Regional Priority*: encourages projects to address site-specific environmental, social, and health priorities relevant to the building's geographical context.

LEED-certified buildings are classified into four certification levels based on the number of points achieved (Fig. 2.3b):

- Certified: 40–49 points
- Silver: 50–59 points
- Gold: 60–79 points
- Platinum: 80 points and above.



a б

Fig. 2.3 - Figure 2.3. The American green building certification standard LEED: (a) categories for building evaluation; (b) certification levels[39]

British BREEAM System (Building Research Establishment Environmental Assessment Method). **BREEAM** is an independent, comprehensive, and international certification and sustainability assessment system for individual buildings, communities, and infrastructure projects. It can be applied at various stages of the life cycle or throughout all phases — from design and construction to operation and refurbishment.

Developed in 1990 by BRE Global, BREEAM evaluates projects according to nine categories: management, energy, health and well-being, transport, water, materials, waste, land use and ecology, and pollution (Fig. 2.4).

The BREEAM certification system encompasses a range of categories, from pollution to management, and defines their sustainability. Each of these categories relates to the most influential factors, including low-impact design and reduction of carbon emissions, durability and resilience of structures, climate change adaptation, and ecological value and biodiversity protection.

Fig. 2.4 – Environmental assessment categories of buildings in the BREEAM system [40]

At the core of BREEAM certification lies a rating system. Each project is awarded a number of stars for each category, ranging from Acceptable, Pass, Good, Very Good, Excellent, to Outstanding, which corresponds to the number of stars displayed on the certificate (up to six stars).

The system allows buildings to be certified at different stages — from design and construction to operation and major refurbishment.

The DGNB System (Deutsche Gesellschaft für Nachhaltiges Bauen – German Sustainable Building Council) is one of the leading international building certification systems, integrating the environmental, economic, social, and technical aspects of sustainable development. It was developed in Germany in 2007 and has officially operated since 2009 as an independent, non-profit organization — DGNB e.V.

The primary objective of the DGNB system is to comprehensively evaluate the quality of buildings and urban areas based on the “life-cycle” principle, considering not only environmental but also economic, sociocultural, technical, functional, and process-related parameters.

Unlike most other systems (such as LEED, BREEAM, or EDGE), DGNB emphasizes the balance among three dimensions of sustainability (Fig. 2.5):

- *Environmental Quality* – includes energy efficiency, CO_2 emissions, resource use, environmental impact throughout the life cycle, and indoor air quality;
- *Economic Quality* – includes life-cycle costs, building flexibility, economic resilience, and potential for conversion or reuse;
- *Sociocultural and Functional Quality* – considers user comfort (lighting, acoustics, temperature), aesthetics, accessibility, and safety.

Additionally, DGNB evaluates:

- *Technical Quality* – operational convenience, system reliability, fire safety, noise protection, and ease of maintenance;
- *Process Quality* – project management efficiency, construction quality, and integration of sustainable approaches during the design stage;
- *Site Quality* – urban context, transport accessibility, social infrastructure, and climatic conditions.

The DGNB certification determines a building’s Sustainability Index, calculated as a weighted sum of points across all criteria. The certification level depends on the percentage of compliance achieved and includes Bronze, Silver, Gold, and Platinum levels. Additionally, the DGNB Diamond distinction is awarded for exceptional architectural quality (Fig. 2.6).

The DGNB system covers a wide range of project types:

- New buildings (residential, public, industrial, etc.);
- Existing buildings (modernization or operation);
- Urban districts, neighborhoods, and city areas (DGNB Urban Districts).

Рис. 2.5 – Categories of Building Certification in the DGNB System (Deutsche Gesellschaft für Nachhaltiges Bauen) [41]

	DGNB Platinum	DGNB Gold	DGNB Silver	DGNB Bronze*
Total performance index	80% and higher	65% and higher	50% and higher	35% and higher
Minimum performance index	65%	50%	35%	-- %

Рис. 2.6 - Certification Levels in the DGNB System [41]

In the 2020s, the DGNB developed versions of the system for building renovation and sustainable deconstruction, making it particularly relevant for post-war reconstruction efforts.

The DGNB system is used in more than 30 countries worldwide and features an international version, DGNB International, which is tailored to national regulations and climatic conditions. A distinctive feature of DGNB is its focus on the full life cycle, including Life Cycle Assessment (LCA). The system requires: an assessment of environmental impacts throughout the entire service life of the building (from material extraction to demolition and disposal); a calculation of life cycle costs (Life Cycle Costing – LCC); and determination of the ecological and economic optimum at the early design stages.

The EDGE system (Excellence in Design for Greater Efficiencies) is an international green building certification system developed by the International Finance Corporation (IFC), a member of the World Bank Group. Its main goal is to promote a large-scale transition to energy-efficient, water-saving, and resource-efficient construction, particularly in developing countries. Unlike more complex systems (LEED, BREEAM, DGNB), EDGE is designed for widespread adoption and considers local climatic and economic conditions.

The EDGE system is based on a quantitative approach and evaluates three key areas:

1. **Energy** — reduction of energy consumption through energy-efficient measures (insulation, efficient lighting, air conditioning systems, renewable energy sources, etc.);

2. **Water** — reduction of water use through smart engineering systems and rainwater reuse;

3. **Embodied energy in materials** — assessment of the energy used in the production, transportation, and installation of building materials, and finding ways to reduce it through the use of more sustainable materials.

The system includes three certification levels, which reflect the degree of sustainability achieved (see Table 2.1).

EDGE certification has been implemented in over 100 countries worldwide, including Ukraine, Georgia, Poland, Vietnam, Kenya, Colombia, India, and Indonesia.

As of 2024, the system covers over 65 million m² of certified floor area globally. In Ukraine, the first EDGE Advanced certified project was the ProCredit Bank headquarters in Kyiv (2022).

The IFC actively collaborates with the Ukrainian Green Building Council (UGBC) to promote EDGE standards for the country’s green reconstruction.

Table 2.1

Certification Levels in the EDGE System

Level	Main Requirements	Description
EDGE Certified	≥ 20% savings in energy, water, and embodied energy in materials	Basic level of building sustainability
EDGE Advanced	≥ 40% energy savings and ≥ 20% savings in other categories	Highly energy-efficient building
Zero Carbon	100% compensation or absence of operational CO_2 emissions	Net-zero carbon building

Table 2.2

Main characteristics of leading international green building certification systems

Indicator	DGNB (Germany)	LEED (USA)	BREEAM (United Kingdom)	EDGE (IFC, World Bank Group)
Year established	2007	1998	1990	2014
Developing organization	Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)	U.S. Green Building Council (USGBC)	Building Research Establishment (BRE)	International Finance Corporation (IFC), World Bank Group
Geographical coverage	30+ countries (Europe, including adaptations for Central and Eastern Europe)	180+ countries	80+ countries	100+ countries, focused on emerging markets
Main objective	Comprehensive assessment of sustainability throughout the building life cycle	Energy efficiency and reduction of CO_2 emissions	Improving the environmental performance of buildings	Simple and affordable measurement of energy, water, and material efficiency
Key criteria	Environmental, economic, sociocultural, technical, process, and site quality	Energy, water, materials, indoor air quality, transport, and site	Management, energy, water, materials, health, transport, waste, pollution, land use	Energy, water, and embodied energy in materials
Evaluation principle	Multi-criteria approach, LCA, and LCC calculation	Point-based system according to compliance with criteria	Point-based system according to compliance with criteria	Percentage savings (minimum 20% in each of three areas)
Certification levels	Bronze, Silver, Gold, Platinum, Diamond (for architecture)	Certified, Silver, Gold, Platinum	Pass, Good, Very Good, Excellent, Outstanding	Certified, Advanced, Zero Carbon
Life-cycle assessment focus	Complete life-cycle assessment (LCA + LCC)	Partial (mainly operational phase)	Partial	Limited (energy, water, materials)
Types of projects	New buildings, existing buildings, renovations, and urban districts	All building types	All building types	Residential, office, and commercial (simplified)
Certification cost	High (due to detailed LCA analysis)	High	Medium to high	Low

Implementation complexity	High (requires qualified experts)	High	Medium	Low, suitable for rapid assessment
Advantages	Comprehensive, scientifically grounded, aligned with EU policy	High international prestige, universal applicability	Flexibility and detailed methodology	Simplicity, speed, affordability, and IFC financial support
Disadvantages	Complex methodology, high cost, requires expert involvement	An expensive audit, more suitable for large-scale projects	Less adapted to non-European contexts	Less comprehensive, simplified assessment
Relevance for Ukraine	Promising for EU harmonization and post-war reconstruction	Prestigious for international developers	Partially adapted, requires localization	Most practical and accessible for large-scale implementation

CHAPTER 3. MODERN ECO-FRIENDLY BUILDING MATERIALS

3.1. Ecological Materials for Load-Bearing Structures

3.1.1. Ecological Concretes

Traditional concrete has a significant environmental impact due to its intensive consumption of natural resources. The production of each ton of Portland cement is associated with the emission of approximately one ton of CO_2.

This industry accounts for about 8% of global CO_2 emissions—more than the aviation sector. Over the past twenty years, these emissions have doubled. Annual concrete consumption has reached 30 billion tons, which is three times more than it was 40 years ago. In fact, concrete is the second most consumed substance in the world after water.

To achieve the goals of "net zero" emissions and the UN Sustainable Development Goals (SDGs), the construction sector must actively implement sustainable alternatives to traditional concrete.

Promising substitutes offering sustainability benefits are listed below.

Green Concrete differs from traditional concrete in several key aspects:

- Its composition utilizes industrial waste (e.g., from power plants, mining operations) as a substitute for cement or aggregates.
- Its production requires less energy, is associated with lower CO_2 emissions, and causes less environmental damage.
- It is more durable and requires less maintenance, increasing the service life of structures.
- The use of waste makes it more cost-effective by reducing the need for virgin materials and their transportation.

Green concrete also offers improved workability, strength, and reduced permeability, protecting it from water damage and crack formation.

Alongside cement replacement, using alternative fine and coarse aggregates (e.g., glass, plastic, paper, wood) is another path to increased sustainability. Such materials help reduce energy consumption and conserve resources. However, depending on the type of substitute, some properties, such as compressive strength and resistance to chemical corrosion, may be reduced.

Fig. 3.1 - Production of concrete with wood aggregate [42]

Ashcrete is an ecological alternative that uses fly ash from coal combustion. Approximately 93% of its composition is recycled material. Adding ash increases the strength, durability, and cost-effectiveness of the mix. A disadvantage is its slower strength gain compared to traditional concrete, which can impact construction project timelines.

Silica Fume, a by-product of silicon alloy production, significantly improves concrete properties. Its addition increases compressive strength by approximately 30% and enhances durability by reducing permeability and improving abrasion resistance. Thus, it is a very important component for high-strength concrete, especially in infrastructure projects exposed to harsh environmental conditions.

Incorporating silica fume into concrete not only enhances its performance characteristics but also aligns with the principles of sustainable construction. As a supplementary cementitious material, it replaces a portion of ordinary Portland cement in the mixture, thereby reducing the overall carbon footprint. It enables the utilization of industrial waste and lowers energy consumption associated with cement production.

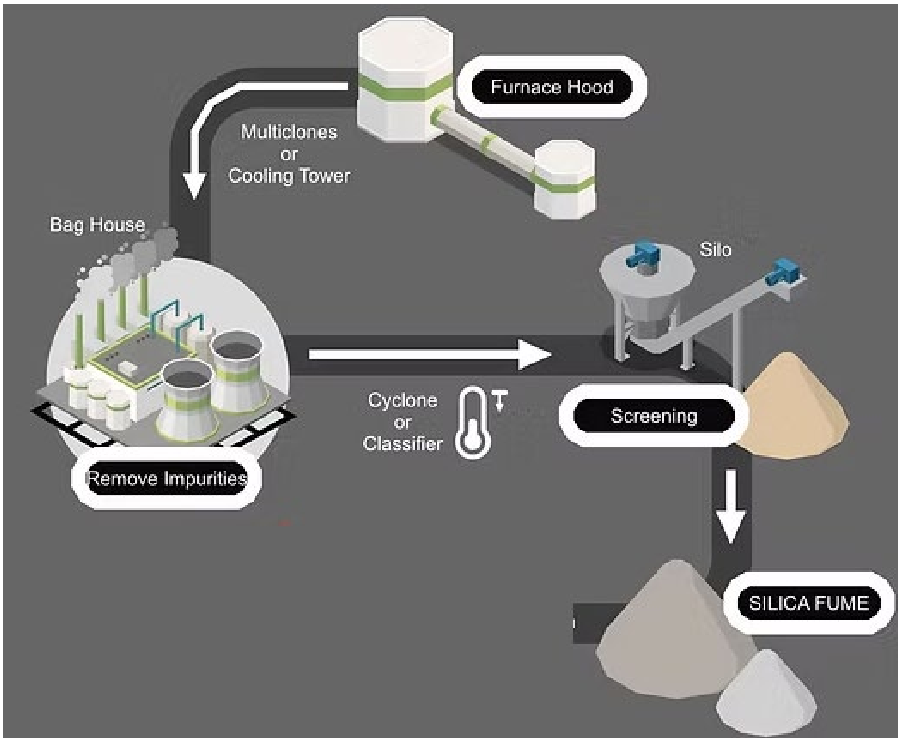


Fig. 3.2 - Manufacturing Process of Silica Foam [43]

Blast furnace slag concrete is a type of concrete where blast furnace slag, a byproduct of iron smelting, is used as a binding component or aggregate. The use of slag enables the replacement of 20% to 70% of Portland cement, thereby reducing the cost of concrete and decreasing the greenhouse gas emissions associated with cement production.

Research shows that slag concrete exhibits improved resistance to aggressive environments and enhanced durability. At elevated temperatures, slag concrete sets more slowly, making it easier to handle. Partial replacement of cement with slag can also improve the concrete's resistance to freeze-thaw cycles.

The main disadvantage is its prolonged setting time, particularly at low temperatures, making this type of concrete less suitable for projects requiring rapid strength development.

Mycelium is considered one of the most promising emerging alternatives to traditional concrete binders in the construction industry. This material is derived from microscopic fungal threads and, when mixed with organic matter, forms a dense, durable, and naturally fire-resistant material that can be easily molded into any shape.

Although a key limitation of mycelium is its insufficient strength compared to standard concrete, it is significantly lighter and more environmentally friendly. It is already being used as a packaging material, and according to experts, it holds potential for remediation in other environmentally harmful industries, such as the fashion and oil production sectors (Fig. 3.3).

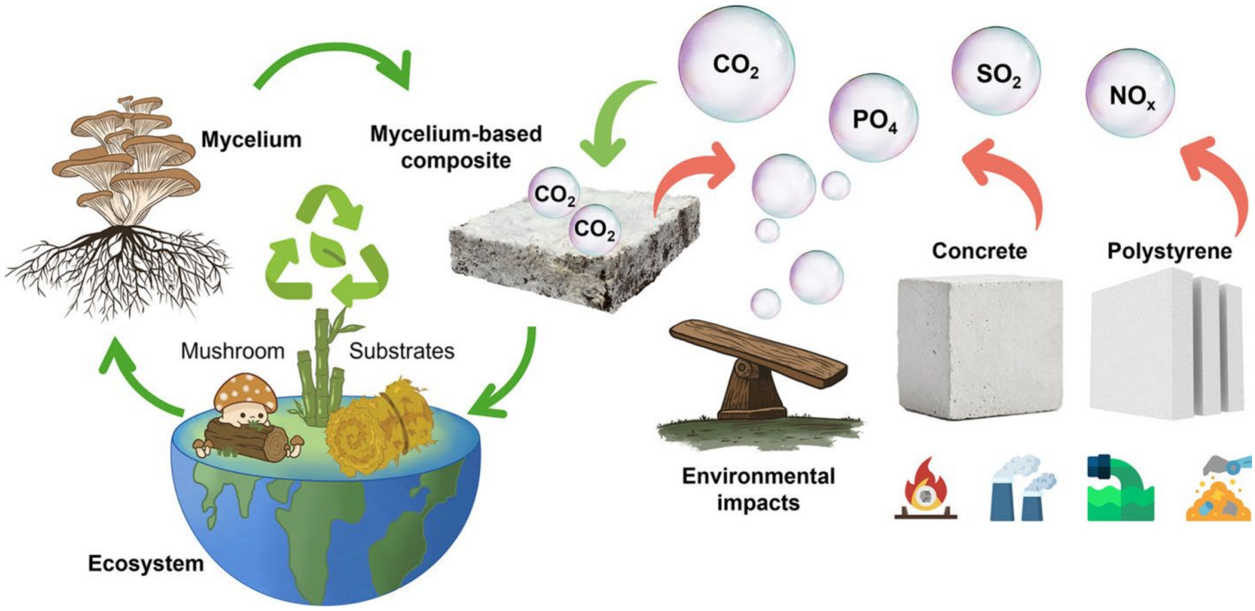


Fig. 3.3 - Use of mycelium as a binder substitute in concrete [44]

3.6.2. Engineered Wood Products

Glued Laminated Timber (Glulam) is the most important and oldest member of the engineered wood product family, contributing to the expansion of structural wood use and the development of lumber processing technologies. Large-sized lumber is limited in availability and not sufficiently efficient due to defects like knots and cracks. Glulam eliminated the limitations associated with using large timber regarding cross-sectional size, log length, and inherent structural defects. Glulam members consist of several wood layers (or "laminations") bonded together with adhesive. During the process, the boards are pressed with hydraulic equipment to ensure a tight bond. Laminations are typically made from softwood lumber, ensuring the wood grain is oriented parallel to the member's longitudinal axis. Besides the benefits related to large cross-sectional areas, laminations are often finger-jointed lengthwise to create glulam members longer than the original lumber. Glulam is often used as straight elements for lintels, purlins, floor beams, columns (round, square, complex shapes), as well as curved beams and roof structures.

The construction industry is increasingly using new large-sized wood composites known as Mass Timber.

Cross-Laminated Timber (CLT) is a relatively new wood product with great potential to significantly expand the use of wood in construction. CLT consists of large panels made by bonding several layers of structural softwood boards. Each layer of boards is typically oriented perpendicular to adjacent layers and bonded on the wide faces, usually symmetrically, so the outer layers have the same orientation. These products are used in building projects as floor slabs, load-bearing walls, and shear walls.

As a viable alternative for mass construction manufacturers, CLT is generating growing interest and offers an ecological alternative to steel and concrete. CLT provides the high strength and structural simplicity required for cost-effective buildings while having a lower environmental impact compared to concrete or steel. CLT panel production allows for a wide range of sizes and thicknesses. Architects use CLT panels as load-bearing slab and panel elements in building projects. Excellent strength properties open opportunities for use in multi-story buildings. CLT can also be processed as a "finished" building component, customizing its dimensions precisely to reduce construction material waste.

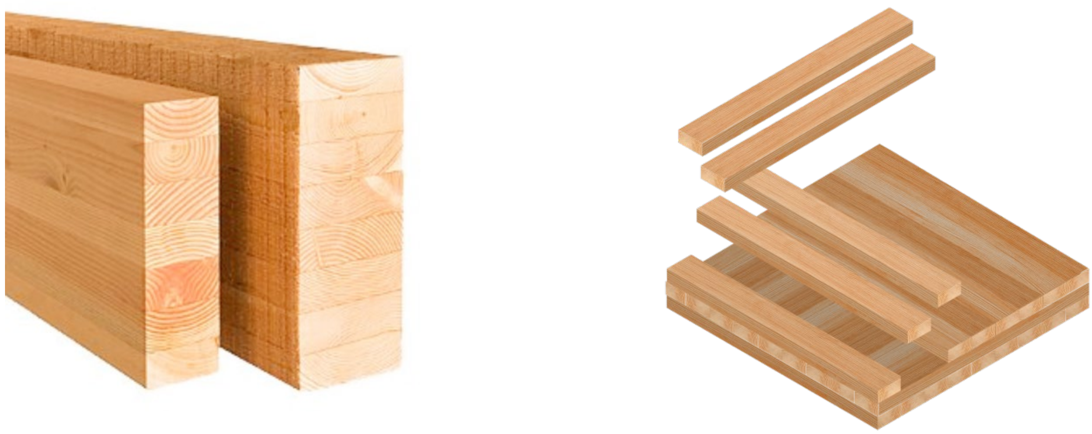


Fig. 3.4 - Glued Laminated Timber (Glulam) and Cross-Laminated Timber (CLT)

While Glulam and CLT panels are made from sawn boards, other engineered wood products are made from wood veneer.

Laminated Veneer Lumber (LVL) is one of the most widely used engineered wood products for structural applications. It is a composite panel made from several thin veneer layers aligned along the length of the finished lumber. This product was invented in the late 1960s and has become a reliable high-strength element for beams and headers in both residential and commercial construction. Because it is made from veneer, LVL allows for 35% more efficient use of logs than solid wood. During production, veneer is dried to 8% moisture content and sorted by strength and width before layup. Adhesive is applied, and the panel is pressed under heat and constant pressure until cured. LVL is designed for use as high-strength load-bearing beams to support structural weight over windows and door openings, as well as in floor and roof systems of residential and commercial wood-frame buildings. It can be used for both panels and beam/column elements (Fig. 3.6).

Fig. 3.5 - Example of Glulam and CLT use in high-rise construction (Mjøstårnet building, Norway — 85 m height)

Fig. 3.6 - Laminated Veneer Lumber (LVL) [47]

Laminated Strand Lumber (LSL) is manufactured from surplus, overmature aspen trees, which are typically not large, strong, or straight enough for traditional wood products. In this process, logs are used to produce strand material, which can be up to 300 mm long. These strands are then dried, coated with adhesive, and pressed into large billets through a process that involves steam injection. Billets can be up to 140 mm thick, 2.4 m wide, and 10 m long. After sanding, they are cut into various sizes for applications such as headers, beams, and columns. LSL is also used for sheathing and modular homes (Fig. 3.7).

Fig. 3.7 - Laminated Strand Lumber (LSL) [47]

Parallel Strand Lumber (PSL), commonly known by the brand name Parallam, is designed to replace solid lumber in large-section elements (beams, columns). Parallel strand lumber was developed in Canada and introduced to the market in the late 1980s. PSL is produced in many thicknesses and widths and can be manufactured up to 20 m long. Strands are typically taken from veneer peeled from the outermost part of logs, where more fibers are located. The veneer is dried to 11% moisture content and strength-graded before being cut into strands. They are then aligned parallel to each other, coated with waterproof adhesive, pressed, and cured. This lumber is used for large elements in residential construction and as medium to large-sized elements in commercial construction (Fig. 3.8).

Fig. 3.8 - Parallel Strand Lumber (PSL)

One of the most important and well-known building materials made from veneer is **Plywood**. It is widely available worldwide and has proven to be a highly successful material. Plywood is used for many lightweight building materials. It is also used for roof and floor sheathing, concrete formwork, and webs for wood I-joists. It can be used to carry vertical loads or to resist horizontal loads as part of shear diaphragms. Plywood is made from veneer layers stacked in an odd number of plies, with the outer plies' grain oriented along the panel's long direction. The cross-laying of veneer layers provides strength, stiffness, and dimensional stability.

Oriented Strand Board (OSB) is one of the most commonly used products for structural construction in the residential sector due to its excellent properties. OSB is a structural panel made from wood strands cut from small-diameter logs and bonded with exterior-grade adhesive under heat and pressure. OSB is produced in various grades with enhanced moisture resistance. It is widely used for wall sheathing, floor underlayment, roof decking, and I-joists in both commercial and residential construction (Fig.3.9).

Fig. 3.9 - Plywood and Oriented Strand Board (OSB) [47]

An example of a load-bearing structure that can utilize plywood or OSB is the Wood I-Joist. This engineered product has high strength relative to its size and weight. A wood I-joist is a lightweight beam composed of a web and flanges connected to form an I-shaped section. The joist flanges are typically made from Laminated Veneer Lumber (LVL) or solid wood. The web is made from plywood, LVL, or OSB. Wood I-joists are available in lengths up to 25 m. They are used in residential and commercial construction for floor, roof, and exterior wall framing systems. I-joists are ideal for structures requiring stiffness, thermal insulation, and cost-effectiveness (Fig. 3.10).

Fig. 3.10 - Wood I-Joist [47]

3.2. Efficient Eco-Friendly Thermal Insulation Materials

Buildings are a central part of everyday life, and we spend a significant portion of our time inside them. Effective thermal insulation of residential spaces is a crucial condition for reducing energy consumption, improving living conditions, and ensuring the decarbonization of the building sector.

Certain strategies aimed at reducing carbon dioxide emissions focus on improving building design and thermal insulation performance — both for new and existing buildings — to enhance heating efficiency and provide indoor comfort while minimizing the waste of valuable resources.

Insulation offers the most significant potential for reducing CO_2 emissions. The energy saved through insulation can offset the energy consumed during its production, while the CO_2 retained by natural insulating materials can even exceed the emissions generated during their manufacture. This is why the shift toward natural thermal insulation materials is key to achieving energy efficiency and creating net-zero buildings.

In general, natural insulation materials are derived from plant-based sources (various plant fibers) and even from animal-based sources, primarily sheep's wool (often reused). In addition, waste streams from textiles (cotton) and paper (cellulose) are also utilized, as well as experimental sources such as mycelium.

Some traditional insulation materials, such as mineral wool, are also made from natural raw materials like stone. However, they are not generally considered environmentally friendly forms of insulation due to the high amount of energy required for their production and recycling.

3.2.1. Hemp.

Hemp is derived from the hemp plant, which has strong fibrous stems and excellent insulating properties. Insulation made from hemp shives (hemp hurds) is characterized by outstanding environmental benefits. This plant is a renewable and biodegradable raw material, and its cultivation requires minimal energy inputs and maintenance.

Hemp can grow in almost any type of soil and does so remarkably quickly — the full growth cycle takes about 100 days. It is non-toxic, requires no pesticides or insecticides, and consumes very little water. Moreover, hemp captures more carbon than is emitted during the construction process, making it a highly sustainable material (Fig. 3.11).

Fig. 3.11 – Hemp Insulation [48]

3.2.2. Straw

Straw bales and straw–clay blocks have a long history of use in construction as natural and affordable materials with excellent thermal insulation properties. Traditionally, building walls were formed by stacking straw bales and coating them with a clay mixture, which provided structural strength and protection against external influences.

In modern construction, straw-building technologies have evolved: prefabricated straw panels and industrially produced insulation materials have appeared on the market, combining environmental sustainability with high performance characteristics.

Straw bales are made from the agricultural residues of cereal crops, meaning they are derived from renewable and secondary raw materials, thereby reducing the need for primary resources. Moreover, straw is an effective carbon sink, so such constructions act as temporary carbon storage, helping to reduce the overall carbon footprint of a building.

An essential advantage of this material is its high level of sound insulation and ability to regulate indoor humidity, which contributes to a healthier and more comfortable indoor microclimate (Fig. 3.12).

3.2.3. Flax

Flax used as a raw material for thermal insulation production is a byproduct of the flax industry. It is obtained from the stem part of the plant, which has a lower commercial value compared to fibers intended for textile manufacturing. Although this raw material is not a waste product in the strict sense, its use in construction contributes to the rational utilization of residual bioresources and reduces the environmental impact of production.

Fig. 3.12 – Straw insulation [49]

3.2.4. Cellulose.

Cellulose fiber insulation is primarily composed of shredded paper fibers treated with inorganic additives that act as fire retardants and mold inhibitors. The base material for cellulose fibers is usually recycled newspaper obtained from unsold or recovered paper. A newspaper is typically made from mechanical pulp. Recycled newspaper or chemical cellulose can also be used. Unlike chemical pulping, mechanical pulping removes only a small portion of the lignin content. Mineral and organic additives, such as kaolin, porcelain clay, or cationic starch, are also added to the paper pulp to enhance its properties — for example, paper opacity, moisture retention, and strength. The inks commonly used in paper production are made from inorganic carbon, while colored inks are based on organic pigments (Fig. 3.13).

Fig. 3.13 – Cellulose insulation

3.2.5. Wood

It is made from wood waste generated during forest thinning and from residues of the woodworking industry. Wood fiber insulation emerged as a result of woodworking companies seeking to reduce waste and convert it into useful products (Fig. 3.14).

Fig. 3.14 - Wood Fiber Insulation

3.2.6. Wool.

Wool insulation is made almost entirely from sheep's wool, which is usually reused. This material is environmentally friendly and biodegradable. Wool-based products can be fully recycled, producing high-quality raw material once again (Fig. 3.15).

Fig. 3.15 - Wool insulation

3.2.7. Grass.

Grass is a renewable natural raw material that is widespread across most climatic zones of the world, characterized by rapid growth and low cultivation requirements. The use of grass biomass in construction allows the transformation of mown vegetation waste into a valuable resource, helping to reduce the volume of organic waste and support local ecosystems. Processed grass can serve as a raw material for producing thermal insulation panels that combine environmental sustainability with high energy efficiency. Thus, the application of grass-based insulation materials in construction contributes to the development of a closed-loop bioresource system and the implementation of sustainable development principles (Fig. 3.16).

Fig. 3.16 – Grass-based insulation material

Summary data on the characteristics of ecological thermal insulation materials are presented in Table 3.1.

Table 3.1.

Summary of characteristics of ecological thermal insulation materials

Type of materials	Specific gravity, kg/m^3	Thermal conductivity, W/(m K)	Carbon footprint, kg CO_2 eq/kg
Hemp mats	30-42	0,038	-2.11
Straw insulation	90-100	0.041	-16.9
Flax roll insulation	20-30	0.038	-1.27
Cellulose insulation	28-65	0.037	-1.21
Wood fiber insulation	35-38	0.041	-2.88
Wool insulation mats	18-20	0.038	6.58
Grass mats	30-80	0.04	-8.04

3.3. Strategies for Managing Construction Waste and Materials

3.3.1. General Provisions.

One of the key strategies for addressing sustainability, environmental impact, and resource scarcity issues in the construction industry is the integration of recycled and upcycled materials. This approach not only helps solve environmental problems but also opens the way for new opportunities to improve efficiency in design and construction.

Among materials created by transforming waste into new materials are recycled concrete, metals, glass, and plastic. Repurposed materials retain their natural qualities for new purposes, contributing to the reduction of raw material extraction.

The production of recycled and upcycled materials often requires less energy than producing new materials, thereby reducing carbon emissions. From an economic perspective, structures using such materials are cost-effective and offer market advantages. They also ensure competitiveness, as buildings made from eco-friendly materials are more attractive to environmentally conscious customers.

Repurposing materials stimulates creativity in problem-solving and design, sometimes creating unique and aesthetically impressive structural designs.

The financial benefits of using recycled and reused materials make them attractive options for modern construction projects.

Table 3.2 presents the main differences between recycling and upcycling, including related processes, results, and environmental impact.

3.3.2. Types of Recycled and Upcycled Materials in Construction Projects

1. Metal

The production of metal products, from ore mining to manufacturing, is energy-intensive. However, metal has the most significant potential for further processing, remelting, and other forms of recycling. Most importantly, repeating this process can extend the life cycle of the raw material. Proof of the value of metals lies in the fact that they are separated during building demolition and are rarely sent to landfills. Metal components are often repaired and restored because they can be disassembled and used in other structures.

Steel structural elements with standardized cross-sections have the highest potential for reuse. Metal recycling is an energy-efficient process, as it consumes significantly less energy than mining and producing new metal products. Examples of structural elements made from recycled steel include beams, columns, and reinforcement (Fig. 3.17).

Besides common steel, aluminum is another recyclable metal often used in construction. Its lightness, strength, and corrosion resistance make it ideal for various applications, including windows, roofing, and facades.

Overall, recycling and upcycling metals enable the creation of new, reliable structures, extend the service life of existing structures, and conserve resources.

Table 3.2

Differences between Upcycling and Recycling

Criterion	Upcycling	Recycling
Definition	Transforming waste into more valuable or higher-quality goods.	Transforming waste into new, comparable, or less valuable goods.
Process	Minimal processing and reuse of materials.	Processing materials after disassembling them into their simplest forms.
Product Value	Higher or similar quality to the original material.	Often have the same or lower value as the original material.
Environmental Impact	Minimizes waste while conserving resources and energy.	Minimizes waste but requires energy for processing.
Example	Transforming old furniture into original designs.	Using melted plastic bottles to create new plastic products.
Resource Efficiency	Uses existing goods with minor changes to enhance efficiency.	Resource-intensive, as it uses energy to process materials.
Level of Innovation	High, as it depends on creative, imaginative, and inventive design.	Moderate, as the focus is on recovering raw materials rather than design.
Raw Material Use	Uses existing products, does not require or minimally requires purchasing raw materials.	Requires adding components (additives) or additional resources to complete the recycling process.

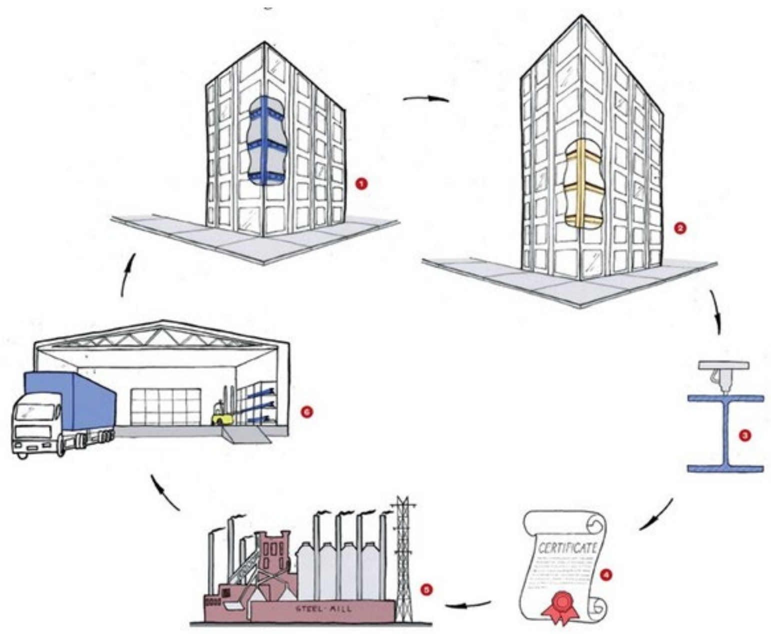


Fig. 3.17 - Metal Upcycling [50]

2. Wood

Wood, a common component in construction, is easily recycled and upcycled. Reclaimed wood from old houses or furniture adds a unique appearance and historical significance to architectural projects. For example, the natural beauty of oak makes it a popular choice for beams, floors, and accent elements.

Among the ways to recycle wood industry waste that would otherwise be wasted is to convert it into engineered products such as Laminated Veneer Lumber (LVL) beams and Oriented Strand Board (OSB) panels, which have excellent structural characteristics. Furthermore, using wood harvested responsibly in construction reduces the need for solid wood and promotes ethical forestry practices. This also has significant environmental benefits, including reduced carbon emissions and improved energy efficiency in construction designed for a long service life. (Fig. 3.18).

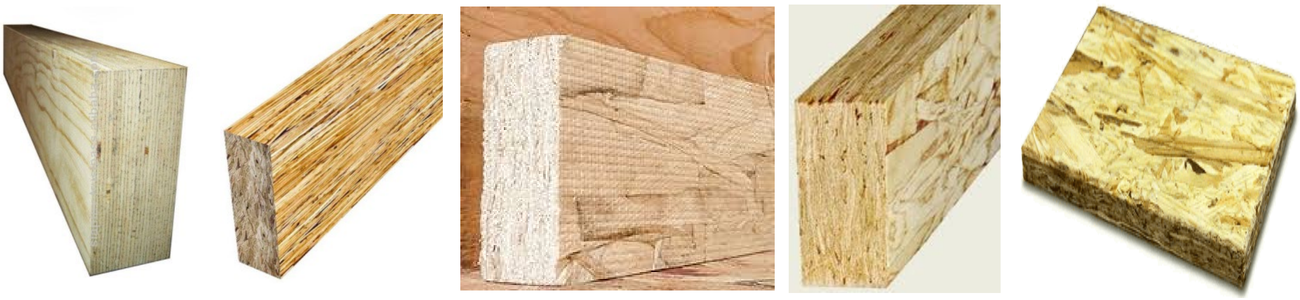


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Fig 3.18 – Types of Composite Products from Recycled Wood:
a) LVL beam; b) PSL beam; c) LSL beam; d) OSL beam; e) OSB panels

3. Brick

Masonry elements from demolished buildings can be reused or restored for reuse. Reused ceramic brick has a particular visual appeal and offers a sustainable alternative to new materials. Such bricks can be used as wall cladding, landscape accents, or even as structural elements to add character to both traditional and contemporary designs (Fig. 3.19).

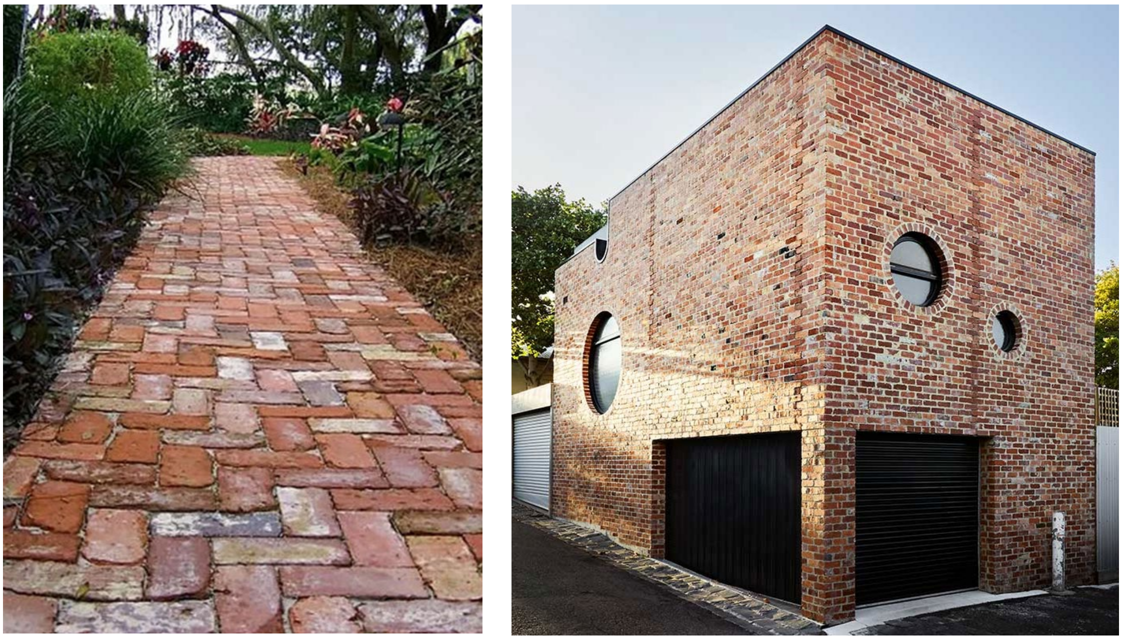


Fig. 3.19 - Reused Bricks in Landscape Design and Building Structures [51, 52]

A common method of recycling masonry is to crush and reuse the fragments as aggregates in new concrete mixtures. This conserves natural resources by reducing the need for new raw material extraction and prevents excess waste (Fig. 3.20).

Incorporating elements of recycled or reused brick into projects improves environmental performance and sustainability while preserving the heritage of old buildings.

Fig. 3.20 - Brick Recycling by Crushing into Secondary Aggregate [53]

4. Glass

Glass is often used in buildings for interior doors, windows, facade panels, and fencing. Restoring glass to its original state and reusing it in another facility is an innovative and eco-efficient approach. However, the dismantling and transportation of glass is challenging due to the risk of damaging fragile elements. Recycled glass is a versatile material suitable for numerous construction projects.

Glass recycling involves collecting, cleaning, and melting used glass to produce new glass products. This process consumes less energy than producing glass from primary raw materials, making it an environmentally responsible choice. Recycled glass is suitable for, among other things, tiles, countertops, and insulation materials. It can also be integrated into building facades as aesthetic elements.

Glass upcycling involves artistic reprocessing into unique design elements or decorative components in interiors and exteriors. The aesthetic flexibility of recycled glass helps architects enhance the visual appeal of their projects while promoting sustainable practices (Fig. 3.21, 3.22).

Fig. 3.21 - Recycling Window Glass for Glass Polymer Products [54]

Fig. 3.22 - Glass Upcycling (Reuse in a Greenhouse) [55]

5. Concrete

Concrete is a primary component of buildings. Among the materials used in recently constructed structures, this combination of cement, water, aggregates, reinforcing steel, and chemical admixtures constitutes the largest share, despite the fact that these materials burden the natural environment. Concrete elements typically become waste after the building's life cycle ends. Since there is no way to recover individual components in concrete, it has low value as a material upon demolition and is considered construction debris. However, it is possible to convert crushed concrete remnants from repair or demolition work into secondary aggregate. Its use in new concrete mixtures reduces the need for primary raw materials and conserves natural resources. In addition to recycling old concrete, concrete upcycling involves the inventive reuse of concrete elements, for example, using precast reinforced concrete panels. The strength of concrete allows it to be shaped into architectural installations, landscape elements, or decorative ornaments (Fig. 3.23, 3.24).

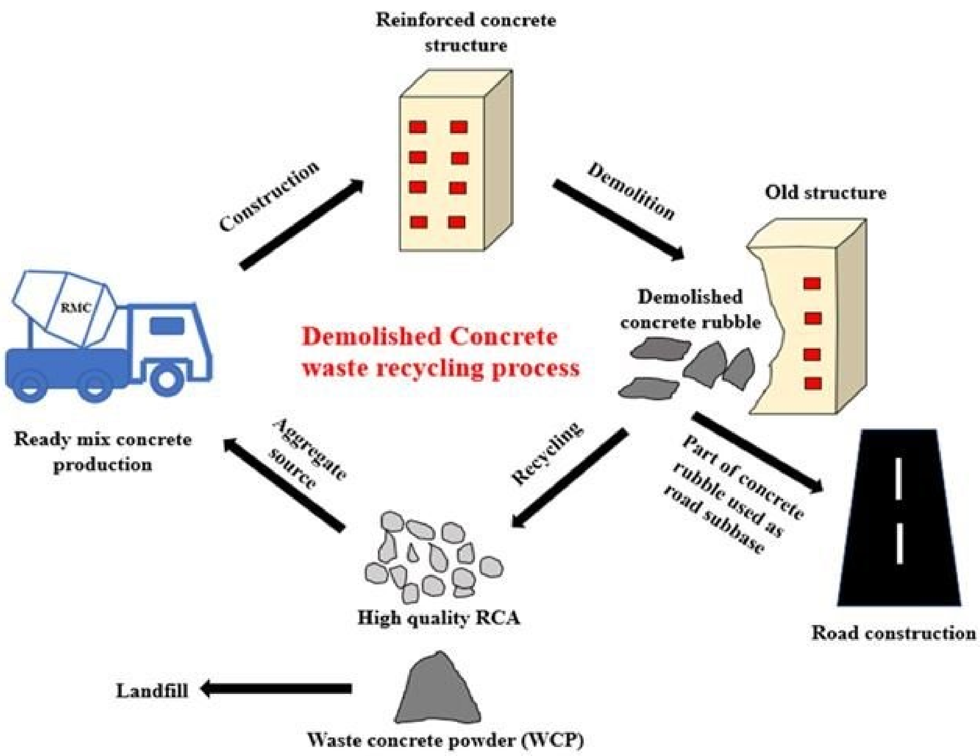


Fig. 3.23 - Concrete Recycling into Secondary Aggregate [56]

Fig. 3.24 - Concrete Upcycling (Reuse of Wall Panels in Road Pavement) [57]

6. Plastics

Polymers such as Polyvinyl Chloride (PVC), High-Density Polyethylene (HDPE), Polypropylene, and Polystyrene are widely used in construction. Depending on their composition, plastic materials can be recycled into various products such as window frames, insulation, carpets, tiles, interior linings, synthetic coatings, and mounting components. The increasing use of recycled plastic in modern civil construction and architecture is due to its adaptability and lightness. Various plastic wastes not related to construction (bottles, containers, packaging) can also be transformed into new building materials. For example, recycled plastic is used to make plastic planks or lumber, which should not be confused with wood-plastic composites. These products are widely used for creating outdoor decks, as well as for moldings, trim, and garden furniture, such as park benches.

An example of the artistic incorporation of recycled plastics into architectural projects is their use as decorative elements or facade panels. A creative way to use plastic waste is to recycle it into insulation, tiles, and structural elements. Plastic recycling promotes resource conservation and environmental responsibility by reducing the amount of plastic waste going to landfills (Fig. 3.25).

а

б

Рис. 3.25 - Examples of Using Recycled Plastic:

a) plastic plank and lumber; b) plastic paving stones [58, 59]

3.6.3. Strategies for Integrating Recycled and Upcycled Materials into Construction Projects

A clear strategy, including material selection, design adaptation, collaboration with designers, and life cycle assessment, is crucial when integrating recycled and upcycled materials into construction projects. Encouraging the use of recyclable and local materials can significantly reduce a building's environmental impact.

1. Material Selection

One of the most important steps in integrating recycled and upcycled materials into construction projects is careful material selection. Architects should use local materials with high recycling potential. Using reclaimed wood, recycled metal, and recycled brick reduces the need for primary materials and minimizes the transportation required. Local extraction and manufacturing help support local businesses and reduce carbon emissions compared to long-distance transportation. This approach also helps create authentic projects with elements of national traditions, giving buildings uniqueness (Fig. 3.26).

Fig. 3.26 - Photos of Modern Individual Houses Made from Locally Sourced Materials (cob - clay and straw mixture, timber walls, thatched roof) [60, 61]

2. Design Adaptability

Design flexibility is important when using recycled and upcycled materials, as they do not always meet current standards. The building design should have forms and dimensions that allow for the creative use of non-traditional materials. This adaptability can lead to new architectural solutions that challenge traditionally accepted design principles. For example, an architect might use irregularly shaped repurposed wood in construction to create unique designs that add aesthetic value while serving functional purposes (Fig. 3.27).

3. Collaboration with artists, craftsmen, etc.

One way to implement reused materials in construction projects is to collaborate with artists and craftsmen. This collaboration can lead to creative solutions that would not be obvious in conventional construction. Artists often have a unique perspective on material use and explore creative methods that prioritize originality. For example, a project might transform waste into a focal design point using sculptural elements made from recycled metal or glass. Such collaborations encourage clients to adopt sustainable practices and improve knowledge about them (Fig. 3.28).

Fig. 3.27 - Example of Reusing Wooden Planks in Facade Finishing [62]

Fig. 3.28 - Interior and Decor Elements from Upcycled Materials (in this case, wood) [63]

4. Life Cycle Assessment

Life cycle assessment is a key component of environmentally safe projects. Designers who understand the long-term consequences of material use enhance the environmental safety of their projects. They can prioritize the use of materials that have a high recycling rate or low embodied energy. LCA influences material selection and encourages consideration of the building's entire lifespan, leading to economically and ecologically beneficial projects. Integrating recycled and upcycled materials such as metal, wood, glass, concrete, plastic, and masonry reduces waste, energy consumption, and carbon emissions. Table 3.3 summarizes the principles of integrating sustainability goals at all stages: production, construction, operation, recycling, and disposal.

Table 3.3

Life Cycle of Recycled and Upcycled Materials

Material	Sustainability Goal	Materials & Production	Construction	Use Phase	Recycling Phase	Upcycling Phase	Disposal Phase
Metal	Reduce mining, energy, emissions	Recycled steel & aluminum from scrap & industrial waste	Easy integration into load-bearing structures	High durability, corrosion resistance, energy savings	Remelting for new metal products	Reuse of beams	Fully recyclable without quality loss
Wood	Forest conservation, carbon sequestration	Reclaimed wood from old buildings, construction waste	Frames, sheathing, floors	Long service life, renewability, biophilic design	Chipping for particleboard, mulch, biofuel	Furniture, smaller structures	Natural decomposition or incineration
Glass	Reduce sand mining, energy, and emissions	Recycled glass from bottles, windows, and industrial waste	Windows, facades, decorative elements	High thermal insulation properties, energy efficiency	Crushing into cullet, remelting	Decorative tiles, mosaic	Infinitely recyclable without quality loss
Concrete	Reduce CO_2 emissions, use of primary aggregates	Recycled aggregates, fly ash, slag, microsilica	Foundations, road surfaces, prefabricated elements	High compressive strength, durability, low maintenance	Crushing into recycled aggregate	Landscape design, barriers	Landfilling (if not recycled), high embodied energy
Plastic	Reduce landfills, oil consumption	Recycled plastic from bottles, packaging, industrial waste	Pipes, insulation, lightweight structures	UV resistance, flexibility, lightness	Remelting into new products	Innovative materials (e.g., eco-bricks)	Non-biodegradable, landfilling, incineration
Masonry	Reduce demolition waste, promote circular economy	Recycled brick & masonry from construction waste	Walls, paving, landscape design	High thermal mass, durability, and low maintenance	Crushing into aggregate for new masonry	New buildings, art installations	Reuse, repurposing, crushing

3.5. Databases of Environmental Parameters for Construction Products and Processes

The implementation of the sustainable development concept in construction is of significant importance due to the high rates of resource use, expressed in excessive consumption of energy, water, and various types of raw materials. Buildings and the construction industry contribute significantly to pollutant emissions into the environment and the use of natural resources. Therefore, against the backdrop of current concerns about climate change, the importance of assessing the environmental impact of buildings at all stages of their life cycle is gaining widespread recognition. After all, besides the energy and carbon required for the operation, heating, and lighting of a building, the materials for its construction need to be extracted, quarried, or harvested; transported to plants and manufactured; and then delivered to sites, lifted, and installed in place. Throughout its expected service life, a specific building will require maintenance, repair, and replacement of elements before eventually being demolished, and all its components disposed of through landfilling, incineration, recycling, or reuse.

Calculating the carbon footprint of materials used in construction, as a component of a building's life cycle assessment, is a complex and labor-intensive task. Therefore, the transition to climate-neutral construction necessitates practical tools for sustainability assessment.

This is where Environmental Product Declarations (EPDs) come to the rescue. This is a standardized way of providing data on a product's environmental impact throughout its entire life cycle.

An Environmental Product Declaration (EPD) is a document that provides transparent information about the environmental impact of any material or product throughout its life cycle.

The declaration is verified by a third party and registered in an EPD system.

In Europe, EPDs must comply with two standards: the European standard EN 15804 and the international standard ISO 14025, meaning that all environmental declarations use a common methodology, a common set of environmental indicators, and have a common reporting format.

Declarations contain data on environmental impacts associated with various stages of a building's life cycle, including:

- Raw material extraction, transportation, and manufacturing.
- Transportation to the construction site and construction/installation works.
- Use, maintenance, repair, replacement, and renovation.
- Demolition, transportation, recycling, and waste disposal.
- Potential reuse, energy recovery, and recycling.

Declarations include information on seven environmental impact indicators: global warming potential, acidification, eutrophication, ozone depletion potential, photochemical ozone creation potential, and two types of abiotic resource depletion.

The standardized methodology inherent to EPDs allows sustainability specialists, architects, consumers, policymakers, and other stakeholders in construction projects to make informed decisions based on verified environmental impact assessments.

Today, in every country and worldwide, there is a large number of manufacturers, which, along with a significant variety of types and categories of construction products, can significantly complicate a comprehensive review of environmental characteristics and decision-making regarding the choice of a particular material or product.

The solution to this problem was the creation of EPD databases, which consolidate all the information, making it accessible to a wide range of users.

An EPD database is a digital platform that serves as an archive of product reliability, providing verified, detailed "environmental quality labeling" for construction materials and products.

The main function of an EPD database is to provide a transparent, standardized portal for environmental impact assessment. By accumulating these declarations as they are created, the database supports compliance with regulatory requirements, industry standards, and verification against sustainability criteria.

Among the platforms facilitating access to and dissemination of EPDs, a key player and benchmark is the ***ECO Platform*** *(www.eco-platform.org)*. The ECO Platform is a non-profit association that brings together operators of Environmental Product Declaration (EPD) programs in Europe and worldwide to create a global, coordinated system for exchanging reliable digital life cycle data for products. The ECO Platform unites operators of the European EPD program with nodes representing these operators or their respective databases. These nodes, created by national EPD providers, are responsible for collecting and verifying environmental data on construction products to create unified, high-quality EPDs, ensuring data compatibility and recognition across Europe (Fig. 3.29).

For users, the ECO Portal is accessible on the platform's website, which serves as a search engine that aggregates EPDs from all participating national databases. Through this portal, the ECO Platform provides a single point of access to thousands of verified declarations from various European sources, significantly simplifying information retrieval for international projects. All EPDs in this system comply with uniform requirements and standards, making them acceptable for use in various national building certification schemes.

This platform is particularly useful for architects, engineers, and manufacturers operating internationally, as it eliminates the need for separate data verification and adaptation for each country. The ECO Platform serves as an important tool for promoting a single market for environmental products in Europe, fostering transparency and standardization in the field of sustainable construction.

Access to the ECO Platform is available free of charge via the website for scientific, educational, and public initiatives. Professional access for commercial use, such as life cycle assessment software developers, is paid.

The next platform is ***EPD International*** (*https://www.environdec.com*), a global system for the verification and registration of environmental product declarations based on international ISO standards. This system enables manufacturers worldwide to create standardized EPDs that are recognized internationally. The main advantage of EPD International is its versatility - it is suitable for various industries and product types, not limited to the construction sector. The system operates through a network of accredited operators in different countries, ensuring adherence to uniform quality standards and product life cycle assessment methodology.

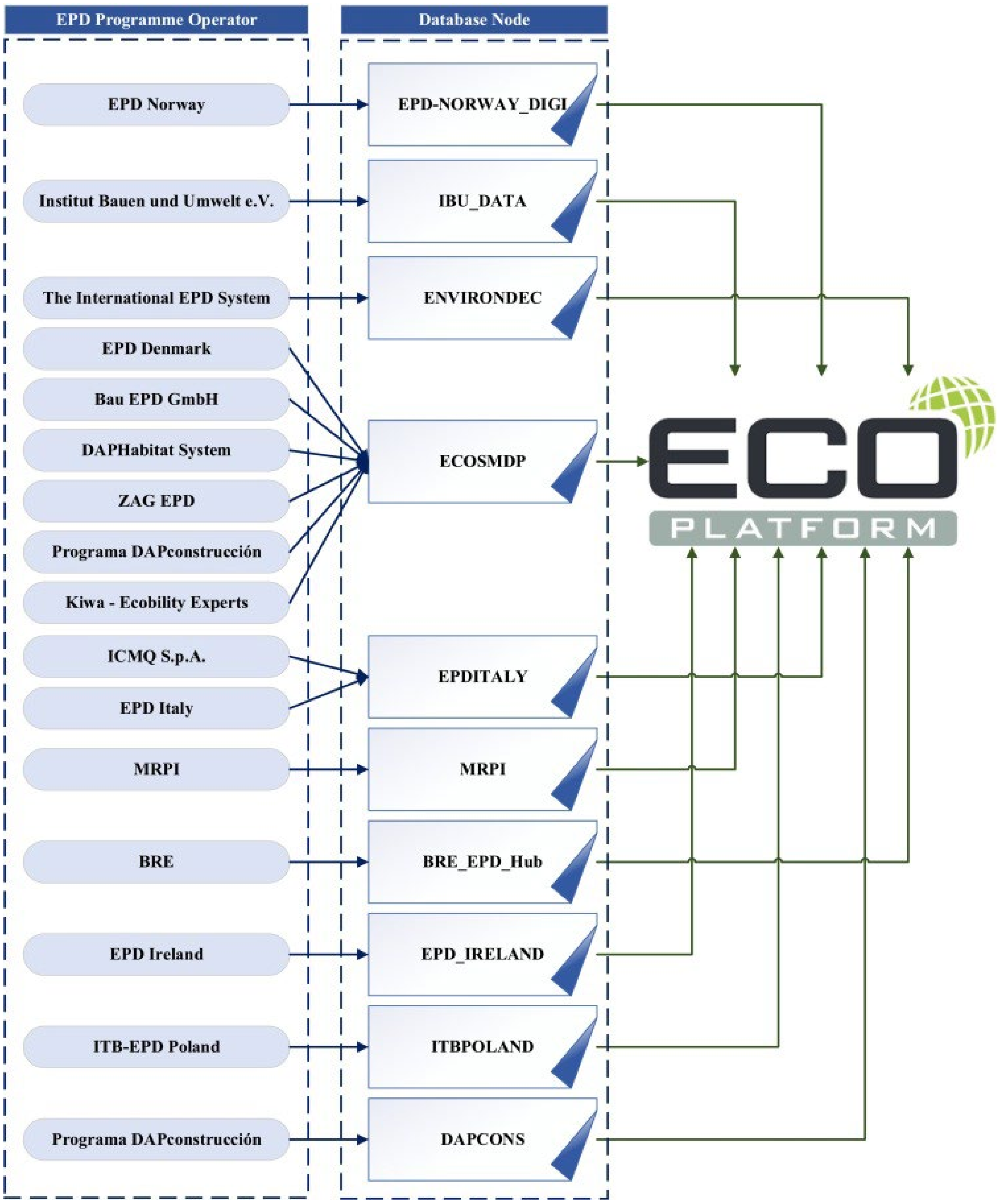


Fig. 3.29 - ECO Platform structure [64]

EPD International plays a crucial role in ensuring the global comparability of environmental product characteristics, which is particularly important for companies operating in international markets or as part of global supply chains. The system also promotes the dissemination of best practices in environmental management and sustainable manufacturing, offering manufacturers a clear framework for assessing and improving the environmental performance of their products. Due to its international recognition, EPD International has become an essential tool for multinational corporations and suppliers seeking to demonstrate their environmental responsibility on a global level.

The EPD Library on *Environdec.com* is a centralized digital database where verified Environmental Product Declarations (EPDs) registered in The International EPD System are published and stored. It serves as a public tool for disseminating standardized information on the environmental impact of products. The library includes environmental declarations for various sectors, such as construction, the food industry, textiles, and packaging. The system also simplifies the process of green building certification under international standards such as LEED, BREEAM, and DGNB, where the availability of an EPD is an important requirement.

Access to the library is free and organized through a convenient search system (*https://www.environdec.com/library*), which allows users to filter declarations by product type, country of origin, manufacturer, and publication date. This platform is continually updated with new declarations, reflecting the growing awareness among manufacturers of the need for transparency in environmental indicators.

The **Ökobaudat** database (*https://www.oekobaudat.de/en.html*) is the official platform of the German Federal Ministry of Housing, Urban Development, and Building, providing standardized data on the environmental characteristics of construction materials and products. It serves as a fundamental tool for the life cycle assessment of buildings. It is a mandatory source for calculating embodied carbon in German building industry standards, such as the DGNB certification system and the BNB assessment system for federal buildings. All data in Ökobaudat is presented in a clearly structured format, allowing for easy integration into specialized software for modeling the environmental impact of construction projects.

Ökobaudat contains both generic data, averaged for typical product categories, and specific declarations from individual manufacturers, which undergo thorough verification before inclusion in the database. This platform plays a key role in ensuring the transparency, comparability, and reliability of environmental information, promoting the transition of the construction industry to a more sustainable format.

The datasets meet strict quality requirements and can be used in many different building assessment systems. The database system with search and filter functions provides convenient online searching of datasets.

The data published in ÖKOBAUDAT is available for free, without charge. The respective owner of the datasets is responsible for the content and values.

The **INIES** database (*www.inies.fr*) is the national French platform that provides access to the environmental and sanitary-hygienic characteristics of construction products and equipment. This database was created under the auspices of the French HQE association and is the official source of information for assessing the environmental impact of buildings in France.

INIES contains both generic data developed by technical committees and specific data from manufacturers that have undergone a strict verification procedure. A distinctive feature of INIES is its comprehensive approach to product assessment, which includes not only traditional environmental indicators, such as carbon footprint and energy consumption, but also data on impacts on human health, including emissions of volatile organic compounds. This database is a mandatory tool for all professionals working in the field of sustainable construction in France, particularly for those involved in building certification under HQE standards.

Since INIES is a national French database, the primary language of the documents is French. Access to the INIES database is free of charge. Searching and viewing information about the required product is done on the database page (*https://base-inies.fr/tableau-de-bord*).

Data in INIES is presented in a standardized format, allowing for easy integration into software for building life cycle assessment. The database is constantly updated with new data and expands its coverage, including more and more product categories and manufacturers. INIES plays a key role in promoting environmentally responsible construction in France, providing access to verified and reliable information about the environmental impact and health effects of building materials.

Similar principles govern the operation of EPD databases in other countries, notably the Norwegian **EPD Norway** (*https://epd-global.no/*), the Italian **EPD Italy** (*https://www.epditaly.it/*), and others.

In Ukraine, the national EPD system is in the development stage. The state standard DSTU EN ISO 14025:2022 "Environmental labels and declarations. Type III environmental declarations. Principles and procedures", identical to EN ISO 14025, has come into force. Some Ukrainian manufacturers (especially those focused on exports to the EU) have already started obtaining EPDs for their products (for example, cement, concrete, metal products) through international systems such as EPD International.

CHAPTER 4. ENVIRONMENTAL LIFE CYCLE ASSESSMENT MODEL

4.1. Impact of Architectural and Building System Typologies on the Environmental Indicators of the Life Cycle

All architectural, structural, and technological solutions must ensure the required level of environmental, social, and economic performance.

Design considering the requirements for the balanced use of natural resources directly depends on the architectural and building solutions of the structure, and is determined by:

- planned durability and life cycle duration;
- planned or potentially possible change in architectural and layout solutions or purpose;
- predicted repairs, reconstructions, or replacement of individual elements as they age.

Rational use of natural resources throughout the building's life cycle depends on specific criteria, which include:

- maintainability of the building and, in particular, its structural framework;
- possibility of reusing individual structural elements;
- use of materials suitable for processing and recycling;
- use of materials that are not scarce, do not require high energy consumption during production, have sufficient natural reserves, or are rapidly renewable.
- percentage of materials not subject to recycling and processing, but whose disposal is not an environmental problem.

During the design of the building system, it is recommended to distinguish between structural elements that remain unchanged throughout the entire life cycle and variable (transformative) elements of the architectural and building systems.

For permanent structural elements, maintainability must be provided in case of weakening or destruction.

Compensation for the aging of building parts, associated with their limited effective service life, increasing regulatory requirements for these structures, and the emergence of new effective solutions, is ensured by scheduled major repairs or reconstructions involving the replacement of these parts without interfering with the main structural elements and the connections of the structural framework.

The variable part of the architectural and building system should be composed of structures that ensure the convenience and economic feasibility of replacement or layout changes, using the same structures or products resulting from their processing.

According to the specified requirements, all components and elements of the building system are classified as follows:

1. Depending on the responsibility category of structures according to DBN V.1.2-14

- A - Failure (destruction or unsuitability for operation) of the element leads to progressive (avalanche-like) collapse of a significant part of the building or the entire building as a whole. These are elements on which the integrity of the entire structural system depends -- foundations, columns, main beams supporting a large number of other elements; elements ensuring spatial rigidity (bracings, shear walls), key support nodes.
- B - Failure of the element leads to the destruction of individual elements but does not cause progressive collapse. Consequences are limited to a local zone. These include secondary beams, floor slabs, and roofing elements.
- C - Failure of the element does not lead to the destruction of other structures. Consequences are limited to damage to the element itself. For example, stair treads, fencing elements, balconies, parapets, partitions, suspended ceilings, etc.

2. Depending on the service life

- up to 10 years;
- 10-30 years;
- 30-60 years;
- 60-100 years;
- more than 100 years.

3. Depending on the degree of stability and variability of elements

- Load-bearing system (frame);
- Enclosing structures (envelope);

- Elements of variable layout structure (partitions).

According to this classification, all building elements, from the perspective of design, considering the environmental parameters of the life cycle, are divided into three types (Table 4.1):

Type 1 - Load-bearing structures, Category A, service life 60-100 years and more;

Type 2 - Enclosing structures, Category B, service life 30-60 years;

Type 3 - Partitions, plumbing, equipment, Category C, service life less than 30 years.

Table 4.1

Classification of Building Structures for Design Considering Environmental Life Cycle Parameters

Type	**Classification Feature**		
	Responsibility category	Service Life	Degree of Stability in the System
Type 1	A	60-100 years or more than 100 years	Load-bearing system, frame
Type 2	B	30-60 years	Envelope (Enclosing structures)
Type 3	C	10-30 years and less	Replaceable elements

This classification enables the optimization of material choices, construction methods, and maintenance strategies, thereby reducing resource intensity throughout the life cycle.

Depending on the distribution of component reliability, three classes of architectural and building systems are distinguished:

- Class 1 (Optimal systems) -- Designed for a service life of over 100 years. Include differentiated structures (Types 1-3), allowing easy changes to layout solutions without interfering with load-bearing elements.
- Class 2 (Rational systems) -- Service life 30-60 years. Structures of Types 1 and 2 are often combined (e.g., an external wall is simultaneously a load-bearing frame and an enclosing element), which reduces construction costs but complicates future changes. At the same time, Type 3 elements remain separate and do not impact load-bearing and enclosing structures.
- Class 3 (Critical systems) - Service life 10-30 years. Characterized by undifferentiated structures (e.g., a combination of not only load-bearing and enclosing functions, but also load-bearing and architectural-layout functions), low adaptability, and high reconstruction costs.

Architectural and building systems of Class 1 are defined as optimal for implementing sustainable construction concepts in structures designed for long service lives (over 100 years). Compared to rebuilding new structures on the site of dismantled buildings, considering the costs of disposing of the dismantled buildings, this concept should provide at least a 30% savings. At the same time, the most valuable part of the building is preserved in a reliable condition, and the moments of replanning and adaptation to new needs and functions should not be tied to the stages of the object's life cycle.

When designing Class 1 buildings, the emphasis is on the use of automated control and monitoring systems for technical condition, maintainability, the possibility of replacing enclosing structures and partitions without stopping operation, and the use of materials with high reuse potential after the end of their life cycle.

Architectural and building systems of Class 2 are defined as rational for implementing the sustainable construction concept for structures designed for medium (30-60 years) service life. These systems are rational within their time range. Provided reconstruction, repairs, replacement of elements and structures, and adaptation to new needs, the service life can be extended to 100 years. Monitoring systems, energy-saving measures, and the use of ecological materials improve the characteristics of Class 2 systems.

Architectural and building systems of Class 3 have the following features:

- Impossibility or increased risk of emergency conditions when attempting to adapt to another purpose (e.g., replanning apartments for modern requirements or ground-floor premises for public functions);
- Significant cost and technological complexity of conducting reconstruction or major repairs, with suspension of the object's operation for the duration of such works.

Design and construction of Class 3 structures generally contradict the requirements of sustainable construction and are recommended for temporary or short-life cycle buildings (from 10 to 30 years). After the end of the life cycle for such buildings, dismantling and processing of materials into new raw materials is advisable.

4.2. Basic Principles of Environmental Life Cycle Assessment of a Building

The integrated life cycle assessment of a building considers methods of construction, functioning, operation, maintenance, repair, modernization, reconstruction, including dismantling and demolition, as well as reuse and recycling.

The purpose of sustainability assessments is to collect and present information to support decision-making at various stages of the building's construction, design, and operation. Various sustainability assessment tools are available on the construction market, for example, BREEAM in the UK and LEED in the USA. In addition, there are software products for building life cycle assessment, for example, Eco-Quantum (Netherlands), EcoEffect (Sweden), ENVEST (UK), BEES (USA), ATHENA (Canada), and One Click LCA (UK).

The list of parameters presented in Fig. 4.1 reflects the functional requirements for the building, which encompass impacts on environmental, social, and economic indicators, collectively forming the overall sustainability assessment.

Fig. 4.2 shows a block diagram of the integrated life cycle assessment of a construction object. The mandatory criterion is the assessment of environmental impact.

Sustainable development indicators provide information about the environmental impact of a specific industry. There are different approaches to selecting indicators due to social differences between countries, industrial production traditions, and natural, climatic, and geographical conditions.

Environmental Indicators	Social Indicators	Economic Indicators
Climate Change: • Global Warming Potential. Emissions to Air, Water, and Soil: • Ozone Depletion; • Acidification Potential of Soil; • Eutrophication Potential (destruction of water body productivity); • Ground-level Ozone Formation; • Generation of Inert Waste; • Generation of Hazardous Waste. **Water Use Efficiency:** • Potable Water Consumption; • Rainwater Utilization. **Resource Depletion:** • Land Use; • Fossil Fuel Depletion Potential.	**Thermal Comfort:** • Relative Humidity; • Winter Thermal Performance; • Summer Thermal Performance. **Indoor Air Quality:** • Airborne Particulate Matter; • Carbon Monoxide; • Carbon Dioxide; • Ozone; • Formaldehyde; • Volatile Organic Compounds (VOCs). **Acoustic Comfort:** • Airborne Sound Insulation; • Impact Sound Insulation; • Reverberation Time. **Visual Comfort:** • Use of Natural Daylighting; • (Artificial) Illumination.	**Life Cycle Costs:** • Pre-use Costs; • Maintenance Costs; • Operational Costs; • End-of-Life Costs (Disposal/Demolition); • Recycling Efficiency; • Residual Value.

Fig. 4.1 - Parameters influencing the building life cycle

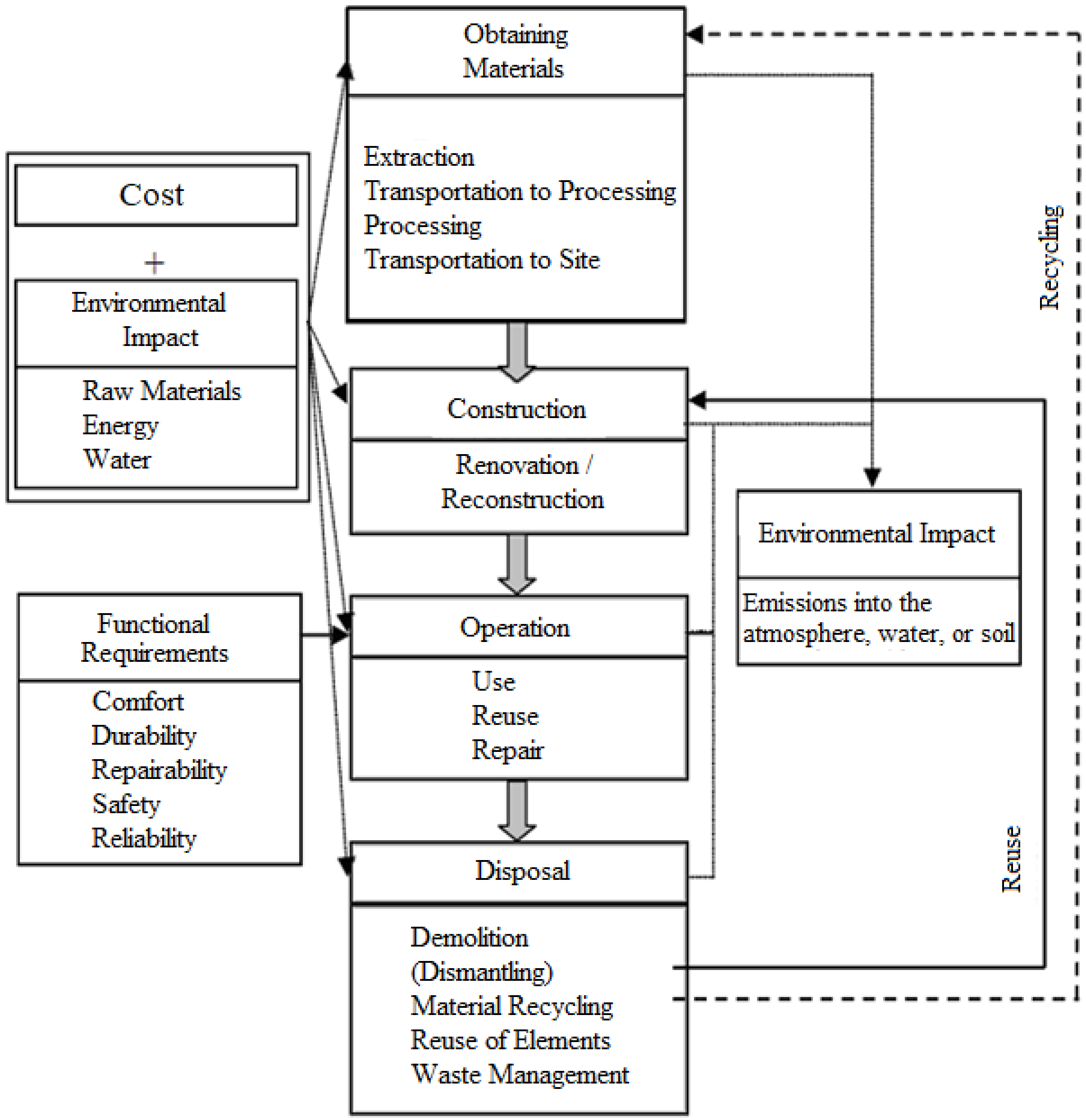


Fig. 4.2 - Block diagram of the integrated life cycle assessment of a construction object

A quantitative assessment of environmental impact, as per the European standard EN 15978:2011 (the current equivalent in Ukraine is DSTU 9171:2021), is conducted considering the full life cycle.

The standard defines the primary environmental impact indicators for buildings, which are listed in Table 4.2.

Table 4.2

List of Environmental Impact Indicators based on EN 15978

Environmental Impact	• Global Warming Potential • Stratospheric Ozone Depletion Potential • Potential for Acidification of Land and Water • Eutrophication Potential • Potential for Formation of Tropospheric Photochemical Oxidants (Ozone) • Abiotic Resource Depletion Potential • Abiotic Resource Depletion Potential for Fossil Fuels
Resource Use	• Use of Renewable Primary Energy, excluding energy resources used as raw materials • Use of Renewable Primary Energy Resources used as raw materials • Use of Non-Renewable Primary Energy, excluding energy resources used as raw materials • Use of Non-Renewable Primary Energy Resources used as raw materials • Use of Secondary Material • Use of Renewable Secondary Fuels • Use of Non-Renewable Secondary Fuels • Net Use of Fresh Water
Waste Categories and Output Flows	• Disposal of Hazardous Waste • Disposal of Non-Hazardous Waste • Disposal of Radioactive Waste • Components for Reuse • Materials for Recycling • Materials for Energy Recovery (non-waste incineration) • Exported Energy

The EN 15978:2011 standard also guides the definition of functional units, system boundaries, and scenarios.

The functional unit is a quantitative representation of the building system's performance, serving as a reference unit and encompassing both the physical and functional characteristics of the building.

System boundaries define which processes will be included in the assessment. For example:

- In the case of a new building, all life cycle stages are considered, from construction to final disposal;
- In the case of an existing building, the time boundary starts from the moment of intervention in the life cycle (e.g., reconstruction or modernization) and ends with disposal.

A scenario is a hypothesis applied to the subject of study, linking physical characteristics with the time variable.

EN 15978:2011 is organized according to the "modular" structure of the building life cycle, which includes four stages:

1. Product stage;
2. Construction process stage;
3. Use stage;
4. End-of-life stage.

All the above stages are considered in separate information modules, for each of which information on environmental impacts and object features is provided.

Information Module A is divided into five subgroups (A1 to A5) and includes emissions during the extraction and supply of raw materials, the manufacturing of building materials, products, and industrial constructions, their transportation to the construction site, and the direct construction process (construction and installation works, as well as related processes).

Information Module B is divided into seven subgroups (B1 to B7) and describes emissions during the use stage, technical maintenance, repair, or replacement of individual elements or the building as a whole, significant repairs, as well as provision of related needs (e.g., maintenance of areas adjacent to the building, lawns, fountains, etc.).

Information Module C is divided into four subgroups (C1 to C4) and describes emissions at the end-of-life stage, which includes dismantling, transportation of waste from the site to processing plants or landfills, processing of waste into secondary raw materials, and waste landfilling.

Information Module D describes environmental impacts not related to the object's life cycle, such as the further use of secondary raw materials obtained through recycling and other reuse possibilities not included in the object's life cycle.

The organizational scheme of the life cycle stages and corresponding information modules is illustrated in Fig. 4.3. Additionally, EN 15978 [23] outlines the structure of results and the list of environmental indicators to be considered. Results must be presented according to the stages (production, construction, use, end-of-life, and recycling/recovery) using information modules (A, B, C, and D).

The methodological basis for assessing information modules according to EN 15978 is Environmental Product Declarations (EPDs), which enable the assessment of resource intensity and environmental impact based on a dataset obtained from studies using a standardized method. This, in turn, simplifies the search for source information for carbon footprint assessment. Environmental Product Declarations are developed, approved, and registered in the international database in accordance with the procedure and content structure outlined in the international standard ISO 14025. This standard has been implemented into the national standardization system as DSTU ISO 14025:2008 "Environmental labels and declarations. Type III environmental declarations. Principles and procedures (ISO 14025:2006, IDT)".

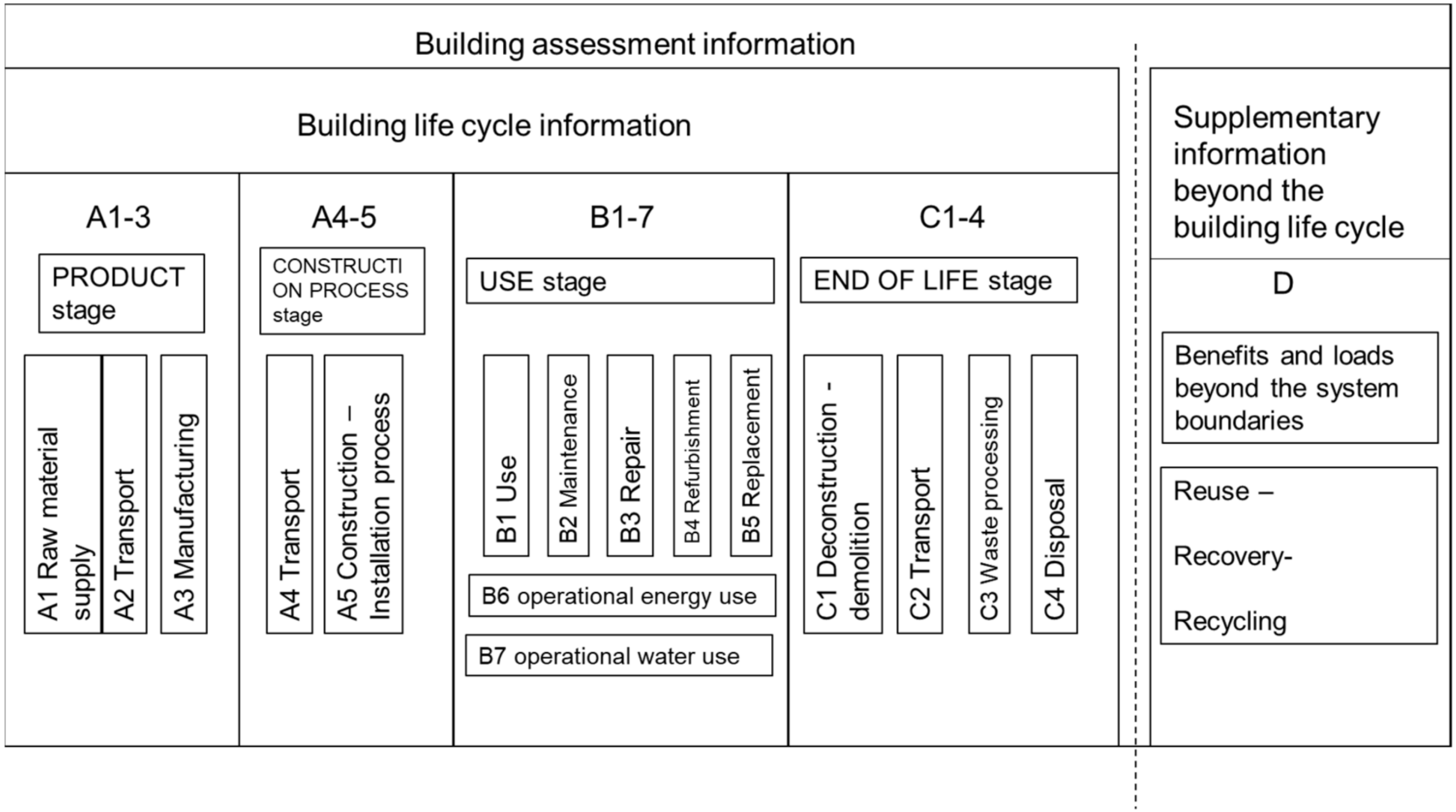


Fig. 4.3 - Fig. 5.3. Organizational scheme of life cycle stages and corresponding information modules

4.3. Environmental Life Cycle Assessment at the Design Stage

Introducing an environmentally oriented approach throughout the entire life cycle of an object, from material production to decommissioning, reuse, or recycling, is a key principle of balanced and rational resource use in modern construction.

Environmental life cycle indicators of materials for the construction, repair, or reconstruction of a building must be considered at the design stage.

Key requirements for design solutions include the use of materials and products that ensure:

- minimization of technological processes through the development of appropriate architectural and structural solutions;
- confirmation of compliance of environmental characteristics of materials and products with regulatory document requirements;
- development of design solutions aimed at limiting the generation of material residues and waste formation at the construction site;
- minimization or reduction of the quantity and range of new materials used in the project;
- consideration of the specifics and type of work when choosing design solutions (new construction, reconstruction, repair, demolition).

For the quantitative assessment of a building's environmental performance, the Global Warming Potential (*GWPc*) indicator is usually used. The formula for calculating the characteristic indicator *GWPc* for a building is as follows:

$$GWP_c = \sum_{i=1}^{n} GWP_{cat,i} \cdot Q_s ,$$

where $GWP_{cat,\, i}$ is the characteristic global warming potential indicator for the i-th type of building element per unit of measure (material, product, process, etc.);

n is the number of building elements assessed within the system;

Q_s is the quantitative volume of assessment elements related to the building element (volume of materials, quantity of products, machine-hours, etc.).

Data on the volumes of elements can be obtained from material consumption schedules, design and estimate documents, as-built documentation, survey materials, process charts, and invoices, among other sources.

Characteristic global warming potential indicators per unit of measure are contained in specialized databases compiled based on Environmental Product Declarations (EPD), manufacturer, and supplier data.

Environmental life cycle assessment can be conducted at different levels of detail: 1 - load-bearing frame of the building; 2 - load-bearing frame and enclosing structures of the building; 3 - load-bearing frame, enclosing structures, partitions, and auxiliary elements; 4 - load-bearing frame, enclosing structures, partitions, auxiliary elements, and engineering systems. The level of detail can vary depending on the purpose and defined system boundaries for the assessment.

Aggregated characteristic global warming potential indicators for main building structural materials for express assessment of the environmental impact of load-bearing systems, enclosing structures, partitions, and auxiliary elements are contained in DSTU 9171:2021. They are provided in an abbreviated form in Table 4.3.

From Table 4.3, it is evident that different materials exhibit varying global warming potential indicators. For example, for steel, the indicator ranges from 0.687 to 2.766 kg CO_2-eq./kg, for concrete (class C30/37) - 303.4 kg CO_2-eq./m^3, and for wood (e.g., oak), the indicator is negative (-114.37 kg CO_2-eq./m^3), indicating its ability to sequester carbon.

When forming design solutions, several options (scenarios) should be considered, and the one that ultimately has the least global warming potential while complying with all requirements for architectural and layout solutions, structural reliability, comfort, and safety should be chosen.

Table 4.3

Aggregated Characteristic Global Warming Potential Indicators of Main Building Structural Materials

Type of Material or Product	Measure unit	$GWP_{cat,\ i}$, kg CO_2-eq.
Welded and rolled steel elements (ordinary steel)	kg	0,713
Closed steel sections and tubes	kg	0,921
Reinforcing bars, smooth and ribbed, wire	kg	0,687
Welded and rolled steel elements (stainless steel)	kg	2,766
Rolled steel sheets (2-20 mm) (ordinary steel, hot-dip galvanized)	kg	1,103
Profiles and structures (aluminum alloys)	кг	2,793
Concrete strength class C20/25	m^3	248,899
Concrete strength class C30/37	m^3	303,399
Cement-sand mortar	m^3	380,639
Blocks based on granulated slag	m^3	365,099
Solid ordinary and facing brick	m^3	544,320
Aerated concrete blocks with an average density of 472 kg/m^3	m^3	267,141
Precast reinforced concrete floor slabs, thickness 20 cm; weight 504 kg/m^2; concrete with average. density 2.4 t/m^3; reinforcement 120 kg/m^3	m^3	88,781
Precast reinforced concrete wall panels, thickness 12 cm; weight 291.3 kg/m^2; concrete with avg. density 2.4 t/m^3, reinforcement 0.5% of volume	m^3	41,512
Expanded clay concrete hollow blocks for internal walls, with an average. density 1600 kg/m^3	m^3	398,413
Expanded clay concrete hollow blocks for external walls, with an average. density 500 kg/m^3	m^3	176,042
Glued laminated timber from softwood	m^3	88,715
Glued laminated boards from softwood; avg. density 515 kg/m^3 at 12% moisture	m^3	85,615
Sawn timber from solid spruce (12% moisture content)	m^3	-55,269
Sawn timber from solid pine (12% moisture content)	m^3	-56,998
Sawn timber from solid larch (12% moisture content)	m^3	-33,212
Plywood products (5% moisture content)	m^3	265,117

A systematic approach to evaluating options includes analyzing resource efficiency by comparing generalized costs of material resources, energy, and waste, which includes:

- the quantity of required materials and their cost at the time of construction and cost trends during the operation stage;
- utilization of local and/or regional resource and industrial base capabilities;
- factory and construction labor intensity; possibility of optimizing labor costs for building erection, for example, through the use of prefabricated and demountable assembly technologies;
- need for non-standard and/or unique tools, mechanisms, equipment;
- feasibility of conducting technical condition monitoring, repair and restoration measures, technical modernization during operation, and decommissioning of the object;
- necessity and possibility of removal, processing, and disposal of waste.

When selecting materials and products for the project, the criterion of minimizing the generation of their residues should be followed, both during construction at the building site and during the operation stages (including repair and restoration works) and decommissioning (during dismantling).

The hierarchy of measures to reduce residue generation may include measures from simple prevention of residue formation or landfilling (destruction) of residues. However, from the perspective of life cycle environmental friendliness, more complex planning is better, including architectural and structural solutions suitable for direct reuse or alternative use, waste recycling, and residue processing. The volume of materials or products that can be obtained from recycling or reuse allows for reducing the amount of resources for new construction, repair, or reconstruction of this or another object. Thereby, the global warming potential of the designed building is reduced.

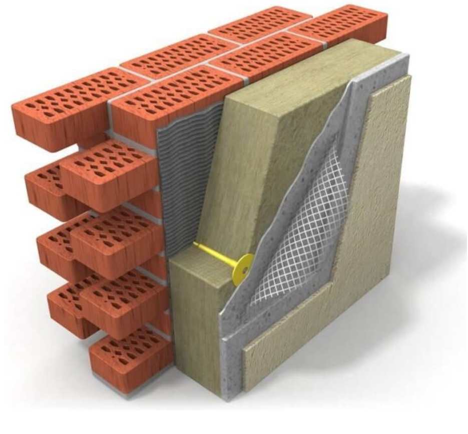
4.4. Example of Life Cycle Assessment and Analysis of Results

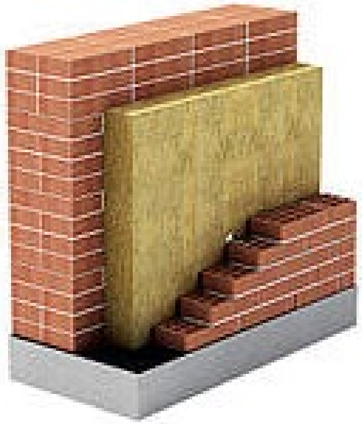
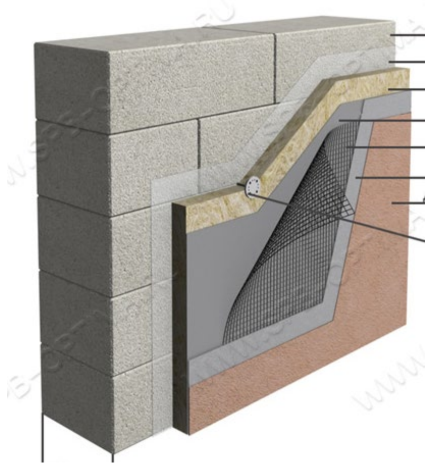
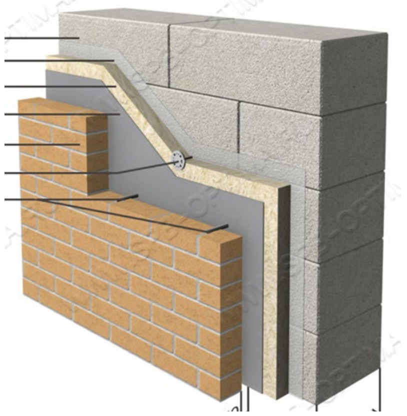
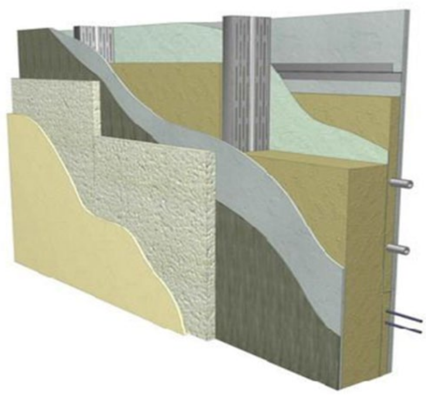
According to the results of a review of existing structural solutions for low-rise buildings, a number of the most common solutions currently, both in Ukraine and abroad, were adopted for carbon footprint analysis:

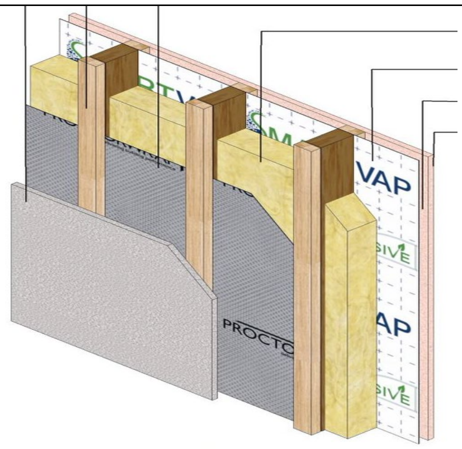
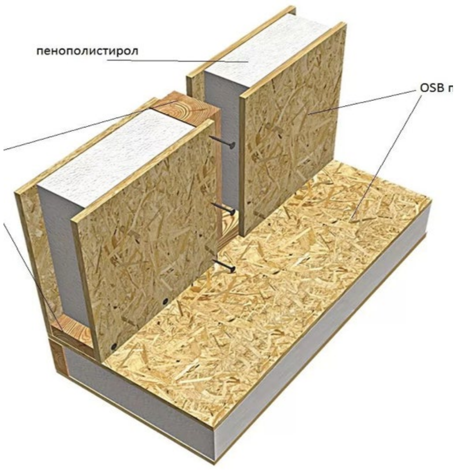
1. Brick masonry with external insulation with expanded polystyrene and plaster;
2. Brick masonry with external insulation with mineral wool and cladding;
3. Aerated concrete block masonry with external insulation with expanded polystyrene;
4. Aerated concrete block masonry with external insulation with mineral wool and cladding;
5. Panel from Light Gauge Steel Framing (LGSF) with an internal layer of mineral wool insulation;
6. Frame-panel with a wooden frame with an internal layer of mineral wool insulation;
7. SIP panel from two sheathing boards with expanded polystyrene laid between them.

Table 4.4

Wall Structure Solutions Adopted for Analysis

Sketch of Wall Structure	Brief Description of Elements	Thermal Resistance, R, $m^2 \cdot K/W$
	Ceramic brick – 380 mm; Extruded polystyrene foam (XPS) – 120 mm; Cement-sand plaster – 20 mm.	4,17

	Ceramic brick – 380 mm; Mineral wool – 120 mm; Facing brick – 120 mm.	4,03
	Aerated concrete block – 300 mm; Extruded polystyrene foam – 50 mm; Cement-sand plaster – 20 mm.	4,57
	Aerated concrete block – 300 mm; Extruded polystyrene – 50 mm; Facing brick – 120 mm.	4,56
	OSB – 18 mm LGSF profile – 45x200 mm Mineral wool – 200 mm Gypsum board – 12.5 mm	4,91

	OSB – 18 mm Wooden stud – 50x175 mm Mineral wool – 170 mm Gypsum board – 12,5 mm	4,23
	ОСП – 18 mm Wooden stud – 50x150 mm Extruded polystyrene – 150 mm ОСП – 18 mm	4,56

Material consumption for each type of wall structure was determined based on the standard wall panel size in frame construction, which is 1.2 x 2.5 m (width x height). These dimensions will be considered a typical unit for determining carbon footprint characteristics.

The material consumption for a typical unit of wall structure was determined in terms of its self-weight. For ceramic and facing bricks, plaster, mineral wool, and extruded material, as well as sheet products OSB and GWB, the weight was calculated by the formula:

$$g_i = b \cdot h \cdot t_i \cdot \rho_i ,$$

where g_i is the total weight of the i-th material per typical wall unit;

b, h are the width and height of the typical wall unit;

ti is the thickness of the i-th material;

ρi is the specific weight of the i-th material.

The weight of wooden studs in the frame-panel was determined as follows:

$$g_w = b_w \cdot h_w \cdot h \cdot \rho_w \cdot n,$$

where g_w is the total weight of wooden studs per typical wall unit;

b_w, h_w are the width and height of the wooden stud;

h is the height of the typical wall unit;

ρ_w is the specific weight of wood;

n is the number of wooden studs per typical frame-panel unit.

The weight of studs in the LGSF wall panel was calculated using the following formula:

$$g_L = h \cdot q_L \cdot n,$$

where g_L is the total weight of LGSF studs per typical wall unit;

h is the height of the typical wall unit;

q_L is the weight of 1 m.p. of LGSF profile;

n is the number of wooden studs per typical frame-panel unit.

The weight of 1 m.p. of LGSF, according to the assortment of domestic manufacturers, for a U-shaped profile with a wall thickness of 1.0 mm and dimensions of 50 x 200 mm, is 2.341 kg/m.p.

The results of determining material consumption per typical wall unit for the types analyzed are presented in Table 4.5.

Calculated data on the carbon footprint of wall structure materials were determined based on Environmental Product Declaration data using the EPD International database and are given in Table 4.6.

Table 4.5

Determination of Material Consumption per Typical Wall Unit

Code	Description	Composition	Specific weight, kg/m^3	Total Weight per Typical Unit, kg
CT1	Brick masonry with external insulation with EPS and plaster	Ceramic brick -- 380 mm	1600	1824
		Extruded Polystyrene -- 120 mm	35	12,6
		Cement-sand plaster -- 20 mm	1800	108
CT2	Brick masonry with external insulation with mineral wool and cladding	Ceramic brick -- 380 mm	1600	1824
		Mineral wool -- 120 mm	100	36
		Facing brick -- 120 mm	1300	468
CT3	Aerated concrete block external insulation with EPS and plaster	Aerated concrete block -- 300 mm	400	360
		Extruded Polystyrene – 50 mm	35	5,25
		Cement-sand plaster - 20 mm	1800	108
CT4	Aerated concrete blocks with external insulation with mineral wool and cladding	Aerated concrete block - 300 mm	400	360
		Extruded Polystyrene – 50 mm	35	5,25
		Facing brick -- 120 mm	1300	468
CT5	Light Gauge Steel Framing (LGSF) with an internal	OSB – 18 mm	1000	54
		LGSF – 1,0mm / 50x200 mm (3 шт.)	2.341 кг/м.п.	17,6

	layer of mineral wool insulation	Mineral wool – 200 mm	100	60
		Gypsum board – 12,5 mm	800	30
CT6	Wooden frame-panel with an internal layer of mineral wool insulation	OSB – 18 mm	1000	54
		Wooden stud -- 50x175 mm (3 pcs.)	600	39,4
		Mineral wool – 170 mm	100	51
		Gypsum board – 12,5 mm	800	30
CT7	SIP panel from two sheathing boards with EPS laid between them	OSB – 18 mm	1000	54
		Wooden stud 50x150 mm (3 pcs.)	600	26,25
		Extruded Polystyrene -- 150 mm	35	15,75
		OSB – 18 mm	1000	54

Table 4.6

Design data on the carbon footprint of wall structure materials

Material	CO2 emissions, kgCO2eq/kg, for the considered life-cycle stages					
	Cbe	Cbt	Cbp	Cd2	Cd3	Cr
Ceramic brick	0,147	1,412541	0,000143	0,00649	0,00339	-0,00563
Aerated concrete block	0,336	4,209302	0,0022	0,00416	0,0048	-0,00366
Ceramic facing brick	0,147	14,26667	0,000143	0,00649	0,00339	-0,00563
Sand Cement Plaster	0,394	0,0072	0,0417	0,00829	0,0148	-0,00224

Extruded polystyrene foam	2,742	0,052975	0,01856	0,00774	3,3978	-1,41
Mineral wool	0,80586	2,0942	0,01944	0,001998	0,00828	-0,03078
OSB	0,1717	3,363995	0,08704	0,007514	0,5457	-0,4862
Drywall	0,2268	0,039357	0,03024	6,108E-17	2,928E-14	-3,324E-14
LGSF	2,58	8	0,0498	0,017	0,00326	-0,0015
Sawn timber	0,058859	3,18	0,003238	0,00303462	0,00143177	-0,211813

- Cbe: Production of building materials
- Cbt: Transportation of building materials
- Cbp: Construction and installation process
- Cd2: Transportation of construction waste
- Cd3: Waste storage in landfills
- Cr: Recycling potential

The results of the carbon footprint determination for the adopted wall structure variants, with a breakdown by individual life cycle stages and total emissions, are provided in Tables 4.7 – 4.13.

The summary table and comparative diagram of the carbon footprint for different wall structures are provided in Table 4.14 and in Fig. 4.4.

Table 4.7

Results of the Carbon Footprint Determination for a Wall Made of Brick Masonry with External Polystyrene Insulation and Plaster (Type CT1)

Material	CO_2 Emissions, kg CO_2-eq.						
	Cbe	Cbt	Cbp	Cd2	Cd3	Cr	CO2
Ceramic brick	268,12800	2576,47525	0,26083	11,83776	6,18336	-10,269	2852,616
Extruded Polystyrene	34,54920	0,66749	0,23386	0,09752	42,81228	-17,766	60,594
Cement-sand plaster	42,55200	0,77760	4,50360	0,89532	1,59840	-0,24192	50,085
Total Emissions	345,229	2577,920	4,998	12,831	50,594	-28,277	2963,295

Table 4.8

Results of the Carbon Footprint Assessment for a Brick Wall with External Mineral Wool Insulation and Cladding (Type CT2)

Material	CO_2 Emissions, kg CO_2-eq.						
	Cbe	Cbt	Cbp	Cd2	Cd3	Cr	CO2
Ceramic brick	268,128	2576,4752	0,260832	11,83776	6,18336	-10,269	2852,616
Mineral wool	29,01096	75,3912	0,69984	0,071928	0,29808	-1,10808	104,364
Facing brick	68,796	6676,8	0,066924	3,03732	1,58652	-2,63484	6747,652
Total Emissions	365,935	9328,666	1,028	14,947	8,068	-14,012	9704,632

Table 4.9

Results of the Carbon Footprint Assessment for a Wall Made of Aerated Concrete Blocks with External Expanded Polystyrene Insulation (Type CT3)

Material	CO_2 Emissions, kg CO_2-eq.						
	Cbe	Cbt	Cbp	Cd2	Cd3	Cr	CO2
Aerated concrete block	120,96	1515,3488	0,792	1,4976	1,728	-1,3176	1639,009
Extruded polysterene	14,3955	0,278119	0,09744	0,040635	17,83845	-7,4025	25,248
Cement-sand plaster	42,552	0,7776	4,5036	0,89532	1,5984	-0,24192	50,085
Total Emissions	177,908	1516,405	5,393	2,434	21,165	-8,962	1714,341

Table 4.10

Results of the Carbon Footprint Assessment for a Wall Made of Aerated Concrete Blocks with External Mineral Wool Insulation and Cladding (Type CT4)

Material	CO_2 Emissions, kg CO_2-eq.						
	Cbe	Cbt	Cbp	Cd2	Cd3	Cr	CO2
Aerated concrete block	120,96	1515,3488	0,792	1,4976	1,728	-1,3176	1639,009
Extruded polystyrene	14,3955	0,278119	0,09744	0,040635	17,83845	-7,4025	25,248
Facing brick	68,796	6676,8	0,066924	3,03732	1,58652	-2,63484	6747,652
Total Emissions	204,152	8192,427	0,956	4,576	21,153	-11,355	8411,908

Table 4.11

Results of the Carbon Footprint Assessment for an LSFC Wall Panel with an Internal Layer of Mineral Wool Insulation (Type CT5)

Material	CO_2 Emissions, kg CO_2-eq.						
	Cbe	Cbt	Cbp	Cd2	Cd3	Cr	CO2
OSB	9,2718	181,656	4,70016	0,405756	29,4678	-26,2548	199,246
LGSF	4540,8	267,52	876,48	299,2	57,376	-26,4	6014,976
Mineral wool	48,3516	125,652	1,1664	0,11988	0,4968	-1,8468	173,940
Gypsum board	6,804	1,1807	0,9072	1,8324E-15	8,784E-13	-9,972E-13	8,892
Total Emissions	4605,23	576,008	883,254	299,726	87,341	-54,502	6397,054

Table 4.12

Results of the Carbon Footprint Assessment for a Timber-Frame Panel with an Internal Layer of Mineral Wool Insulation (Type CT6)

Material	CO_2 Emissions, kg CO_2-eq.						
	Cbe	Cbt	Cbp	Cd2	Cd3	Cr	CO2
OSB	9,2718	181,65572	4,70016	0,405756	29,4678	-26,2548	199,246
Wooden stud	2,319063	7,3746208	0,02388	7,247E-05	1,03761E-07	-2,2E-08	9,718
Mineral wool	41,09886	106,8042	0,99144	0,101898	0,42228	-1,56978	147,849
Gypsum board	6,804	1,1807143	0,9072	1,8324E-15	8,784E-13	-9,97E-13	8,892
Total Emissions	59,494	297,015	6,623	0,508	29,890	-27,825	365,705

Table 4.13

Results of the Carbon Footprint Assessment for a SIP Panel with Two Sheathing Boards and Expanded Polystyrene Core (Type CT7)

Material	CO_2 Emissions, kg CO_2-eq.						
	Cbe	Cbt	Cbp	Cd2	Cd3	Cr	CO2
OSB	9,2718	181,65572	4,70016	0,405756	29,4678	-26,2548	199,246
Wooden stud	1,545061	83,475	0,085	0,0796	0,03758	-5,560	79,662
Extruded polystyrene	43,1865	0,834357	0,29232	0,121905	53,51535	-22,2075	75,743
OSB	9,2718	181,65572	4,70016	0,405756	29,4678	-26,2548	199,246
Total Emissions	63,275	447,621	9,778	1,013	112,489	-80,277	553,898

Table 4.14

Carbon emissions for the considered life-cycle stages and the total carbon footprint for load-bearing wall structures of low-rise buildings

Wall structure	CO2 emissions, kgCO2eq/typical unit, for the considered life-cycle stages						
	Cbe	Cbt	Cbp	Cd2	Cd3	Cr	CO2
CT1	345,23	2577,92	5,00	12,83	50,59	-28,28	2963,30
CT2	365,93	9328,67	1,03	14,95	8,07	-14,01	9704,63
CT3	177,91	1516,40	5,39	2,43	21,16	-8,96	1714,34
CT4	204,15	8192,43	0,96	4,58	21,15	-11,35	8411,91
CT5	4605,23	576,01	883,25	299,73	87,34	-54,50	6397,05
CT6	59,49	297,02	6,62	0,51	29,89	-27,82	365,70
CT7	63,28	447,62	9,78	1,01	112,49	-80,28	553,90

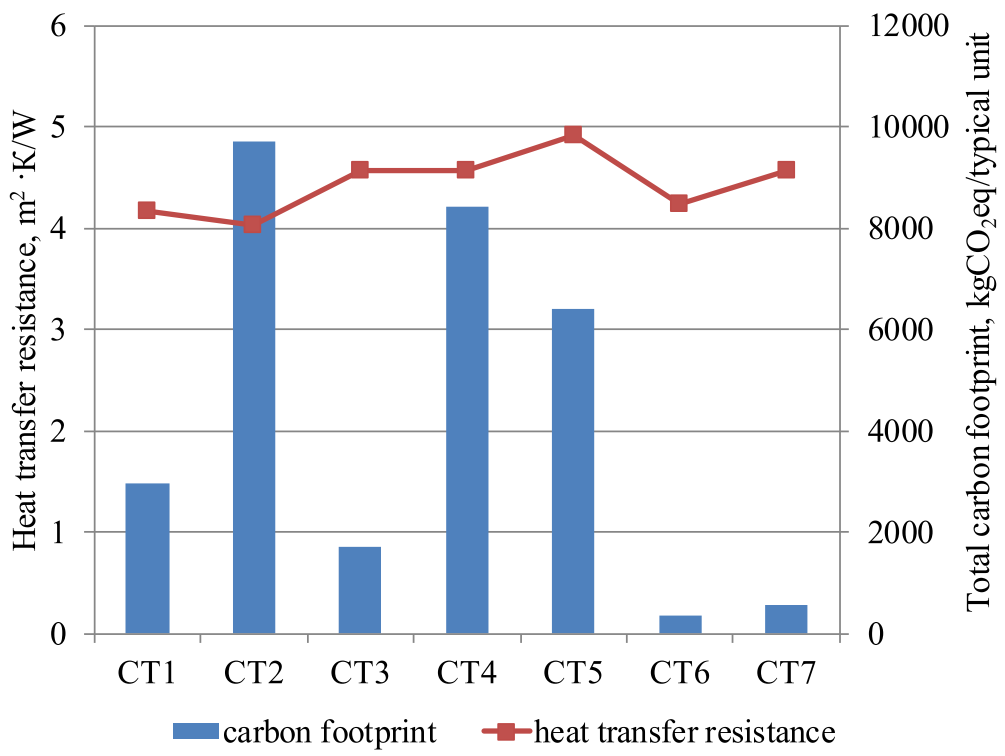


Fig. 4.4 - Comparative diagram of total carbon footprint considering the heat transfer resistance of wall structures

As can be seen from the obtained data, the wall structure ST5 with LGSF and mineral wool insulation is characterized by the highest emissions at the production stage of building materials, with Cbe=4605.23 kg CO_2-eq. At the same time, for other types, this value is an order of magnitude lower – for brick walls, 345.23 and 365.93 kg CO_2-eq, and for aerated concrete block walls, 177.91 and 204.15 kg CO_2-eq.

At the stage of transporting building materials, the highest emissions are associated with both variants of walls with ceramic brick cladding – Cbt=9328.67 kg CO_2-eq for wall ST2 made of ceramic brick and Cbt=8192.43 kg CO_2-eq for wall ST4 made of aerated concrete block. Emissions for wall ST1, amounting to Cbt=2577.92 kg CO_2-eq, and ST3, which equals Cbt=1516.40 kg CO_2-eq, are also significant.

Regarding the stages of construction and installation works and the transportation of construction waste, for all wall options, the emissions are not significant and range within Cbp=1.03..9.78 kg CO_2-eq and Cd2=0.51..14.95 kg CO_2-eq. The exception is the ST5 variant with LGSF, which is characterized by emissions of Cbp=883.25 kg CO_2-eq and Cd2=299.73 kg CO_2-eq.

The highest carbon dioxide emissions from waste storage in landfills are generated by structures ST7, ST5, and ST1, which have insulation made of extruded polystyrene - Cd3=112.49 kg CO_2-eq; 87.34 kg CO_2-eq and 50.59 kg CO_2-eq, respectively.

The minimum emission values at all stages are found in walls in the form of wooden frame-panel walls.

All considered wall variants have recycling potential. For example, ceramic bricks after disassembly can be sorted and used in their whole form in new building structures or processed into secondary aggregate. A disadvantage of aerated concrete blocks is that they cannot be reused in the form of building blocks like traditional clay bricks; however, with appropriate crushing, they can replace fine aggregate (sand) in concrete production. Wood from building structures can serve as fuel for heating in solid fuel boilers in the form of pellets or be processed into chips for creating new engineered wood products. According to modern recycling technologies, extruded polystyrene is used to produce new insulation, packaging materials, or fuel briquettes. Mineral wool waste can be used in various manufacturing sectors (ceramics, filler for composite materials based on wood, cement industry, etc.), as well as a raw material for the reproduction of the same insulation. Overall, the recycling potential contributes to the reduction of total emissions, which is why it has a negative value in the results.

The final carbon footprint value is the largest for walls with ceramic brick cladding, amounting to 9704.63 kg CO_2-eq for brick wall ST2 and 8411.91 kg CO_2-eq for aerated concrete wall ST4. At the same time, the brick wall ST2 with cladding also has the lowest thermal resistance value among all the considered options ($R = 4.03$ $m^2 \cdot K/W$). The minimum carbon footprint of 365.70 kg CO_2-eq, with an optimal corresponding thermal resistance value of $R = 4.23$ $m^2 \cdot K/W$, belongs to wall ST6—a frame-panel wall with a wooden frame and an internal layer of mineral wool insulation.

CHAPTER 5. BIM-INTEGRATED BUILDING LIFE CYCLE ASSESSMENT

5.1. Automating Life Cycle Assessment Using the OneClickLCA Web Platform

As noted in previous chapters, Life Cycle Assessment (LCA) is a standardized methodology for quantifying the environmental impact of a building or construction product across all stages of its existence. This includes:

- Material Production (stages A1-A3): Raw material extraction, transportation, and manufacturing.
- Construction (stages A4-A5): Transportation to the site, installation.
- Use (stages B1-B7): Energy efficiency, maintenance, replacements.
- End of Life (stages C1-C4): Demolition, transportation, disposal, recycling.
- Beyond the System (stage D): Potential benefits from reuse and recycling.

The result of an LCA is a series of environmental indicators, including Global Warming Potential (GWP, also known as "carbon footprint"), Acidification Potential, Eutrophication Potential, and others.

Traditionally, conducting LCA manually was an extremely labor-intensive process, requiring:

- Manual data collection from hundreds of invoices and specifications.
- Searching for relevant databases with environmental profiles of materials.
- Complex inventory processes for all materials, components, and processes.
- Constant updating of knowledge regarding changes in production technologies, etc.

Such challenges slowed down the process and limited its application. The solution to the above problems is the implementation of automated software with the ability to import data from BIM models, such as OneClickLCA.

OneClickLCA is a leading platform for digital environmental certification of buildings and products, automating and significantly speeding up the process of environmental life cycle assessment. It integrates databases, global standards, and data import tools, making complex calculations accessible to engineers, architects, and consultants.

The platform offers a comprehensive set of tools, organized around several key functions:

1. Databases and Calculation Methodologies

OneClickLCA contains pre-loaded data from over 60,000 types of materials and products from authoritative sources (e.g., EPD, ICE, GaBi, ELCD). The platform supports most global standards and is regularly updated to meet the requirements of certification systems, including LEED, BREEAM, DGNB, as well as national regulations. Regional settings are available to the user (selecting a country to account for transport flows, regional energy profile, etc.).

2. Data Import Tools

The most powerful feature of OneClickLCA is the ability to import BIM models (Revit, IFC) directly. The software automatically recognizes elements, matches them with materials from its database, and creates a basis for calculation. Files containing lists of materials and their quantities, such as those from estimates (in Excel or CSV format), can also be imported as source data. The platform has an intelligent assistant that helps match material names with the database. Data can also be entered manually.

3. Calculation and Analysis

After importing or entering data, the platform automatically calculates all environmental indicators for each life cycle stage. The results are presented in the form of charts and graphs, showing the contribution of different material categories (such as reinforced concrete, steel, and brick) to the overall impact.

The user can create different scenarios (e.g., "as designed" and "alternative") to compare the impact of other materials or design solutions in the early stages of design. This makes LCA a tool for justifying and making design decisions.

4. Reporting and Certification

The platform automatically generates detailed reports required for submission for building standard certification. Reports include all necessary data, track changes, and ensure compliance with criteria. Results can be exported in various formats (PDF, Excel, etc.) for further analysis or submission to the client.

Key benefits of using OneClickLCA:

- Reduction in time required to conduct life cycle assessment.
- Minimization of errors in calculations and data matching.
- Lower cost of conducting life cycle assessment.
- Optimization of the project's environmental performance.
- Possibility of collaborative work on the project in the cloud service.

OneClickLCA not only simplifies the life cycle assessment process, but it also streamlines it. Automated tools transform the assessment from an expensive, exclusive, and retrospective analysis into an accessible, strategic tool for proactive design. Thanks to integration with BIM and powerful analysis tools, the use of automated software, such as OneClickLCA, becomes an indispensable assistant for the construction industry on its path to decarbonization.

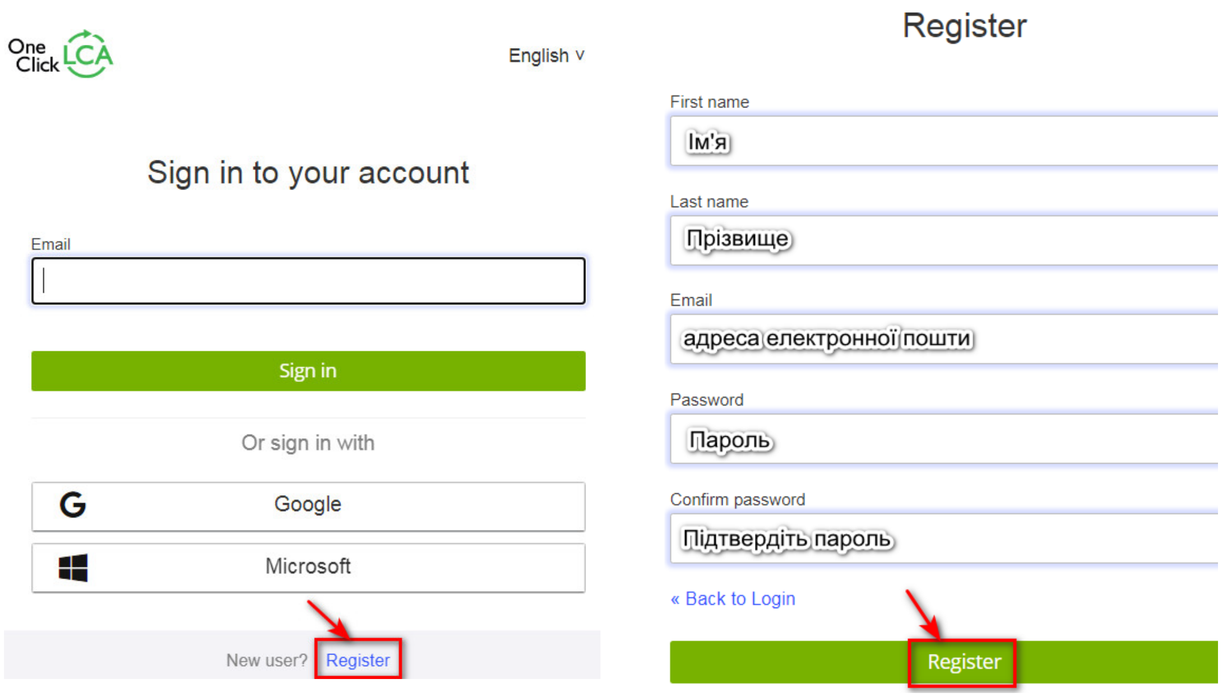
5.2. OneClickLCA Web Platform Interface and Project Preliminary Setup

Work with One Click LCA begins by logging into the platform via the link: oneclicklcaapp.com.

On the start page (Fig. 5.1, a), it is necessary to proceed with registration. In the new window, you should fill in the user data and click **Register** (Fig. 5.1, b). After logging in, the user lands on the **Home Page**, where we can access the tabs of the web service (Fig. 5.2):

- **Projects** - During the first login, a series of demonstration projects (Public Demo) available for viewing will be displayed. Once you start adding your own projects, they will appear in the "Your Projects" tab.
- **Licenses** - Contains available subscriptions and allows adding licenses.
- **Help** - Provides access to the user help center, service update log, database, training, etc.

User -- Provides access to the personal account.



a b

Fig. 5.1 - OneClickLCA Start page (a) and Registration page (b)

To start creating a building life cycle assessment project, click the **+Add** button in the upper right part of the screen and select **Building** (Fig. 5.3).

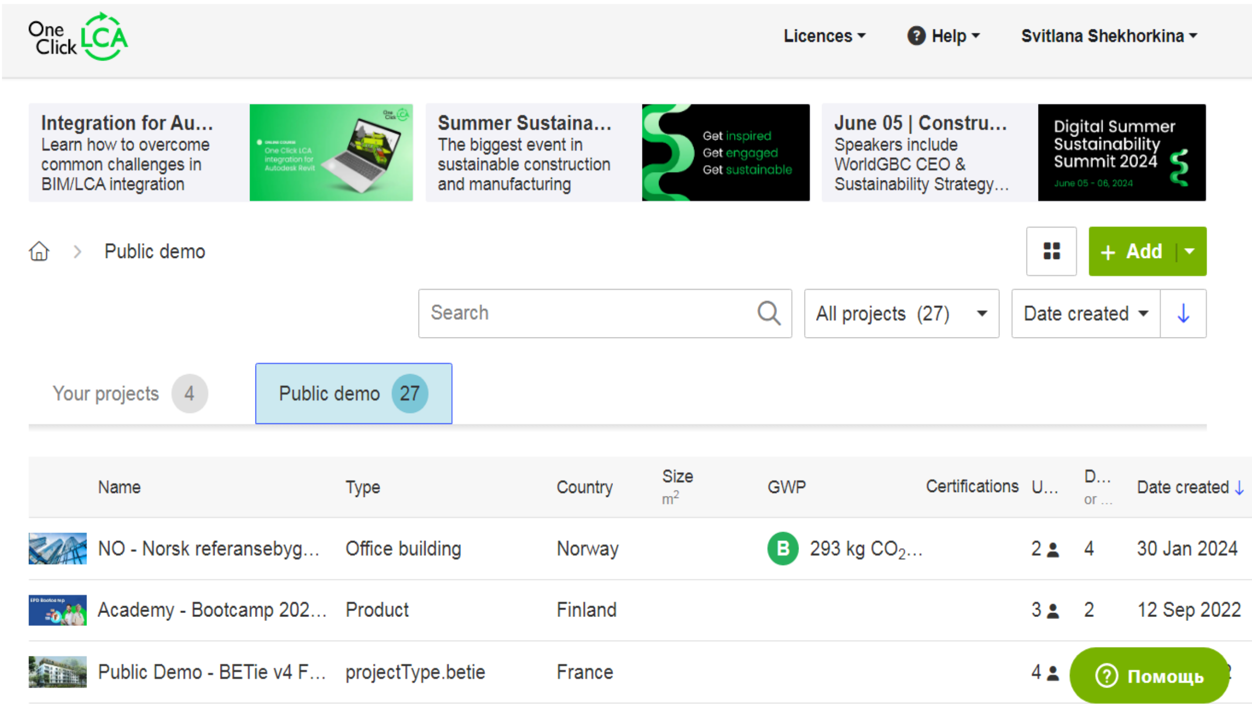


Fig. 5.2 - OneClickLCA Web Service Home Page

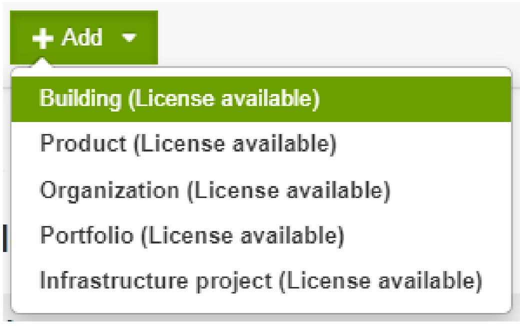


Fig. 5.3 - Creating a Project

After this, a pop-up window appears (Fig. 5.4), in which in the **Basic information** tab you should enter:

– License - click **Enter license key** and apply the provided license key.

– Your project name in the **Name** field, for example, "My First Project";

– Building type in the **Type** field -- select from the drop-down list, for example, Apartment building;

– The country where construction is planned in the **Country** field. This will not affect the results but will improve data search in the software by prioritizing data points for the given region.

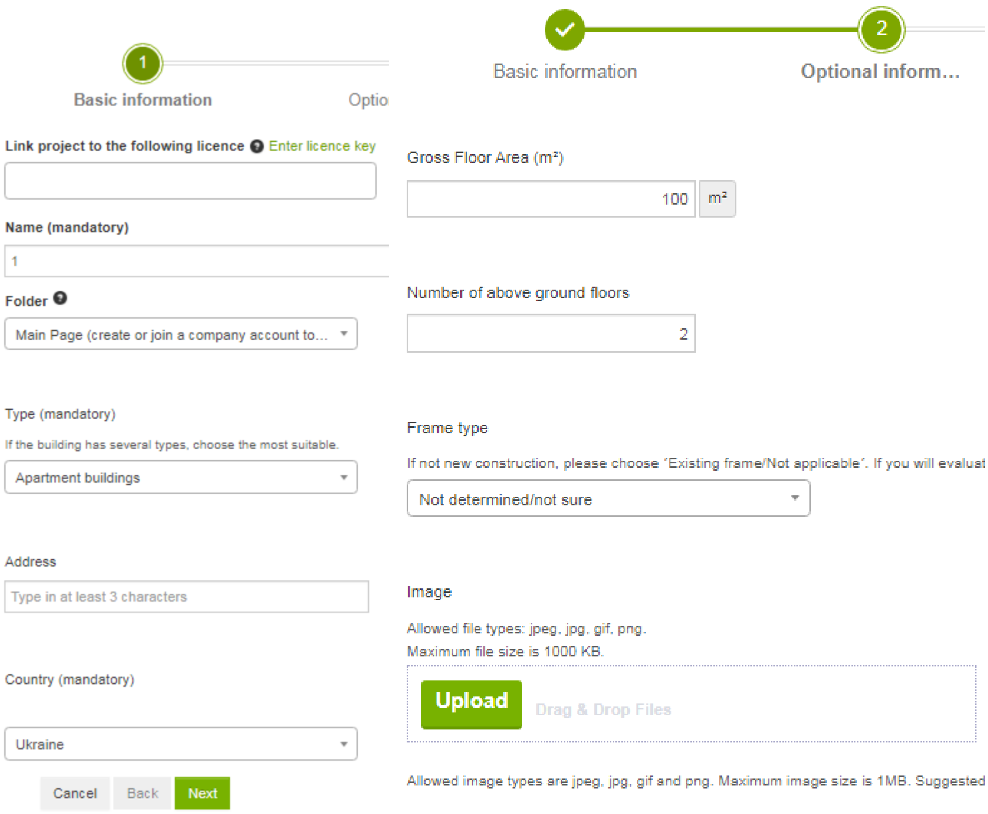


Fig. 5.4 - Window for Filling in Information about the Created Project

Then, in the **Optional information** tab, you can add data regarding the building's gross floor area (**Gross floor area** field), the number of above-ground floors (**Number of above ground floors** field), and the frame type (**Frame type** field). There is also an option to add an image for the project (**Image** field).

After clicking the **Next** button, you are redirected to the project homepage **Project homepage** (Fig. 5.5), which contains the tabs:

- **Information** - View license and other project information;
- **Requests** - Project information requests;
- **Attachments** - Attaching additional files;
- **Notes** -- Creating text notes.

To start working on the project, click the **Get Started** button.

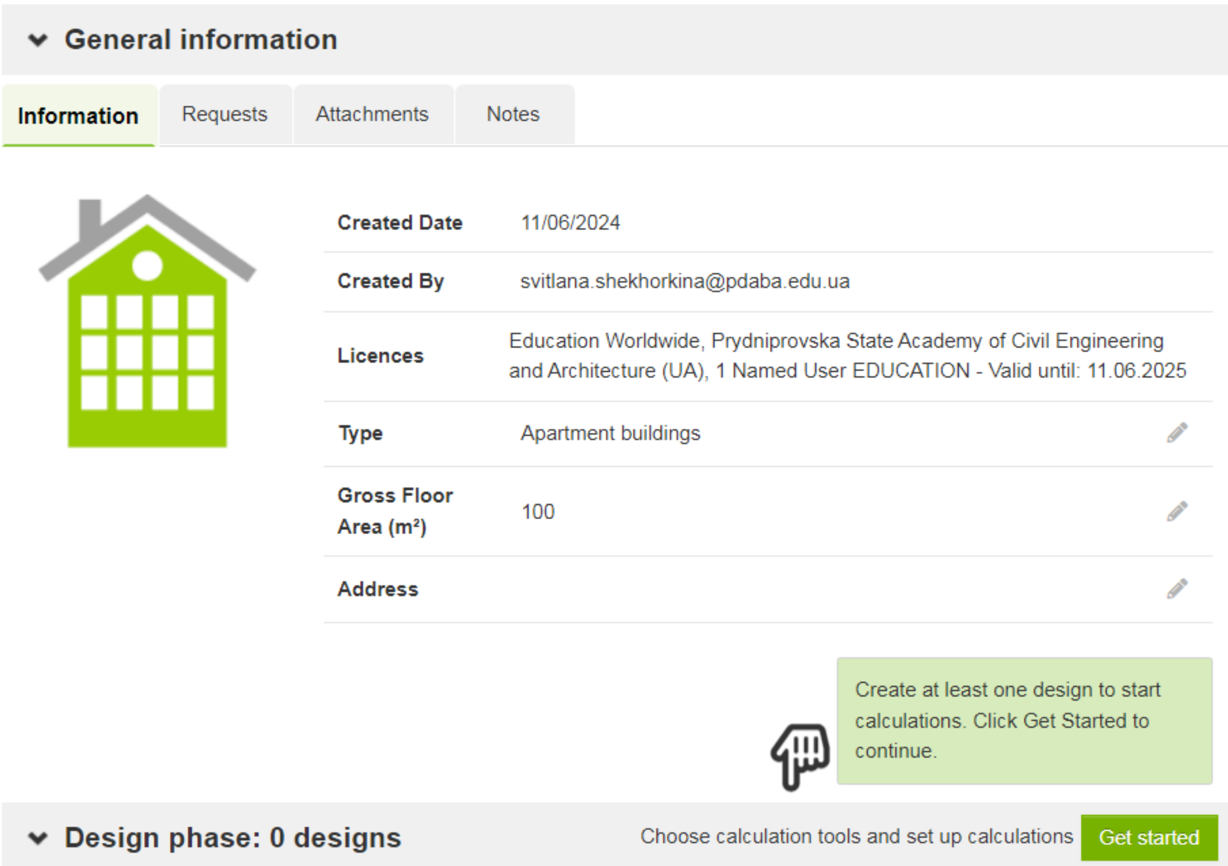


Fig. 5.5 - General View of the Project Homepage

In the new window (Fig. 5.6), you need to enter the name (**Name** field) and provide additional information about the construction stage (**Stage of construction process** field), project type and volume (**Project type** field), and the structural parts of the building to be included in the analysis (**Included parts** field). Then click **Next**. In the new window (Fig. 5.7), select all available assessment tools and click **Next** again.

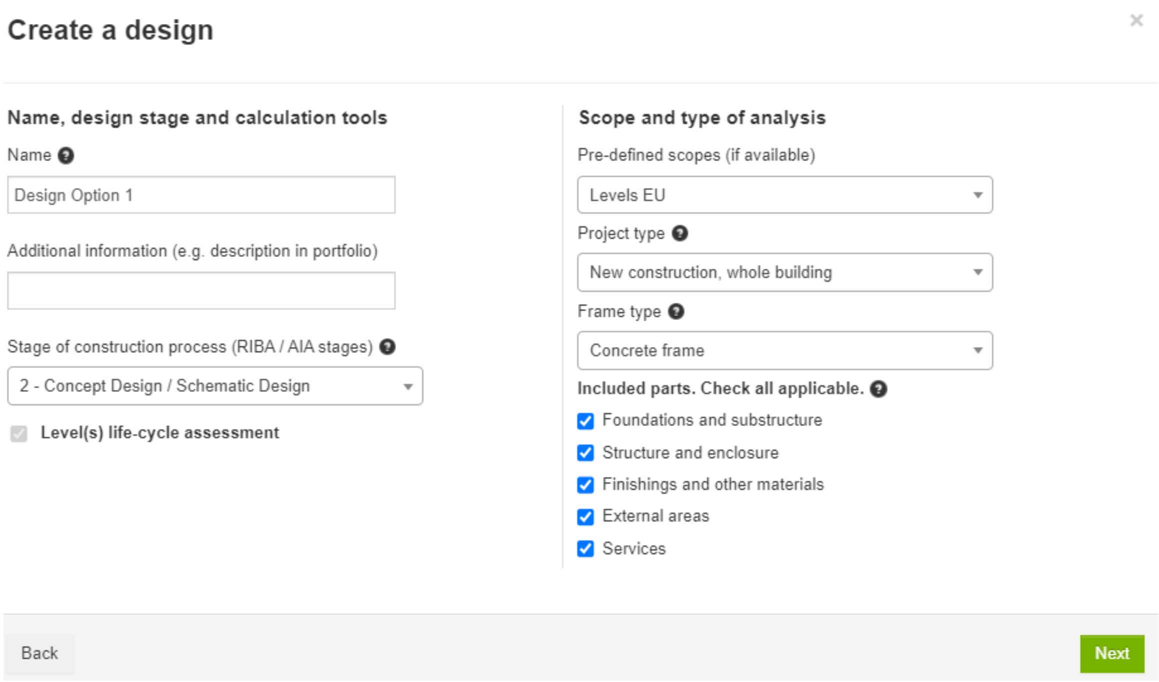


Fig. 5.6 - Project Settings Window

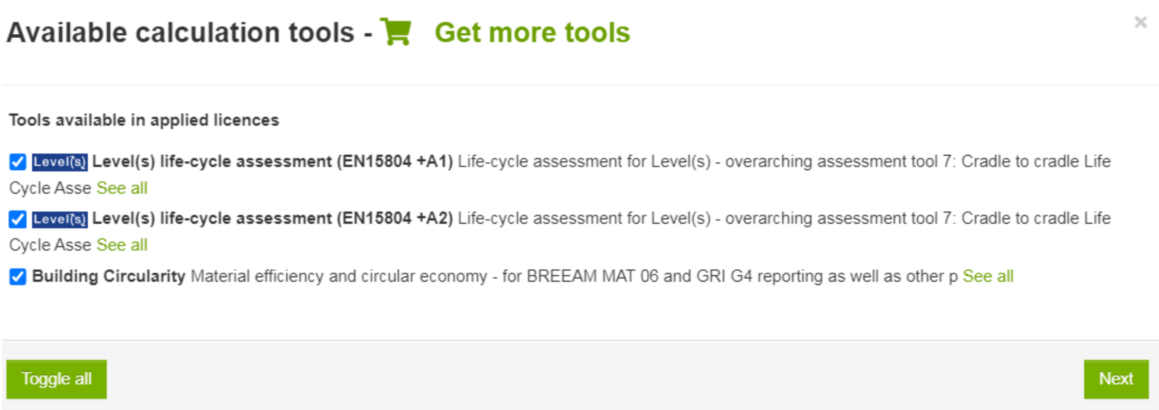


Fig. 5.7 - Assessment Tools Selection Window

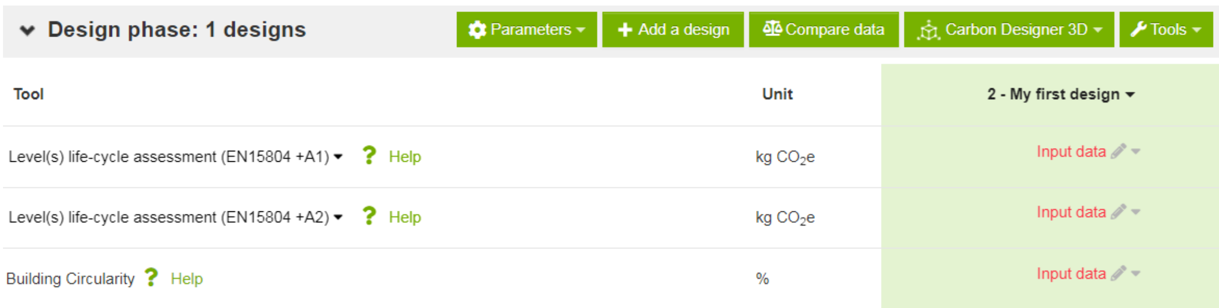


Fig. 5.8 - Project Work Window

After completing all preliminary settings, the project work window opens (Fig. 6.8). To start entering data for analysis, click the **Input data** button for the first **Tool**. Data will be automatically transferred to other tools.

5.3. Entering Data for Life Cycle Analysis on the OneClickLCA Web Platform

After clicking the **Input data** button, the user proceeds to the data entry tabs for analysis.

The first is the **Building materials** tab (Fig. 6.9), where, for the structural element categories selected during setup, you need to select the materials for their manufacture in the corresponding tabs and enter their quantities.

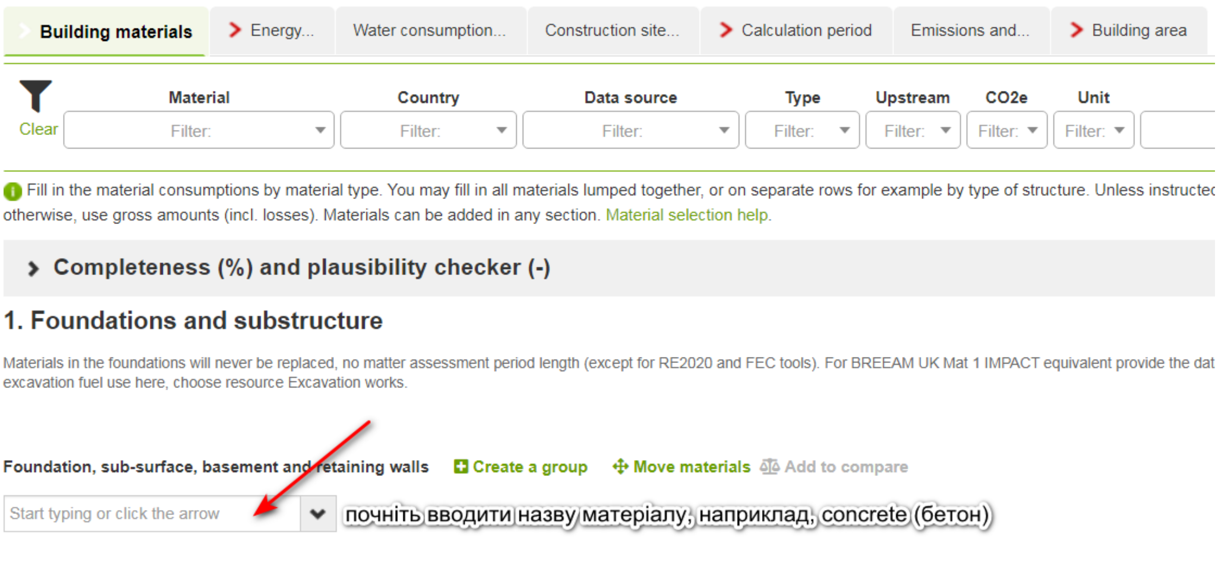


Fig. 5.9 - **Building materials** Tab

By default, the following categories of structural elements are provided:

1. **Foundations and substructure**
2. **Vertical structures and facade**

2.1. External walls and façade

2.2. Columns and load-bearing vertical structures

2.3. Internal walls and non-bearing structures

3. Horizontal structures: beams, floors and roofs

4. Other structures and materials

4.1. **Stairs, terraces**

4.2. **Windows and doors**

4.3. **Finishes and coverings**

a) External areas and site elements -- sidewalks, paving, etc.

b) Building technology -- plumbing, electrical, automation, etc.

For example, for foundation construction, it is planned to use concrete class C20/25 in the amount of 26.4 m^3. The sequence of entering data about this material is shown in Fig. 5.10. Data entry for all subsequent tabs is performed similarly.

In the next tab, **Energy consumption**, data on annual energy and fuel consumption for domestic needs, heating, and cooling of premises is entered (Fig. 5.11). The following fields are provided:

1. **Electricity consumption**

The estimated electricity consumption rate is 100 kWh per family with one person. For each additional family member, an additional 30 kWh per month is given, but not more than 220 kWh in total.

2. **Fuels demand, stationary units**

The estimated gas consumption rate is 3.3 m^3 per person per month if there is a gas stove and centralized hot water supply. If natural gas is used for individual heating -- 5 m^3 of natural gas per 1 m^2 of heated area per month during the heating season.

Next, in the **Water consumption, annual** tab, data on annual water consumption for domestic and technical needs is filled in (Fig. 5.12). Two values need to be entered:

1. **Tap water**
2. **Wastewater from residence**.

Estimated water consumption per person per month is:

6.3 m^3/month -- in houses with sewerage and a bathroom with shower, without centralized hot water supply (with gas/electric water heater);

5.1 m^3/month -- in houses with autonomous sewerage (septic tank) and a bathroom with shower, without centralized hot water supply (with gas/electric water heater).

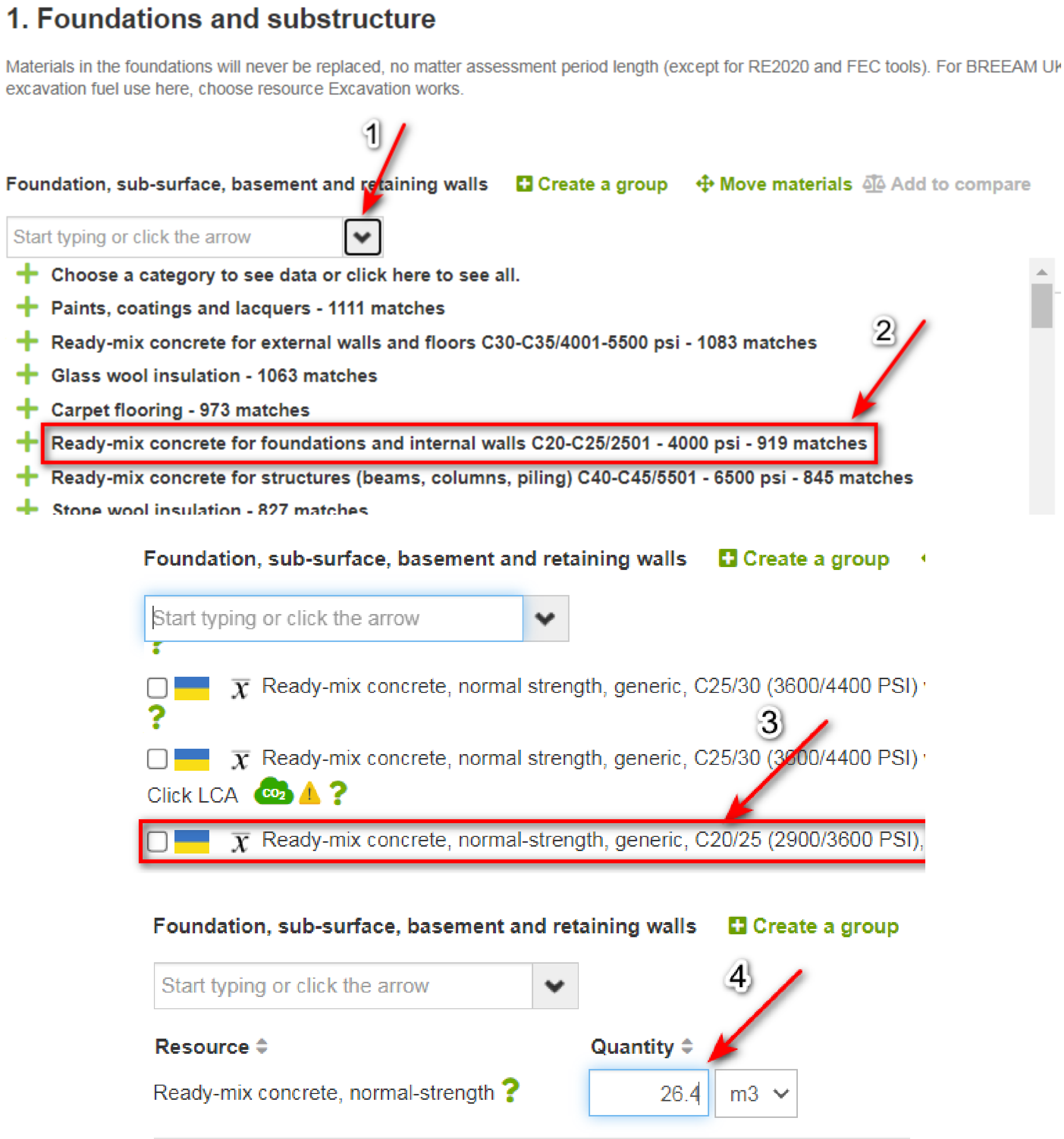


Fig. 5.10 - Sequence of Entering Data on Material Type and Quantity in the Building materials Tab

The **Construction site scenarios** tab allows obtaining data on emissions associated with electricity consumption, fuel consumption, and waste production during construction and installation work for erection at the beginning of the life cycle, as well as during demolition at the end of the building's life cycle. If the user does not have detailed information about these processes, the web service uses industry-average data for the corresponding region, related to 1 m² of building area. In view of this, in this tab, you should enter the value of the building's total area in the corresponding field (Fig. 5.13).

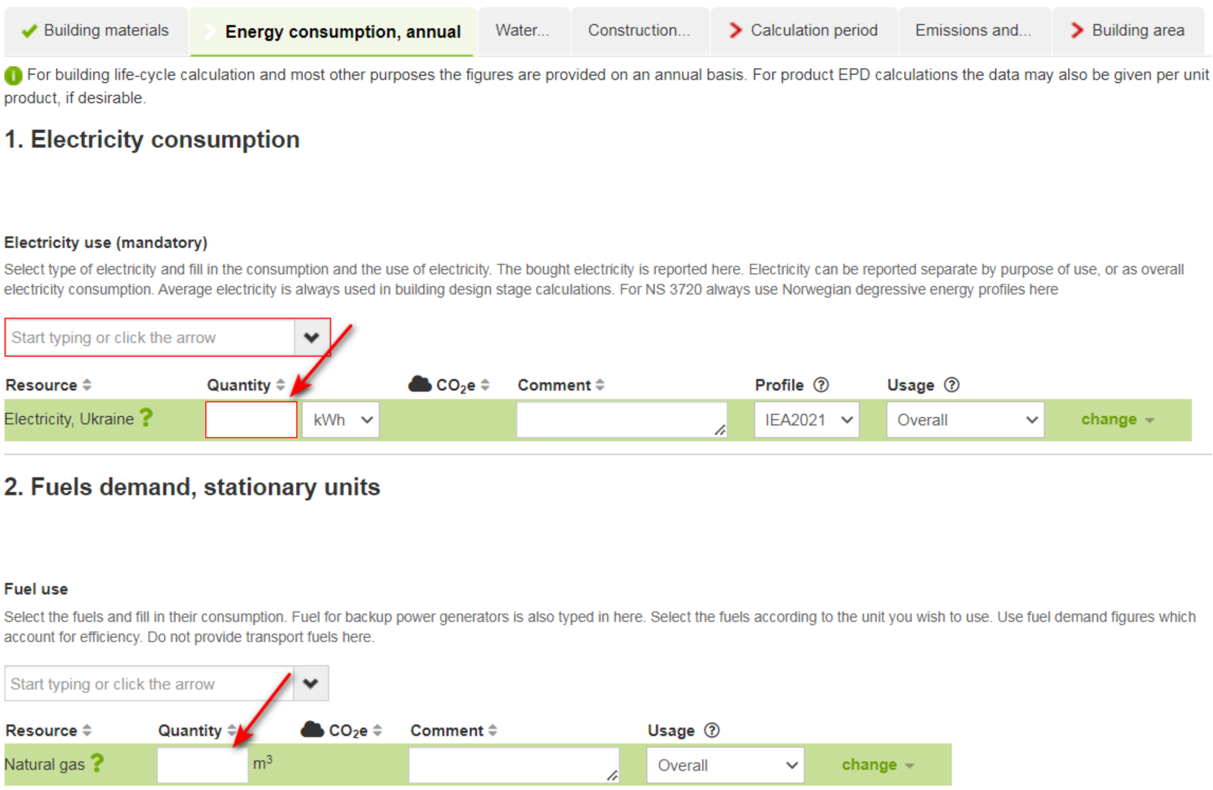


Fig. 5.11 - Energy consumption Tab

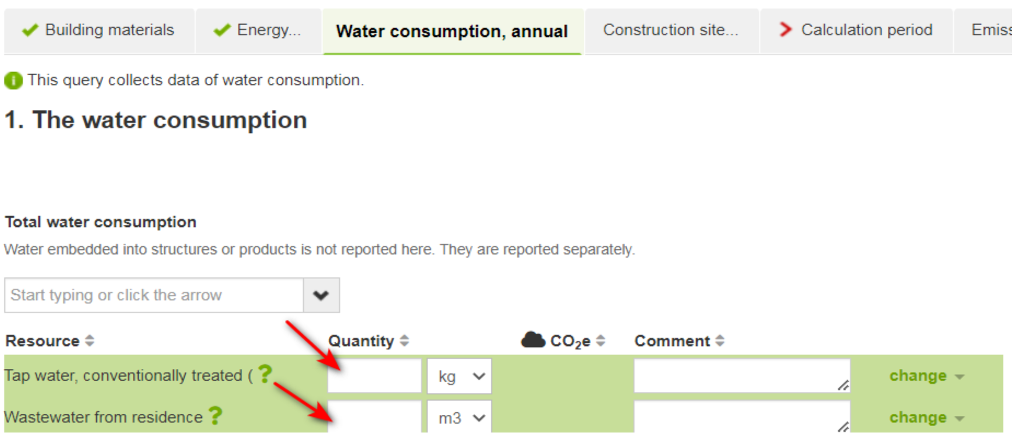


Fig. 5.12 - Water consumption, annual Tab

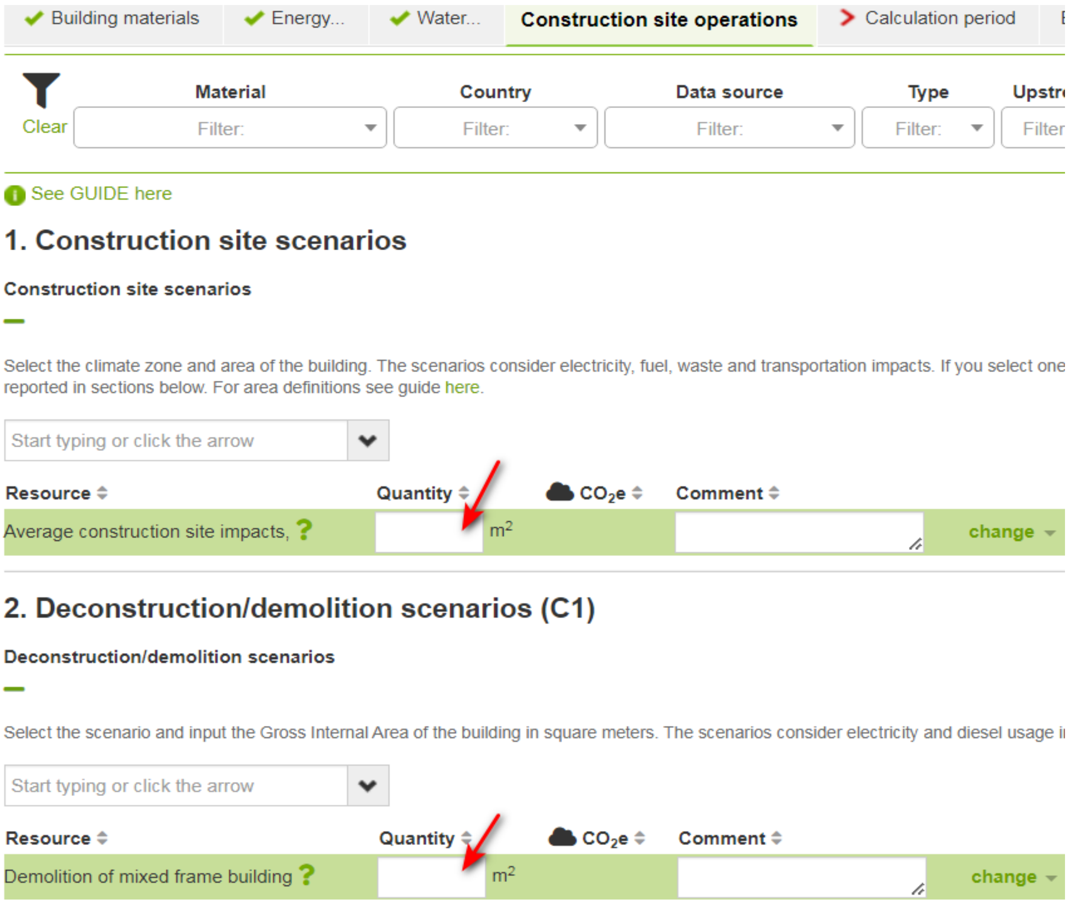


Fig. 5.13 - Construction site scenarios Tab

The last tab, Calculation period, involves entering the building's service life. The recommended value for residential buildings is a period from 50 to 100 years. The period is entered in the corresponding field of the tab (Fig. 5.14).

After completing data entry, you need to click the Results button to start the calculation and proceed to the analysis results (Fig. 5.15).

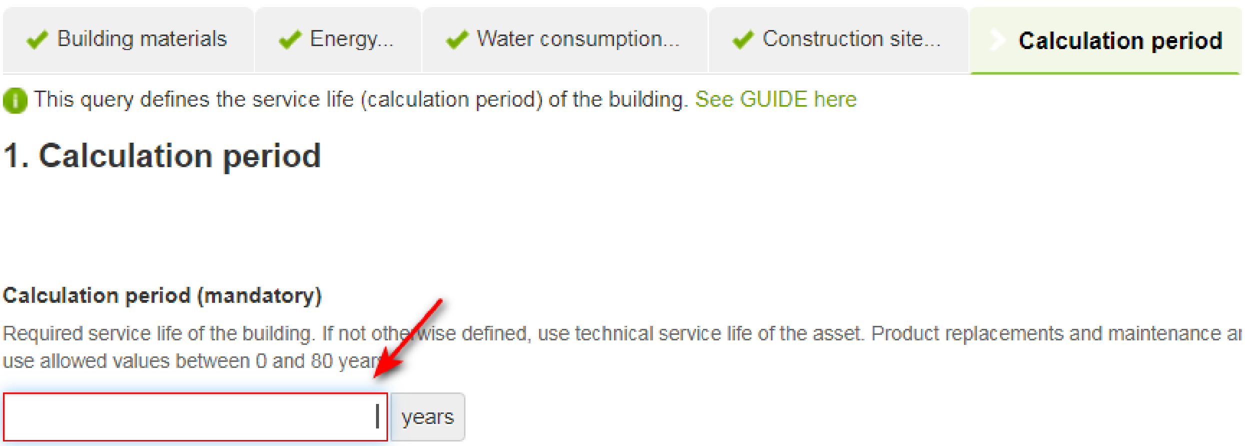


Fig. 5.14 - Calculation period Tab)

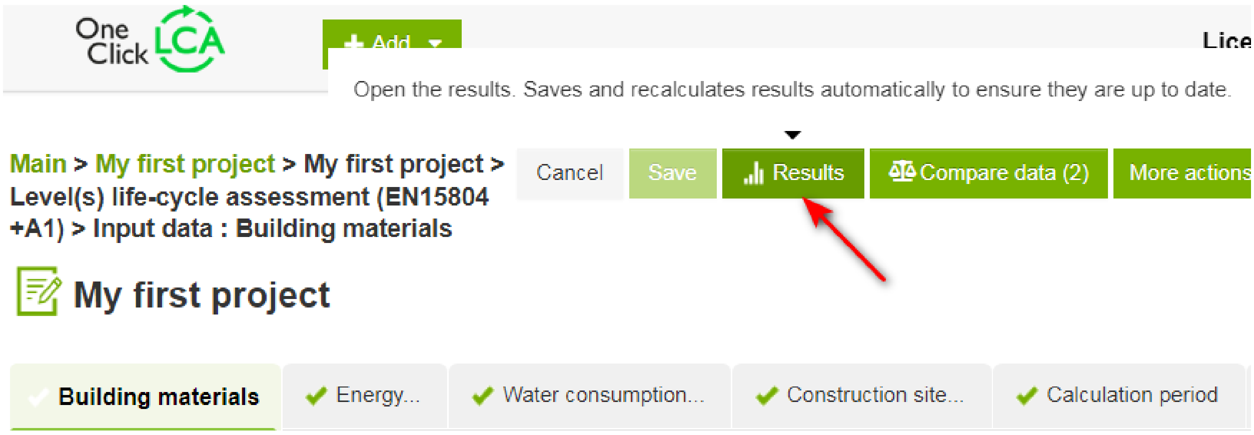


Fig. 5.15 - Starting the Calculation

5.4. Viewing Life Cycle Analysis Results on the OneClickLCA Web Platform

On the results viewing page (Fig. 5.16), a number of tabs are available to assess the building from the point of view of its environmental impact.

The **Carbon Heroes Benchmark** tab displays a scale with 7 classes for carbon dioxide emissions (from the worst G to the best A) with an indication of the class corresponding to the building (Fig. 5.17).

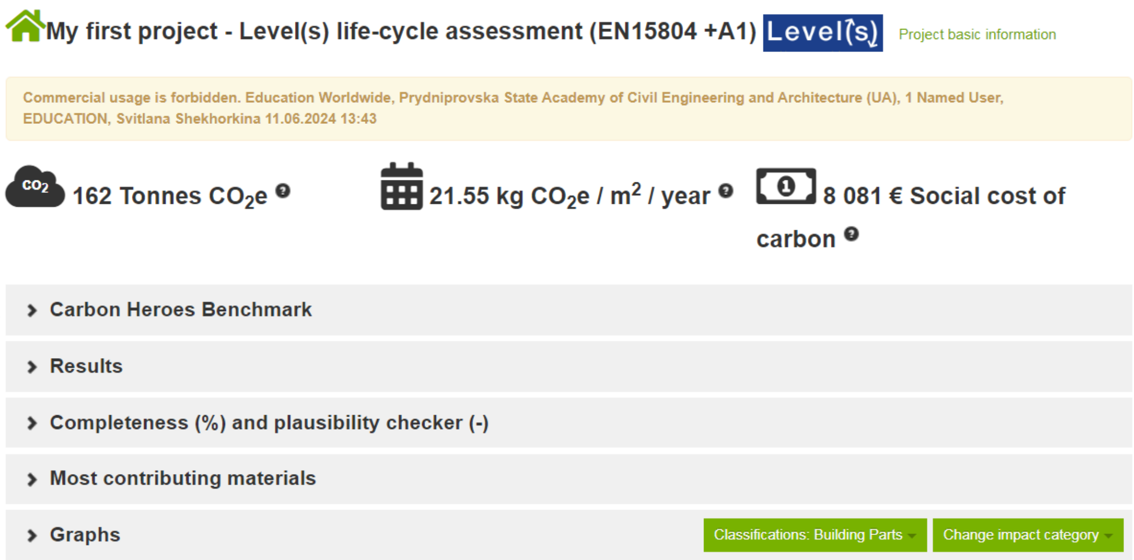


Fig. 5.16 - General View of the Results Page

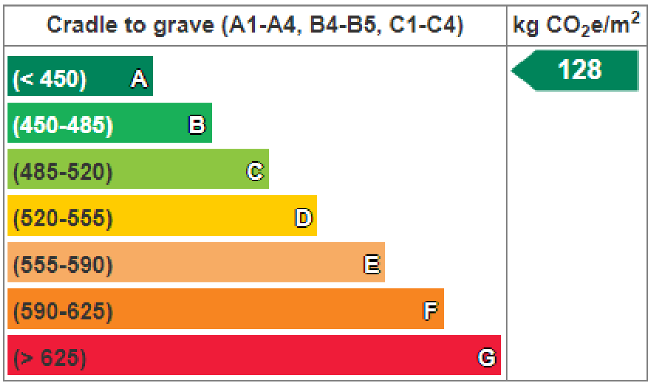


Fig. 5.17 - **Carbon Heroes Benchmark** Scale

The **Results** tab contains detailed results of the calculation of emission quantities for different impact categories (Fig. 5.18):

- **Global warming**
- **Biogenic carbon storage**
- **Ozone Depletion**
- **Acidification**
- **Eutrophication**
- **Formation of ozone of lower atmosphere**
- **Abiotic depletion potential for non-fossil resources**
- **Abiotic depletion potential for fossil resources**

From this tab, you can download the obtained data to an Excel file by clicking the **Download Results Summary** button.

The **Completeness and plausibility checker** tab provides information on how complete the obtained results are based on the entered input data. The software provides recommendations on desirable additions to the source data to obtain more reliable data. Program warnings do not mean that the current results are incorrect.

The **Most Contributing Materials** tab displays a list of materials characterized by the highest global warming potential. The program also offers to view more environmentally friendly alternatives; to do this, click the Show sustainable alternatives button (Fig. 5.19).

Results

Life-Cycle Assessment for Level(s) in compliancy with EN 15978 Download Results Summary

	Result category	Global warming kg CO2e	Biogenic carbon storage kg CO2e bio	Ozone Depletion kg CFC11e	Acidification kg SO2e	Eutrophication kg PO4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
A1-A3	Construction Materials	1,63E+04	0,00E+00	7,42E-04	4,58E+01	2,04E+01	1,89E+00	1,46E+00	1,50E+05
A4	Transportation to site	1,68E+03		2,84E-04	2,46E+00	5,03E-01	2,53E-01	2,13E-04	2,22E+04
A5	Construction/installation process	3,80E+03		2,37E-04	1,96E+01	4,97E+00	7,77E-01	2,46E-01	5,15E+04
B1	Use phase								
B3	Repair	0,00E+00		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
B4-B5	Material replacement and refurbishment								
B6	Energy consumption	1,37E+05		4,57E-03	8,19E+02	2,77E+02	4,19E+01	7,20E-01	1,65E+06
B7	Water use	7,07E+02		6,68E-05	5,80E+00	2,35E+01	2,34E-01	3,52E-03	5,85E+03
C1-C4	End of life	2,00E+03		3,35E-04	8,75E+00	2,15E+00	3,50E-01	4,58E+00	3,71E+04
D	External impacts (not included in totals)	-1,57E+04		-1,75E-04	-9,04E+01	-2,21E+01	-3,02E+00	2,83E-02	-4,04E+05
	Total	**1,62E+05**	**0,00E+00**	**6,24E-03**	**9,02E+02**	**3,28E+02**	**4,54E+01**	**7,01E+00**	**1,92E+06**

Fig. 5.18 - **Results** Tab

Most contributing materials (Global warming)

No.	Resource	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)	Sustainable alternatives
1.	Reinforcement steel (rebar), generic, 0% recycled content (only virgin materials), A615	33 tonnes CO_2e	47.9 %	Show sustainable alternatives
2.	Ready-mix concrete, normal-strength, generic, C20/25 (2900/3600 PSI), 0% recycled binders in cement (240 kg/m3 / 14.98 lbs/ft3)	25 tonnes CO_2e	35.9 %	Show sustainable alternatives
3.	Perforated clay blocks, for walls, 910 kg/m3	11 tonnes CO_2e	16.2 %	Show sustainable alternatives

Fig. 5.19 - **Most Contributing Materials** Tab

The **Graphs** tab allows you to view and download the obtained results in the form of various types of charts (pie, bar, line, and tree diagrams). The charts are interactive, so hovering the cursor over them shows the associated numbers. Clicking on a data series in the chart legend temporarily removes it from view. Downloading charts in several formats is also available.

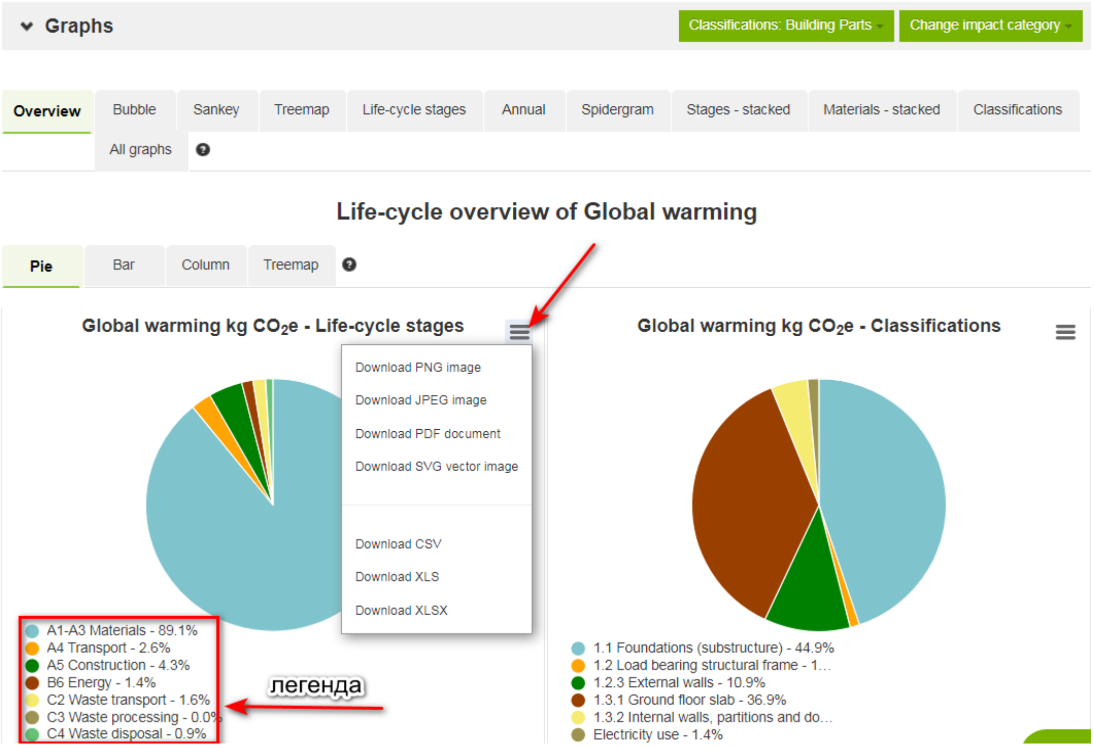


Fig. 5.20 - **Graphs** Tab

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LECTURE NOTES

Editors: M. Savytskyi, S. Shekhorkina, M. Bordun

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