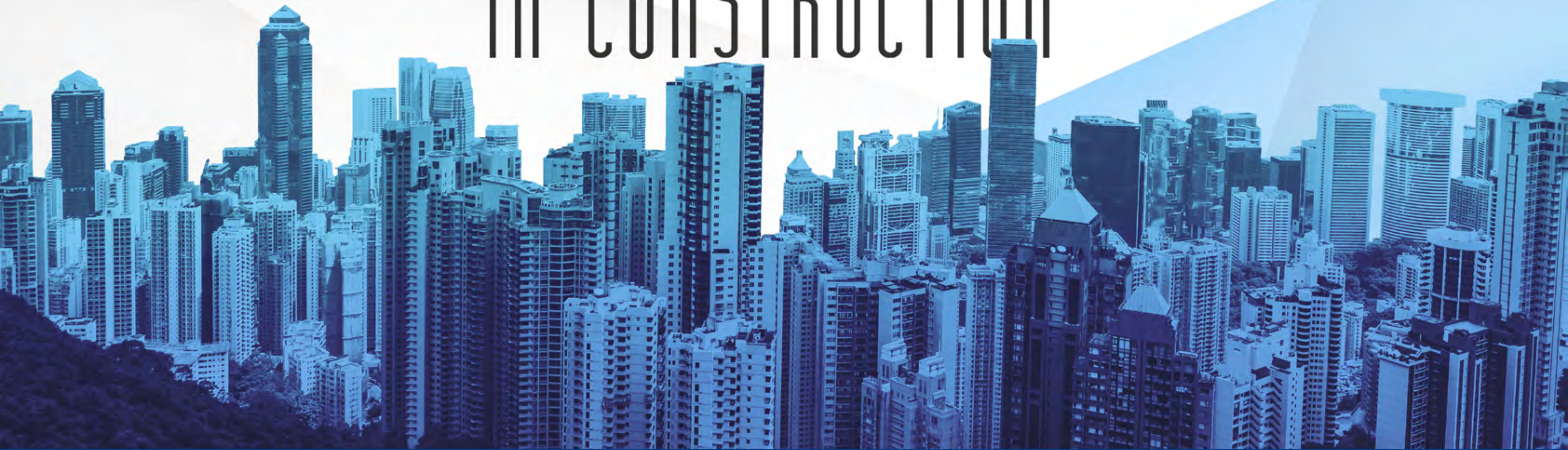
A GUIDE TO CIRCULARITY IN CONSTRUCTION



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A guide to circularity in construction

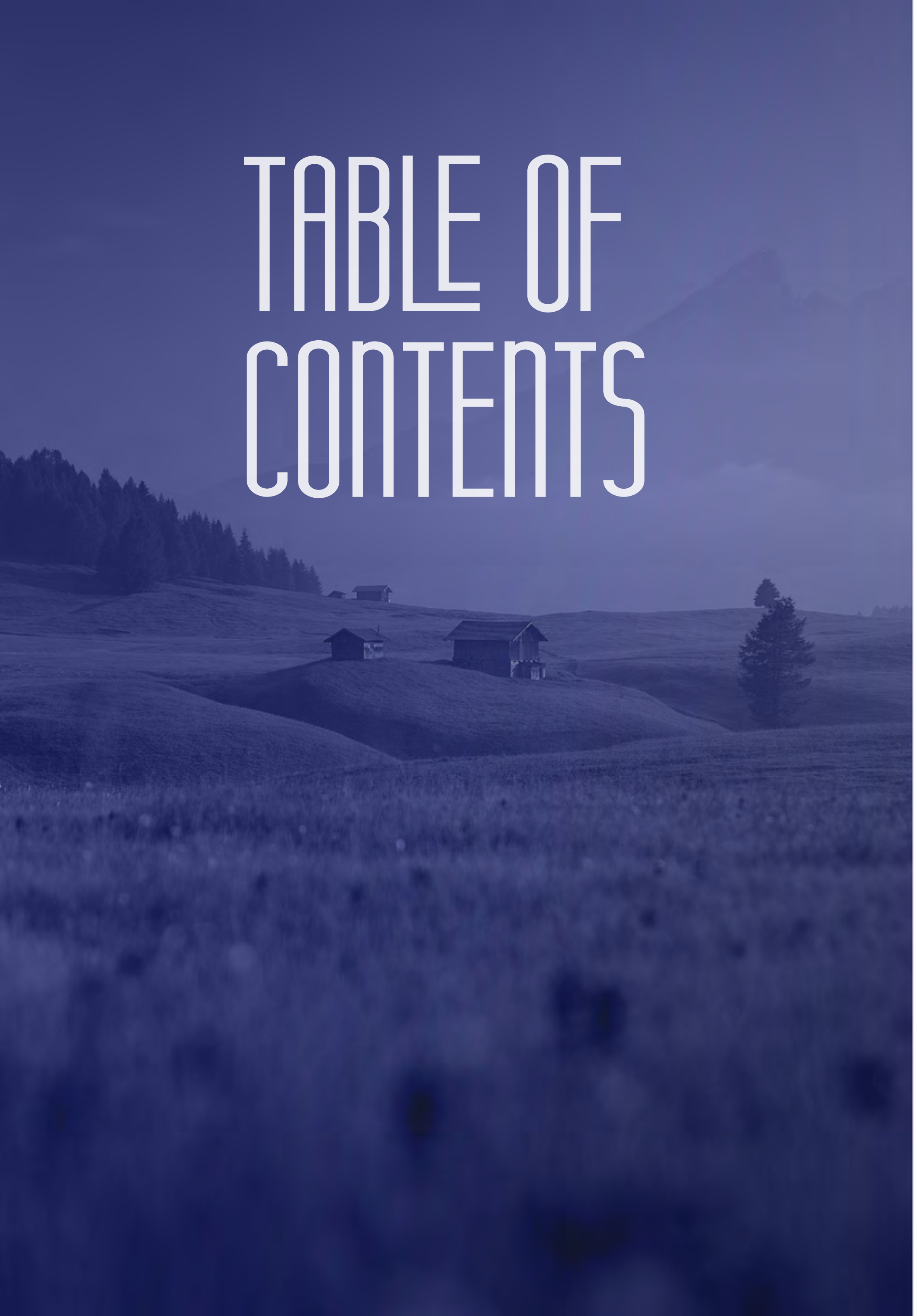
The United Nations estimates that the global populace reached a staggering 8 billion individuals by 2022, and it's predicted to surpass 9 billion individuals within the next 15 years. It's a big challenge for us and for the environment to meet all the needs of such a large population. The dominant linear economic paradigm has negative environmental consequences, primarily resulting from the growing demand for natural resources and the diminishing value of manufactured goods and the raw materials they comprise. The absence of a solid plan for natural resource management could lead to the exhaustion of readily available raw materials. Hence, it is imperative to curb the excessive utilization of our planet's resources, particularly in the context of the construction industry, whose waste constitutes one of the largest waste streams in the European Union. The solution is urgently implementing an alternative model, such as the circular economy. The construction industry has a chance to take innovative steps to reduce the amount of raw materials used and waste generated by returning them to economic processes. Implementing the principles of the circular economy in construction requires the involvement of all key stakeholders, from designers, building material manufacturers, and construction companies to investors, construction developers, and users. To achieve a successful outcome, construction project teams should collaborate to implement specific strategies that minimize the consumption of increasingly scarce raw materials while utilizing existing materials already in use.

Recognizing the significant obstacle to implementing the circular economy (CE) in construction, the Polish Green Building Council, in collaboration with Green Building Council Iceland and the Silesian University of Technology, embarked on the CIRCON Project: The circular economy in construction: eco-design of circular buildings. The main objective of the project activities is to educate all stakeholders in the building sector about the principles of circular building design. This project has produced practical guidelines for implementing a circular design approach and circularity indicators in which the specificities of the Polish and Icelandic building sectors were considered. The proposed indicators will provide designers and other actors in the building sector with tools to measure and assess the level of building circularity achieved. It is essential to monitor progress towards more efficient material management and continuous improvement of sustainable construction.

A guide to circularity in construction was developed as part of implementing the CIRCON project.

The CIRCON project, titled „CIRCON - The circular economy in construction: eco-design of circular buildings", benefited from a € 361,422 grant from Iceland, Liechtenstein, and Norway through the EEA and Norway Grants and co-funding by the national funding of Poland. Co-funding from the Polish state amounts to € 54,213.

"Working together for a green Europe"



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INTRODUCTION

NEED AND MOTIVATION FOR CE IMPLEMENTATION

According to the UN estimates, the number of people in the world has exceeded 8 billion, meaning there are 3 times more of us than in the 1950s, and forecasts predict that the population will reach 10 billion no later than 2060. Providing adequate living conditions for such a vast population is a challenge. The broader economy is a system of meeting the population's diverse needs expressed by a sense of security and guaranteed access to food, clean air, medical care, and education; it is also a job and living space. The previous linear model of the economy, on which more than 90% of the industry is currently based, simply does not work. Today we already know that access to primary raw materials is limited, critical raw materials are running out, we don't manage the waste we generate, and we waste energy on disposal instead of implementing recycling or reuse measures. The aforementioned population growth and its increasing needs have led to a state where nature cannot keep up with its regeneration and renewal of resources.

The solution to this situation is the urgent implementation of an alternative model, such as the circular economy. Taking the alternative steps of minimizing the consumption of raw materials and the generation of waste and returning them to economic processes is an opportunity for the ecosystem. The concept of a circular economy, known to this day, emerged as early as the 1960s, evolving over the years to become a global economic model implemented in strategies and policies not only in Europe but worldwide.

The authors of the publication „Closed-loop economy in policy and research" [20] draw attention to the conditions of the Polish economy, which is characterized by high material intensity and very low eco-innovation compared to EU countries, thus emphasizing the need to define CE as an economic development strategy with appropriate legal and financial instruments and indicators to monitor both the progress of its implementation and reliance on the latest IT solutions. The aforementioned publication proposes the following definition:

A CIRCULAR ECONOMY IS A GLOBAL ECONOMIC DEVELOPMENT MODEL THAT PROMOTES ECO-INNOVATIVE SOLUTIONS AND MEETS THE FOLLOWING OBJECTIVES:

- the added value of raw materials/resources, materials, and products is maximized along the value chain, i.e., from the designer to the consumer
- the amount of waste generated is minimized, and the waste generated is managed under the waste hierarchy (waste prevention, preparation for reuse, recycling, other recovery, disposal).

It is worth noting that the rapid development of the global economy contributes primarily to the overuse of natural resources, whose reserves are being depleted. A perfect example of this is sand, which is essential for the development of almost all industries and plays a crucial role in the construction sector. It is estimated that about 40-50 billion tons of sand and gravel are consumed yearly, causing irreversible damage that leads to catastrophic ecosystem disruption, the disappearance of islands, and the flooding of riverbeds. In 2019, more than 100 billion tons of materials were used worldwide, of which nearly 40 billion tons were consumed by the residential sector. Construction is thus considered the most material-intensive sector of the economy. As natural resources are depleting, without attention to proper management of raw materials, material scarcity will become a challenge that future generations will face.

Overusing the Earth's resources also contributes to creating a significant amount of waste. According to Bigrentz, author of one report on the state of the global economy, the total amount of waste generated worldwide in 2018 was 145 million tons and is estimated to increase to 2.2 billion tons by 2025 [6]. In the European construction sector context, inert* construction and demolition waste accounted for 37.1% of all waste generated in 2020 [64], thereby becoming the largest waste stream in Europe. The challenge, therefore, is not only to reduce the amount of waste generated but also to manage it properly, emphasizing the preservation of its value as much as possible. Currently, in the EU, inert construction and demolition waste is mainly used as backfilling and landscaping material [12]. However, unfortunately, in many cases, it should be classified as downcycling, i.e., a significant reduction in the quality and functionality of the material concerning its original values [12].

A major cause of resource waste is basing the global economy on linear models that operate on a „take-make-dispose" basis. This approach assumes that raw materials are extracted, processed into products, consumed, and when they lose their usefulness or utility, they become waste, eventually landfilled [12].

DID YOU KNOW...

NO SAND

Demand for sand has been growing exponentially for the past few years, and its reserves are running out due to over-extraction. It is estimated that more than 70% of the world's sand reserves are already used up, and if current trends continue, the world will run out of sand by 2050. It should be noted here that not all sand can be used for construction purposes. A perfect example of this is the world's tallest building, the Burj Khalifa (Dubai), for the construction of which about 7 million tons of sand were imported from Australia at an estimated cost of $450 million. The sand was transported to Dubai by ship, resulting in a carbon footprint of 3,000 tons of CO_2.

* waste that do not undergo significant physical, chemical or biological transformations; are insoluble, do not react physically or chemically, do not cause environmental pollution or danger to human life or health, are not biodegradable and do not adversely affect the matter with which they come into contact; the overall content of pollutants in these wastes and their leachability, as well as the negative impact on the leachate environment, are insignificant, and in particular do not pose a threat to the quality of surface water, groundwater, soil and land [53].

Notwithstanding that, it should be noted that the linear economic model contributed to industry development because it was based on large quantities of easily and quickly available and cheap raw materials and energy. Without this, it would have been impossible to achieve humankind's rapid technological, infrastructural, and social development. However, the linear model must be replaced because raw material resources have been reduced to an extent that is impossible to ensure future production and supply continuity. Therefore, it is necessary to transform business models to improve the efficiency of raw materials management and take measures to reduce the excessive use of natural resources. To this end, a new model has been proposed, namely the circular economy, the main idea of which is to keep materials in circulation for as long as possible. This approach focuses on maximizing the potential of the raw material, extending the useful life of materials, or reusing them. Therefore, the circular economic model should replace the linear model to save raw materials, the environment, and society.

As mentioned, the construction sector is the largest consumer of natural resources of all economic sectors and has the most significant negative environmental impact. Introducing principles and good practices related to the circulation of raw materials can reverse this trend by maximizing the use of raw and construction materials. It is possible through thoughtful and concerted action by all those involved in the construction process, from design, through the construction and operation phases, to the recovery and reuse of materials and elements at the end of the building's life.

Building materials that have been depleted for their original purpose should be given a new life, such as becoming part of a new building - this should be the goal and mission of circular architecture. In parallel with implementing the circular economy concept, there should be an effort to use materials with a low environmental impact, considering their carbon footprint over their entire life cycle, and to minimize energy consumption or use renewable energy.

All stakeholders in the construction sector should be involved in implementing CE principles in construction, from designers through material producers and contractors to developers. Therefore, teams working on construction projects should jointly determine and implement specific solutions that minimize the use of ever-dwindling raw material resources, maximizing materials circulation.

DID YOU KNOW...

CONSTRUCTION WOOD...
NATURAL, RENEWABLE, BUT IN LINE WITH A CIRCULAR ECONOMY?

Wood can be used in various buildings, including houses, barns, sheds, and even entire cities. It is also an excellent insulation material and can be used to save energy in buildings. Since wood is lightweight, it is easy to work with and requires less energy to use than other materials.

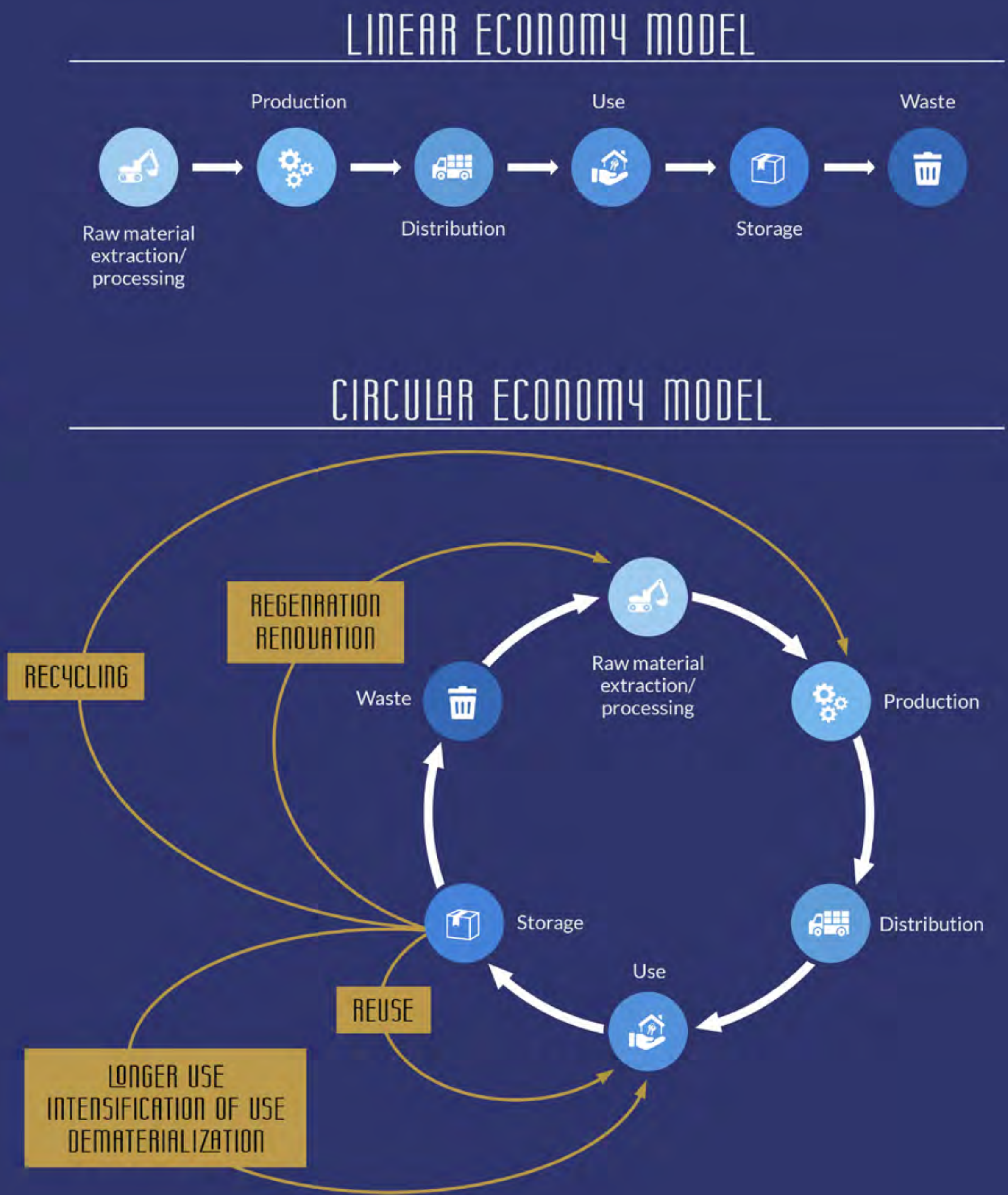
In general, wood is an excellent material for implementing a circular economy. It has been used for centuries to build structures that stand the test of time. Its renewable nature, energy efficiency, and durability make it an ideal choice for sustainable building projects. However, its water and land requirements, as well as fertilizers, must be considered when considering its use in construction based on a circular economy.

THE CONCEPT OF A CIRCULAR ECONOMY: GOALS AND PRINCIPLES

A circular economy (CE) is a model that involves keeping raw materials and products in circulation for as long as possible while maximizing their intrinsic value and maintaining their performance, which is in opposition to the principles of a linear economy (Fig. 1.). The result of implementing the new model on a global scale will be a significant reduction in the consumption of natural resources and their preservation for future generations.

The circular economy model has been adapted from the natural environment, where the phenomenon of the circulation of matter in an ecosystem can be observed; for example, dead plants become fertilizer for subsequent crops. Based on the natural biological cycle, a technical cycle can be presented in which a previously used product can be reused. Another activity that fits with the tenets of CE is the sharing of products to maximize their use over time. An example of this would be the currently popular car or bicycle sharing.

To implement the CE model in practice, it is necessary to thoroughly understand its concept and assumptions about how materials can circulate in a closed loop, how they can be used, and where and at what stage in the entire life cycle of products or services. It is also essential to understand the value of the design of individual products and services as it determines their circular potential (Fig.1.). The appropriate choice of the material used for a product already at the design stage will enable it to be easily recycled or reused in the future. It will ensure that products are designed sustainably, respecting natural resources and preserving the environment. The basis is a simple assumption - at the end of their life cycle, products will not be wasted, will not pollute the environment, but will serve as new material for the economy.



▶ Figure 1. Concept of the linear and circular economy models [12]

The transition to a circular economy should be a systemic change. All activities at every stage of the supply and value chain, in all sectors and areas, especially key ones, should be directed towards changes related to introducing the CE model. It is also essential to create the conditions in which a circular economy can succeed by creating mechanisms for supporting and promoting environmentally friendly solutions, which in their assumptions, take care of the rational management of raw materials and, in particular, their use at different stages of the life cycle, starting with the implementation of activities related to reuse, longer use, intensification of use, dematerialization, remanufacturing, renovation, and finally recycling. It should be borne in mind that the economy's transition to a model based on the CE assumptions will be a complex and time-consuming process.

In a Delloite report [9], analysis results were presented, showing that currently, only 8.6% of the world economy is based on the circular model. This shows that only a small proportion of primary raw materials are being circulated. This does not seem like much so far, but it shows that such a model works and brings benefits.

The International Resource Panel [24] published a report stating that the sustainable use of raw materials and energy, including their circulation, can contribute an additional $2 trillion to the global economy by 2050. Resource-efficient policies can reduce the consumption of raw materials by 25%, thereby enabling the implementation and development of sustainable economies [12].

According to the World Economic Forum [44], some waste management companies, including those dealing with construction and demolition waste, will function much more efficiently through CE implementation. By 2023, a circular economy could generate as much as $4.5 trillion in economic benefits, mainly through the elimination of waste and the rational use of raw materials. The construction and demolition waste processing alone could generate about $315 million in profits annually.

In addition, the CE also assumes, among other things, a transition to renewable energy, which can reduce global greenhouse gas emissions by 55% [45]. Since construction accounts for a significant portion of the total energy consumption in European countries (42%), this sector is considered one of the priority sectors needing improvement in this regard [16]. Using the CE model in the manufacturing sector, particularly for cement, aluminum, steel, plastics, and food, could yield a reduction in CO_2 of 3.7 billion tons by 2050, equal to emissions from all forms of transportation [45].

The strategic goal of the CE is a systemic change that will eventually replace the linear model of the economy with a circular one, with the priority goal of reducing the amount of waste and raw materials used in all processes at every stage and extending the life of products, such as by reusing or repairing them. Only if products or materials cannot be reused are recycling, recovery, reprocessing, or composting activities implemented. This concept aligns with the EU's environmental and sustainability goals and is a part of the regulations and strategies being developed currently.

CE, therefore, is not only about **protecting the environment, saving resources, and reducing energy consumption but also an economic strategy** focused on building a strong economy that will follow the path of sustainable development, emphasizing efficient use of the Earth's resources. At the same time, it is almost a mandatory change, without which, at some point, the world will not be able to develop further, facing a crisis of raw material shortages.

The main goal of CE is to maintain the sustainability and value of materials and products in a closed loop, making it consistent with the twelfth goal of the Sustainable Development Strategy: Responsible Consumption and Production and Climate Action [72].

The circular economy is based on various business models that incorporate the goals of CE to a greater or lesser extent, but all reflect its primary objective. These models are designed to help companies define at what stage, in which process, or how and with what to replace a given material to save raw materials and energy and to choose an economically beneficial solution in the process.

Appropriate CE models should have defined core values to guide them [5, 9, 14, 15, 42, 44, 45].

The development of CE and technology is causing the evolution of existing concepts, creating new business models governing their operation and implementation. Work is underway to define official and uniform CE guidelines. In the available literature, one can find descriptions of many circular economy concepts, and among the most common are the 3R model, RESOLVE model, 7R model, DISRUPT framework, Circle Economy's model, IMSA's model, and the BS 8001 standard [67]. This guide presents the models most applicable to the construction sector. These models can aid in implementing CE and support selecting a business model and changing the product or service production.

THE MAIN PRINCIPLES FOR IMPLEMENTING CIRCULAR ECONOMY MODELS ARE AS FOLLOWS

- Avoid harmful substances
- Minimize energy and resource consumption (in the transportation and production phases)
- Minimize energy and resource consumption (during the use phase)
- Design so that it can be easily repaired and expanded
- Extend the life of products
- Minimize the weight of products
- Make the product resistant to external factors
- Use materials (whenever possible) that can be reused
- Avoid multi-material items that are more difficult to recycle
- Design in a simple block
- Continuously improve processes and products

MODEL 3R

The first published CE model is the 3R model (Fig. 2), based on the basic guidelines for implementing CE in the context of raw materials and the hierarchy of resource management. The principles to be followed are reduce, reuse, and recycle. The model's concept emphasizes life-cycle thinking with eco-design and collaboration along the value chain.

▼ Figure 2. Model 3R

MODEL RESOLVE

A more comprehensive model is the ReSOLVE model (Fig. 3.), which defines the 6 principles as follows:

▶ Figure 3. Diagram of the ReSOLVE concept, the basis for the circular economy model [15]

Re — **REGENERATE**
a principle indicating the necessity to strive first for the regeneration of materials and components of a product.

S — **SHARE**
a principle indicating the need to share products or services, such as sharing space or real estate and movable property (e.g., car-sharing), thereby maximizing the efficiency of the use of a product.

O — **OPTIMISE**
the principle of increasing the efficiency of production processes, minimizing waste generation, or using data sets and automating processes where it is possible.

L — **LOOP**
the principle according to which the circuits of individual companies or structures are closed by reusing components, introducing recycling of materials, recovery of biochemical components from bio-waste, etc.

V — **VIRTUALISE**
a principle that refers to replacing the use of material resources through the use of technology (i.e., the so-called smart technology), such as, for instance, remote building management limiting required visits on-site and, consequently, transportation.

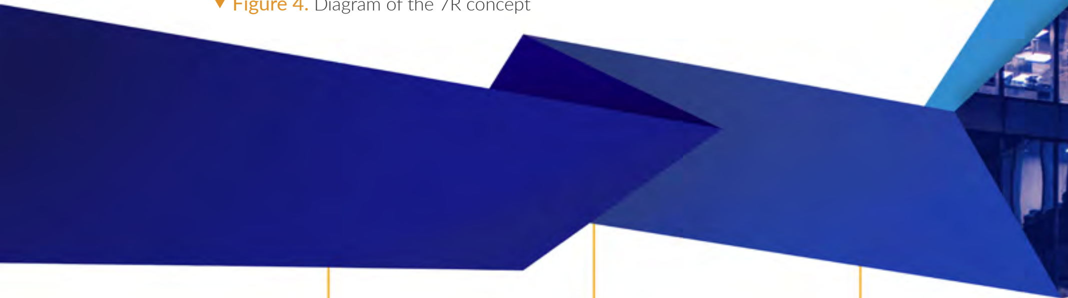
E — **EXCHANGE**
a principle based on the exchange of particular products or services for others, including also the use of new technologies (such as 3D printing, which can replace the costly production of reusable or disposable items), the spread of new forms of transportation (e.g., hyperloop) and new products and services that can replace current products made from non-renewable resources.

7R PRINCIPLES

Another CE model is based on the 7R principles (Fig. 4.), including, among others, activities related to repairing or refurbishing products, which are nowadays becoming popular with consumers again.

Adapting the circular economy by some sectors will be a natural consequence of eco-design. An example of this is the choice of a more durable material that extends a product's life. Moving the global economy toward circularity will maintain the current pace of development and meet the demand for natural resources. Each time, however, the economic and environmental viability of implementing CE must be examined.

▼ Figure 4. Diagram of the 7R concept



RETHINK
rethink your product selection habits, try to assess whether a material or product is needed or whether you can replace it with something, and choose materials that can be reused or recycled

REDUCE
reduce energy, materials, and water consumption whenever possible; pay attention to selecting appliances with low energy consumption

REUSE
reuse everything that allows you to do so and avoid disposable items, make the most of what you already have, look for circular products, and find new uses for unused products

REPAIR
always consider repairing products, appliances, and equipment first; choose second-hand, recycled, aftermarket products

REFURBISH
renew and recycle old items and materials, choose those that offer the opportunity, and reuse old parts or components, transforming them into new things

RECYCLE
segregate and recycle waste, choose recycled products, and ensure that your products and materials can be recycled and recyclable

RECOVER
recover and reuse all or part of the waste

ECONOMIC AND ENVIRONMENTAL EFFECTS OF IMPLEMENTING A CIRCULAR ECONOMY LOCALLY AND GLOBALLY

Attempts are being made to implement circular economy models on many levels. Numerous documents and regulatory requirements are being developed and published to accelerate the process. Synergies can be observed with the broader regulatory ecosystem, including the EU taxonomy for sustainable activities, the EU Environmental Footprint methods, the Sustainable Development Strategy, and other directives and regulations on the CE. However, there is still a need to systematize knowledge in this area by precisely identifying courses of action and creating guidelines, definitions, and indicators to measure the results of the CE implementation [19].

SOCIAL EFFECTS

As a result of the comprehensive transformation of the economy from a linear to a circular model, new jobs will be created in many sectors for people with different skills. Experts and specialists will be needed to carry out a series of changes: legislative, technological, environmental, and social, to implement CE models correctly in companies and the broader economic environment. It is estimated that 2 million new jobs will be created in the EU [18]. Implementing CE will also allow for social inclusion (i.e., due to focus on product/service sharing and introducing new business models oriented toward human inclusion) and will increase environmental awareness, including natural resource depletion. An important aspect is to educate consumers and users in making selective choices and taking the right actions. Examples include sharing products or spaces, promoting cooperation, and building communities while reducing consumption levels.

ENVIRONMENTAL EFFECTS

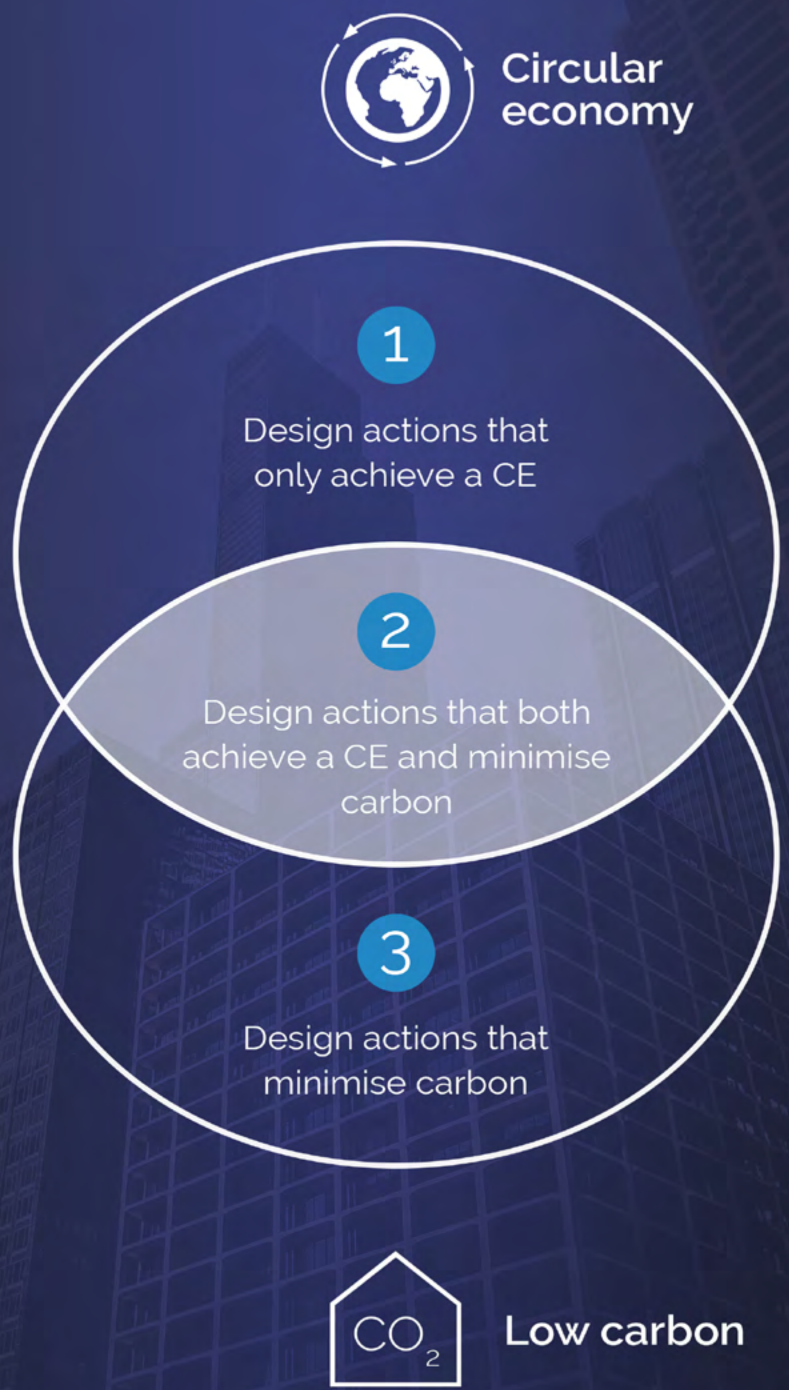
The model change and closure activities will help save raw materials and represent the potential to reduce the adverse environmental impact of the economy.

Environmental effects on the construction industry can vary in nature. They can include soil and water pollution, changes in biodiversity, greenhouse gas and dust emissions, changes in landscape, acoustics and noise levels, and increased energy demand. Soil and water pollution results from improper waste and wastewater management, as well as from the use of chemicals in the construction process. Changes in biodiversity can result from deforestation and changes in the landscape, among other things. By designing buildings and building products following the CE concept and reusing materials, it is possible to reduce greenhouse gas emissions into the atmosphere and reduce soil and water pollution.

The overall effect of the activities on the environment is referred to as the **cumulative environmental effect,** which is a combined effect of past, present, and future activities and processes [8]. It provides an overview of the environmental impact rather than focusing on the direct effects of individual activities as these effects individually often might be relatively small, but when combined, they might reflect significantly on the environment. The cumulative environmental effect can be determined using LCA analysis, which allows consideration of all stages of the life cycle, all elements of the analyzed system, as well as all potential negative or positive environmental impacts.

Moving toward the circular economy aligns with the EU's top priorities related to employment and economic growth, increasing investment levels, caring for the climate, optimizing energy consumption, social development, industrial innovation, and innovation for sustainable development. In the construction sector, CE models represent a potential for implementing innovative solutions, especially **in waste processing, construction techniques (e.g., joints between elements), and the use of alternative and more readily available raw materials.**

Reducing life-cycle carbon emissions (i.e., embedded and operational emissions) while promoting the circular economy are considered critical factors in building design, construction, and operation. The interrelationship between reducing greenhouse gas emissions and implementing the circular economy is a global challenge and the subject of much discussion. The proposed strategies require a continuous search for global solutions to resource scarcity, environmental degradation, and climate risks. Even though CE and greenhouse gas emissions minimization largely support each other, there may be situations and actions where it is impossible to achieve maximum effects in both strategies simultaneously. In [27], using the Venn Diagram (Fig. 5.), the interrelationships and discrepancies between the reduction of greenhouse gas emissions and CE implementation are presented.



▲ Figure 5. Interdependencies of measures related to climate and circularity targets

ECONOMIC AND BUSINESS EFFECTS

One of the expected indirect effects of introducing CE is decoupling national economies from the need to import raw materials. To this end, the resources introduced into the market should be maximized by closing them in a closed loop - reusing and recovering them after using them in other processes. Developing a circular economy will contribute to the competitiveness of individual economies, protecting companies from production and supply instability when raw materials run out. It also protects against volatility in raw material prices, especially related to increased transcontinental exports and imports. Therefore, CE benefits new business and technological solutions and supports the development of innovative activities and more efficient modes of production. Since CE is primarily related to saving raw materials, special attention should be paid to the scarce raw materials, which are either running out of resources, are poorly available, or are found in small or inaccessible areas. Currently, most of the raw materials on the list of critical raw materials are sourced in only a few countries, mainly China, Russia, the US, the Democratic Republic of Congo, and Brazil. Hence, strengthening independence and using raw materials already in circulation is crucial, especially for the resource-poor EU economy. The acquisition of raw materials is related not only to production but also to the development of new alternative energy extraction and storage technologies.

The transition to a circular economy could be one of the most welcome changes in the modern world. Estimates presented in a Deloitte report show that the European Union could achieve net savings of $630 billion, or about 3% of GDP, by implementing a circular economy model [9]. Even small changes in how materials are managed can bring considerable benefits to the economy, both nationally and globally. As the availability of raw materials increases, supply and demand can be seen to increase, resulting in a significant increase in GDP. Several circularity principles and guidelines aimed at extending the life of a building, reusing or adapting it for other purposes, and optimizing the use of materials can dramatically reduce the costs of the construction sector. According to an analysis by the World Economic Forum, savings from introducing the circular model to the European Union's construction sector by 2030 could amount to more than €1 trillion compared to the status quo. Nearly 30% of these benefits can be achieved by optimizing the use of primary raw materials, fuels, and electricity from non-renewable sources [44].

DID YOU KNOW...

HEMP CONCRETE – HOW IS IT POSSIBLE?

Standard concrete is a mixture of mineral aggregate and cement, while in the case of hemp concrete, the role of aggregate is played by pieces of hemp shavings produced from hemp straw (industrial hemp) mixed wet with a lime-based binder. Hemp concrete can be used in wooden structures as a filling for partitions and can act as a form of structural stiffening. Due to its low thermal conductivity coefficient, it can also provide good thermal insulation. Moreover, hemp concrete is non-flammable, resistant to fungal and mold growth, and 100% decomposable after demolition.

CIRCULAR ECONOMY IN LEGISLATION

EUROPEAN UNION

Since 2015, the EU has been steadily introducing regulations that stimulate the transition from a linear model to a circular economy model. In 2020, more than 80 new EU directives and action plans for the following years related to the CE were created. The most important of these are shown in the diagram (Fig. 6). These documents should therefore be considered not as a proposal that can be implemented but as guidelines for necessary changes, which the sooner they are implemented, the greater the effect they will have.

ACTION PLAN FOR A CIRCULAR ECONOMY

In 2015, the first EU Action Plan for a Closed Cycle Economy was adopted, titled „Closing the Cycle - EU Action Plan for a Closed Cycle Economy," with the overarching goal of reducing the amount of waste generated and increasing the efficiency of natural resource use through recycling and reuse. The plan outlines areas where CE needs to be implemented, such as production, consumption, waste management, stimulating the market for secondary raw materials, and water reuse. It also identifies priority areas where action toward CE should be taken first. These areas include plastics, food waste, critical raw materials, construction and demolition waste, and biomass and bioproducts. The plan specifies the specific tasks for successful implementation of the CE (e.g., innovation, investment, and horizontal measures) and establishes how progress toward its goals will be monitored.

▼ Figure 6. Timeline of CE regulations being implemented

EXTENDED PRODUCER RESPONSIBILITY (EPR)

In 2015, the EU adopted a Roadmap for a Circular Economy, as a result of which legal changes began to be implemented. The document initially addressed waste, packaging, and plastics, as well as eco-design and extended producer responsibility (EPR) [47]. In the construction sector, EPR applies to frequently used products made of plastics. An example is window frames made of PVC, which are difficult to recycle due to the complexity of their construction and the number of components. The amendments to waste directives adopted in 2018 introduced significant changes in waste management and packaging use. It has reduced the possibility of landfilling and introduced high requirements for recycling specific waste fractions. It also gave rise to thinking about waste in the context of CE. A CE monitoring framework was also established at that time, defining the first principles of the concept.

THE EUROPEAN STRATEGY FOR SINGLE USE PLASTIC (SUP)

The European Plastics Strategy announced in 2019 and the Plastic Directive [48] (the so-called SUP, or Single Use Plastic) that followed it have brought about significant changes in the plastics market. Their goal was to increase recycling rates and reduce the amount of plastic on the market. The SUP Directive focuses primarily on significantly restricting and banning single-use products made of plastic. The Waste Directives and the Plastics Directive introduce extended producer responsibility for packaging waste from products they put on the market, leading to the closing of plastic circuits.

ECO-DESIGN

A package of amendments to the ecodesign directives was also adopted in 2019 [17]. Ecodesign aims to reduce negative environmental impacts throughout a product's life cycle, including requirements for energy efficiency, materials used, durability, and repairability.

EUROPEAN GREEN DEAL

The European Commission (EC) created and published a new action plan for Europe called the „European Green Deal" in 2019 [54], of which one element is the circular economy. The European Green Deal outlines a series of actions to achieve a climate-neutral Europe by 2050, which in the context of the CE means, among other things, responsibly designed products, reducing waste, and strengthening consumers' ability to, among other things, repair products or replace components. It also includes increasing the durability of materials and components and thinking of their reusability in the future. In February 2021, the EC adopted the EU's CE Action Plan, outlining directions and areas for additional action to implement a CO_2-neutral, environmentally sustainable, toxin-free, and fully circular economy by 2050, including the adoption of stricter recycling regulations.

FIT FOR 55

One of the essential measures directly influencing the implementation of CE is a package of legislative proposals called „Fit for 55" [65], which the European Commission adopted in July 2021. Introducing this package aims to modernize legislation, particularly to achieve the 2030 targets and to support the implementation of transformational changes in the economy, society, and industry. The measures are intended to support the achievement of climate neutrality by 2050 and to reduce net CO_2 emissions by at least 55% by 2030 compared to 1990. The Fit for 55 package includes support for sustainable products, consumer empowerment for a green transition, a review of building product regulations, and a strategy for sustainable products and services [45].

EU TAXONOMY

The EU Taxonomy for sustainable activities came into force in June 2020. The EC Taxonomy Regulation [52] establishes criteria for determining whether a business activity can be considered sustainable. The strategy provides directions for transforming business models that support the six environmental goals:

- climate change mitigation,
- climate change adaptation,
- sustainable use and protection of water and marine resources,
- **the transition to the circular economy,**
- pollution prevention and control,
- conservation and restoration of biodiversity and ecosystems.

Technical eligibility criteria for the first two goals have now been published. For the others, including the **goal of transitioning to the circular economy,** guidelines should appear by the end of 2023.

According to the assumptions of the taxonomy, an economic activity qualifies as environmentally sustainable if it meets all four conditions listed below:

- makes a significant contribution to **at least one** of the six environmental goals included in the taxonomy
- does not cause severe damage to any of the other environmental objectives
- is carried out following minimum guarantees
- meets the technical qualification criteria

DID YOU KNOW...

OLDER BUILDINGS – NOT NECESSARILY LESS CIRCULAR...

The materials used in buildings constructed in the last century are often easier to repair or recycle, as they were usually constructed using natural materials such as stone or wood. An example of this would be walls made of brick and using lime mortar as a binder, which can be easily removed from the bricks and then reused. In the case of the current cement mortar, often enriched with various polymeric additives, it becomes almost impossible to remove, resulting in the inability to reuse the bricks.

The most important document introducing regulations that fall strictly within the scope of the circular economy is Regulation (EU) 2020/852 of the European Parliament and the Council, as amended and delegated acts. These documents force changes in other regulations, ordinances, and guidelines related to introducing, monitoring, and implementing the circular economy. It very precisely specifies the responsibility regarding, for example, installations in the construction industry and regarding construction waste and elements to be reused.

ICELAND

In Iceland, CE implementation is included in the strategy developed in 2021 by the Ministry of Environment, Energy and Climate (is. Umhverfis-, orku- og loftslagsráðuneytið) [28], the implementation of which is divided into six thematic areas. Implementation of each area will occur in two-year periods. Thus, activities related to strengthening CE in the construction sector are planned for 2024-2025, with emphasis mainly on reducing the amount of construction waste generated and increasing its reuse through, among other things, more selective sorting. In addition, the Roadmap to Sustainable Construction by 2030 (is. *Byggjum grænni framtíð*) [69] includes several circular goals and activities guided by the need to reduce carbon emissions from construction activities. First and foremost, by 2030, the plan is to increase the reuse of construction waste to 95% and reduce waste generated by 30% per square meter of building area. To make this possible, some measures are planned, such as mapping buildings scheduled for demolition, opening up landfills for construction waste with potential for reuse, and changing regulations to allow certification of recycled building materials.

POLAND

In 2019, the ***Roadmap for transformation toward a circular economy*** was adopted by the Polish government. It contains a set of tools, not only legislative, which aim to create conditions for the implementation of the new economic model in Poland [35]. The following priorities are listed:

- innovation, strengthening cooperation between industry and academia, resulting in the implementation of innovative solutions in the economy
- creating a European market for recyclable materials, where their movement would be easier
- ensuring high-quality secondary raw materials that result from sustainable production and consumption
- development of the service sector.

The most important document in the context of seeing the implementation of the circular approach in the Polish economy is the amendment to the **Waste Management Act** [53], which introduces an obligation to selectively collect construction and demolition waste divided into at least six fractions: wood, metals, glass, plastics, gypsum, mineral waste (including concrete, brick, tiles and ceramic materials) and stones. Administrative penalties ranging from PLN 1,000 to PLN 1,000,000 are provided for failure to selectively collect and sort construction and demolition waste. The new provisions also emphasize the issues of reducing waste generation, reusing materials, and designing products with recycled materials in mind, as well as reuse. As a result of the amended law, the placement of selectively collected waste for recycling or reuse in landfills has been prohibited. In addition, the law specifies .

CIRCULAR DESIGN, CONSTRUCTION, OPERATION, AND DECONSTRUCTION

CIRCULAR ECONOMY IN CONSTRUCTION

Buildings satisfy many of man's fundamental needs. Since the beginning of time, man has needed shelter, including from adverse weather conditions or wild animals. With the development of civilization, buildings constructed by man became more advanced and began to meet his other needs as well. Nowadays, buildings are designed and constructed taking into account their purpose, by which we can distinguish different types of buildings, such as schools, hospitals, single and multi-family houses, commercial buildings, and others. However, it should be noted that most buildings are not constructed following the principles of sustainable development. Today's way of constructing or retrofitting buildings uses natural resources, converting them into building products that are then used and treated as waste, with no chance of reuse or recycling. This linear approach contributes to over-depleting Earth's resources and increases waste generation and global greenhouse gas emissions.

According to the Ellen MacArthur Foundation, most of the buildings currently being constructed are based on a linear concept, and only 20% to 30% of construction and demolition waste is recycled or reused. The current consumption model is not sustainable, proved by the estimates that by 2025 the annual generation of solid waste will increase to 2.2 billion Mg, with the construction fraction accounting for almost half of this mass [11].

CONSTRUCTION IS CONSIDERED ONE OF THE MOST RESOURCE-INTENSIVE SECTORS, USING THE FOLLOWING MATERIALS:

- **NATURAL** e.g., stone, wood
- **PRODUCED BY PROCESSING NATURAL MATERIALS** such as metals, aggregates, wood-based products, concrete, bituminous binders, ceramics, glass, binders
- **SYNTHETIC** e.g., plastics, glass and ceramics

In the EU, construction waste accounts for 37.1% of all waste generated, with about 13% in Poland and about 50% in Iceland (according to data for 2020). Much of this waste is used only as filling material (e.g., in road construction). Estimates from Iceland indicate that about 98% of waste is managed this way, while in Poland, it is less than 70% [13]. At the same time, more than half of global industrial carbon dioxide emissions (55%) come from the production of just five materials: steel (25%), cement (19%), paper (4%), plastic, and aluminum (3%). The construction industry is the primary consumer of cement, consuming about 26% of aluminum, 50% of steel, and 25% of plastic. [41]

It is estimated that the global population will grow by 22% to 9.7 billion by 2050, and according to the Circularity Gap Reporting Initiative, 60% of the urban infrastructure needed to meet this growth does not exist today [7]. With the current consumption pattern, it's not hard to imagine the environmental burden and material shortage that the creation of this infrastructure will lead to, especially since there has been an intense urbanization process for quite some time. Currently, cities are home to 55% of the global population. They consume more than 75% of natural resources, produce more than 50% of all global waste, and emit 60-80% of global greenhouse gases. [43]

During the design and operation of a building, we can make choices that will have consequences for the consumption of mineral resources. These choices are related not only to the building materials used but also to the finished elements, such as fasteners, and heat and electricity consumption throughout the life cycle. To get the complete picture, it is necessary to acquire precise data on material consumption (in terms of quantity and quality). The environmental quality of a given material is expressed in terms of impact categories and indicators (e.g., those contained in EPDs). In the case of CE, an important indicator is the consumption of minerals (Abiotic Depletion Potential), which includes information on the scarcity of materials and resources.

To calculate circularity indicators (e.g., SMU and MRP, discussed in detail later in the guide), it is necessary to know the multiplicity of antimony equivalent consumption for the production of various materials. Data on this subject are included in Appendix: Summary of APD index value of the present study. They were compiled based on available databases and should be regarded as estimates, broadly representative of the types of equipment or building materials involved. When designing a building, it is best to use precise material passports that contain data for the specific component used. Digital product passports are currently the subject of discussion, which focuses primarily on the scope of data that should be included and which products should be covered by the passports in the first place.

Material passports contain detailed information about the materials used in the production of a given product, making decision-making in line with the principles of a circular economy much more precise and easier. The material passport system created in the BAMB project [55] has become the inspiration and basis for other material data initiatives. The ideal solution to this issue would be to issue material passports for each product, which would ultimately enable a full assessment of the circularity of a project and allow informed choices of materials and components for construction projects.

The growing amount of regulation may indicate not only that the circular economy will be a desirable model for the entire European Union but also a necessary one, especially for the construction sector. Companies and industrial sectors that are quicker to consider CE in terms of benefits and change their business models by closing the circuits on various levels will certainly be able to expect faster results. They will also be prepared for the moment when doing business following CE will be mandatory due to the lack of primary raw materials and other environmental reasons.

CE in sustainable development is related to the following:

1. Responsible use of materials. Minimizing waste of raw materials and energy and maximizing the use of resources through continuous processing and recovery.
2. Increasing energy efficiency. In a circular economy, minimizing energy consumption is a priority. Therefore, the building sector can benefit from solutions that improve the energy efficiency of buildings, such as thermal insulation, energy-efficient ventilation systems, and LED lighting, which contribute to savings of operational costs (including energy costs).
3. Environmental responsibility. A circular economy promotes the reduction of greenhouse gas emissions and air and water pollution. The construction sector, which is responsible for a significant share of CO_2e emissions, can, through the use of CE-compliant solutions such as passive buildings, contribute to reducing its negative impact on the environment.
4. Creating new markets and jobs. Implementing the concept of a circular economy requires the development of new solutions and technologies, which can create new markets and jobs in the construction sector, including in the design, production, installation, and maintenance of modern CE-related solutions.

THE ENVIRONMENTAL IMPACT OF CONSTRUCTION PRODUCTS IS RELATED TO THE FOLLOWING

GREENHOUSE GAS EMISSIONS

The production of building materials is associated with the emission of greenhouse gases or other harmful substances. Choosing materials with a lower environmental impact, such as green, circular, recycled, or natural materials, reduces emissions.

ENERGY AND WATER CONSUMPTION

The production of building materials requires a significant amount of energy and water. By choosing materials with lower energy and water requirements, such as wood, and recycled materials, you can reduce the consumption of primary resources.

WASTE AND RECYCLING

Large amounts of waste are generated in the construction sector. Choosing materials that can be easily recycled or used in other ways, such as circular materials, reduces waste and disposal costs.

MATERIALS QUALITY

Some building materials, such as asbestos in the past, can be harmful to human health and the environment. By choosing environmentally safe materials, you can minimize the risk of adverse health and environmental effects.

SUSTAINABILITY

Choosing sustainable materials that use renewable energy, reused or recycled materials contributes to sustainable development and the creation of greener buildings and infrastructure and the achievement of CE goals.

CIRCULAR DESIGN GOALS

The answer to the enormous impact of construction on the depletion of the Earth's resources and increasing environmental pollution is circular construction, which involves the efficient use of materials throughout their life cycle. The circular economy in construction means maximizing the use of the materials used in the first place through long-term planning and design with an eye toward longer life, the ability to easily change the building's function, repair and maintenance of building resources, reuse, and recycling.

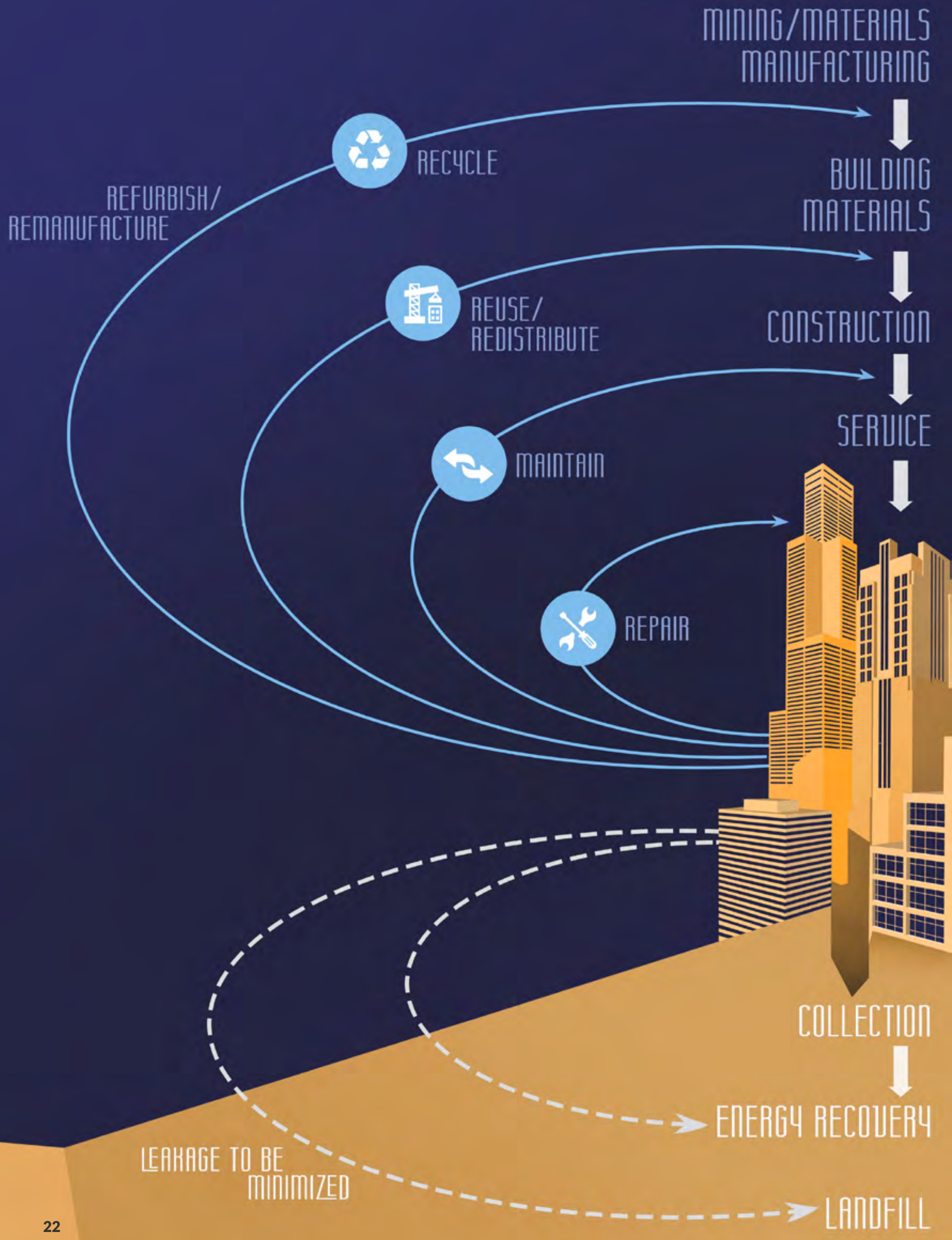
Fundamental principles of circular building design:

- priority use of local or readily available resources
- optimizing the use of primary resources
- reducing energy consumption throughout the life cycle
- ensuring product durability and reparability or upcycling
- eco-design aimed at reducing the environmental footprint, including the material footprint
- continuous development, improving the design with a change in raw material streams or a new product application.

According to the Ellen MacArthur Foundation [73], implementing the aforementioned principles through new technologies and business models can lower production costs, reduce negative environmental impacts and make urban areas more livable, productive, and comfortable.

In December 2015, the European Commission announced a roadmap for a circular economy, which set two primary goals for the construction sector - proper waste management and facilitating the assessment of the environmental performance of buildings. The document emphasizes the importance of design decisions and informed selection of technologies and materials with consideration of the demolition phase as early as the planning phase of a building [51].

▶ Figure 7. Circular economy diagram for the construction sector according to the Ellen MacArthur Foundation [73]



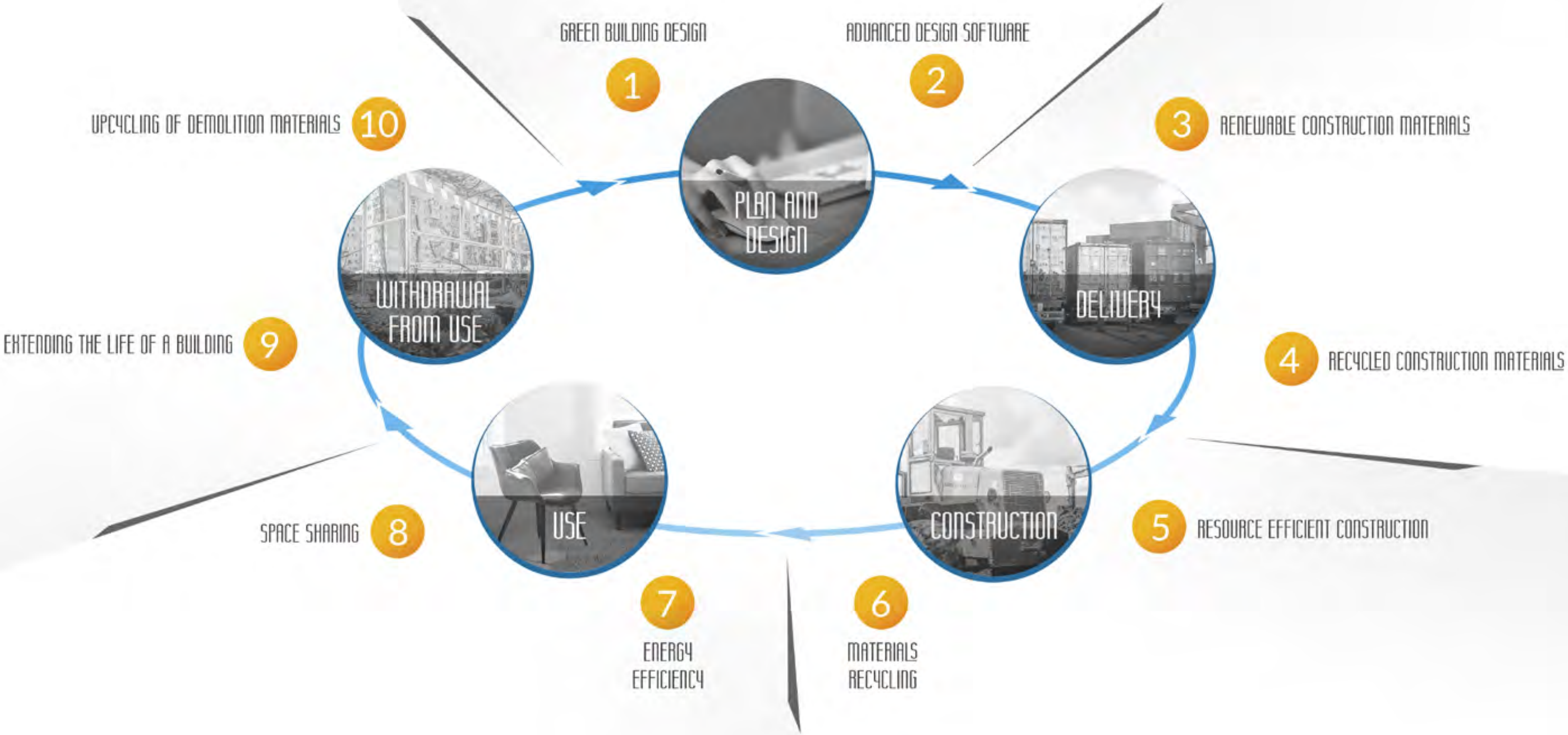
In supporting the transition to a circular economy, a modified economic approach and regulations play a key role. Therefore, buildings should also be developed based on circular business models, with adaptation to actual needs, the anticipation of the possibility of flexible changes, or the assumption of using as few raw materials and generating as little waste as possible. The result of such activities will be to improve resource efficiency, such as by extending the life of products, to achieve environmental benefits while meeting economic goals [1].

Based on the global literature, 10 innovative circular business models [70] have been identified for construction (Fig. 8.) to drive sustainability. They address the phase from planning through the production of construction materials, the construction phase, the recycling of waste materials occurring at each stage of construction and use, the use of optimization digital tools, and the decommissioning and demolition phase.

Adopting a more circular business model poses a number of challenges - the construction industry must first and foremost prioritize circularity over a linear approach by creating a specific ecosystem of cooperation, made up of investors, designers, and builders, for developing the most optimal solutions.

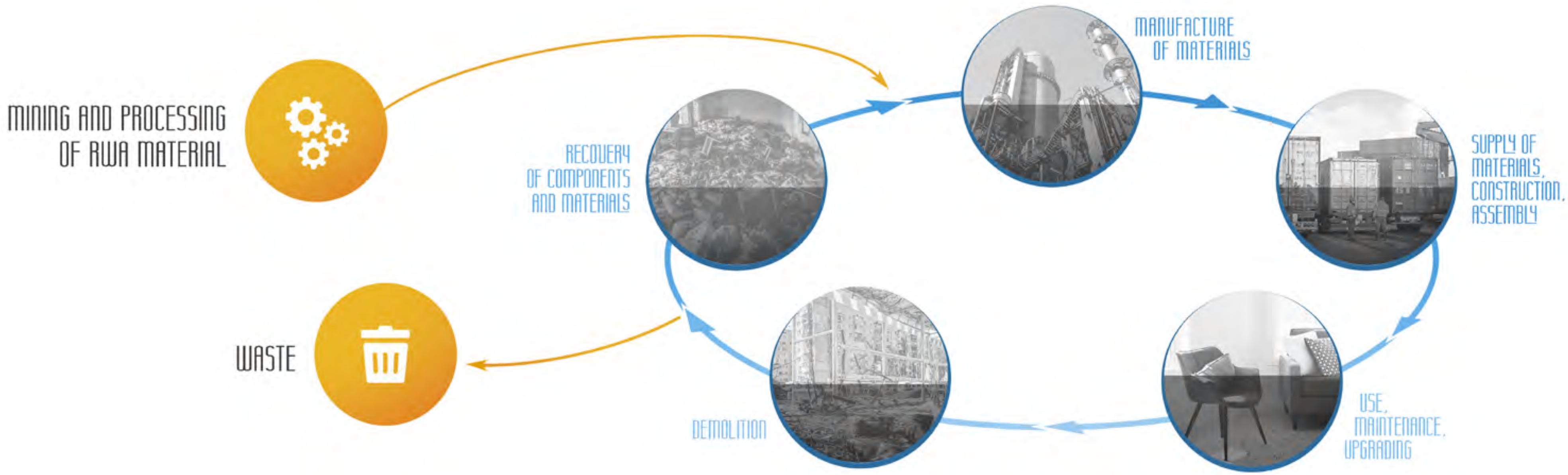
Behind the development of circular construction are social welfare, respect for the environment, and economic factors. The circular model in construction allows buildings and structures to be treated as banks of materials with which financial benefits can be easily obtained. In addition, having access to complete information on the materials and components of which a building is composed will enable owners to optimize maintenance and further capital investment.

▼ Figure 8. Circular business models for sustainable construction, according to Roland Berger [70]



CIRCULARITY IN THE LIFE CYCLE OF BUILDINGS

The vision of total decarbonization of building stock by 2050 goes beyond the operational greenhouse gas emissions that have been the focus to date. It is crucial to remember that buildings are banks of materials in which resources are deposited over many decades, and how they are designed significantly impacts life-cycle emissions in both new and renovated buildings [56]. Minimizing greenhouse gas emissions over such a long period requires saving resources and implementing CE principles. The global warming potential expresses a building's overall contribution to emissions leading to life-cycle climate change. It represents both embodied carbon emissions in building materials and direct and indirect carbon emissions during the use phase.



Life Cycle Assessment (LCA, or Life Cycle Analysis), most often prepared by architects and engineers during the development phase of building projects, is a new but essential component of building design. LCA is a method used to assess buildings' resource use and environmental impact, including materials and operational energy use. Using LCA, it is possible to isolate the elements with the greatest environmental impact throughout the life cycle and propose solutions for optimizing the selection of appropriate materials. Life cycle estimation identifies risks that arise from the mismanagement of building structures' production, construction, and operation processes. The LCA considers all ecosystems and their components, so it is possible to fully assess a product's environmental impact and the consumption of individual resources. The analysis looks at all stages of a building's lifespan, i.e., from acquiring raw materials through the production and use stages to demolition. Thanks to this approach, no phase of the product's existence is overlooked, making it possible to analyze the environmental risks that construction production may pose comprehensively.

Decarbonization efforts in the construction sector are shifting from optimizing building energy consumption during the use of the buildings **to optimizing its full life cycle.** It is necessary to increasingly emphasize the importance of the fact that a building's entire life cycle also impacts the environment through the materials used to construct it, the full process of construction, use, renovation, and finally, in the end, demolition.

Estimates of CO_2 emissions in buildings vary widely as to the contribution of the embedded carbon footprint to total lifecycle emissions, indicating that it accounts for between 10% and 50% [39]. The One Click LCA report [31] states that, depending on building type and location, the embedded carbon footprint is 450 $kgCO_2e/m^2$. These figures confirm analyses published by DGNB [10], where the average value of a building's embedded carbon footprint is 435 $kgCO_2e/m^2$, assuming a 50-year life cycle. Another analysis by Ramboll [36] reports an embedded carbon footprint of 600 $kgCO_2e/m^2$, emphasizing that **70% of this value is embedded emissions.**

▲ Figure 9. Example diagram of the full life cycle of a building

At present, life-cycle assessment analyses of buildings are not required by Polish regulations and are not standardly performed by investors or designers. They are mainly prepared for multi-criteria certifications (e.g., BREEAM, LEED, GREEN HOUSE, etc.). As a rule, they are made by specialized offices, usually on a project basis, while the greatest potential for optimization/reduction of CO_2 emissions through incorporating recycled and recyclable building materials is in the conceptual phase. However, it should be emphasized that the basis for the dissemination and reliability of LCA analyses is a legislatively adopted uniform and consistent methodology for calculating the carbon footprint of buildings, which is still lacking in Poland. Most EU member states have introduced appropriate regulations implementing mandatory life-cycle carbon footprint reporting, often based on LCA analyses. Selected countries have introduced emission limits for different building types, both in terms of operational and embedded carbon footprint.

An example is Denmark, where new LCA-based regulations take effect in 2023 and will introduce emission limits of 12 kg CO_2e per m² of building per year, with a more ambitious option of 8 kg CO_2e per m² of building per year. [59]

Sustainable construction is not just about choosing building materials or components with a lower carbon footprint but verifying how a product will act in the long term. For example, highly durable, more easily adaptable, and reusable components are a greener choice than products with a lower carbon footprint but less durable and impossible to recycle or reuse. Only such a holistic approach and consideration of all aspects will allow for the complete decarbonization of the construction sector.

With a tremendous emphasis on retrofitting existing building stock, using LCA to assess the environmental impact of renovation projects for operating buildings is also expected to increase soon.

To facilitate the development of waste management plans at the design stage, specialized databases should be used to assess and compare the environmental impact of different demolition scenarios. An example is the Scandinavian countries' efforts to develop similar methods of building databases so that design and construction companies can offer low-carbon solutions in all partner countries. This is being implemented as part of the Nordic Sustainable Construction project [69]. Databases of this type will make reusing materials from end-of-life buildings easier. They will also contribute to correctly assessing the feasibility of using waste generated at the end of a building's life in both traditional and selective demolition scenarios.

It is also vital to implement the Life Cycle Thinking (LCT) approach, according to which one should not consider only one or some of the stages of a building's life cycle but the whole. Elements that may seem ideal at one stage, such as operation, may consume a lot of resources at other stages, such as their manufacturing or decommissioning stages. Hence, a holistic approach is indispensable in circular building design and should be based on the entire life cycle of buildings.

In the context of buildings, this approach includes [30]:

STAGE 1

◆ **planning the implementation of the building (selection of the function of the building, location analyses, economic calculations, determination of the quality standard)**

◆ **programming involving the detailed definition of a functional and spatial program, providing design guidelines**

◆ **design (architectural design, preliminary branch concepts, and technical design)**

STAGE 2

◆ **implementation of the project (construction and inhabitation of the building)**

STAGE 3

◆ **facility use**

◆ **adapting to changing needs (modernizations, adaptations, expansions, additions, renovations)**

STAGE 4

◆ **sale or decommissioning (demolition and disposal of materials) of the building.**

CIRCULAR ECONOMY IN MULTI-CRITERIA CERTIFICATION

The documents providing information on the environmental characteristics of manufactured construction products are crucial for implementing measures in the construction industry. The Type III Environmental Product Declaration (EPD) is a good example of such a document. This declaration is a document that transparently communicates the environmental impact of a building product or material. An EPD declaration is not a typical certificate but a testimony to the environmental impact of a product throughout its life cycle, i.e., from the sourcing of materials, through the production stage, transportation, assembly, and use, ending with disposal and recycling. EPDs are prepared following relevant standards, i.e., ISO 14040/14044, ISO 14025, EN 15804, or ISO 21930, and are usually issued for five years from the date of preparation.

The practical use of EN 15804 for environmental declarations has shown that EPD issuing bodies in Europe interpret many areas in the standard differently. Differences in declarations can be caused by factors such as the selection of appropriate data, data quality and availability, methodological details and assumptions, use scenarios, handling of Module D (recycling), or exclusions of certain life cycle stages [32]. In response to these issues, a representative industry group has begun active cooperation with a group of EPD issuing bodies in EU member states, which has resulted in the formation of the ECO-Platform association, which brings together EPD-issuing bodies for construction products in Europe [62]. The organization ensures a unified interpretation of EN 15804 and its harmonized implementation into national practices. It should be noted that some of the still valid EPD declarations contain information only in terms of the product phase (A1-A3, according to the EN15978 standard). In the circular economy context, however, phases C and D include the end-of-life of materials/products (i.e., their future possible reuse/recycling, etc.).

The availability of EPD declarations allows architects, engineers, and designers to select the most circular and least environmentally damaging products, and the manufacturers can optimize their products' environmental impact with the information obtained from EPD [18, 19, 63, 70].

Environmental product declarations form the basis for performing LCAs as part of popular multi-criteria certifications, such as BREEAM, DGNB, LEED, and GREEN HOUSE, in which the use of natural materials and reuse of materials are given a premium in the context of CE.

DID YOU KNOW...

CAN CONCRETE BE CONSISTENT WITH THE CONCEPT OF A CIRCULAR ECONOMY?

Concrete can comply with the circular economy concept; however, it does not always. For example, it can be used in structures that require long life and reuse, such as buildings and bridges. In addition, concrete can be partially made from recycled materials and can itself be recycled, which helps reduce waste. Finally, concrete can also be used with renewable energy sources, such as solar panels, to create a more efficient, sustainable energy system. The use of recycled materials for concrete has increased by 10.5% each year since 2011.

BREEAM

In BREEAM, the most premium is given to the efficient use of materials throughout the life cycle. As part of this, measures to minimize the use of materials, increase the proportion of reused materials from demolition, as well as the use of materials with higher recycled content are evaluated. These measures should be introduced and properly documented as early as the discussions with the project team and then at the conceptual design, engineering, and construction stages. It is imperative that during discussions with the project team, goals, indicators, and measures are set for the efficient use of materials and then demonstrate their achievement in subsequent stages. The certification also evaluates the durability of materials found in exposed building components, intending to reduce the frequency of their replacement and thus reduce material consumption. To this end, appropriate protective measures must be taken to prevent damage to internal and external building elements, as described in the evaluation criteria. In addition, the possibility of functional adaptation of the building is also taken into account through the use of solutions proposed in the criteria, such as systems that facilitate the replacement of major installations, modular construction, and the possibility of expanding the building vertically or horizontally [3].

LEED

LEED certification also features assessment areas that fit the CE concept and a premium point system for implementing measures in this direction. One of the prerequisites to be met is preparing a waste management plan (including construction and demolition waste) to monitor waste reduction and increase recycling or reuse. In this regard, premium points can be earned for reducing the generation of construction waste to a maximum of 50 kg/m^2 of building floor area and increasing the level of recovery of materials from construction waste to a minimum of 50% or 75%. LEED certification also places a premium on reusing historic or abandoned buildings, which should be renovated to a minimum of 50% of the building's floor area to meet appropriate technical requirements. Additional points can also be earned for the reuse of building components, such as floors, roofing, walls, doors, and ceiling systems, for example. It should also be noted that the LEED system prefers the use of environmentally certified materials or those with information on their source, such as C2C or EPD Type III certification [26].

DGNB

DGNB certification has introduced a bonus point system for CE-friendly measures within selected areas. Additional points can be earned for reusing building materials or using recycled materials, reducing waste, minimizing material inputs, and increasing building shareability and intensity of its use. Bonuses can also be received for improving the environmental performance of heavily contaminated land and implementing systems that allow using graywater and rainwater. In addition, the certification assesses the consideration of building adaptation in the context of structural modifications during use, as well as the origin of materials certified with the appropriate certificates and responsible planning for the dismantling of the building at the end of its useful life, which should be taken into account already at the design stage, along with the selection of building materials. Given the above, DGNB certification can be considered one of the most advanced systems in the context of the implementation of CE objectives [61].

GREEN HOUSE

GREEN HOUSE, Poland's first multi-criteria certification for residential construction, also includes areas that fit into the CE concept. Among other things, the level of use of natural materials in the building is evaluated. In this regard, the use of wood in the construction, the use of natural materials in the insulation of the building envelope at a level of at least 70%, and the construction of a wooden façade of the building representing a minimum of 40% of the surface of the building envelope are given preference. Another criterion for certification is the degree of reuse of materials (a minimum of 10%) and the number of materials produced from recycled materials at a level of at least 50%. In addition, the use of existing buildings that will be revitalized and represent a minimum of 20% of the planned area of the new development is given a bonus. In GREEN HOUSE certification, there is a strong emphasis on the use of building products with EPD environmental declarations, and FSC certification of origin is required for the use of wood. [58].

THE NEW ROLE OF THE ARCHITECT, BUILDER, DESIGNER, INVESTOR, AND USER

The transition to a circular economy will require a new systemic and holistic approach to how buildings are designed, used, and maintained by everyone involved in the construction process. Unfortunately, the implementation of CE principles in the construction sector has been relatively slow, with only a few taking appropriate action, and close cooperation between designers, investors, and contractors in this regard is rare. Thus, education in CE is a major challenge for the industry.

Designing buildings according to CE principles is about preserving the highest possible value throughout their life cycle. During the design process, architects and engineers should consider the latest circularity trends regarding the building's erection, operation, and end-of-life, also considering the potential of recycled materials. Unfortunately, design teams often do not include recycled materials and products in their choices, primarily due to the widespread belief that such materials have much lower quality and durability. Given the above, it is necessary to popularize circular solutions that can be implemented in construction and promote good practices. This means strengthening the architect's role as a designer of circular buildings, taking care of functionality and costs throughout their life cycle.

Implementing a circular economy applies to all sectors and groups of consumers. However, considering each economy sector's share of material consumption, construction is regarded as one of the priority areas for CE implementation. This is due, among other things, to the fact that the construction sector is integrated with many industries and encompasses an extensive range of activities and the number of people involved in the construction process. The circular building is sustainable, adaptable, and throughout its life cycle, measures are taken to reduce waste and reduce the consumption of raw materials. Consequently, many stages can be distinguished in the construction project in which circular activities and solutions can be implemented. The most important are:

1

DESIGN STAGE

including sustainable and secondary materials in the design, design-for-disassembly, and design-for-adaptability

2

CONSTRUCTION STAGE

reuse of construction components and equipment, responsible and sustainable construction waste management

3

OPERATIONAL STAGE

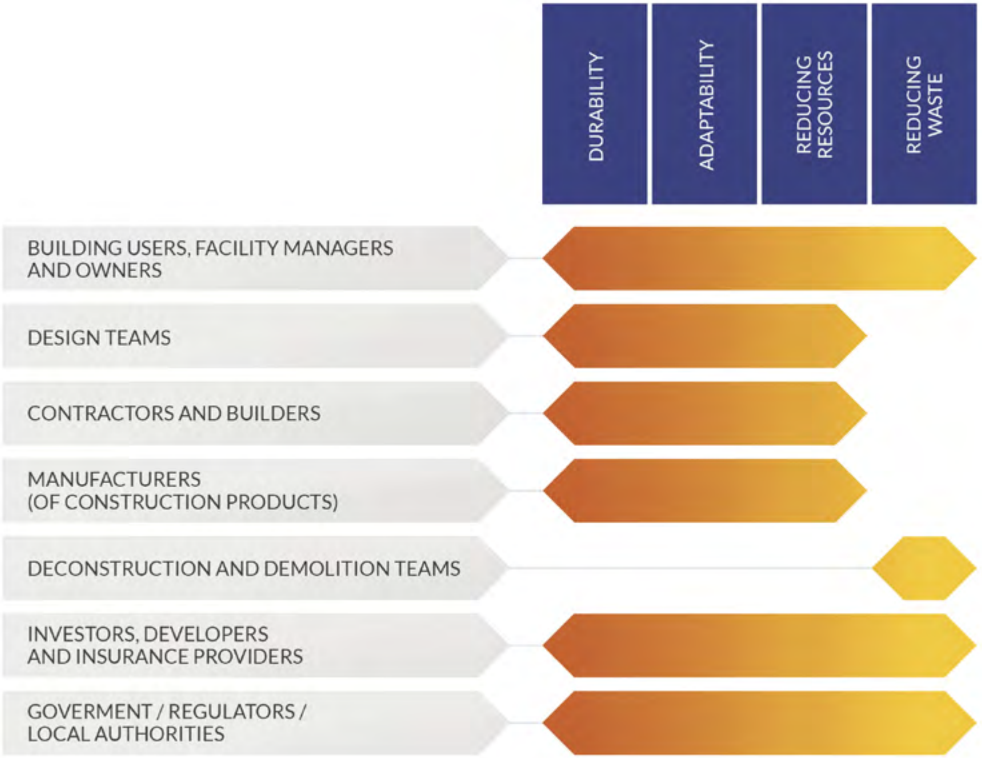
conscious maintenance and repair, optimisation of energy consumption

4

DEMOLITION STAGE

selective demolition, responsible and sustainable demolition waste management

It is also necessary to consider several interactions and linkages of different stakeholder groups in the construction process chain with specific aspects of circularity (Fig. 10.).



▲ Figure 10. Interest in the CE model by stakeholders group for the main CE goals

In the context of CE, designers and architects should take into account the following:

- sustainable design strategies and requirements
- concept of life cycle assessment
- potential to increase the use of recycled materials
- potential for reuse in the future (regarding materials, components, and the building)
- potential for construction products to be recycled.

The role of the architect cannot be overestimated. They should include solutions that fit with CE principles at the initial design stage, and by expanding the consultation to include designers, manufacturers, investors, and users, has the chance to create a team that implements appropriate circular materials, operations, and practices. As a result, this will enable a synergy that engages all participants in sustainability efforts (Fig. 11.).

▲ Figure 11. Collaboration model for circular design stakeholders

The architect should design the building in cooperation with those involved in the construction process to develop joint solutions that fit the principles of a circular economy. Working with manufacturers, builders, investors, users, and recyclers is necessary to ensure the building has the least possible environmental impact. It is also crucial to develop synergies that involve all market participants and require them to work together in sustainability efforts by implementing circular solutions (Fig. 11.).

The role of the end users, i.e., building users and owners, is equally important, as they determine how the building is used. Therefore, educating users about the circular economy and its new solutions is necessary. One such example could be the sharing of components or space, which can be owned by someone who will provide a lease or service to the user. Such a solution will preserve the value of the components and reduce the likelihood that the building will become an inconvenient liability and source of problems in the future.

DID YOU
KNOW...

BACK TO THE PAST - HOUSES MADE OF CLAY

In Hungary, building houses from mud and straw is becoming increasingly popular. This forgotten method returns thanks to its limited environmental impact and high energy efficiency. Such houses can last up to 200 years and are described as “naturally smart” because the thermal properties of the clay used as building material make the buildings naturally cool in summer and warm in winter in temperate climates. In addition, such houses naturally regulate their humidity and are fireproof and non-toxic. It should also be noted that only natural materials (clay and straw) are used as building blocks, and they do not require processing and can be fully returned to the environment after use without any associated burdens.

To strengthen circular construction, users, managers, building owners, investors, developers, and insurers should be interested in the abovementioned aspects. Users, managers, building owners, and potential customers can pressure investors and developers to include circular solutions in the construction process. Insurance companies, on the other hand, can provide important support in managing risks to reconcile security requirements with sustainability. The case is similar for state and local governments, which should strengthen the implementation of the circular economy in the construction industry by creating appropriate regulations to include circular solutions as relevant in the public procurement process.

The role of project teams is to consider the investors’ requirements in terms of circularity or, conversely, to educate them by proposing specific circular solutions. **Contractors, on the other hand,** have a real impact on reducing the consumption of raw materials (at the stage of ordering and using construction materials/products) and on reducing the amount of waste generated (during construction). They can work with component manufacturers (e.g., steel components or gypsum board) who supply components ready for assembly and to the desired size. In this way, it is possible not only to reduce the consumption of raw materials at the production stage and to reduce the amount of waste (material fragments) generated but also to increase the productivity of contractor teams by eliminating the need to adjust the usable dimensions of components. In addition, contractors can reduce the amount of waste generated at the construction site by, among other things, properly sorting waste, educating employees on proper waste management, actively involving themselves in the design process, and reducing waste already at this stage.

For manufacturers, the focus should be mainly on sustainability, adaptability, and reduction of raw materials in terms of creating new, more sustainable products and, at the same time, new solutions that will enable future room conversions. Examples include new elements of partition construction and new materials used to make it easier to repurpose a room in the future. Lastly, **demolition teams** have a real impact on reducing the waste generated during the demolition phase by separating and segregating waste into reusable or recyclable materials.

HOW TO DESIGN BUILDINGS ACCORDING TO THE CONCEPT OF CIRCULARITY

The decisions made at the design stage primarily affect a building's environmental footprint and its potential to recover energy and raw materials throughout its life cycle [40]. In contrast to the linear model, in designing buildings following the CE principle, it is necessary to define secondary materials and their recovery potential, the level of use of building space, and conservative building demolition to ensure high-quality reusable raw materials. A truly circular building consists of non-toxic elements and fully reusable or recyclable elements.

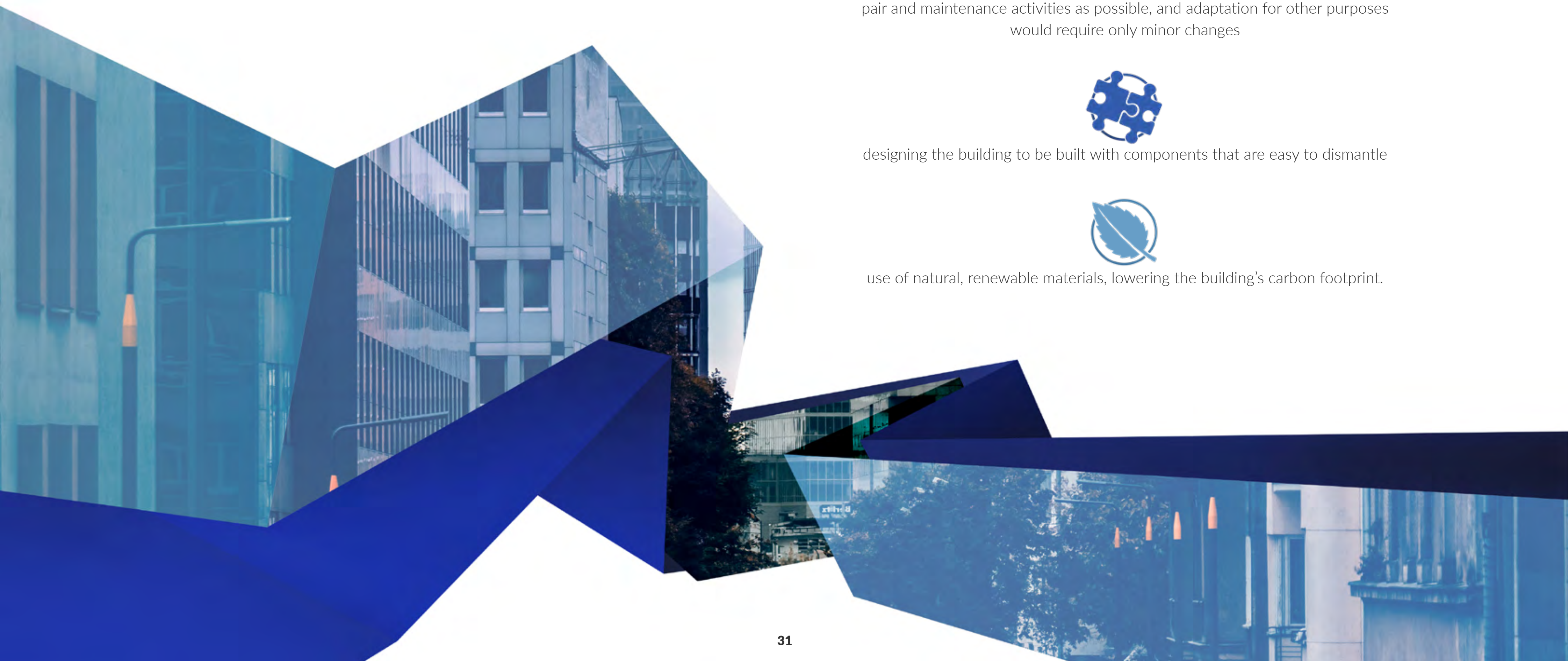
The recyclability of building components should be considered at the design stage by shaping the building in layers and defining potential reuse scenarios early in the design process. Such an approach will motivate building product manufacturers to design durable and easy-to-repair products.

INTRODUCING THE PRINCIPLES OF THE CIRCULAR ECONOMY IN THE CONSTRUCTION SECTOR DURING THE DESIGN PHASE IS FIRST AND FOREMOST

a way to design the building so that the use of the building requires as little repair and maintenance activities as possible, and adaptation for other purposes would require only minor changes

designing the building to be built with components that are easy to dismantle

use of natural, renewable materials, lowering the building's carbon footprint.



It is essential to assess the potential for material reuse and recycling of a building at an early design stage using the various means available, combined with digital tools, to develop scenarios based on feasible solutions. One such tool is intelligent modeling (BIM), with which material and energy savings can be estimated at an early design stage, thereby optimizing the project from the outset.

To meet the above objectives, designers should be guided by the following principles:

- designing for adaptability
- design for disassembly

Adaptability is the ability to easily modify a building or part of it throughout its life cycle, depending on changing needs and future circumstances [60]. Adaptability is necessary to accommodate changes in the type of use, demographics, and user needs or because of the need to adapt to external factors such as climate change. Over time, users' needs may also change regarding their physical capacity limitations associated with advancing age. In the case of residential buildings, adaptability features can allow users to adjust their dwellings to meet their needs as they change with age.

According to the requirements of the ISO 20887 standard for design for disassembly and adaptation, adaptability is divided into two categories:

- specific - for a known/anticipated adaptation
- general - for unknown future adaptations.

Adaptability enables making changes during the building's operation at the lowest possible cost. This means designing buildings with an open plan, in which, for example, partitions are installed without disturbing the structure, and worn-out installations and building elements (such as facades) are easily replaceable. Implementing these principles helps to avoid the costly and challenging changes needed to adapt the building to its new functions in the future.

The design of the building should also take into account elements and components that can be easily disassembled and reused in another building in the future. This, however, is associated with the risk of a general lack of customer acceptance of previously used products or those bearing signs of use. Moreover, products are designed with a short life expectancy, as users require frequent replacement of components with new ones. To move away from business models based on this principle, a change of mindset is needed. Compared to the linear economy model, introducing circularity principles will require a higher initial investment but can increase the residual value at the end of life.

GENERAL DESIGN PRINCIPLES FOR ADAPTABILITY ARE

versatility - refers to floor space that has multiple uses throughout the day, week, or month without requiring changes to the building's design (e.g., space with a width of doors and no thresholds enabling to maneuver a wheelchair or a gymnasium that can function as a theater if equipped with portable seating and acoustic panels integrated into the ceilings and walls)

convertibility - refers to floor space designed so that it can be easily repurposed, e.g., an office building can be designed and built so that it is possible to convert it into a residential building in the future. Another example is sports facilities, which can be used for organizing non-sports events, such as concerts or trade shows

expandability - refers to the ability to add additional floors or floor space without significant changes to the building structure.

DID YOU KNOW...

WATER RECYCLING

Recycling water in buildings can have a significant impact on water conservation. According to the EPA, the average household can save more than 38 000 l of water per year by using water-efficient appliances and practices. In addition, capturing rainwater can save up to 50% of a building's water needs. Graywater reuse can save up to 30% of a building's water needs, while condensate* capture can save up to 10%.

* Condensate capture is the process of collecting and collecting water that is formed by condensation, most often on cooled surfaces such as air conditioners, air ducts and water pipes.

These savings can contribute to significant water conservation. In addition, these practices can help reduce water bills and energy costs. Installing water-saving devices, such as toilets and low-flow taps, can reduce water consumption and energy costs associated with water heating. Capturing and reusing rainwater, graywater, and condensate can also reduce energy costs associated with water treatment and pumping.

HERE ARE SOME WAYS TO EFFICIENT USE WATER IN BUILDINGS:

COLLECT RAINWATER

Installing a rainwater harvesting system can capture and store rainwater for reuse in buildings, which can be used for irrigation, cleaning, and even drinking in some cases.

INSTALL EFFICIENT APPLIANCES

Installing water-efficient appliances like low-flow toilets and faucets can help reduce water consumption and waste.

REUSE GRAYWATER

Graywater is wastewater from sinks, showers, and washing machines that can be reused for irrigation or landscaping.

CAPTURE THE CONDENSATE

Installing a condensate recovery system can capture condensate from air conditioners and other cooling systems and reuse it for other purposes, such as irrigation.

These are just a few ways to recycle water in buildings and promote the concept of a circular economy. Using these methods, buildings can reduce water consumption and conserve resources.

KEY ELEMENTS OF CIRCULAR BUILDINGS

The viability of building elements and ensuring easy access to them is the basis for shaping a building according to the **Theory of Layers** [2], which was first developed by Stewart Brand. According to the theory, recovery determines the form of an object in the design process for dismantling the structure. This approach is possible because the building has transformed (due to the development of construction technology and techniques) from a monolithic structure to a layered structure, with different strengths of individual elements and the possibility of their design and adaptation. According to Stewart Brand, a building consists of 6 parts (Fig. 12.) with different durabilities (Fig. 13.).

Treating a building as a layered structure and extending its lifespan allows for more cost-effective management of its repairs and modifications and high adaptability. It can also radically contribute to the simple dismantling of the building and the recovery of as much economic value from it as possible [22].

From the point of view of the Theory of Layers, the key elements of a building are structures with the shortest lifespan, which repairing is sometimes uneconomical or impossible. These include, among others, furniture, carpets, wall coverings (wallpaper, paneling, tiles), lighting, audio-visual and household appliances. Unfortunately, frequent replacement is dictated not only by a limited lifespan relative to other building components but primarily by changing fashion trends and modern society's growing consumption of material goods. As a result, these activities significantly reduce the overall circularity of buildings. Therefore, it is also essential to continuously educate and raise consumer awareness of this issue and encourage a change in current attitudes.

▲ Figure 12. Building layers according to Stewart Brand's so-called „6 S" [2]

LAYER	DESCRIPTION	DURATION
SITE	Geographic location, urban location, and legally defined parcel of land whose boundaries and context last longer than generations of ephemeral buildings	Eternal
STRUCTURE	Foundation and load-bearing elements that are dangerous and costly to replace	Lifespan of the building structure is 30-300 years, usually about 50-60 years
SKIN	Exterior surfaces of the buildings - facade, roofing	Usually 20 years, depending on fashion, newer technologies or the need for renovation
SERVICES	Internal installations: electrical, water and sewage, telecommunications, heating, ventilation, and mobile parts of the building related to communication (escalators, lifts)	Wear out every 7-15 years, many buildings are demolished if it turns out that installations are too deeply embedded
SPACE PLAN	Partition walls, suspended ceilings, doors, floors	For commercial buildings 3 years, for residential buildings max. 30 years
STUFF	Furniture, lamps, paintings, kitchen equipment, etc.	From weeks, months to several years

▲ Figure 13. Definitions and durability of building layers according to Stewart Brand [2]

CONSTRUCTION PROCESS

Implementing the CE concept in the construction industry is mainly linked to the design, use, and decommissioning phases of buildings. Nevertheless, the construction process itself should not be overlooked, the optimization of which can reduce negative environmental impacts, saving materials and utilities used in the construction phase.

At the beginning of construction, an area should be set aside for any activity that strongly interferes with the project site. In addition, the communication and transportation routes of construction materials on and off the construction site should be clearly defined and optimized. Materials used during construction should be sourced from local manufacturers to minimize the consumption of raw materials for transportation.

The construction process should be optimized to achieve minimum consumption and waste production levels, and the collected waste should be properly sorted and sent for further management at waste processing plants.

Topsoil masses, especially those with a high humus content, should be removed before the commencement of work to be reused for site development and reclamation after the project completion. If the regional development plan, zoning decision, or construction permit do not specify the conditions and management of earth or rock masses removed or moved during construction, such earth masses are treated as waste and should be managed appropriately.

One of the principles of a circular economy is the idea of sharing, i.e., using goods without owning them. This idea should also be applied within the construction process to, for example, construction machinery, scaffolding, or reusable formwork. In addition, instead of purchasing new building components, one can often take advantage of warehouses of reusable materials such as BAMB [55], offering old bricks, roof tiles, fence spans, railings, windows, and doors [55]. In addition to the purely economic and ecological aspects, the resulting buildings will gain individuality and uniqueness.

Finally, for the negative impact of construction on the environment to be as limited as possible, the use and transformation of natural elements are allowed only to the extent necessary. If the protection of natural elements is not possible, both the developer and the contractor are obliged to take measures to repair the damage caused, leading to the restoration of the natural balance in the area and the preservation of landscape values [49, 50].

USE OF BUILDINGS ACCORDING TO THE CONCEPT OF CIRCULARITY

CIRCULARITY IN CONSTRUCTION ALSO INCORPORATES THE USE OF THE BUILDING, INCLUDING:

- the impact of the building on the environment
- the economical use of utilities
- the comfort and quality of life of residents/users.

One of the most important aspects during operation is the energy efficiency of the building, which can be reduced by:

- the use of renewable sources of heat and electricity in a way that does not cause excessive consumption of natural resources
- waste heat management, such as through heat recuperation (from ventilation) or water (heat recovery from water flowing into the sewer system)
- the use of home appliances (household appliances, multimedia, lighting) with high energy class and longer life
- periodic inspection and servicing of thermal and electrical installations and equipment to maintain proper technical conditions (high energy efficiency).

The idea of the so-called „smart home," so using automation and digital technologies, also helps achieve tangible results in saving energy and utilities. An example would be smart outlets, which allow you to turn electrical appliances on and off, and schedule and monitor electricity consumption. Another example is painting walls in bright, reflective colors, which reduces electricity consumption due to lighting (i.e., lighting can be turned on later).

Water consumption during the operational phase of the building can be reduced as well by:

- using household appliances with lower water requirements, such as washing machines, dishwashers
- using rainwater in toilets or for irrigation of home gardens
- using devices that allow rational use of water for daily purposes, such as aerators, basins, and shower faucets that respond to movement.

RENOVATION OF BUILDINGS ACCORDING TO THE CONCEPT OF CIRCULARITY

To serve its users for a long time, a building requires periodic maintenance and, where necessary, repairs. Renovation refers to improving or upgrading an old, dilapidated, or defective building in the construction industry. Renovation plays a vital role in the EU's existing buildings and increasing their energy efficiency, and is an essential element in achieving EU climate neutrality by 2050. The renovation also provides an opportunity for better resource management. A considerable challenge is to change current practices of tearing down buildings instead of renovating them, driven by the economic aspects.

Adopting the principles of a circular economy in building renovation can, therefore, reduce material consumption in existing buildings and also minimize emissions contained in building materials.

The primary goal of the measures mentioned above is the reduction of the need for new construction, which generates more material consumption than the renovation of existing buildings, and thus has a much more significant negative impact on the environment.

CIRCULAR GOALS FOR RENOVATION ACTIVITIES ARE SIMILAR TO THOSE DURING BUILDING DESIGN AND CAN BE ACHIEVED THROUGH THE FOLLOWING [13]:

LIFE EXTENSION

Increasing the intensity of use by converting existing spaces into mixed-use areas, an example being the use of office cafeterias as restaurants outside office hours. This reduces the need for new space in new buildings.

•

Modernization - when a building no longer meets current requirements, and it is necessary to upgrade its features. Modernization leads to an increase in the useful life of existing buildings and a decrease in the demand for new ones.

•

Choosing durable building materials and products - replacing the least durable components with longer-lasting alternatives during renovation. This reduces the frequency of future renovations and delays demolition.

REDUCE MATERIAL CONSUMPTION

Use products with the potential for reuse (according to Design for Disassembly principles), ultimately reducing the need for raw materials when reusing products after future renovation.

•

Maximize recycled renovation materials, reducing the need for raw materials.

•

Maximize reuse, which models strategies to optimize reuse (e.g., debris removal or minor repair operations to increase efficiency). This saves an equivalent amount of new raw materials.

USE OF NEXT-GENERATION MATERIALS

Use prefabricated facades, including cladding and insulation, generates material savings compared to non-prefabricated options.

•

Select bio-based materials/products whenever possible during the renovation of a building element, thus saving non-renewable resources.

•

Use nature-based solutions that assume that all roof and facade renovations will include the installation of a green roof/facade.

DECONSTRUCTION OF BUILDINGS ACCORDING TO THE CONCEPT OF CIRCULARITY

Frequently, it is much cheaper to demolish and build a building from scratch than renovate an existing building. Very often, an investor, when buying a property, immediately assumes the demolition of buildings located on the project site. However, although financially viable, such actions generate much higher emissions from using new materials and disposal of elements of the demolished building.

Existing building stock contains many building materials that may be available for reuse and recycling in the future. Currently, there is no public database in Poland or Iceland that reflects the potential of existing buildings as building material banks. Such a database should include detailed information about the building, such as volume, roof areas, elevations, floors, windows and doors, building typology, construction period and location, as well as the type of materials used.

MATERIAL BANKS WILL REDUCE THE AMOUNT OF CONSTRUCTION AND DEMOLITION MATERIALS DEPOSITED IN LANDFILLS OR DISPOSED OF IN WASTE INCINERATORS, AND THIS WILL ALLOW:

- creation of new jobs and the development of recycling-related businesses, which will affect the development of business opportunities in local communities
- reducing the cost of the construction investment by reducing the cost of purchasing new materials and removing old materials that have been decommissioned; reusing materials will also reduce transportation costs
- reducing the environmental impact resulting from the extraction of primary raw materials and the production of new materials
- saving landfill capacity

Unlike dismantling and demolition, deconstruction is a process of dismantling buildings to recover components for reuse or recycling. Deconstruction keeps usable materials in circulation and avoids generating significant amounts of waste.

The advantages of deconstruction include:

- high level of material recovery
- protection of forest resources (through the use of demolition wood)
- preservation of primary raw materials through reuse.

Different directions of construction and demolition waste management may be considered depending on the demolition scenario. The approach is based on the potential for direct reuse, processing, and subsequent recycling or final disposal of waste. Knowledge of the associated environmental impact expressed by the global warming potential (GWP) of the recycling process of a given material and the abiotic depletion potential (ADP) will allow the selection of an appropriate action scenario with the lowest environmental impact.

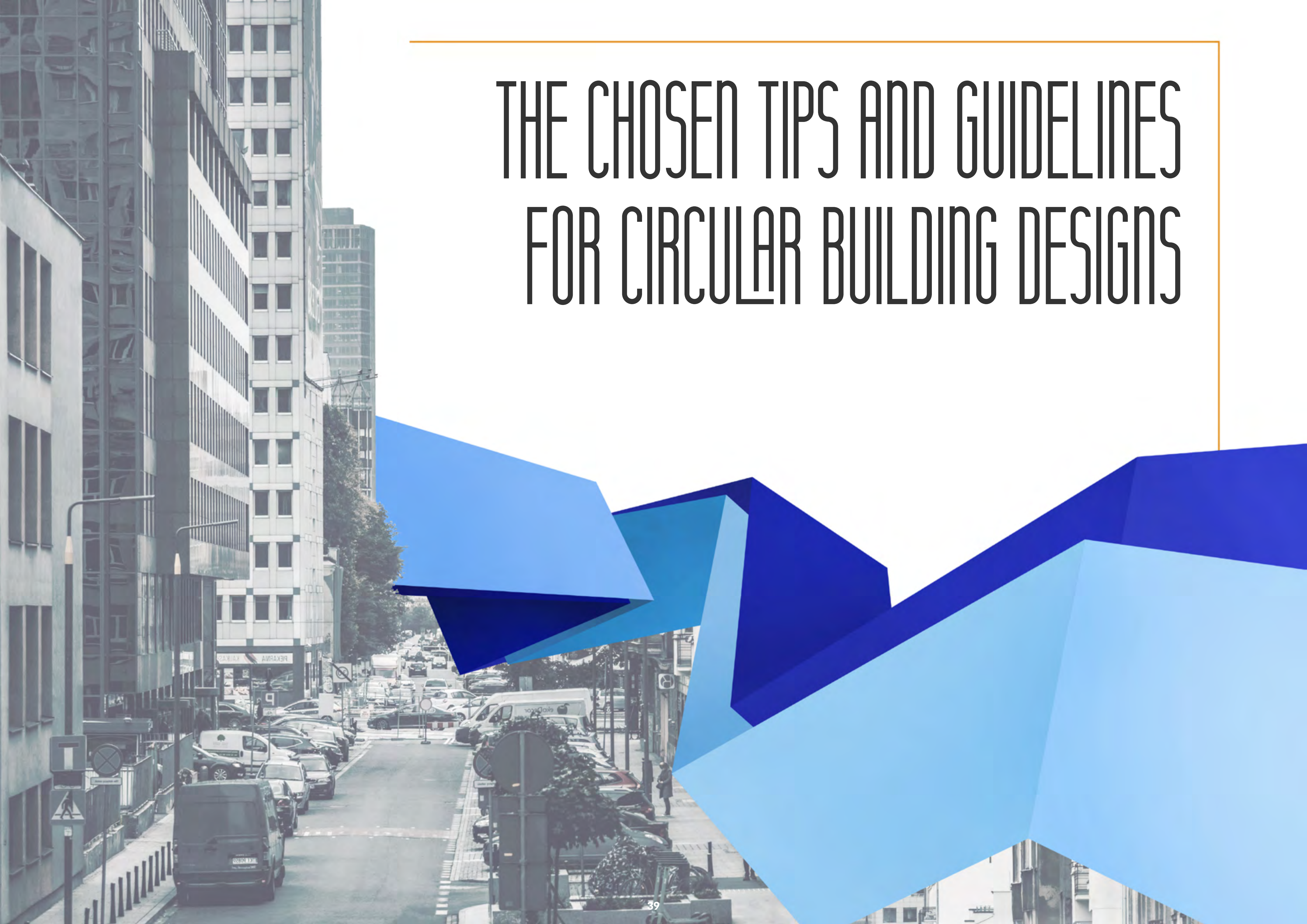
As part of the LCA analyses (according to EN 15978 [34]), building deconstruction activities are included in Phase C:

- selective demolition process or traditional demolition of building elements
- construction waste collection and sorting process on-site
- transportation to a treatment facility for recycling/recovery processes
- disposal of waste to landfill.

In addition, in Phase D, beyond the life cycle, it is possible to assess the benefits and burdens of the recycling, reuse, and recovery process.

Creating a platform for demolition waste will increase awareness of its environmental impact and the need to reuse and recycle materials. The combination of environmental and economic impacts will enable selecting the most sustainable and cost-effective solutions, allowing for better and more efficient decision-making in waste management.

THE CHOSEN TIPS AND GUIDELINES FOR CIRCULAR BUILDING DESIGNS



This chapter presents good practices in circular construction with hints and guidelines for implementing projects in line with CE. In the context of good circular construction practices, it is essential to emphasize the role of design teams that make decisions affecting the circularity of buildings at various stages of the construction process, i.e., at the conceptual, design, implementation, use, and end-of-life stages. Designers should make design modifications for CE at the conceptual and design phases, whereas the project manager and the developer are responsible for implementing CE measures at the implementation stage. Contractors should consider guidelines for waste reduction and reuse of construction elements during and after construction. CE-related decisions made during the construction process should also be reviewed by team leaders and the project manager after the process completion, particularly concerning waste and building maintenance.

The entire project team is responsible for implementing solutions for saving raw materials, minimizing waste, and using appropriate materials. Designers have a crucial role in this regard, as they are responsible for planning the entire project. However, circularity should already be considered while planning the investment, and the investor should see its benefits and support the design team in CE implementation.

Table 7 presents a list of tips for project teams on how to include circularity in their project. The list is based on the expert opinion of the Circon project working groups in Poland and Iceland and the Level(s) system guidelines [68].

TIPS

▼ Table 7. The list of tips for project teams implementing CE in the construction industry

- **Use the potential of existing building structures.**
  Include:
  - the possibility of adapting the building and making it suitable for other functions in the future
  - the possibility of using the existing supporting structure
  - the possibility of using materials and elements of the building (e.g., floor elements, bricks).
- **Choose the location with the greatest accessibility of road infrastructure, electricity grid, water supply, etc., to minimize extra work related to supplying them to the project site.**
- **Plan for repurposing and life-cycle adaptability of the newly designed building.**
  Include:
  - the possibility of adapting the building to the future needs of users
  - the possibility of changing the function of the building.

TIPS

- **Design the structure to enable room expansion, rearrangement, or repurpose without significant construction work so that the space can be shared, transformed, or modified.**

  Include:
  - appropriate column grid spacing - wider column spacing allows for more flexible floor layouts
  - arrangement of facade elements - narrower bays provide better options in terms of interior space configuration
  - interior wall system - non-load-bearing interior walls allow easier changes in room layout
  - greater floor height for placing service ducts (e.g., gas, water) in a way that they are not embedded in the building structure increases flexibility in routing internal utilities
  - room size and access - easy access to the rooms or a separate group of rooms will increase the possibility in terms of sublease
  - non-load-bearing facades – using non-load-bearing facades enables changes in the interior layout and exterior elements without needing significant construction work
  - future-proof structural load-bearing capacity – a redundant structural load-bearing capacity enables broader changes in the facade and use of the building in the future
  - structural design with future expansion in mind - structural designs with a solid horizontal structure to bear additional floors allow for future vertical expansion
  - possibility of converting the ground floor to serve another function
  - easy access to all parts of the space, providing access for people with disabilities, older people, and children.

- **Design the premises with their versatility and adaptability to the needs of people with disabilities in mind.**

  Include:
  - the versatility of floor layout, taking into account the safety and convenience of users
  - accessibility to rooms and their functions - use wide doors, the convenient height of countertops, contrast lighting, and handrails, among others
  - ease of movement - safe and stable floor surfaces, avoiding stairs and other obstacles.

DESIGN STAGE

ASPECTS

DESIGN

TIPS

- **Design the building structure so that it can be disassembled (i.e., providing easy access to individual components and avoiding permanent connections of structural components).**

  Include:
  - independent and easily separable components and their parts
  - reducing the number of connections between elements (i.e., hierarchical building structure instead of horizontal) to increase their disassembly potential
  - sequential hierarchical assembly structure (i.e., dividing components into levels, assembling the same levels in parallel and in order from the highest to the lowest) enables parallel disassembly
  - using connections and components with as simplified geometry as possible and prefabricated – off-site prefabrication enables using standardized connections, increases accessibility to components, and reduces waste from on-site component preparation
  - prioritize mechanical, reversible, and non-destructive connections (e.g., click, bolt, or nut connections) and only secondarily chemical and non-reversible bonding (e.g., glue or weld connections, chemical anchors)
  - readily accessible connections
  - specification of elements with standardized dimensions
  - the potential of modular construction.

DESIGN STAGE

ASPECTS

MATERIALS

TIPS

- **Use digital tools to minimize (optimize) the use of materials.**

  Use:
  - BIM models for better visualization, work coordination, and material consumption optimization
  - 3D models for fast and accurate calculation of dimensions and material performance indicators
  - prefabrication design techniques to reduce material consumption.

- **Take measures to minimize the use of materials.**

  Include:
  - reused and recycled materials as much as possible. it should be assumed that the preferred method for using building materials/components after their useful life is reuse, followed by upcycling, recycling, and, eventually, downcycling.
  - least-processed materials with the highest durability and resistance.
  - materials not containing critical raw materials
  - materials of known origin, preferably from certified sources
  - reducing the overall amount of materials use
  - using materials and products with type III EPD declarations
  - using technological solutions, materials, and installations that are circular and reduce environmental impact and minimize the use of primary raw materials.

DESIGN STAGE

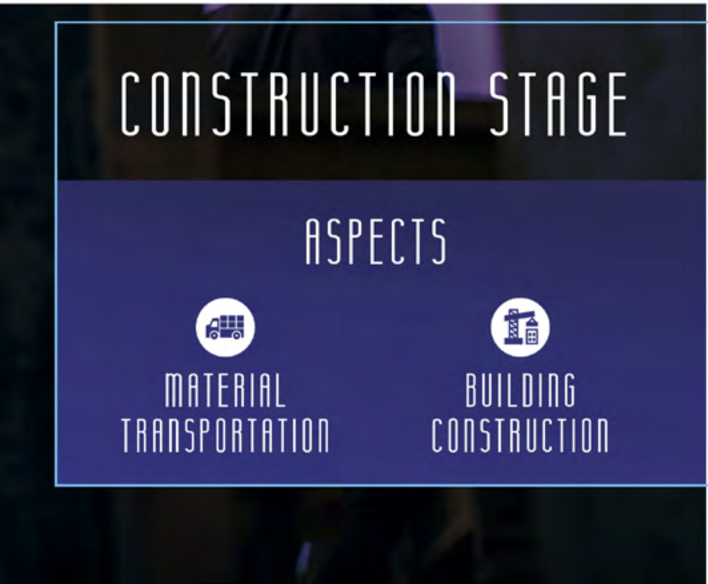
ASPECTS

INDOOR INSTALLATIONS AND TECHNICAL EQUIPMENT

TIPS

- **Design and select indoor technical equipment with the longest possible service life, which can accommodate changes and adaptations and be easily repaired.**

  Include:
  - service ducts (e.g., gas, water) not embedded in the building structure to improve access to them
  - easily accessible technical rooms and equipment, which facilitate the future replacement of technical equipment
  - longitudinal ducts for running services, which provide flexibility for placing the service points
  - higher ceilings for service ducts (e.g., gas, water) so that they are not embedded in the building structure increase the flexibility of their routing
  - providing separate servicing to individual parts/wings of the space, which increases their subletting potential and enables the individual maintenance of sanitary facilities.
- **Design a building with high energy efficiency, according to the current regulations contained in the national building code (if existing), using renewable energy sources.**
- **Avoid or possibly minimize energy use from sources negatively impacting the environment.**
- **Design solutions to reduce water consumption, using rainwater and graywater for domestic purposes.**
- **Design appropriate building automation and control systems for optimal energy savings.**
- **Consider using heat recovery.**



CONSTRUCTION STAGE

ASPECTS

MATERIAL TRANSPORTATION

BUILDING CONSTRUCTION

TIPS

- **Obtain building materials from local sources whenever possible.**
- **Maximize and optimize transportation efficiency.**
- **Pay attention to the type of packaging of the supplied materials - it should be reusable or recyclable.**
- **Use high-quality equipment, machinery, and appliances with high energy class to reduce electricity consumption.**
- **Use circular elements that support the construction process, e.g., 3D printed parts, prefabricated parts, or any other reusable materials (e.g., formwork).**
- **Utilize renewable energy sources and rainwater during the construction process.**

CONSTRUCTION STAGE

ASPECTS

CONSTRUCTION WASTE

TIPS

- **Take advantage of the equipment offered through rental services.**
- **Design appropriate space for collecting and segregating construction waste to enable proper sorting and further recycling.**
- **Develop a construction waste management plan for the project site:**
  - include ways to handle hazardous and non-hazardous waste
  - reserve resources for the selective collection of specific types of construction waste
  - store building materials under a roof, protecting them from the effects of adverse weather conditions.
- **Implement good practices that can reduce waste generation on-site such as, for instance:**
  - maximizing the use of prefabricated elements
  - applying appropriate sorting techniques adjusted to the waste type
  - categorizing and labeling waste according to national regulations
  - reducing the risk of damage to delivered materials by limiting the time materials are stored in bulk on-site (through optimizing the delivery times) and storing the materials adequately (weatherproofing)
  - minimizing the amount and number of materials ordered in excess (e.g., through specific key performance indicators and contract clauses).
- **Set targets and key performance indicators following the national waste hierarchy and the national waste list:**

  Consider:
  - disposal of ≤10% of non-hazardous waste in a landfill
  - recycling and reusing ≥40% of all inert waste
  - recovery, recycling, and reuse of ≥95% of inert waste fractions.

CONSTRUCTION STAGE

ASPECTS

EVALUATION

TIPS

- **Calculate the sub-indicators and the collective circularity indicator CI, given in this guide.**
- **Check whether the preferred method of obtaining materials/components for construction is reuse, followed only by upcycling, recycling, and, after all, downcycling.**
- **Check that attention has been paid to ensure that the building is a material bank and contains the highest possible proportion of elements that can be reused, upcycled, recycled, or, after all, downcycled.**
- **Check that attention has been paid to ensure that the construction process includes optimizing energy consumption and minimizing consumption of primary raw materials and construction waste. The building's circularity analysis should be compared with other environmental impact analyses to select the most favorable final solutions.**

CIRCULARITY POTENTIAL OF BUILDING MATERIALS

Circular materials are gaining popularity among building materials and product manufacturers and users (customers). This is not only for environmental reasons (the use of circular materials involves a reduction in the use of natural resources and a concomitant reduction in the amount of waste generated) but also because they can provide a cheaper and, above all, accessible alternative to new materials. They also can have their disadvantages and limitations, such as, for example, lower strength and durability compared to new materials, so they should be considered on a case-by-case basis, taking into account their type and planned application.

In circular construction, materials that meet one or more of the above criteria should be selected first by project teams. However, to fully assess the environmental quality of a given material, its Abiotic Depletion Potential (ADP) should also be considered, providing comprehensive information on the rarity of a given material or its components. Estimated ADP values for selected materials, compiled from databases, are included in the appendix: Summary of APD index value to this paper.

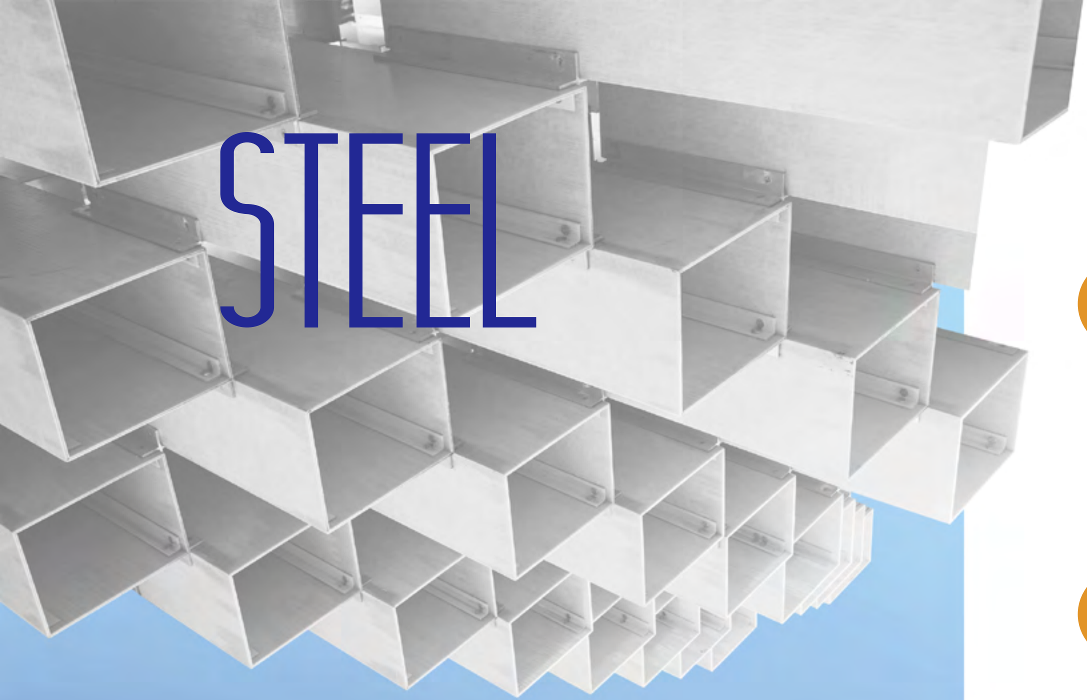
In contrast, EPD declarations for specific construction products can provide specific ADP values for a particular product, often considering the manufacturing process of the product in more detail than in generic databases. The resultant ADP value of a product is affected by the constant updating of ADP values for raw materials, which should be used with the most up-to-date declarations. Due to the lack of accepted boundaries of the system for determining ADP, its values for similar products can vary significantly. Therefore, when utilizing specific ADP values, it is imperative to possess sufficient expertise to omit extreme values.

Today, the most commonly reused or recycled materials in construction are steel, wood, glass, bricks, concrete, cement and concrete elements, as well as plastics or lighting fixtures. The following subsections discuss the most important of these.

CONSTRUCTION MATERIALS (INCLUDING THEIR PRODUCTION PROCESS AND THE ACQUISITION AND USE OF RAW MATERIALS) WITH A LOW NEGATIVE IMPACT ON THE ENVIRONMENT [33] ARE THOSE THAT:

- are relatively easy to install, adaptable to new applications (e.g., ceiling systems that allow easy access to installations), and do not require additional environmentally harmful components for the installation
- are characterized by low levels of embedded energy
- are made from renewable raw materials, recycled raw materials, certified raw materials (e.g., FSC--certified wood), or reprocessed materials (waste)
- do not emit harmful substances during the production, use, and at the end of life
- are recyclable or directly reusable
- have been produced relatively close to the site location, thereby reducing the transportation of material
- have been packaged with recyclable or reusable materials

STEEL



The importance of steel to the construction industry

Steel is one of the primary materials in the construction industry because of its high strength, durability, relatively low weight, and weather resistance. Steel is also fireproof, making it an ideal choice for buildings located in areas prone to natural disasters. Steel's remarkable versatility (strength and ductility) enables its use in various structures and components, from frames and columns to roof trusses and beams. In addition, steel can be recycled multiple times without risking a reduction in its properties, which, combined with the high demand for the material, has led to the development of processing infrastructure, thereby reducing its negative impact on the environment.

Energy intensity of steel production and usage in contraction

Energy consumption in the production and use of steel in construction depends on the type of steel, its finish, application, and the size of the building. Generally, energy consumption for steel production is estimated at 10 GJ/t of steel produced. Therefore, its use is more energy-intensive than, for example, the use of wood, but it is associated with greater strength and durability.

The use of steel in construction in the context of a circular economy.

As mentioned earlier, steel can be recycled repeatedly without losing its properties. Therefore, it is one of the most recycled materials in the world and can be reused in the form of, for example, rebar, structural steel, steel floor beams, or other components. However, there is an increasing emphasis on the direct reuse of structural steel in its original form (e.g., building load-bearing structures, facades) or its regeneration from composite structures (e.g., steel-concrete composite structures), which allows a significant reduction in carbon footprint and water consumption by avoiding the need to process scrap steel [4, 33, 46]. It should be mentioned that the direct reuse of steel components is further facilitated by standardizing their dimensions [33]. In addition, in the context of a circular economy, steel can also be used to construct buildings designed for disassembly and reuse, such as Pre-Engineered Steel Buildings (PEBs).

Environmental impact of steel production and use in construction

Steel production and use in construction can significantly impact the environment, as they are a source of air pollutants, including sulfur dioxide, nitrogen oxides, and particulate matter. Using fossil fuels in steel production also contributes to global climate change. In addition, steel production generates hazardous waste, such as slag and dust, which have to be disposed of in a way that does not harm the environment. Finally, as mentioned earlier, the steelmaking process is also associated with significant water consumption.

Opportunities to recycle and reuse steel in construction

- **Direct reuse of structural steel:** structural steel is a durable material that can be reused in several ways, both in its original and modified forms (e.g., by resizing - cutting). It makes steel elements an attractive option for reuse in various types of projects, such as, for instance, beams, roof cladding, pipes, stairs, or decorative elements [33]. An example of such use is the facade made from used steel sheet at the Kringloop Zuid recycling center in Maastricht, the Netherlands, or the use of steel elements from an old vehicle hall in the construction of the Almere Recycling Center in Almere, the Netherlands, and a recycling platform.
- **Recycling scrap steel:** steel can be recycled and reused to create building components.
- **Reusing steel in interior design:** steel can be used to create furniture or other furnishings, giving any space an industrial yet modern look.

WOOD

The importance of wood to the construction industry

Wood as a building material has many advantages, as it is renewable, and its production and processing have a lower environmental impact than other building materials such as concrete and steel. Wood is also durable, resistant to corrosion, and has natural insulating properties, saving the energy required for space heating. Nowadays, wood is used in the construction of houses (both as a load-bearing and decorative material), as well as in roof structures, window frames, doors, floors, railings, or stairs.

Energy intensity of wood production and usage in construction

The production and use of wood in construction have a much lower energy intensity compared to other building materials such as concrete or steel, which is high because:

- The concrete and steel production process is associated with significant energy and heat requirements (mainly due to the need for thermal processes, such as cement production or mining aggregates), while wood processing is much less energy-intensive.
- Wood is a renewable material, unlike concrete or steel, which means that, with sustainable forest management, wood resources can be renewed continuously without compromising the biodiversity of forest ecosystems.
- Wood has excellent insulating properties, so its use can reduce energy consumption in buildings by preventing heat loss.

The use of wood in construction in the context of a circular economy

The use of renewable raw materials is crucial for sustainable development. Therefore, wood is one of the most important materials that can be used in circular construction. It can be used as so-called reclaimed wood, that is, wood that has been recovered from old structures and given new life in construction projects, in the form of, among others, furniture, structural elements (e.g., rafters), or finishing materials (e.g., parquet floors, stairs, wall cladding). It should be mentioned, however, that an important aspect related to the reuse of wood in construction is its preservation (protecting it from the harmful effects of weather, insects, or fungi), which can hinder wood recovery may not be possible. It is due to the use of toxic preservatives, which pose a risk to human health during processing or prevent the joining of elements by undesirable reactions between preservatives and adhesives [33]. It is also essential to store wooden components to avoid moisture resulting in damage or deformation [21].

Environmental impact of wood production and use in construction

The production and use of wood in construction have an environmental impact; however, it is usually much less than that of conventional materials such as concrete or steel. Nevertheless, emphasis should be placed on sustainable forest management, which minimizes the negative impact of the timber industry on biodiversity and forest resources.

Opportunities for recycling and reusing wood in construction

Wood is a material that can be easily recycled and reused, which is an environmental benefit because it reduces waste and the consumption of natural resources. The possibilities for recycling and reusing wood in construction are as follows:

- **Direct reuse of wooden elements:** wooden elements, such as window frames, doors, ceiling beams, and rafters, for example, can be reused after checking their technical condition. An example is the reuse of 80-90% of materials (doors, beams, wall cladding, among others) from demolishing the local government headquarters in Terneuzen, the Netherlands, in other construction projects.
- **Recycling wooden elements:** wooden elements such as furniture, pallets, and crates can be recycled into other furniture, flooring, ornaments, decorative elements, or garden structures. An example of such use is recycling bar stools and flooring from a nearby monastery into flooring at the Circl pavilion in Amsterdam, the Netherlands.
- **Recycling wood waste:** wood waste (e.g., sawdust or wood construction waste) can be used to produce, for example, insulation materials (such as wood wool), OSB-type particleboard or composite panels [33], glulam [37], or walls made from renewable materials produced using 3D printing technology [25].

GLASS

The importance of glass to the construction industry

Glass is vital in the construction industry because of its properties, such as transparency, strength, UV protection, and thermal insulation. Examples of the use of glass in construction include windows, doors, partitions, balustrades, and staircases. Glass is also a popular material for creating building facades, including facades, as they allow large amounts of natural light to enter a building, which improves the comfort of tenants and users.

Energy intensity of glass production and usage in construction

The energy intensity of the use of glass in construction is related not only to its production process but also to its use. The glass production process is complex and requires large amounts of electricity and heat (from the combustion of fossil fuels) needed to operate the high-temperature furnaces in which mineral raw materials (mainly silica, sodium carbonate, and calcium oxide) are melted and formed in glass. In addition, the transportation and assembly of glass components, often requiring special vehicles and equipment, is also fraught with relatively high energy consumption due to the weight and fragility of glass products. Lastly, glass directly affects energy consumption during the operation of a building because, having a low thermal insulation value, it can amplify heat loss, thereby increasing the energy demand for space heating.

However, glass is a material that can be easily recycled without losing its original properties. Recycling glass can require much less energy than manufacturing it, so the greater the amount of glass recycled, the less energy is used to produce new glass, minimizing its environmental impact.

The use of glass in the construction sector in the context of a circular economy

As mentioned earlier, glass is a material that can be easily recycled without losing its original properties, making it an attractive material in the context of CE. However, direct reuse of glass elements is difficult due to the fragility of the glass itself, the difficulty of dismantling it, and its insufficient insulating properties. Crushed glass (cullet), on the other hand, can be used for the production of new glass products (e.g., windows, doors, glass carriers, façade, and partition elements) and as a substitute for aggregate in the production of concrete, a source of silicon in the production of ceramic products, or for the production of foamed glass [33]. However, it is essential to sort glass waste properly, considering its color, type, and production method. Proper sorting ensures the quality of the material during processing as the glass batch can become contaminated without proper sorting, and thus its quality can deteriorate significantly.

Impact of glass production and use in construction on the environment of glass production and use in construction

The production and use of glass in construction have positive and negative environmental impacts. The negative impacts are associated with, among other things, the intensive consumption of raw materials necessary for its production (quartz sand, sodium carbonate, and calcium oxide), high energy consumption, and emissions of pollutants (greenhouse gases, nitrogen oxides, sulfur oxides). However, as mentioned earlier, glass can be easily recycled, thus significantly reducing the consumption of natural resources used in its production. However, it should be noted that glass recycling is not a carbon-neutral process as it also involves the emission of greenhouse gases, contributing to global warming.

Opportunities for recycling and reusing glass in construction

- **The direct reuse of glass elements** is often associated with technical problems due to glass fragility and disassembly problems. However, glass elements are being used successfully in construction, as in the case of the facade and roof made of glass from end-of-life vehicles at the Glass Chapel in Masons Bend (USA).
- **Production of glass components and products from cullet:** cullet can be recycled many times (provided there is no contamination and the glass waste is sorted correctly), allowing the production of new products, such as facade components, balustrades, doors, windows, and lighting, for example.
- **Production of insulation from cullet:** cullet can be used in producing insulation materials, such as glass wool or foam glass, which reduce energy consumption in buildings and improve room acoustics.
- **Production of building materials from cullet:** cullet can be used as a substitute for raw materials used in the production of building materials, for example, as a substitute for aggregate in the production of concrete or as a source of silicon in the production of ceramic products, or bricks [33].

BRICK

The importance of brick for the construction industry

Brick is one of the oldest building materials that are still of great importance to the construction industry today because of the following:

• **Durability:** brick is a durable building material that can last many decades without replacement. As a result, buildings built with brick are very stable and resistant to various weather conditions, as well as to fires and earthquakes.

• **Energy intensity:** the production of bricks requires a relatively small amount of energy compared to other building materials, such as concrete or steel.

• **Aesthetics:** bricks can be used in various architectural styles, giving buildings a unique and elegant look. Brick also comes in a wide diversity of colors and textures to create unique designs.

• **Easy to install:** bricks are relatively easy to install and can be used to build various elements, such as walls, columns, arches, stairs, and more.

Environmental friendliness: bricks are made using natural materials and can be easily recycled or directly reused.

Energy intensity of brick production and usage in construction

Producing bricks requires relatively little energy compared to other building materials such as concrete or steel. In traditional brick production, energy is used for the clay firing process, as well as for processing and transportation. However, many manufacturers are using heat recovery and other innovative solutions to reduce the brick production process's energy intensity and environmental footprint. In addition, since brick is a good thermal insulator, its use can help reduce the energy required to heat or cool the building.

The use of brick in the construction sector in the context of a circular economy

In the context of CE, brick can be used in various ways to minimize construction waste and increase the efficiency of construction resources. One way is directly reusing brick, in which the key is the proper way to demolish masonry. Brick can be recovered from abandoned or demolished buildings and then processed and cleaned so that it can be reused in new constructions. The brick cleaning process can occur mechanically without using water and additional chemicals, and the recovered bricks can be CE-certified [57]. It should be mentioned, however, that the possibility of recovering bricks is significantly influenced by the type of mortar used. Thus, cleaning bricks from modern types of mortars (fast-setting and hard-to-get-off bricks) often causes damage to the bricks and can be a much more time-consuming process than when using lime mortar [33]. If it is impossible to demolish the masonry without significant damage to the bricks, it is sometimes possible to directly use whole sections of masonry. Crushed bricks can also be used as aggregate for new construction materials, such as concrete mix, or, ultimately, as backfilling material in, for instance, road construction.

The impact of brick production and use in construction on the environment of brick production and use in construction

The environmental impact of the production and use of brick in construction depends mainly on local conditions, such as the availability of natural resources, production methods, and transportation. Therefore, it is crucial to take measures to maximize the use of brick from local sources and, where possible, reclaimed demolition brick.

Opportunities to recycle and reuse brick in construction

- **Direct reuse of brick masonry:** brick masonry can be used directly in the form of panels, such as in the case of the Resource Rows project in Copenhagen by the Danish company Lendager.

- **Direct reuse of reclaimed bricks:** a brick can undergo a reclamation process that involves removing old mortar or paint, cleaning it, and then reusing it in construction, as in the case of the Ravensburg Art Museum (Germany), which used bricks from the demolition of a 14th-century monastery, thereby embedding the new building in the historic landscape of the city. A similar example of preserving cultural heritage through the use of demolition bricks is the Historical Museum in Ningbo (China), where the façade was made of bricks dating back a thousand years.

- **Use of bricks to build drainage systems:** bricks can be used to build drainage systems in gardens, parks, or other green spaces.

- **Recycling crushed bricks:** crushed bricks can be used, for example, as aggregate for new construction materials [33].

CONCRETE

The importance of concrete to the construction industry

Concrete is one of the most important building materials used in construction around the world because of its:

- **Durability and strength:** concrete is one of the most durable and robust building materials. Its compressive and tensile strength makes it an ideal material for bridges, skyscrapers, roads, canals, and other types of structures.
- **Versatility:** concrete can be molded into various shapes of different size dimensions, so it can be used to build virtually any type of structure, from small residential buildings to large industrial facilities.
- **Fire resistance:** concrete is one of the most fire-resistant materials, increasing the fire safety of structures.
- **Low price:** concrete is relatively cheap compared to other building materials, making it more accessible.
- **Ease of production:** concrete production is relatively simple and requires few raw materials, such as water, cement, gravel, and sand. For this reason, concrete is widely used worldwide, especially in developing countries.

Energy intensity of concrete production and usage in construction

The energy intensity of concrete use in construction is mainly related to cement production. To reduce the energy intensity of the cement production process, in addition to process automation, proper maintenance, and operation of machinery and equipment, several technologies can be applied (e.g., more efficient grinding technologies or the use of waste heat to generate energy). Additionally, clinker can be replaced with other materials (e.g., calcinated clay) [23], or cement can be partially replaced, for example, with waste from combustion processes (i.e., slag or fly ash) [33].

The use of concrete in the construction sector in the context of a circular economy

In the context of a circular economy, concrete can be directly reused (in the form of structural elements, such as beams, floors, columns, large slabs, or concrete blocks used, for example, as garden slabs) and recycled in crushed form. In the case of recycled crushed concrete, one of the biggest challenges today is maintaining the required parameters of the final product [38]. Therefore, recycled concrete is often used in road construction or for non-load-bearing elements [33].

Environmental impact of concrete production and use in construction

The production and use of concrete in construction are associated with significant energy consumption and greenhouse gas emissions. According to a report by the ***Global Cement and Concrete Association*** [66], cement production is responsible for about 8% of global greenhouse gas emissions. Moreover, concrete manufacturing processes require energy and raw materials, such as water, which negatively impact the environment. However, energy use during concrete production can be reduced with technological innovations and the introduction of greener alternatives, such as using fly ash in concrete production.

Opportunities for recycling and reusing concrete in construction

Direct reuse of concrete elements as part of their original function: elements that are free of design, technological and functional defects can be reused as part of their original function, as exemplified by the use of existing walls, basement ceiling, elevator shaft, and entrance walkway in the Brunnerstasse 9 project by Brandlhuber & Emde & Burlon in Berlin, or the use of a large slab in a bungalow project in Berlin by Carsten Wiewiorra.

Direct reuse of concrete elements in other than its original function: concrete elements can also be used to serve a new function, such as using concrete blocks as garden and sidewalk slabs, as was the case with the Urban Outfitters HQ project by D.I.R.T. Studio in Pennsylvania, USA.

Recycling of crushed concrete: crushed concrete can be used as a source of unhydrated cement [23], waste aggregate [38] (which can be used for both structural and non-structural elements, such as drainage), and, ultimately, as a base for roads, parking lots or filling pits on a construction site [33].

CIRCULARITY ASSESSMENT

CIRCULAR BUILDING AND INDICATORS

The concept of circularity of buildings is not new; however, it has not yet received a comprehensive definition and is often understood in different ways. Usually, when talking about a **circular building,** we think of a building constructed and used without excessive use of natural resources and pollution of the environment. In doing so, not only material aspects are important, but also environmental and economic ones. In addition, factors related to the buildings' function, versatility, and adaptability to different uses are important.

The above description indicates the direction the construction sector should follow rather than defining the concept of a circular building. Evaluating the circularity of a given building is problematic, as is comparing two different designs in terms of compliance with the goals of a circular economy.

It is, therefore, advisable to create a mechanism for assessing circularity based on indicators relating to individual phenomena and processes. Creating a final indicator that would be the ultimate measure of circularity is also desirable. Such indicators can be used as a basis for evaluation and comparison and as an element of support for decision-making.

A technical, economic, social, and environmental assessment determines the rationale and effectiveness of any project. Circularity assessment is a new, additional element. It is somewhat related to environmental assessment; however, it is not intended to replace it **but to supplement it with elements closely related to circularity in terms of the efficient use of materials and the implementation of the main principles of CE.**

The mechanism for assessing circularity is based on Life Cycle Thinking (LCT) and the principles of the circular economy, including, in particular, the ReSolve scheme.

From the point of view of evaluation, it is essential to assess the quality of *closing the loops*, that is, to guarantee the appropriate use of raw materials, waste, and, in particular, the reuse of building components so that raw materials are kept in circulation for as long as possible while maintaining their value as high as possible.

Circularity is associated not only with the efficient use of raw materials but with the implementation of new functionality trends, consequently leading to the optimization of raw material use. An example of this is the optimization of the organization and use of space so that it can be shared, adapted straightforwardly and without high additional economic and environmental costs to serve different functions, and easily expanded.

> A COMPREHENSIVE EVALUATION OF CONSTRUCTION PROJECTS MUST BE BASED ON ENVIRONMENTAL ANALYSIS (LCA), CIRCULARITY ANALYSIS, ECONOMIC ANALYSIS (LCC), AND TECHNICAL ANALYSIS. CIRCULARITY EVALUATION SHOULD THEREFORE BE CONSIDERED A NEW ELEMENT TO MORE OBJECTIVELY SUPPORT THE DECISION-MAKING PROCESS BY CONSIDERING THE LATEST TRENDS IN IMPLEMENTING SUSTAINABLE DEVELOPMENT PRINCIPLES.

▼ Figure 14. The place and role of the circularity assessment process

CIRCULAR BUILDING – DEFINITION

Circular construction should be based on good practices, which mainly include minimizing the use of mineral resources, reducing energy consumption, not using toxic materials, and being that materials and raw materials are limited. In such an approach, the reuse of the entire building and individual materials and components should always come first, and recycling should be a last resort.

Social welfare, environmental concerns, and economic factors support such a concept. Business-wise, the circular model in construction enables treating buildings and structures as material banks from which the financial value can be recovered in the future. Creating an appropriate database with complete information on the raw materials, parts, and materials in the building enables optimizing building maintenance and further investment in circular construction. It also aligns with new regulations being prepared in the EU.

To be able to talk about circular construction, it is necessary to develop a definition of a circular building, especially since there is no such definition in the current state of the law. The authors of the guide, relying on the knowledge of experts from different areas of construction, their own experience, and an extensive review of the literature on circularity, present the developed definition, which might be helpful to stakeholders in the construction sector in discussions and efforts to implement CE in construction.

Constructing a 100% circular building is very difficult and downright impossible with the current state of the construction sector. Nevertheless, the goals set out in the below definition, which should be pursued, should guide the actions taken throughout the building's life cycle.

A CIRCULAR BUILDING IS A BUILDING THAT, THROUGHOUT ITS LIFE CYCLE, DOES NOT DEPLETE THE EARTH´´S NON-RENEWABLE RESOURCES AND DOES NOT DEGRADE THE ECOSYSTEM

To achieve this, the building should:

- **be designed, operated, and dismantled following the above principle**
- **be made entirely of materials that were already in use**
- **be energy efficient in the construction and use phases, and be based on renewable energy that does not deplete the Earth's non-renewable resources over its entire life cycle**
- **minimize waste generation during the construction and use phases**
- **allow for its flexible use and expansion**
- **allow its reuse in whole, in parts, or as individual materials**

CIRCULARITY INDICATORS

The circularity of buildings can be assessed using circular indicators, which measure the CE to various extents. According to the OECD nomenclature, an indicator is ***a quantitative or qualitative factor or variable that provides a simple and reliable way to measure achievements, reflects changes related to implementation, or helps assess the results achieved.***

The main advantages of the circularity assessment approach in construction include greater attention to the renewability of resources used during the construction phase, a greater focus on the use phase and reusability of materials, and the introduction of an assessment of the recyclability of materials after use. Existing indicators mostly rely only on information on the mass of recycled or recyclable materials or the renewability/non-renewability of the materials used and do not consider the actual environmental impact of buildings (most often considering only energy aspects).

The most widely accepted indicator worldwide for circularity in construction is the **Material Circularity Indicator (MCI)** [11]. It is based on three main parameters, describing:

- the origin and quantity of the raw material
- product use (lifespan)
- amount of non-recyclable waste generated

Complementing MCI is the Disassembly Determining Factors (DDF) indicator, and they together form the Product Circularity Indicator (PCI). The DDF index identifies opportunities for independent disassembly of materials during the product design phase, focusing on function integration and connection types. For example, the potentially high MCI score of recycled wall tiles will be significantly reduced because the chemical connections cannot be easily disassembled without damage.

Products are also classified into systems based on building layers, according to Brand's Theory of Layers [2]. The relative amount of each product in a system is determined by its mass. System Circularity Indicators (SCIs) are multiplied by a life factor (which varies by layer), yielding the Building Circularity Indicator (BCI), which applies to the entire building. In circularity assessments, especially in the BCI assessment, the building layer's service life significantly impacts the building circularity score. Building materials in the space plan or sheathing are replaced more often (shorter functional life) than materials in the structure (longer life), so their impact on the total building circularity score is greater. Another critical factor is the mass of the building material, which, relative to the total mass of the building layer, determines its impact on the layer's circularity. As a result, stone materials have a greater impact on circularity than, for example, insulation materials and wood products such as window frames and stairs.

The BCI currently appears to be the most comprehensive tool for measuring the circularity of buildings [29]. Still, it is important to note that it considers only material aspects (materials from which the building is constructed) and does not address the functionality of the building (e.g., optimizing the organization and use of space).

The most popular indicators discussed above, developed by various research centers, vary in their usefulness depending on the purpose of the analysis (i.e., existing or newly constructed buildings), the type of building (i.e., residential, public, historical), the level covered (i.e., material, product or building level) and, as already mentioned, most often use quantitative methods and do not address qualitative methods (i.e., social aspects such as health, culture, well-being).

To date, no standardized methodology has been developed for circularity indicators, and existing ones vary in terms of the scale of application, the scope adopted, and the definition of circularity, and they are still under discussion.

The indicators developed and presented below result from an in-depth analysis of the problem and are based on the best knowledge of CE in the construction industry regarding material and functional areas. The proposed indicators are a new take on the problem but build upon existing knowledge and developed measurements so far. The selection of indicators and their shape were repeatedly consulted with a wide range of practitioners and representatives of construction industry companies.

The indicators developed in this guide describe the various elements of circularity.

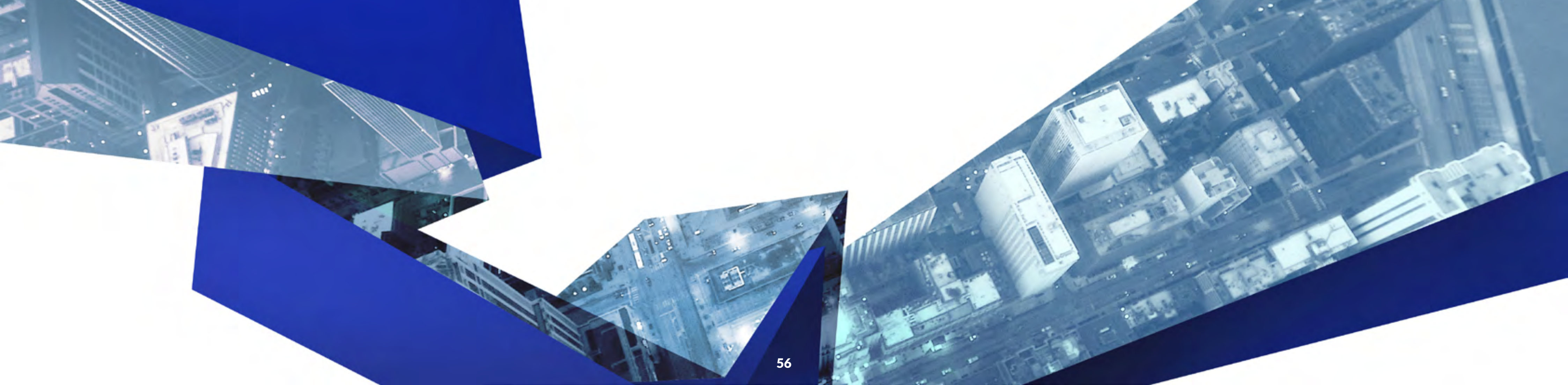
Accordingly, an entirely circular building is one for which all indicators have maximum values.

The assessment of the circularity of a construction project is based on the calculation of sub-indices related to the material area and the functional area. Based on the sub-indices, the final indicator can be calculated.

THE SUB-INDICATORS ARE:

- **SMU** – SECONDARY MATERIALS USE INDICATOR
- **MRP** – MATERIALS REUSABILITY POTENTIAL INDICATOR
- **SR** – SPATIAL REVERSIBILITY INDICATOR
- **SSP** – SPACE SHARING POTENTIAL INDICATOR

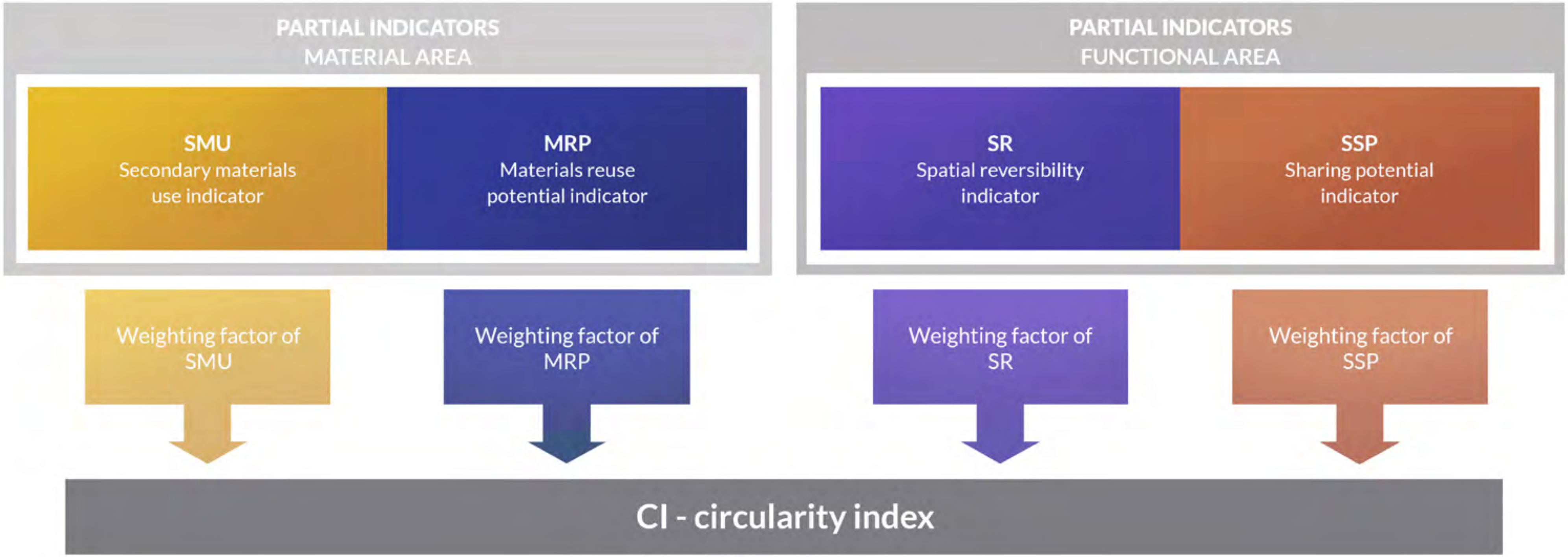
The SMU indicator illustrates the processes involved in the construction process; the **SR and SSP indicators** are related to the building operation, and the **MRP** indicator is related to the end-of-life stage. They, therefore, cover the entire life cycle. However, all building circularity measures must be planned at the design stage. Indicators should be calculated as early as the investment planning stage and adjusted during further project development.



▲ Figure 15. Relationship between circularity indicators and life cycle

All of the above-mentioned indicators can be aggregated into a single Circularity Index (CI), a measure of a building's circularity. Achieving a CI value of 100% means that the building is fully circular.

▼ Figure 16. Indicator evaluation scheme



SMU - SECONDARY MATERIALS USE INDICATOR

An important element in the concept of building circularity is the minimization of the use of primary raw materials. It means that one should strive for a situation in which new buildings are constructed from materials that have already been used - that is, recycled materials and those that have been reused as material or building elements.

To meet the assumptions of circularity to the fullest extent, a building should be built with 100% secondary materials, that is, materials that do not come directly from primary sources. If this is not possible, we should strive to make the percentage of secondary materials used as high as possible.

However, it should be noted that materials are qualitatively different, for example, in terms of their scarcity, availability, or associated market value. Hence, treating all materials as equally valuable would be a mistake, and it is reasonable to conduct quantitative and qualitative evaluations. The Abiotic Depletion Potential (ADP), used in environmental analyses, can be used to measure the weight of individual materials. It is determined based on individual raw materials' consumption and global resources, which are related to a reference resource, antimony (Sb). It determines the potential for depletion of non-renewable resources (i.e., minerals, oil, natural gas, metals) due to the extraction and processing of resources needed to produce a given material. ADP considers the quantity and quality of the resources consumed and their potential renewal time. The higher the ADP for a given material, the greater the depletion of the Earth's natural resources and, thus, the greater the burden on the environment.

MINERAL DEPLETION IS A WIDELY RECOGNIZED IMPACT CATEGORY IN VARIOUS ENVIRONMENTAL IMPACT EVALUATION METHODOLOGIES.

Using the indicator of mineral depletion (ADP) makes it possible to evaluate quantitatively and qualitatively. By analogy with economic analysis, we can say that ADP is a measure of value, a kind of „environmental price" of a given material. For example, suppose we use two materials and want to determine their value. In that case, we have to have information on their quantity (e.g., kg) and unit price (i.e., related to the volume of the material, e.g., EUR/kg). Similarly, in the case of circularity assessment, knowledge of quantities of individual substances is not enough. We need to consider both the quantities of material (e.g., kg) and their „unit environmental price," which is ADP (expressed in kg Sb/kg).

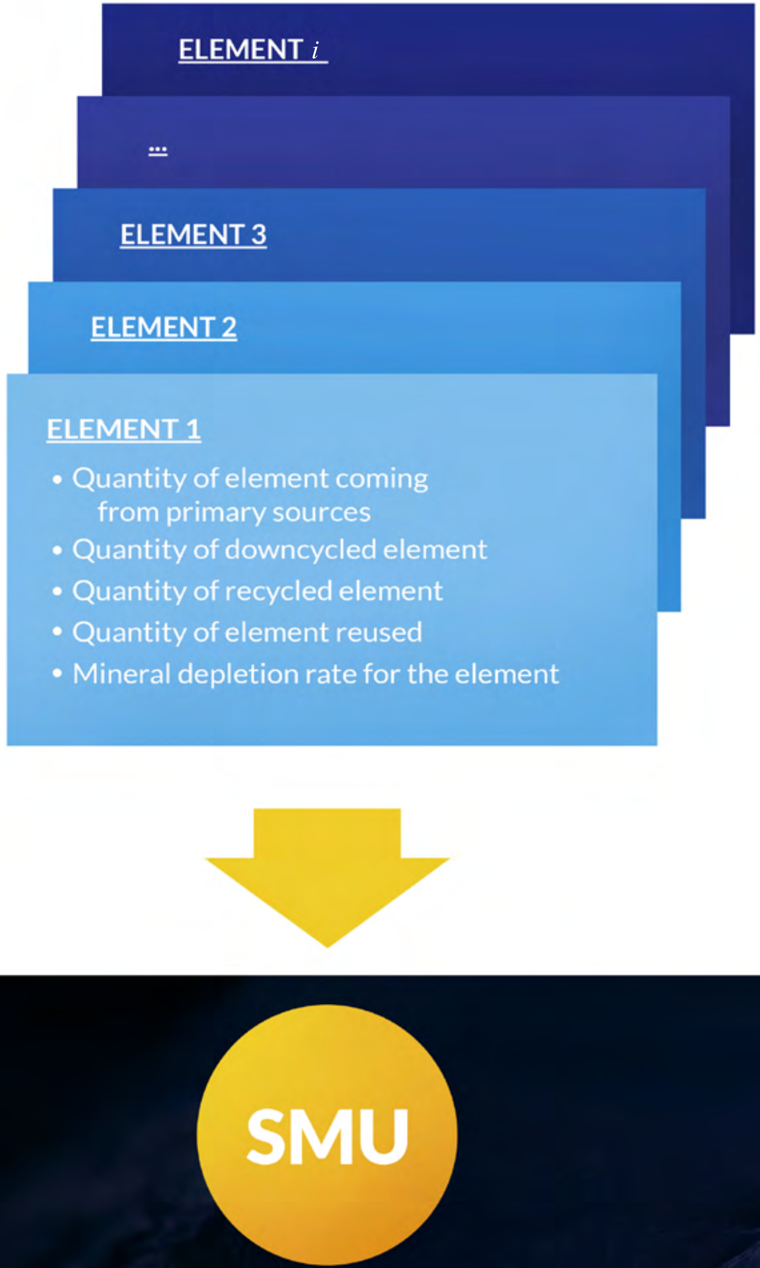
The primary objective of circularity is to conserve primary raw materials, making it crucial to distinguish between recycled, downcycled, and reused materials. Recycling typically involves applying technological processes, such as the preparation of materials, which often require electrical energy to grind aggregates sourced from demolished buildings. This energy consumption further necessitates the use of raw materials for its generation. On the contrary, if materials are reused, for instance, in the form of finished components, there is no need for extensive adaptations. Structural steel beams are a prime example of such reuse, as they can be directly utilized without any modifications. Therefore, acknowledging the disparities between reuse, recycling, and downcycling becomes vital in the assessment process of circularity.

SMU is the sum of the magnitudes (e.g., masses) of the individual components that make up a building, taking into account their value from an environmental point of view as well as the source of origin, and related to the sum of the magnitudes of all these components also taking into account their environmental value.

To be conclusive, the indicator **should take into account all elements of the building.** *An element* can be any finished element (window, door, structural elements) and materials such as sand, gravel, or cement. From the evaluation process's point of view, the individual material and the entire structural element are treated in the same way. For each such element, it is necessary to know the APD of the whole element (expressed in kg Sb/functional unit of the element). The functional unit of the element or item quantity (IQ) can be weight (in the case of basic materials such as cement, sand, etc.), surface area (in the case of finished items such as specific roofing), or piece (in the case of finished items with specific dimensions).

> THE SMU SECONDARY RAW MATERIAL USE INDICATOR MEASURES THE SHARE OF SAVED RAW MATERIALS EXPRESSED IN TERMS OF ANTIMONY EQUIVALENT WEIGHT UNIT. THUS, IT CONSIDERS NOT ONLY THE WEIGHT OF THE RAW MATERIALS SAVED BUT ALSO THEIR IMPORTANCE FROM THE POINT OF VIEW OF THEIR SCARCITY.

▼ Figure 17. Schematic diagram of the determination of the SMU indicator



The SMU indicator refers to the construction phase.

The Secondary Materials Use indicator is defined as follows:

$$SMU = \frac{\sum_i (M_{i,reu} \cdot WF_{reu} + M_{i,upc} \cdot WF_{upc} + M_{i,rec} \cdot WF_{rec} + M_{i,downc} \cdot WF_{downc}) \cdot ADP_i}{\sum_i (M_i \cdot ADP_i)} \cdot 100\%$$

where:

M_i – total amount of material/element i [IQ – item quantity, e.g., kg, m^3, m^2, or pc.]
$M_{i,reu}$ – quantity of material/element i from reuse [IQ]
$M_{i,upc}$ – quantity of material/element i from upcycling [IQ]
$M_{i,rec}$ – quantity of material/element i from recycling [IQ]
$M_{i,downc}$ – quantity of material/element i from downcycling [IQ]
ADP_i – abiotic Depletion Potential value for the material/element i [kg Sb_{eq}/IQ] – according to the attachment to this study or according to the EPD declaration (phases A1-A3)
WF_{reu} – weight factor related to material from reuse [–]
WF_{upc} – weight factor related to material from upcycling [–]
WF_{rec} – weight factor related to material from recycling [–]
WF_{downc} – weight factor related to material from downcycling [–]

The values of weight factors were developed based on the discussions with a panel of experts from the construction industry and are as follows:

- reuse: WF_{reu} = 1.0
- upcycling: WF_{upc} = 0.7
- recycling: WF_{rec} = 0.6
- downcycling: WF_{downc} = 0.3

The ADP values are not always easy to obtain. If no such data is available, the simplified evaluation methodology can be adopted, which does not consider the environmental *value of* individual materials due to their availability in the environment. Thus, such a solution has disadvantages, but sometimes it may prove to be the only option with limited availability of information. In the simplified evaluation methodology, the mass units of the materials used are the basis.

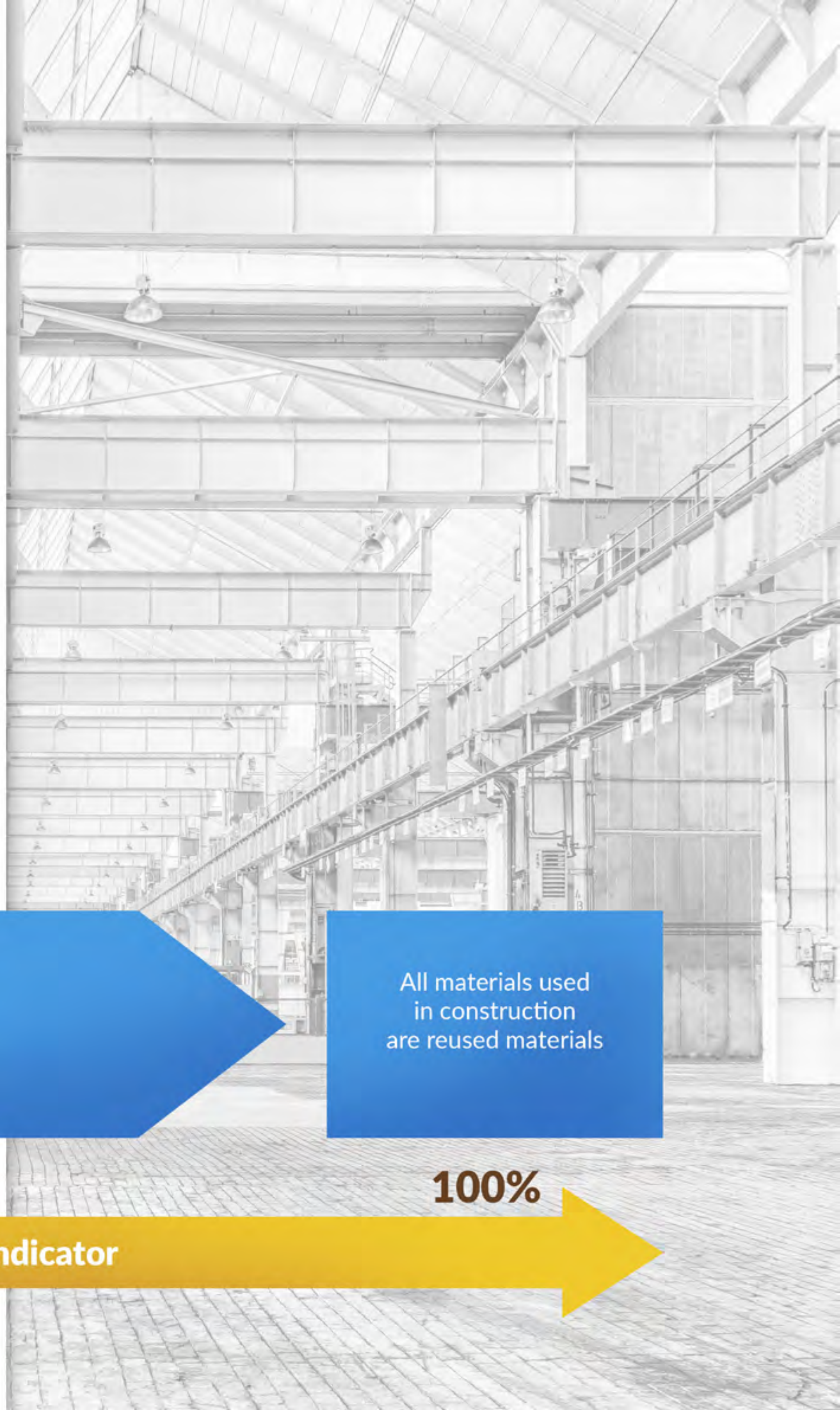
SMU indicator relates to construction stage

The simplified Secondary Materials Use indicator (SMU_s) is defined as follows:

$$SMU_s = \frac{\sum_i (M_{i,reu} \cdot WF_{reu} + M_{i,upc} \cdot WF_{upc} + M_{i,rec} \cdot WF_{rec} + M_{i,downc} \cdot WF_{downc})}{\sum_i M_i} \cdot 100\%$$

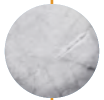
In the above formula, consider only those elements for which the quantity of an element (IQ) is expressed in a unit of mass. If we have information about the quantity of some elements in another unit (e.g., pieces of steel elements, etc.), estimating their mass is necessary for calculation.

▼ Figure 18. Illustration of the state of 0 and 100% circularity of the SMU indicator and factors affecting its improvement



EXAMPLE

The following materials were used for construction:



CEMENT
5 t (ADP = 1,10e^{-06} Mg_{Sb}/t)
entirely from raw materials

SAND AND GRAVEL
40 t (ADP = 2,26e^{-09} Mg_{Sb}/t)
30 t raw material and 10 t reused material

BRICKS
40 t (ADP = 1,13e^{-07} Mg_{Sb}/t)
10 t raw material and 30 t reused material

FABRICATED METAL COMPONENTS
4 t (ADP = 3,79e^{-06} Mg_{Sb}/t)
2 t raw material and 2 t recycled material

For such conditions, the calculations are as follows:

$$\sum_i (M_{i,reu} \cdot WF_{reu} + M_{i,upc} \cdot WF_{upc} + M_{i,rec} \cdot WF_{rec} + M_{i,downc} \cdot WF_{downc}) \cdot ADP_i =$$
$$= 10 \cdot 1 \cdot 2.26e^{-09} + 30 \cdot 1 \cdot 1.13e^{-07} + 2 \cdot 0.6 \cdot 3.79e^{-06} = 7.96e^{-06} [tSb_{eq}]$$

$$\sum_i (M_i \cdot ADP_i) = 5 \cdot 1.10e^{-06} + 40 \cdot 2.26e^{-09} + 40 \cdot 1.13e^{-07} + 4 \cdot 3.79e^{-06} =$$
$$= 2.53e^{-05} [tSb_{eq}]$$

$$SMU = \frac{7.96e^{-06}}{2.53e^{-05}} \cdot 100\% = 31.5\%$$

The obtained value means that the evaluated design is circular regarding the use of secondary materials in 31.5%. In other words: thanks to the use of secondary materials, it was possible to avoid the consumption of 31.5% of antimony-equivalent weight compared to the case in which all materials consumed came from primary sources.

Note that the calculated indicator should capture **all materials and elements of the** building under evaluation. The above example is simplified for clarity of the message.

For the above case, the simplified indicator SMU_S, which takes into account only material and elements masses, is as follows:

$$\sum_i (M_{i,reu} \cdot WF_{reu} + M_{i,upc} \cdot WF_{upc} + M_{i,rec} \cdot WF_{rec} + M_{i,downc} \cdot WF_{downc}) =$$
$$= 10 \cdot 1 + 30 \cdot 1 + 2 \cdot 0.6 = 41.2 [t]$$

$$\sum_i M_i = 5 + 40 + 40 + 4 = 89.0 [t]$$

$$SMU_S = \frac{41.2}{89.0} \cdot 100\% = 46.3\%$$

The value of the simplified indicator SMU_S is significantly higher than that of the SMU indicator (the circularity of 46.29% vs 31.50%). It means it was possible to „save" 46.29% of the total mass of raw materials used in construction.

The lower SMU value than that of SMU_S is mainly caused by the fact that cement is much more environmentally valuable (in the sense of resource depletion) than other materials (ADP =1.1E^{-06} kg Sb/kg cement). Thus it affects the value of the SMU indicator much more than other materials.

MRP – MATERIALS REUSABILITY POTENTIAL INDICATOR

A well-designed building should include easy and efficient end-of-life use of materials. The more reused materials, the less waste is generated, and fewer primary raw materials will be used on future construction sites.

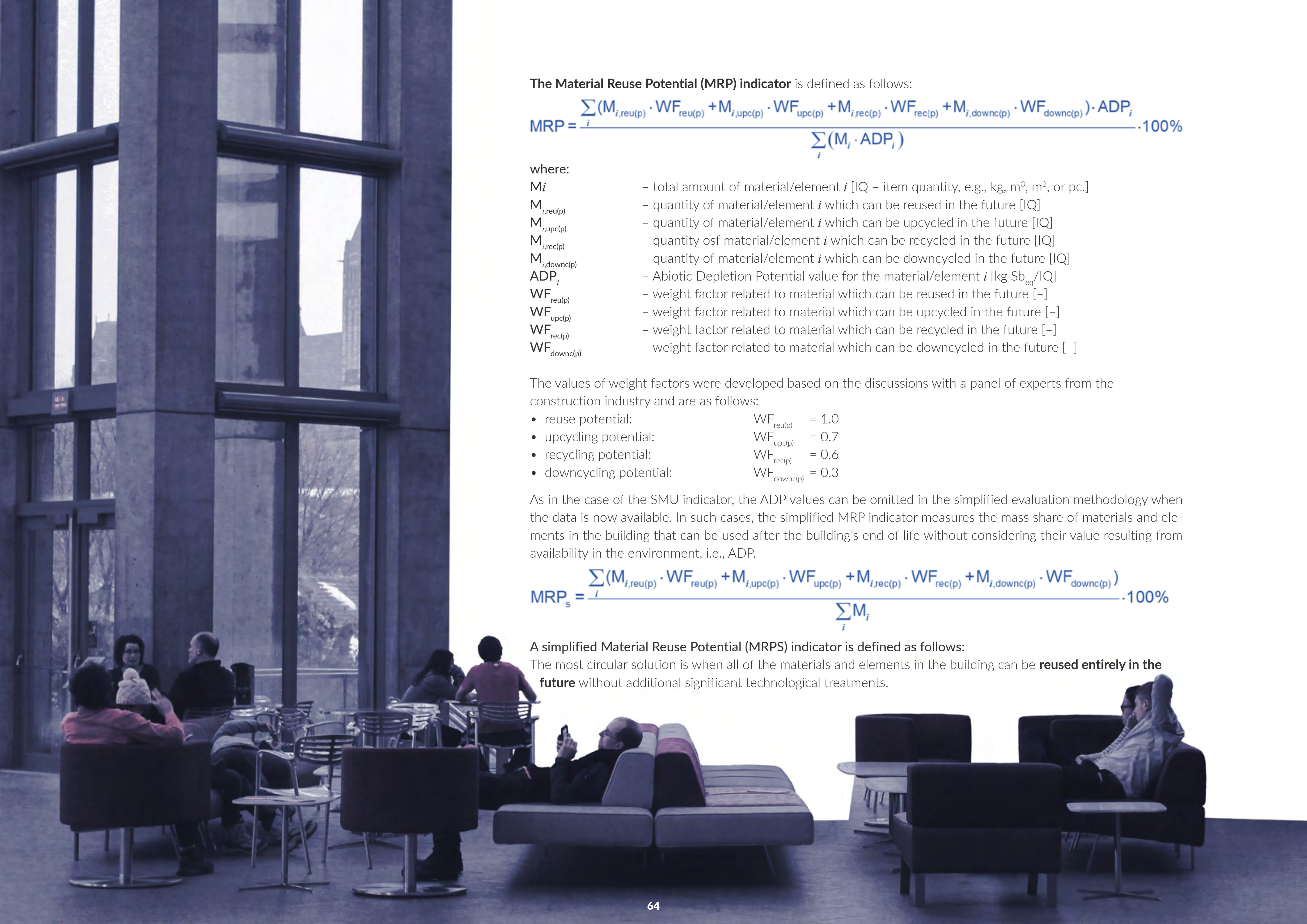
Thanks to a circular design, materials in buildings can retain their value as the buildings become banks of valuable materials, preventing waste of materials.

The MRP indicator describes to which extent the materials used in the building construction can be used in the future and thus contribute to resource conservation. It is, therefore, a measure of the potential for future use of materials used in construction.

The indicator in its design is similar to the SMU indicator. It considers all building materials and elements with their ADP mineral depletion potential. Unlike SMU, however, it considers the **future possible** use of the materials and elements rather than their origin.

The MRP refers to the end-of-life stage of a building's life.

▼ Figure 19. Illustration of the state of 0 and 100% circularity of the MRP indicator and factors affecting its improvement



The Material Reuse Potential (MRP) indicator is defined as follows:

$$MRP = \frac{\sum_i (M_{i,reu(p)} \cdot WF_{reu(p)} + M_{i,upc(p)} \cdot WF_{upc(p)} + M_{i,rec(p)} \cdot WF_{rec(p)} + M_{i,downc(p)} \cdot WF_{downc(p)}) \cdot ADP_i}{\sum_i (M_i \cdot ADP_i)} \cdot 100\%$$

where:

M_i	– total amount of material/element *i* [IQ – item quantity, e.g., kg, m^3, m^2, or pc.]
$M_{i,reu(p)}$	– quantity of material/element *i* which can be reused in the future [IQ]
$M_{i,upc(p)}$	– quantity of material/element *i* which can be upcycled in the future [IQ]
$M_{i,rec(p)}$	– quantity osf material/element *i* which can be recycled in the future [IQ]
$M_{i,downc(p)}$	– quantity of material/element *i* which can be downcycled in the future [IQ]
ADP_i	– Abiotic Depletion Potential value for the material/element *i* [kg Sb_{eq}/IQ]
$WF_{reu(p)}$	– weight factor related to material which can be reused in the future [–]
$WF_{upc(p)}$	– weight factor related to material which can be upcycled in the future [–]
$WF_{rec(p)}$	– weight factor related to material which can be recycled in the future [–]
$WF_{downc(p)}$	– weight factor related to material which can be downcycled in the future [–]

The values of weight factors were developed based on the discussions with a panel of experts from the construction industry and are as follows:

- reuse potential: $WF_{reu(p)} = 1.0$
- upcycling potential: $WF_{upc(p)} = 0.7$
- recycling potential: $WF_{rec(p)} = 0.6$
- downcycling potential: $WF_{downc(p)} = 0.3$

As in the case of the SMU indicator, the ADP values can be omitted in the simplified evaluation methodology when the data is now available. In such cases, the simplified MRP indicator measures the mass share of materials and elements in the building that can be used after the building's end of life without considering their value resulting from availability in the environment, i.e., ADP.

$$MRP_s = \frac{\sum_i (M_{i,reu(p)} \cdot WF_{reu(p)} + M_{i,upc(p)} \cdot WF_{upc(p)} + M_{i,rec(p)} \cdot WF_{rec(p)} + M_{i,downc(p)} \cdot WF_{downc(p)})}{\sum_i M_i} \cdot 100\%$$

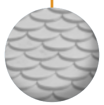
A simplified Material Reuse Potential (MRPS) indicator is defined as follows:

The most circular solution is when all of the materials and elements in the building can be **reused entirely in the future** without additional significant technological treatments.

EXAMPLE

The building structure includes the following materials:

BRICKS
30 t (ADP = 1,13E^{-07} Mg_{Sb}/Mg)
10 t reusable and 20 t recyclable



CERAMIC ROOF TILES
2 t (ADP=4,58E^{-05} Mg_{Sb}/Mg),
100% reusable

For such conditions, the calculations are as follows:

$$\sum_i (M_{i,reu(p)} \cdot WF_{reu(p)} + M_{i,upc(p)} \cdot WF_{upc(p)} + M_{i,rec(p)} \cdot WF_{rec(p)} + M_{i,downc(p)} \cdot WF_{downc(p)}) \cdot ADP_i =$$

$$= (10 \cdot 1 + 20 \cdot 0.6) \cdot 1.13e^{-07} + 2 \cdot 1 \cdot 4.58e^{-05} = 9.41e^{-05} [tSb_{eq}]$$

$$\sum_i (M_i \cdot ADP_i) = 30 \cdot 1.13e^{-07} + 2 \cdot 4.58e^{-05} = 9.50e^{-05} [tSb_{eq}]$$

$$MRP = \frac{9.41e^{-05}}{9.50e^{-05}} \cdot 100\% = 99.1\%$$

For the above case, the simplified indicator MRPs, which takes into account only material and elements masses, is as follows:

$$\sum_i (M_{i,reu(p)} \cdot WF_{reu(p)} + M_{i,upc(p)} \cdot WF_{upc(p)} + M_{i,rec(p)} \cdot WF_{rec(p)} + M_{i,downc(p)} \cdot WF_{downc(p)}) =$$

$$= 10 \cdot 1 + 20 \cdot 0.6 + 2 \cdot 1 = 24 \, [t]$$

$$\sum_i M_i = 30 + 2 = 32 \, [t]$$

$$MRP_S = \frac{24}{32} \cdot 100\% = 75\%$$

Note that the calculated indicator should include **all materials and elements of the building.** The above example is simplified for clarity of the message.

In the example shown above, the MRPs and MRPs are significantly different from each other, due to the relatively high ADP of the tiles, which at the same time can be fully reused.

SR – SPATIAL REVERSIBILITY INDICATOR

Spatial and structural transformations, as a change in the function of a building and their impact on the building structure, are analyzed at the feasibility and preliminary design stage. During design, the adaptability of the space and building structure to various functions **without causing major reconstruction work, demolition, and material losses** should be ensured. The less effort required to transform a building and the greater the variety and number of modification options, the higher its transformation potential (building reuse options). Consequently, the greater the transformation potential, the more compatible the solution is with the circular economy concept and the more significant impact on reducing the use of primary raw materials.

Three main types of possible transformation [55] can be distinguished:

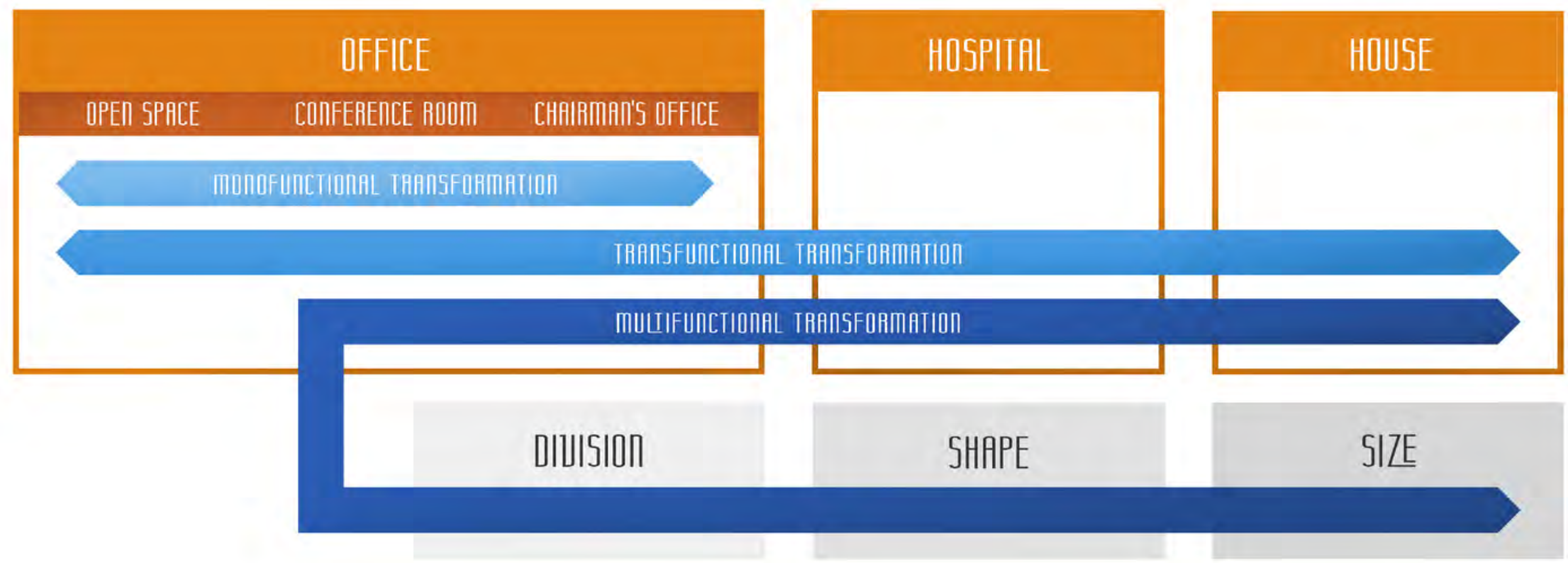
- monofunctional
- transfunctional
- multidimensional.

Monofucational transformation is the ability to transform the layout of a building within a single function. For example, an office building with traditional room divisions can be transformed into an open office or meeting room without extensive adaptation work [55].

Transfunctional transformation is the ability to transform the function of the building. For example, an office building can be transformed into an apartment building, school, or other public building [55].

Multidimensional transformation is the ability to transform a building's function by expanding it, changing its size, modifying its shape, or even moving the building to another location [55].

▼ Figure 20. Schematic diagram of different types of transformation



The Spatial Reversibility (SR) indicator refers to the use phase and describes the extent to which a building's floor space can be used in other functions than planned initially.

The spatial reversibility indicator is defined as follows:

$$SR = \frac{A_{mono(t)} \cdot WF_{mono(t)} + A_{trans(t)} \cdot WF_{trans(t)} + A_{multi(t)} \cdot WF_{multi(t)}}{A_{tot}} \cdot 100\%$$

where:

$A_{mono(t)}$ – the usable area in the building which can be transformed monofunctional [m^2]
$A_{trans(t)}$ – the usable area in the building which can be transformed transfunctional[m^2]
$A_{multi(t)}$ – the usable area in the building which can be transformed multi–dimensional [m^2]
A_{tot} – the total usable area of the building [m^2]
$WF_{mono(t)}$ – weight factor related to the area which can be transformed monofunctional [–]
$WF_{trans(t)}$ – weight factor related to the area which can be transformed transfunctional [–]
$WF_{multi(t)}$ – weight factor related to the area which can be transformed multi–dimensional [–]

The values of weight factors were developed based on the discussions with a panel of experts from the construction industry and are as follows:

- monofunctional transformation: $WF_{mono(t)} = 0.5$
- transfunctional transformation: $WF_{trans(t)} = 0.8$
- multi–dimensional transformation: $WF_{multi(t)} = 1.0$

The SR indicator will reach 100% when the whole building's usable area can be multidimensionally transformed. Such a situation is most in line with the concept of a circular economy and is most desirable.

EXAMPLE

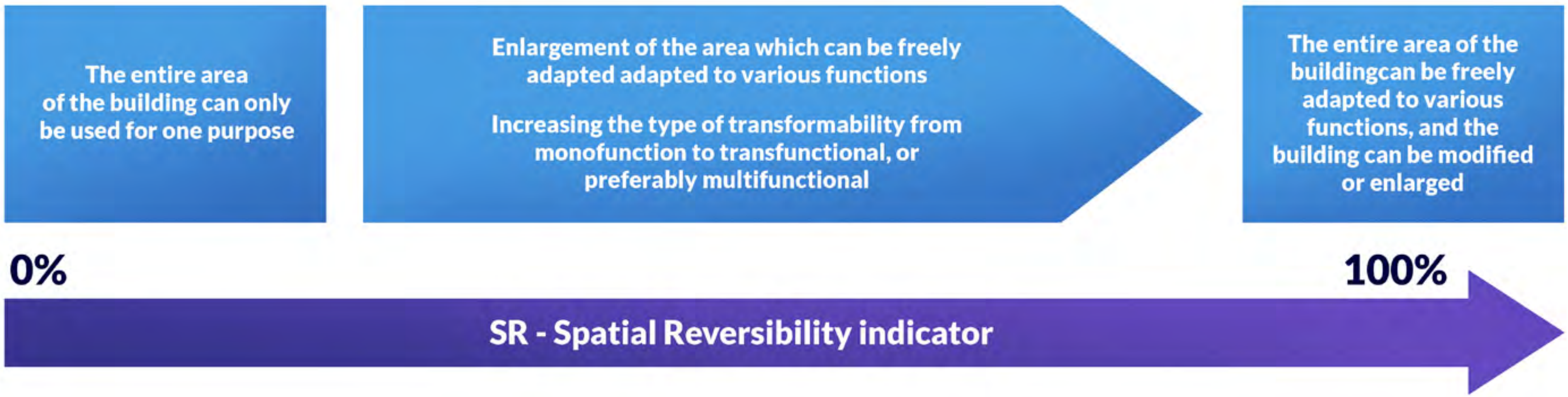
The total usable area of the office building is 1200 m^2. It was designed so that a significant part (1000 m^2) could be easily transformed and adapted to various purposes but falling within the scope of office activities. The rest of the building is fully adaptable to various functions - so it can be used as an office but also for residential purposes. The building has such a structure that there is no possibility of changing its shape and size.

In the case of this building, 1000 m^2 can be transformed monofunctionally, and the rest (200 m^2) multidimensionally.

$$SR = \frac{1000 \cdot 0.5 + 200 \cdot 1}{1200} \cdot 100\% = 58.3\%$$

For such conditions, the calculations are as follows:
As can be seen from the above example, full spatial reversibility can be achieved if the design enables not only modification of the layout within a single function (in the analyzed case – office function) but also has the potential for multidimensional transformation with the possibility for expansion and change of area.

▼ Figure 21. Illustration of the state of 0 and 100% circularity of the SR index and factors affecting its improvement



SSP – SPACE SHARING POTENTIAL INDICATOR

Space sharing plays an important role in the concept of a circular economy as it significantly reduces the need for new constructions by optimizing the use of existing ones. As a result, this leads to a considerable reduction in the consumption of mineral resources. In the design, sharing areas that are not ordinarily shared (such as, for instance, corridors, elevators, staircases, or lobbies) should be considered.

The Space Sharing Potential indicator is defined as follows:

$$SSP = \frac{A_{sh}}{A_{tot}} \cdot 100\%$$

where:

A_{sh} – the usable area of the building that can be shared [m^2]

A_{tot} – the usable area of the building [m^2]

The case in which the usable space is suitable for potential sharing (SSP = 100%) aligns the most with the circular economy concept.

The SSP indicator refers to the use phase

EXAMPLE

The total usable area of the office is 60 m^2. The area is divided into two parts. In the first part, there are built-in cabinets, plus massive desks. In the second part (29 m^2), the area is free of installations and permanent buildings that can be shared.

$$SSP = \frac{29}{60} \cdot 100\% = 48.3\%$$

▼ Figure 22. Illustration of the state of 0 and 100% circularity of the SSP indicator and factors affecting its improvement

INDICATORS FOR BUILDINGS UNDERGOING RENOVATION

The process of evaluating buildings undergoing renovation is analogous to the process of evaluating new buildings (the same formulas can be used). Even though the method of calculating the indicators is similar, it has some differences in applicability as only the renovation scope and activities shall be considered in the indicators, so:

SMU_R

Secondary Materials Use indicator for renovation
is calculated for the raw materials that will be used to carry out renovation work

MRP_R

Materials Reusability Potential indicator for renovation
is calculated for the raw materials that will be used to carry out the renovation work

SR_R

Spatial Reversibility indicator for renovations
is calculated for the target state after renovation

SSP_R

Space Sharing Potential indicator for renovation
is calculated for the target state after renovation

CI – CIRCULARITY INDEX

A completely circular building is one for which all sub-indicators (SMU, MRP, SR, SSP) reach the highest value, i.e., 100%. As achieving the value of 100% is unfortunately difficult (even objectively impossible), it is worth choosing a scenario with the highest possible total circularity in the circular design.

It is worth noting that there may be situations where an assessment of circularity is not always unambiguous and straightforward. For example, when considering two different scenarios for the design of a circular building for the first scenario, we get two sub-indicators of circularity of almost 100% each and the other two of almost 0%, and the opposite in the second scenario. Which scenario is more circular? Here we are dealing with the issue related to the value of individual sub-indicators and their impact on the final Circularity Indicators (CI), which will always be subjective.

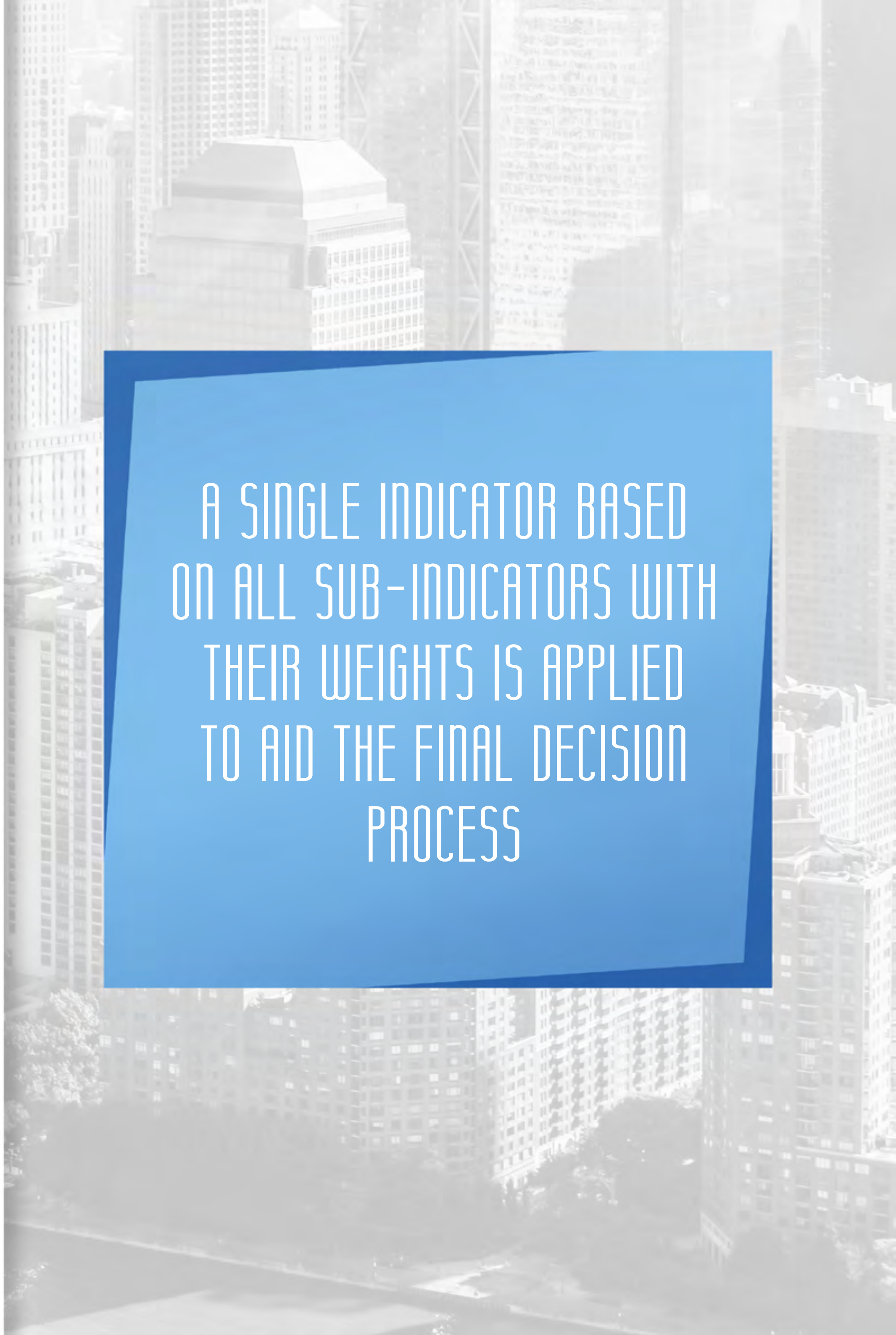
The CI circularity index can be determined from sub-indicators:

$$CI = \begin{cases} SMU \cdot WF_{SMU} + MRP \cdot WF_{MPR} + (0.7 \cdot SR + 0.7 \cdot SPP) \cdot WF_{USE} \\ \qquad \text{if } (0.7 \cdot SR + 0.7 \cdot SPP) \leq 100\% \\ SMU \cdot WF_{SMU} + MRP \cdot WF_{MPR} + WF_{USE} \cdot 100\% \\ \qquad \text{if } (0.7 \cdot SR + 0.7 \cdot SPP) > 100\% \end{cases}$$

where:

SMU – secondary Materials Use indicator [%]
WF_{SMU} – weight factor for SMU, $WF_{SMU} = 0.33$
MRP – materials Reusability Potential indicator [%]
WF_{MRP} – weight factor for MRP, $WF_{MRP} = 0.33$
SR – spatial Reversibility indicator [%]
SSP – space Sharing Potential indicator [%]
WF_{USE} – weight factor for SR and SSP considered collectively), $WF_{USE} = 0.34$

Choosing weight factors for individual sub-indicators is not easy and should be based on extensive discussion among construction experts and environmental impact analyses. The sub-indicator weights' values were developed based on discussions with a panel of experts from the construction industry. Sub-indicators related to materials are valued separately (each has an individual weight). In the case of the indicators relating to the utility and functionality of the building area, they are considered collectively. The combined weight of the SSP and SR indicators is 0.34. It means that the maximum value of this part of the circularity indicator can be obtained when, for example, one of the indicators is 100% or when both are 50% each. This approach was adopted due to the partial functional similarity of the two sub-indicators.



When presenting the result of CI calculations, the sub-indicator values shall also be presented.

A building that has a CI of 100% can be considered fully circular.

EXAMPLE

The following sub-indicators were calculated for the building:

SMU	MRP	SR	SSP
100%	75%	40%	80%

The weights of sub-indicators are:

WF_{SMU}	WF_{MRP}	WF_{USE}
0.33	0.33	0.34

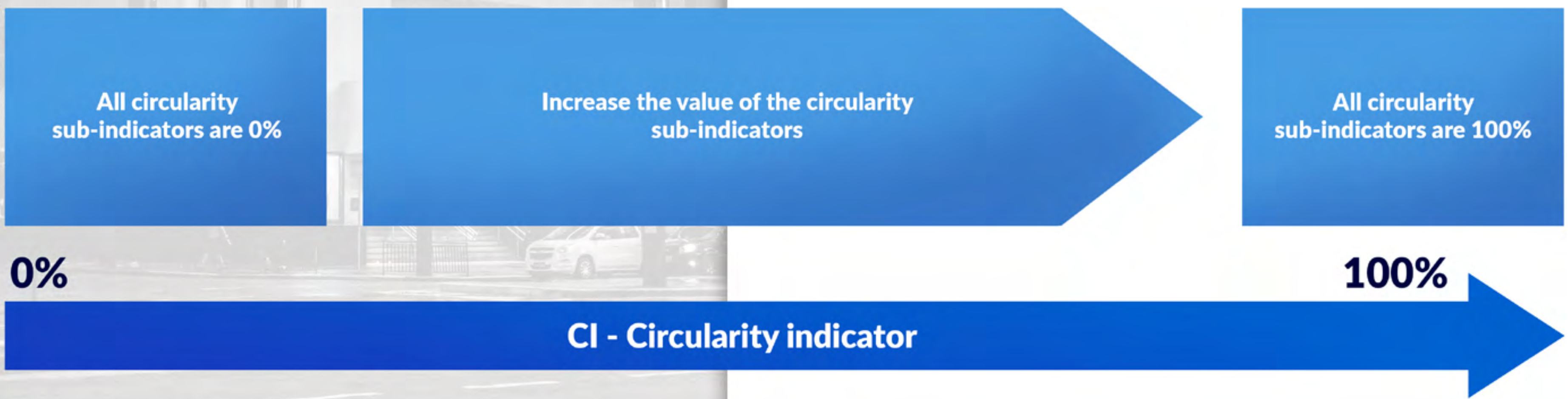
The Functionality Indicator (SF) has a value of 84%, calculated using the formula: SF = 0.7 · SR + 0.7 · SSP.

We can calculate the CI as follows:

$$(0.7 \cdot 40 + 0.7 \cdot 80) = 84\% < 100\% \Rightarrow$$

$$CI = 100 \cdot 0.33 + 75 \cdot 0.33 + (0.7 \cdot 40 + 0.7 \cdot 80) \cdot 0.34 = 86.3\%$$

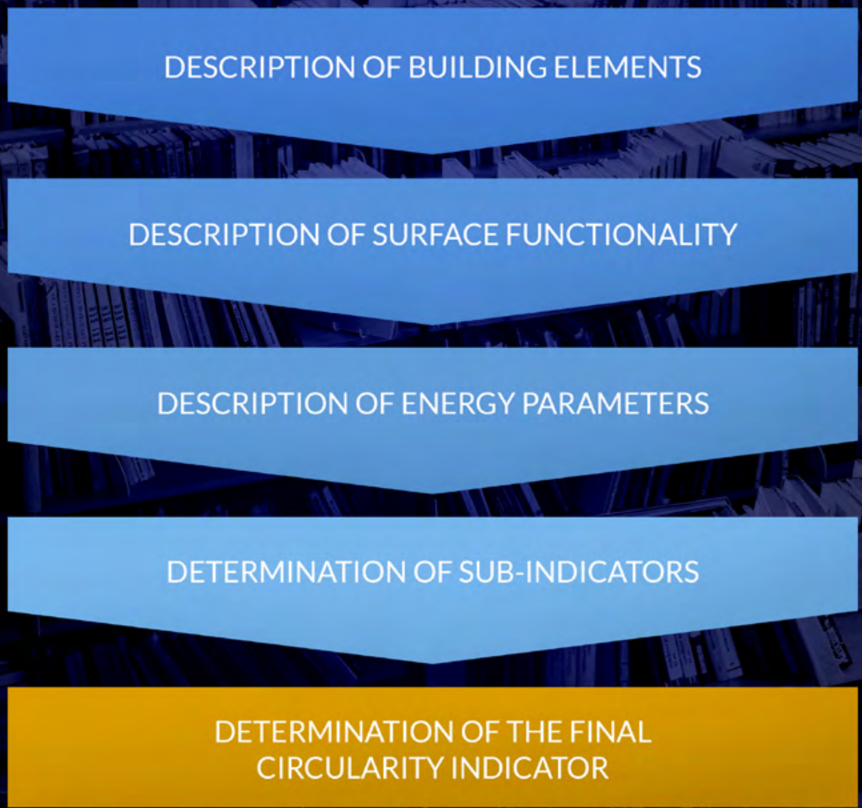
▼ Figure 23. Illustration of the state of 0 and 100% circularity and factors affecting its improvement



EVALUATION PROCESS

The building consists of several elements. These include walls, windows, doors, steel structures, etc. To calculate the circularity index, it is necessary to make a qualitative and quantitative inventory of these elements. It is essential to include as many elements as possible. For example, an element (item) can be considered a concrete block or any material used in its manufacture. This depends mainly on the availability of data. It is easier to use large elements if they have material passports and known ADP values. If we only have quantities of materials used to build the entire house - then each material should be treated as a separate element.

▼ **Figure 24.** Steps in the circularity assessment process



DESCRIPTION OF THE BUILDING ELEMENTS

In this step, it is necessary to specify:

1. The unit of measurement of the entire element, which depends on its type. It is often the unit of mass, but sometimes it can be, for instance, m^2.
2. The total amount of the element expressed in the unit of measurement defined above.
3. Input materials data. This data refers to the resources used to produce the material/element, including what part comes from secondary sources.
4. Output materials data. This data relates to the potential of the materials/elements to become secondary materials in the future.

DESCRIPTION OF SURFACE FUNCTIONALITY

1. The total area of the building.
2. The area that is monofuctionally, transfunctionally, and multidimensionally transformable.
3. The area that can be shared, for example, among several users.

DETERMINATION OF SUB-INDICATORS

After gathering the data on all of the materials/elements in the building, the sub-indicators (SMU - Secondary Materials Use indicator, MRP - Materials Reusability Potential indicator, SR - Spatial Reversibility indicator, and SSP - Sharing Space Potential indicator) can be calculated using the formulas presented in the previous chapters.

DETERMINATION OF THE FINAL CIRCULARITY INDEX

The final step is determining the final Circularity Index (CI) based on the sub-indicators values.

CASE STUDIES

The term "circular buildings" is relatively new, but activities and business models related to the circular economy in the construction industry have been around for several years. Investors and building material companies are increasingly introducing measures to ensure the use of selected recycled materials and the proper collection and sorting of construction waste with a view to recycling. Increasingly, selected buildings are being revitalized, preserving to a large extent the embedded construction and sometimes finishing materials. However, the measures taken are not standard practice, and the solutions implemented realize only a narrow aspect of circularity. It can be argued that fully circular buildings do not actually exist. It is hard to find examples of buildings that incorporate all the essential elements of circularity. They are excellent examples that fulfill the individual aspects of circularity to varying degrees and often introduce pioneering solutions within the framework of CE.

The best examples of circular buildings are presented on the following pages. Each example highlights the aspects of circularity present.

- **use of recycled materials:** reused, recycled materials or biomaterials were used in the construction or renovation of the building
- **potential for reuse:** the construction of the building was made with a view to dismantling it in the future or moving the building in whole or in part to another location
- **space sharing potential:** an area of the building or part of it is publicly accessible (so-called common areas) or available for occasional rental
- **spatial reversibility potential:** the structure and elements of the building or parts of it have been designed to change function in the future.

The above aspects of circularity are relevant to the areas assessed under the circularity indicators, but their values haven't been calculated because there isn't enough data. Instead, the examples present the best solutions for circular buildings, which can inspire future projects.

Moreover, additional examples of activities and buildings that fit into the principles of CE can be found on the Reduce Reuse Recycle platform, which contains more than 200 different examples.

DID YOU KNOW...

ARE COMPOSITE MATERIALS CIRCULAR?

According to a report by the Ellen MacArthur Foundation, 1% of all composite materials used in construction are recycled, while the rest are placed in landfills or incinerated. It is because composites are made of many permanently bonded materials, making it difficult to separate them into component materials for reuse or recycling. In addition, many composite materials contain hazardous chemicals, such as flame retardants or heavy metals, which must be removed before reuse or recycling. Therefore, recycling processes for these materials are among the most costly, time-consuming, and environmentally unfriendly. This show that the construction sector needs to develop better solutions toward a circular economy to reduce its dependence on non-recyclable composite materials.

ALLIANDER HQ

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Duiven, the Netherlands

Area:
21 852 m²

Designer:
RAU architects

Main aspects of circularity:
Reuse most existing buildings and materials/elements from them

Material passports used

Status:
operational

Building purpose:
office building

Type of work:
renovation

Year of completion:
2015

ASPECTS OF CIRCULARITY:

Alliander HQ is the first renovation project in the Netherlands to achieve BREEAM-NL Outstanding Sustainability certification. The facility is designed for 1,550 employees and has a floor area of 21,852 m². The complex was created by combining and renovating existing buildings on the site. The result is a large atrium that connects six different spaces and thus creates one meeting space. Large skylights were placed on the added roof, increasing daylight access in the atrium space. All facades of the existing buildings have been insulated. Large windows were placed on the new atrium's exterior walls to allow natural ventilation. Solar panels have been placed on the parking lot to act as a solar parking lot. The excess energy production over the building's energy needs feeds neighboring buildings in the area through a Smart Grid system.

Use of secondary raw materials

The project involved adapting and renovating existing facilities and integrating them with new structural elements. Materials/elements from the demolition of some of the existing structures on the project site were reused for the building expansion, such as:

- waste wood, which was used for facades
- concrete from some of the demolished parts of the buildings
- steel construction for the expansion of existing buildings
- recycled asphalt from existing roofs
- sanitary facilities
- ceiling tiles
- existing doors that were converted into furniture.

Potential for reuse of materials

A material passport was prepared for each material to increase the potential for reuse. A metal roof structure was used. It was designed for disassembly, minimizing the amount and weight of materials used.

Sources:

https://www.arch2o.com/alliander-hq-rau-architects/ (accessed: 05.05.2023)
https://www.archdaily.com/777783/alliander-hq-rau-architects (accessed: 05.05.2023)

BIOSINTRUM

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Oosterwolde, the Netherlands

Designer:
Paul de Ruiter Architects

Main aspects of circularity:
Biomaterials and recycled materials

Status:
operational

Building purpose:
mixed-use building
(7 conference rooms, lecture hall, restaurant, laboratory, offices)

Type of work:
new construction

Year of completion:
2018

ASPECTS OF CIRCULARITY:

The Biosintrum is a center of knowledge and innovation in the field of bioeconomy. The building is energy-neutral and was constructed with natural materials. The municipality of Ooststellingwerf issued a building permit for the Biosintrum as part of ECOmunity Park (an ecological business park) in 2016. Amsterdam-based architect Paul de Ruiter was in charge of the project and conducted six months of intensive consultation with all stakeholders before construction began. Construction took less than a year. In the middle of the building of about 1,000 m^2 is an atrium with a tree growing under a skylight. The building was built in a Y-shape, symbolizing the three main parties involved in the project: entrepreneurs, educational institutions, and the local government. Each arm is dedicated to a different discipline, connected by the center of the atrium. The first floor houses a restaurant, meeting rooms, a conference room, an educational area, offices, and laboratory facilities. Learning rooms are arranged around the atrium, reinforcing the stimulation of interaction and cooperation.

Many elements from the biomaterials used in the center's construction have been left in plain sight. Among the details are Accoya's untreated wooden window frames, flooring, an insulating dome made from recycled plastic, biocomposite wall cladding, and a vegetable and herb garden.

Use of secondary raw materials

The facility is built from biomaterials (in 80%) and components using recycled materials:

- the wooden structure was made from Accoya wood, native larch from Staatsbosbheer, and a biocomposite from wood waste
- the walls were insulated with hemp, cellulose, and waste denim from community collections
- the floor consists of 50% Miscanthus grass
- the housing of the electrical connections was made of corn
- the ceiling tiles were made of linen
- the flooring in the toilets was made from cocoa shells
- the acoustic wall in the lecture hall was made of mycelium
- the carpet tiles were made from recycled fishing nets
- the chairs were made from recycled PET bottles.

Sources:
https://paulderuiter.nl/en/projects/het-biosintrum/ (accessed: 26.04.2023)
https://biosintrum.nl/ (accessed: 26.04.2023)

BUITENPLAATS BRIENENOORD

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Rotterdam, Netherlands

Designer:
Superuse Rotterdam

Main aspects of circularity:
Reuse of materials

Use of recycled materials

Building open to all

Status:
functioning

Purpose of the building:
public building

Type of work:
new construction

Year of completion:
2020

ASPECTS OF CIRCULARITY:

The Buitenplaats Brienenoord building was constructed on an island on the Meuse River, where the only road to the site is via a bridge with a maximum lifting capacity of 15 tons. This project aimed to build a facility for the local community, using a minimal budget and with the least possible environmental impact. Due to the bridge's load capacity limitations, locally available materials, mainly from other building structures, were reused for construction.

Use of secondary raw materials

The building is built with 90% reused materials. The only new elements are the material fixing the various structural elements, five wooden trusses, columns, and some of the glazing.

The potential for sharing

The building is intended to serve a public purpose. It is a venue for programs for residents, cultural, culinary, and educational events, as well as other community meetings.

Sources:

https://www.superuse-studios.com/projectplus/buitenplaats-brienenoord/ (accessed: 20.02.2023)

CIRCL

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Amsterdam, Netherlands

Designer:
Architekten Cie

Main aspects of circularity:
Re-used elements: window frames, glass facade and partitions, waste wood, and some interior elements

Demountable structure made of unpainted wood

Open space for visitors and common spaces

User-adaptable design

Textile plaster and textile insulation materials from waste clothing

Status:
operational

Purpose of the building:
public building (bank headquarters, service premises, coworking)

Type of work:
new construction

Year of completion:
2017

ASPECTS OF CIRCULARITY:

The Circl Pavilion is a practical example of sustainable and circular design. It is based on the idea of ensuring that the construction of a building can be characterized by minimal consumption of natural resources, and the circular economy was the inspiration for the pavilion.

The project team tested various circular economy concepts, including life extension, value recovery, service models, and renewable energy. Circl uses a state-of-the-art phase change material (PCM) for temperature equalization. Gaia's PCM materials liquefy at 20 degrees, absorbing excess heat, which is then released at night to maintain the right temperature and minimize energy consumption. The proper indoor air temperature is also provided by a geothermal system. LED lighting is powered by rooftop solar panels.

As part of the circular approach, the designers of the facility imposed five important design measures, which took into account:

- Reuse 1:1 - materials and products that can be reused in the future without adaptation to new functions
- Reuse + remanufacture - products or parts of products are reused, rebuilt, and combined with repaired and new parts into new objects/elements with a new function, changing their original specifications
- Recycle - transforming old materials into new materials and objects
- Reusable - optimization of value retention in the design process
- Object as a service - the possibility of leasing building elements.

Use of secondary raw materials

The pavilion is made mainly of recycled materials:

- the floor is made of waste wood from bar stools and flooring from the monastery
- the window frames in the conference rooms are from the old Philips office
- the building is insulated using material made from 16,000 pairs of old ABN AMRO employees' jeans
- textile plaster on the basement walls was made from recycled business clothing from ABN AMRO
- selected furniture is sourced from ABN AMRO's warehouses, while others are built from recycled materials and are fully recyclable
- the building's elevators are mostly „object as a service" and will be returned to the manufacturer after ten years
- all materials, parts, and components used to create the building have been recorded in the form of a „digital twin", which is a building passport, referred to as LLMNT
- cable trays, hardwood flooring, and an old glass facade were taken from various donor buildings and used as interior partitions
- items are given new life in a different context, such as old safes used for storage in the kitchen

CIRCL

- the building's frame is made of new and locally sourced larch wood. The beams are longer than necessary, allowing greater potential for reuse or recycling. When the pavilion is dismantled, the beams can be replaced with standard-sized boards
- the wood is not painted, as this would make recycling more difficult.

Potential for reuse of materials

The entire building has been designed so that it can be dismantled and theoretically recover materials close to their original form. It means that in the future, the materials/products can be resold and used in other buildings:

- a system of joints and bolts connects the wooden structure so that it can be dismantled and used in a new structure or used for another purpose
- the design considered minimizing the use of materials and waste (by taking advantage of the intrinsic qualities of raw materials) and avoiding permanent and destructive connections so that they can be dismantled and materials elements can be reused in the future
- the project reused many materials and products, including old display cases from the Stedelijk Museum ,s-Hertogenbosch and unwanted furniture from the bank's former headquarters.

The potential for sharing

The building is open to visitors. It has planned a public space where passersby and employees can meet. There is more than 2,000 m^2 of meeting and working space inside the building, but space has also been reserved for a „living laboratory" where the latest innovations can be applied and tested. For example, part of the façade has been adapted in cooperation with the Delft University of Technology to evaluate the use of new materials to explore the possibility of even more sustainable applications - there are a year-round indoor climate control solution and a winter garden that provides natural ventilation. It should be noted that the building's owner ABN AMRO is making its plans available through a „copyright" to encourage others to create similar buildings that can positively transform the urban environment.

Spatial reversibility potential

The building's space has been designed to be as flexible as possible, ensuring maximum utilization as well as readiness for future uses. With multifunctional and movable fixtures, the interior can be adapted for a variety of functions, including daycare, performance space, meeting space, indoor market, exhibitions or film screenings. The movable walls are remotely controlled via a control panel, allowing the floor plan to be completely transformed. The movable panels are made of recycled aluminum and expanded metal, with a layer of material made from recycled denim placed inside to provide an acoustic buffer. The Circl pavilion, which is open to the public, can be adapted to different uses by rearranging the movable walls without requiring people inside to leave the building. Thanks to lift-and-slide technology, changing space formats can be done in minutes, and operating the interior is easy and safe.

Sources:

https://inhabitat.com/sustainable-circular-economy-principles-inform-amsterdams-flexible-circl-pavilion/ (accessed: 20.04.2023)

https://www.oneplanetnetwork.org/news-and-events/news/construction-circl-pavilion-amsterdam (accessed: 20.04.2023)

https://architecturenow.co.nz/articles/from-the-inside-sustainability-in-interiors/ (accessed: 20.04.2023)

https://www.doepelstrijkers.com/en//circl_interior_abn_amro/ (accessed: 20.04.2023)

https://circl.nl/ (accessed: 20.04.2023)

CORK HOUSE

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Berkshire, England

Area:
44 m^2

Designer:
Matthew Barnett Howland, Dido Milne, Oliver Wilton

Main aspects of circularity:
Structural components made from forest industry waste

Removable wooden structure equipped with blocks made of natural cork

Status:
operational

Building purpose:
residential building

Type of work:
construction of a new building

Year of completion:
2019

ASPECTS OF CIRCULARITY:

The construction of the Cork House building is based on modular construction with cork blocks connected to wooden elements without using glue or mortar. As a result, the implementation of the building and the estimation of CO_2 throughout its life cycle is 15% less than traditional construction. The building consists of five segments, joined together and covered with pyramidal skylights. The structure is based on cork blocks supported by wooden elements. The building can be easily dismantled, recycled, or re-used in the future.

Use of secondary raw materials

The cork used in the construction is expanded pure bio-material produced from forestry waste. The cork oak bark is harvested by hand every nine years without harming the tree or disturbing the forest.

Potential for reuse of materials

The building's structural system was made using „dry" technology so that all 1,268 blocks of cork can be recovered at the end of the building's life for reuse, recycling, or return to the biosphere.

Sources:

https://www.architecture.com/awards-and-competitions-landing-page/awards/riba-regional-awards/riba--south-award-winners/2019/cork-house (accessed: 14.04.2023)

https://www.dezeen.com/2019/07/29/cork-house-matthew-barnett-howland-sustainable-architecture/ (accessed: 14.04.2023)

https://www.matthewbarnetthowland.com/cork-house (accessed: 14.04.2023)

https://www.designingbuildings.co.uk/wiki/Cork_House (accessed: 14.04.2023)

DE LOSKADE

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Groningen, Netherlands

Designer:
Van Wijnen

Main aspects of circularity:
Fully demountable temporary buildings

Status:
operational/under construction

Purpose of the building:
residential area

Type of work:
new construction

Year of completion:
2019

ASPECTS OF CIRCULARITY:
De Loskade is a prototype for an innovative housing development that includes 46 buildings (14 single-story houses and 32 studios/workshops) and is sized to meet current needs. The estate is located on the Suikerfabriek site, where housing is officially prohibited. The De Loskade Project, which leases the site until 2023, has been granted permission only for temporary house rentals and short-term residences. House rentals are possible for 4 to 6 months (students for up to 10 months). The development also uses renewable energy sources integrated with the SmartGrid system. Energy obtained from photovoltaic panels is used for the estate's energy needs. In addition, installing wind turbines and energy storage systems is planned to make the estate completely energy independent of external sources. The estate also has a system for controlling graywater distribution and rainwater collection for garden watering.

Use of secondary raw materials

- reused cobblestones and wooden masts on which LED lighting was installed
- the walls were made of plastic waste, on which plants were placed to retain rainwater
- furniture in homes made from recycled leather
- carpets are made from recycled products.

Potential for reuse of materials

The estate was designed for quick disassembly. It takes one day to erect a building without using glued joints. Due to the prohibition of permanent residence in the Suikerfabriek area, the entire estate will be completely dismantled and moved to another location after the lease period.

Sources:
https://www.deloskade.nl/circulair-bouwen/ (accessed: 08.05.2023)
https://www.deloskade.nl/ (accessed: 08.05.2023)
https://solarix-solar.com/loskade-opgeleverd-met-solar-design-zonnepanelen/ (accessed: 08.05.2023)
https://www.fijn.com/projecten/groningen/de-loskade-46-woningen (accessed: 08.05.2023)
https://www.vanwijnen.nl/projecten/de-loskade/ (accessed: 20.02.2023)
https://www.czasopismobiologia.pl/artykul/bioniczne-osiedle-czyli-zywe-laboratorium-do-zamieszkania (accessed: 20.02.2023)

DE VOORTUINEN APARTMENT BUILDING

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Amsterdam, Netherlands

Area:
9,300 m^2

Designer:
Elephant

Main aspects of circularity:
Adaptation of office building to residential

Status:
operational

Building purpose:
residential building

Type of work:
adaptation

Year of completion:
2021

ASPECTS OF CIRCULARITY:
Constructed in 1971, the building was the headquarters of the National Bank of the Netherlands and was adapted into a residential building as part of the modernization. ‚De Voortuinen' consists of fourteen floors. With a structure added to the facade, all apartments have a private terrace. The Elephant architectural office designed an entirely new form of a residential building, in which the traditional internal communication core (staircases) was transferred to the external facade. An exterior staircase and elevator allow each resident their entrance from the outside. An important part of the project is the roof, which houses tanks for rainwater storage, further used in an automatic installation for watering 120 trees. This solution keeps the maintenance costs per tree at 30 euros/year.

Use of secondary raw materials - adaptation to another use
The former structure of the office building has been reused in its entirety, which is still visible in all apartments. The original columns of the structure were left on the pedestal, forming a colonnade under the building. It should be noted that in the 1970s, office buildings were often oversized in terms of their load-bearing capacity. It made it possible to create more space and terraces without strengthening the building's structure. The old prefabricated facade, which could not be dismantled and reused, was demolished and recycled into new base materials.

A typical conversion would not have made it possible to make high-quality apartments, so it was decided to divide the structural core of the building into four and translate the elevators to the facade. The staircases are located outside the terraces and have become part of the architecture. The former internal concrete circulation shaft was rebuilt so that it could be used as bathrooms, storage, and technical rooms. The new concept for the building's adaptation was called Coreless by the architects, and it is now also being applied to the new residential towers.

Sources:
https://www.archdaily.com/984776/de-voortuinen-apartment-building-elephant (accessed: 07.05.2023 r.)
https://moss.amsterdam/portfolio_page/voortuinen-elephant/ (accessed: 07.05.2023 r.)
https://vmspace.com/eng/project/project_view.html?base_seq=MjQ0Mw== (accessed: 07.05.2023 r.)

DOCKLANDS LIBRARY

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Melbourne, Australia

Area:
3000 m^2

Designer:
Clare Design I Hayball

Main aspects of circularity:
Reuse of renewable raw materials

Use of technology that does not generate material waste

Use of recycled wood

Status:
operational

Purpose of the building:
public building (library)

Type of work:
new construction

Year of completion:
2014

ASPECTS OF CIRCULARITY:
The Docklands Library is Australia's first public building made with CLT technology. The three-story, 55-meter-long, 3,000-square-meter library in Docklands was constructed using cross-laminated timber mass and recycled hardwood. The use of wood was determined by the building's proximity to the shore, and its relatively low weight reduced the material requirements for a new substructure. In addition to the building materials, Library at the Dock incorporates passive building elements to minimize energy consumption. Full-height glazing on the second floor maximizes the use of natural light. The building was designed with passive ventilation in mind, thus reducing energy consumption and ensuring high indoor air quality. The building has an 85-kilowatt photovoltaic system on the roof, which is expected to meet 30% of the building's energy needs. Low-VOC and formaldehyde materials were used throughout the building. A 55-kilowatt rainwater tank collects water from the roof, which is reused in the building.

Use of secondary raw materials
- the top level of the library uses 100-year-old Ironbark wooden beams that were recovered from a demolished bridge in Brisbane
- decks are made of reclaimed wood from Victoria Harbour's southern waterfront
- cross-laminated timber (CLT), which was used to create the facade, is made of European spruce and recycled hardwoods.

Sources:
https://thefifthestate.com.au/innovation/case-studies/docklands-library-to-be-melbournes-most-sustainable-civic-landmark/ (accessed: 14.04.2023)
https://www.melbourne.vic.gov.au/SiteCollectionDocuments/solar-case-study-library-dock.pdf (accessed: 14.04.2023)
https://www.degruyter.com/document/doi/10.1515/bfp-2015-0009/html (accessed: 14.04.2023)
https://www.melbourne.vic.gov.au/SiteCollectionDocuments/library-dock-sustain-fact-sheet.pdf (accessed: 14.04.2023)

STRAW HOUSE

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Gajówka,
Lower Silesia, Poland

Main aspects of circularity:
Biomaterials
and recycled materials

The structure of the building
can almost entirely be composted

Status:
operational

Purpose of the building:
Individual recreation building
for rent for summer visitors

Type of work:
new construction

Year of completion:
2011

ASPECTS OF CIRCULARITY:

The building was made of straw and clay modules embedded in a wooden structure, acting as the house's skeleton. Construction materials were sourced locally, and some building elements were made on-site, thereby reducing the amount of waste generated. In addition, using straw and clay in the construction is beneficial to the microclimate and provides good thermal insulation. The building is intended for rent during the summer.

Use of secondary raw materials

The roof of the building was covered with reused tiles. The building's structure is made almost entirely of biomaterials (i.e., wood, straw, and clay).

Potential for reuse of materials

After its useful life, the house can almost entirely be composted, and some natural materials (such as the wooden structure) can be reused in other projects.

Sources:
https://nowoczesnastodola.pl/inspiracje/dom-ze-slomy-gliny-i-drewna/ (accessed: 14.04.2023)
https://www.facebook.com/media/set/?set=a.1412608845489542.1073741855.343252785758492&type=3 (accessed: 14.04.2023)

DRANGAR

Location:
Skógarströnd, Iceland

Main aspects of circularity:
Use of existing buildings
Reuse of materials

Status:
operational

Purpose of the building:
private home and hotel

Type of work:
renovation and extension

Year of completion:
2019

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

ASPECTS OF CIRCULARITY:

Drangar was originally a complex of farm buildings (a tractor shed, a cowshed, a farmhouse, a barn, and a hay tower) built in the 1980s and operating as such until 2001. After 12 years of falling into disrepair, the buildings were rehabilitated into a private house (former barn and farmhouse) and a guesthouse (former tractor shed and cowshed). Rehabilitation of existing building stock is already a highly circular activity. Moreover, the project aimed to retain as many existing materials and structures as possible to preserve buildings' heritage and reduce the project's environmental impact. As a privately owned project, Drangar represents an example of a circular mindset on a smaller scale.

Use of recycled materials and adaptation to another use

Examples of preserved materials and structures include:

- the primary structure of the tractor shed
- many of the existing walls of the former barn and farmhouse

Examples of reused materials/elements are as follows:

- the corrugated tin from roofs (which had to be replaced due to its bad technical state) was used as shuttering for new concrete walls
- insulating materials (styrofoam) were reused from other projects
- old concrete slats and steel grills from the cowshed were used as terrace pavings and headboards in the guestrooms, respectively
- the old timber beams and EUR-pallets were transformed into tables
- for landscaping, earth from the site was used
- the manure from the cowshed was used as a fertilizer around the property.

Sources:
https://www.archdaily.com/925031/drangar-renovation-studio-granda (accessed: 20.04.2023)
https://studiogranda.is/Gen/Drangar/Text.html (accessed: 20.04.2023)

HELSINKI CENTRAL LIBRARY

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Helsinki, Finland

Area:
17,000 m^2

Designer:
ALA Architects

Main aspects of circularity:
Almost the whole space available to visitors

Coworking spaces

Easily adapt the design to future needs

Status:
operational

Purpose of the building:
multi-purpose public facility (library, conference rooms, group work space, maker space, laboratory, recording studios, photography studio, editing rooms, office space, cafe, restaurant, cinema, auditorium, multi-purpose hall, exhibition facilities, and information booths)

Type of work:
new construction

Year of completion:
2018

ASPECTS OF CIRCULARITY:

An essential part of a circular economy in construction is also taking care to reduce raw materials and energy inputs during construction. Minimizing the amount of transported materials used in construction is part of this. Reducing transportation by airplane or ship can be environmentally friendly by at least reducing the total CO_2 for building construction, but it is primarily related to saving natural resources. RAMBOLL, a Danish company, built a public building in Helsinki that was awarded among a list of circular solutions in the construction sector. The building was built without importing raw materials from outside the country, except for wood. And one of its greatest assets is its space arrangement, which allows for multi-faceted transformation.

The potential for sharing

The new downtown library consists almost entirely of public space and offers a wide range of services. The building has been designated coworking spaces and multipurpose rooms available for temporary rental. The space is prepared for uses such as a library, conference rooms, co-working space, space for creatives, laboratory, recording studios, photo studio, editing rooms, office space, café, restaurant, cinema, auditorium, multipurpose room, exhibition facilities, and booths.

Spatial reversibility potential

The spatial concept was realized by building the library as an asymmetrical bridge spanning over the open space of the first floor. The bridge structure, consisting of steel trusses and beams, is supported by two massive steel arches. This solution made it possible to create flexible, column-free interior spaces. Secondary steel trusses support a cantilevered balcony and asymmetrical roof canopy to the arch structure, creating a unique structural design to accommodate both permanent and temporary functions for the library and public space and the ability to adapt it to future user needs.

Sources:
https://worldarchitecture.org/article-links/ecghe/ala-architects-bridgelike-oodi-helsinki-central-library-attracted-one-million-visitors.html (accessed: 07.05.2023)
https://architizer.com/projects/helsinki-central-library-oodi/ (accessed: 07.05.2023)

KAJ 16

Location:
Gothenburg, Sweden

Area:
37,500 m^2

Designer:
Dorte Mandrup

Main aspects of circularity:
Reuse of materials

Status:
under construction

Building purpose:
mixed-use residential building (offices and apartments)

Type of work:
renovation

Planned delivery of the building:
2026

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

ASPECTS OF CIRCULARITY:

Kaj 16 is a facility project whose main idea is to reuse as many materials and elements from existing building as possible. The project plans to recycle all the concrete, reuse nearly 70% of all the sheet metal found in the facades and steel frames, reuse half of all the materials for room finishes, and at least 25 different groups of installation products. The project also includes the creation of sustainable streets and offices with adaptable spaces.

Use of secondary raw materials

Planned use:

- 6400 m^3 concrete from an old building reused at the construction site
- 75% of all circular ventilation ducts in residential spaces
- 75% of all sprinkler pipes
- 100% of all cable ladders
- 100% of all steel doors
- 100% of all acoustic ceilings in offices
- 100% of all glass partitions
- 100% of all rebar
- 1100 m^2 facade sheet metal from the old building.

Sources:

Klaudia Moralewicz, Sweco, Wydobywanie „zielonego złota" – gospodarka o obiegu zamkniętym w budownictwie, Spotkanie grupy roboczej projektu CIRCON: Gospodarka o obiegu zamkniętym w budownictwie - ekoprojektowanie budynków cyrkularnych, 12.04.2023

https://www.sweco.se/projekt/kaj-16/ (accessed: 08.05.2023 r.)

https://vasakronan.se/projekt/kaj-16/ (accessed: 08.05.2023 r.)

KRISTIAN AUGUSTS GATE 13 (KA13)

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Oslo, Norway

Main aspects of circularity:
Preservation of existing structures

Reuse of materials

Use of recycled materials

Elements of the building designed for disassembly

Status:
operational

Building purpose:
office building

Type of work:
renovation and extension

Year of completion:
2021

ASPECTS OF CIRCULARITY:

Kristian Augustus gate 13 (KA13) is the first project in Norway to implement circular construction in a significant way by reusing nearly 80% of materials. The project was twofold as it combined the rehabilitation of the existing building (2734 m^2), which itself is already a highly circular activity (reuse of existing building stock), with adding an extra extension (855 m^2) and remodeling the basement (708 m^2).

KA13 focused on two main aspects of circular construction: reuse materials as much as possible and design-for-disassembly. The existing part of the building was rehabilitated, keeping in mind using as many existing structures and materials as possible. Similarly, for the extension, the emphasis was put on reusing as many materials as possible. In this case, however, the secondary materials came from, among others, around 25 local demolition and renovation projects, recycling centers, and surplus or waste material retailers/producers' warehouses. Moreover, design-for-disassembly was highly emphasized while creating new solutions involving secondary materials. Eventually, it was kept in mind that materials not used in KA13 would be used in other projects run by the project leader and manager (Entra ASA).

KRISTIAN AUGUSTS GATE 13 (KA13)

Use of secondary raw materials

The project reused, among other things:

- windows in the extension (4th-7th floor) were all reused and can be dismantled and used again
- approximately 100 m^2 of parquet from scraps and order returns and around 2200 m^2 of carpet tiles (partially reused and partially from leftover stocks of the distributor) were reused
- all of the mineral wool ceiling panels were reused (around 1500 m^2)
- around 70% of steel was reused from other local demolition/renovation projects, temporary construction activities, and private waste companies
- steel stairs between the 8th and 9th floors were reused
- around 340 m^2 of ceramic tiles (sanitary areas) came from the retailer's stocks (wrong orders, surplus stock, discontinued products) and were supposed to be disposed of
- various other elements (e.g., interior doors, stair railings, fire doors in the extension, 12 pc. of fire hose cabinets, sprinkler pipes, cooling baffles, elements of air ducts, around 58 m of cableways, sanitary equipment, radiators, and lamps) were reused on-site and acquired from other demolition/renovation projects and reused in KA13; majority o these elements can be dismantled and reused again.

Potential for reuse of materials

Examples of components and solutions designed to be dismantled and reused in the future as part of the project are:

- the glass facade (1st floor facing the street and backyard) was harvested from a local renovation project and the contactor's surplus stocks; this type of facade is well-suited for disassembly and reassembly in future projects
- the extension's facade is made of pannel cladding from various types of reused materials (metal sheet, fiber cement board, stone composite facade panels); the way of their assembly facilitates their easy dismantling and reusing again
- partition walls (offices and meeting rooms; around 160 m^2) were designed for easy assembly and disassembly
- where possible, the bolt connections in the steel structure were used
- 20,000 bricks were reused in the project, and lime mortar was used to make them removable, easier to clean, and potentially reusable in the future
- around 85 m^2 of granite facade stone slabs and around 100 m^2 of wooden limbs were repurposed for the terrace floor, which can be disassembled and reused.

Sources:

https://www.futurebuilt.no/English/Pilot-projects#!/English/Pilot-projects/Kristian-Augusts-gate--13-Oslo (accessed: 05.05.2023)

Raport - Reuse and transformation - Findings report - KA13 - Kristian Augusts gate 13 (https://www.futurebuilt.no/content/download/35895/195991)

LIANDER OFFICE

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Duiven, Netherlands

Area:
24,000 m^2

Designer:
RAU Architects,
interior:
Fokkema & Partners

Main aspects of circularity:
Preserve existing building structures and use recycled materials in 83%

Material passports

Building structure designed for disassembly

Status:
operational

Building purpose:
office building

Type of work:
renovation and adaptation

Year of completion:
2015

ASPECTS OF CIRCULARITY:
Circularity was the most important aspect of the project, which involved the renovation and adaptation of the complex. The five existing buildings were connected by internal connectors, multi-level communication, and a roof into a single facility with a total area of about 24,000 m2 designed for 1,500 users. The designers assumed the building would be a materials bank, where materials would be stored until they could be reused. The design strategy established three principles: preserving and reusing existing materials, minimizing material consumption, and using materials that can be reused. During the design, a digital twin of the facility was created to identify recyclable materials. It is the first renovation project in the Netherlands that applied for BREEAM-NL certification at the Outstanding level and received it in 2018. Working with designers of roller coaster structures, the roof was designed to use as little steel as possible - saving 30% of steel compared to the traditional approach. The ability to reuse this raw material in the future was also crucial. When designing the roof, the maximum use of natural air circulation inside the building was also considered to minimize ventilation and mechanical circulation. The complex is powered by a renewable energy source - photovoltaic panels located in the parking shelters. The total area of the panels - 10,000 m^2 provides 1.5 million kWh of energy per year. Its surplus is stored by ground storage of heat and cold. Glazed walls and skylights provide access to daylight, reducing the facility's energy demand. Rainwater is used to cool the building and in sanitary facilities.

Use of secondary raw materials

- preserve the original construction of the existing buildings on the site
- using 83% recycled materials: wood, steel, concrete, and furniture
- the new facades are made of 50% waste wood from old cable coils and telegraph poles found in the field
- existing windows have been retained on all elevations except the interior, where larger and open windows were used in favor of natural ventilation.

Potential for reuse of materials

All materials, components, and elements used in the project have material passports to allow easy maintenance, repair, renovation, reuse, reclamation, and recycling. Deconstruction of the complex in the future is possible.

Sources:

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https://www.rau.eu/portfolio/liander/ (accessed: 17.04.2023)

https://panidyrektor.pl/inspirujace-wnetrze-biura-ep-14/ (accessed: 17.04.2023)

https://www.devorm.nl/projects/liander-duiven (accessed: 17.04.2023)

https://www.yumpu.com/en/document/read/56058274/circularity-in-the-built-environment-case-studies (accessed: 17.04.2023)

https://youtu.be/tG5CLRBPflk?t=2994 (accessed: 17.04.2023)

MOATTI - RIVIERIE

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Charenton-Le-Pont, France

Area:
3884 m^2

Designer:
Moatti-Rivierie

Main aspects of circularity:
Adaptation of office building to residential

Status:
functioning

Building purpose:
residential building

Type of work:
adaptation

Year of completion:
2016

ASPECTS OF CIRCULARITY:

The project aimed to convert a 1970 office space into a residential area on which 90 apartments were designed. The building borders the highway and the busy Quai des Carrières street and overlooks the Seine River.

The building on the Quai des Carrières side of the street has been redesigned with a 260-meter-long original facade from the 1970s. The precast concrete elements were retained, while the building's existing windows were removed. Modernization of the building's facade consisted of adding an exterior wall and set back from the existing one, thanks to which the apartments gained a balcony area. The new wall is finished with wood, which creates a striking balcony decoration for each apartment. Carefully selected vegetation found in the garden prevents overexposure to the sun. To meet acoustic regulations for residential construction, windows on the street side are equipped with triple glazing with high acoustic parameters.

Use of secondary raw materials - adaptation to another use

Use of an existing office building.

Sources:

https://www.archdaily.com/800178/transformation-of-office-building-to-90-apartments-moatti-riviere?ad_medium=office_landing&ad_name=article (accessed: 07.05.2023 r.)
https://www.moatti-riviere.com/en/projects/housing/90-housing-and-offices-charenton-pont-94 (accessed: 07.05.2023 r.)

OLIMPIC HOUSE

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Lausanne, Switzerland

Area:
135,000 m^2

Designer:
3XN+ IttenBrechbühl

Main aspects of circularity:
Use of existing building and recycled materials

Transformable and flexible facility structure

Status:
operational

Building purpose:
office building

Type of work:
expansion

Year of completion:
2019

ASPECTS OF CIRCULARITY:

Olympic House is the first international headquarters - and the second building overall - to achieve the highest (platinum) level of the Swiss Sustainable Building Standard (SNBS). It also received the Swiss standard for energy-efficient buildings. The International Olympic Committee's new headquarters is designed for 500 employees who previously worked in scattered offices throughout the city. All wood products used are certified by the Forest Stewardship Council.

Use of secondary raw materials

Over 95% of the former International Olympic Committee headquarters on the project site have been reused or recycled. The amount of materials based on recycled products was maximized in the design.

Spatial reversibility potential

The interior design of the building is characterized by high adaptability of space. The lack of pillars in the open floor plan and mapping of the façade division grid in the ceilings and floors allow for the free change of room layouts. The structure of the building was designed so that all areas could be converted into individual offices and conference rooms.

Sources:

https://olympics.com/ioc/news/olympic-house-becomes-one-of-the-most-sustainable-buildings-in-the-world (accessed: 07.05.2023 r.)

https://cdn.archilovers.com/projects/8894ef67-35f3-4e16-954d-a0aa4ccc6372.pdf (accessed: 07.05.2023 r.)

https://www.buildinganddecor.co.za/olympic-house-a-study-in-sustainability/ (accessed: 07.05.2023 r.)

https://3xn.com/project/ioc-headquarters (accessed: 07.05.2023 r.)

ONE EXCHANGE SQUARE

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
London, United Kingdom

Area:
59,000 m^2

Designer:
Fletcher Priest Architects

Main aspects of circularity:
Reuse of an existing building

Status:
operational

Building purpose:
office building

Type of work:
renovation

Year of completion:
1985

ASPECTS OF CIRCULARITY:

The building is located directly on Liverpool Street station, overlooking Bishopsgate and Exchange Square, the city's largest public square. One Exchange Square is a 13-story building designed by Fletcher Priest Architects. The primary design consideration was to preserve the existing structure. As a result, the building is estimated to have had a 50% lower carbon footprint than a typical office building of comparable size. The building is 100% electric-powered and zero-carbon, mainly due to using an intelligent building management system to keep operational energy consumption to a minimum, including, for example, mechanical systems.

Use of secondary raw materials

Reusing the foundations and 90% of the existing frame of the structure saved about 6,800 m^3 of concrete and thus reduced the number of truck arrivals by more than 1,100. The amount of steel retained in the building's structure is estimated to be equivalent to half the amount used in the Eifel Tower.

Sources:

Klaudia Moralewicz, Sweco, Wydobywanie „zielonego złota" – gospodarka o obiegu zamkniętym w budownictwie, Spotkanie grupy roboczej projektu CIRCON: Gospodarka o obiegu zamkniętym w budownictwie - ekoprojektowanie budynków cyrkularnych, 12.04.2023

https://nla.london/projects/one-exchange-square (accessed: 08.05.2023)

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https://www.buildington.co.uk/buildings/11016/england/london-ec2a/exchange-square/one-exchange-square (accessed: 08.05.2023)

PETITE MAISON

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Esch-sur-Alzette, Luxembourg

Designer:
Carole Schmit, Dragos Ghioca, Christoph Odenbreit and others

Main aspects of circularity:
Reuse of materials

Use of prefabricated materials

Building structure designed for disassembly

3D visualization of elements

Status:
transferred (2023)

Purpose of the building:
demonstration building

Type of work:
construction of new facilities

Year of completion:
2022

ASPECTS OF CIRCULARITY:

Petite Maison is a pioneering initiative to implement CE in construction in Luxembourg. The most important aspect of the project was the reusability of materials and easy demolition (design-for-disassembly). The project is a demonstration building with dimensions of 10.8m x 8.38m and an area of 94.22 m^2. The building is made of prefabricated elements (including prefabricated wooden walls or a demountable steel structure bracing system) assembled on-site with connections enabling their disassembly and assembly again.

Use of secondary raw materials

The wall cladding and terrace partitions were made of wooden panels (about 25 m^2) obtained from an old barn.

Potential for reuse of materials

The building design followed the design-for-disassembly concept. All structural elements were inventoried, scanned, and entered into a database. The database, in the form of an online platform, provides information on the technical properties of the elements and their manufacturers and enables a virtual visualization of the elements in 3D technology (BIM-Y).

Sources:

https://petitemaison.lu (accessed: 20.04.2023)

CONVERSION OF FACTORY BUILDINGS IN ORZESZE

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Orzesze, Poland

Area:
1,474 m^2

Designer:
GIGArchitekci

Main aspects of circularity:
Adaptation of a warehouse hall into an office and staff canteen

Renovation of the gatehouse building

Adaptable spaces to meet users' needs

Status:
operational

Building purpose:
office building and employee canteen

Type of work:
adaptation and renovation

Year of completion:
2021

ASPECTS OF CIRCULARITY:

Built in 1951, the warehouse hall of a former heavy industry complex has been adapted for the new headquarters of the Danish company NT Industry. The building adaptation and renovation project, developed in 2017 by the GIGAarchitekci team, was divided into two stages. In the first stage, the old gatehouse was renovated, and the second stage involved the adaptation of the industrial hall into an office and a new canteen, providing space for 250 employees. Part of the project also included the creation of a garden occupying space in the middle of the complex.

The concept of zero waste was implemented in the project, and existing building structures were used. The window layout was kept in line with the original form, and the interiors were designed in loft style, with exposed brick, concrete, and terrazzo combined with new elements, visible ducts, and engineering details. The wall separating the canteen from the office area and all ceilings were covered with acoustic panels made of natural materials. Walls and roofs were thermally upgraded, and windows with a low heat transfer coefficient were used.

Use of secondary raw materials - renovation and adaptation to another use

The main idea was to preserve the materials and keep as much of the building's original structures as possible. The gatehouse building, which was the first phase's goal, covers the entire complex's entrance area and consists of two parts: a glass building for security personnel with a waiting area for drivers and a bicycle shed.

In the second building, most of the existing structures were preserved. Brick walls were exposed, the existing terrazzo-finished staircases were renovated, and the designed corten steel panels used on the facade were created from the company's unused steel inventory and manufactured on-site. The old roof, gantry structure, and parts of the old installations were also preserved, including restoring the old lamps in the canteen using materials and elements from other old buildings in the complex.

The potential for sharing

The office building and canteen were designed with flexibility of space use in mind. The office was brought up to open space office standards by separating meeting rooms, conference rooms, and offices separated by glass walls. The canteen is a spacious 7.5-meter-high hall with a new functional layout that made it possible to separate dining room zones, catering facilities, sanitary facilities, and locker rooms. During working hours, the building is available to all employees at all times, while in the evenings, it can be transformed into a concert hall or event space.

Sources:

https://gigaarchitekci.pl/projekty/rewitalizacja-zakladu-nt-industry-w-orzeszu/ (accessed: 16.05.2023)

https://www.archdaily.com/984772/nt-industry-polish-headquarters-gigaarchitekci-artur-garbula (accessed: 16.05.2023)

https://www.whitemad.pl/przebudowana-fabryka-zremb-w-orzeszu/ (accessed: 16.05.2023)

https://www.architekturaibiznes.pl/zdegradowane-budynki-pofabryczne-gigaarchitekci,13309.html (accessed: 16.05.2023)

MODULAR SCHOOL IN ZĄBKI

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Ząbki, Poland

Designer:
Touax Sp.z o.o.

Main aspects of circularity:
Building made with modular technology

Status:
dismantled

Building purpose:
Public collective teaching building

Type of work:
construction of a new temporary facility

Year of completion:
2013 (construction), 2015 (expansion)

ASPECTS OF CIRCULARITY:

Due to the renovation work on the building of Elementary School No. 3 in Ząbki, a temporary object made of modules was constructed, thanks to which it was possible to quickly locate some classrooms and provide easy access to education for children and young people. In the first stage, an object consisting of 27 modules was constructed, with a usable area of 400 m^2, and in the following 2 years, 2 modules were expanded. The facility had a separate entrance, classrooms, checkrooms, utility rooms, hygiene and sanitary facilities, a cafeteria, and a daycare center. The facility was equipped with ventilation and air conditioning systems, water and sewage systems, electric heating, and lighting. The installations ensured thermal comfort by regulating the appropriate air temperature in winter and summer.

Potential for reuse of materials

The modules were designed for easy and quick disassembly, and their size allowed for easy transportation. The temporary facility was dismantled once the renovation work on the school building was completed. The modules were handed over to the facility's contractor so that they could be fully reused in the future.

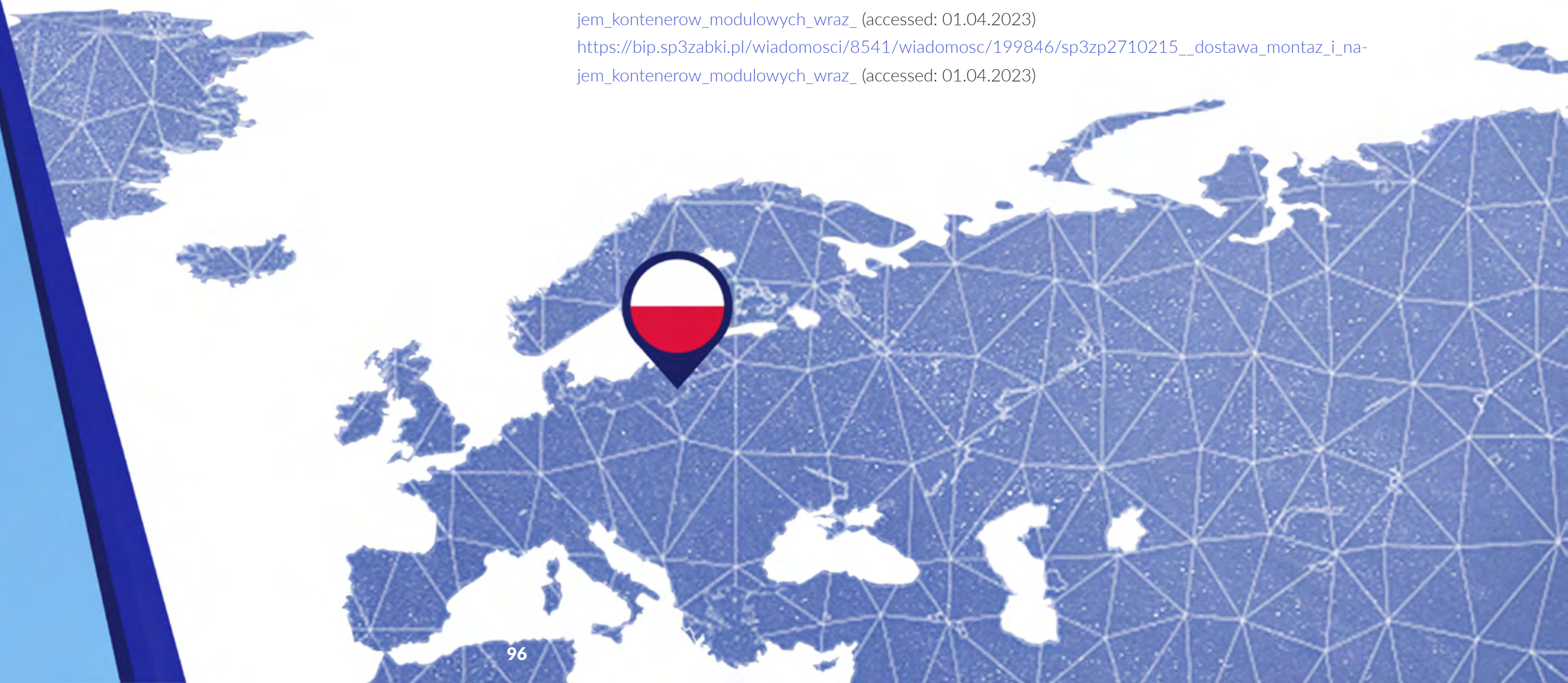
Sources:

https://www.muratorplus.pl/inwestycje/inwestycje-publiczne/budownictwo-modulowe-szkola-podstawowa-w-zabkach-inwestycja-powstala-w-4-tygodnie-aa-h1tZ-jFrW-uHGw.html (accessed: 01.04.2023)

https://www.zabki24.pl/2015/03/kontenerowe-lekarstwo-na-przepelnione-szkoly/ (accessed: 01.04.2023)

https://bip.sp3zabki.pl/wiadomosci/7027/wiadomosc/193378/sp3zp2710213__dostawa_montaz_i_najem_kontenerow_modulowych_wraz_ (accessed: 01.04.2023)

https://bip.sp3zabki.pl/wiadomosci/8541/wiadomosc/199846/sp3zp2710215__dostawa_montaz_i_najem_kontenerow_modulowych_wraz_ (accessed: 01.04.2023)



TEMPORARY COURTHOUSE

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Amsterdam, Netherlands

Designer:
architectenbureau cepezed b.v.

Main aspects of circularity:
Building structure fully removable

Status:
dismantled and relocated (2023)

Purpose of the building:
court

Type of work:
construction of a new temporary building

Year of completion:
2016

ASPECTS OF CIRCULARITY:

The Temporary Courthouse building served as a temporary solution until the permanent courthouse was completed. Until then, the temporary courthouse was a fully functional facility that met the requirements for this type of office. The building was realized in the „Design, Build, Maintain & Remove" mindset. It meant that the facility could be built easily and quickly, then dismantled and given another function without generating waste and maintaining maximum residual value after the first period of use. The building contained no glued parts, and all structural parts were reusable. Removal of the building and its reuse were part of the contract.

Potential for reuse of materials

To make the building as configurable and circular as possible, it was designed as a set of parts and components that could be easily assembled, disassembled, and reassembled. As part of this, a special ceiling fastening system was developed and implemented, which made it possible to detach and reuse the panels without damaging the components. Attention should also be paid to the bolted connections of the steel structure, which made it possible to disassemble and reuse it in another project.

The relocation of the building was supervised by Lagemaat of Heerde, which has solid experience in dismantling and reassembling buildings. The removal of the building used unique coding technology based on a 3D model and 3D scanning. As a result, each part's exact location and size were known, making it significantly easier to move the building. Smaller parts were transported in containers, while larger parts were loaded directly onto trucks. Marginal amounts of materials that could not be reused in other projects were recycled in a high-quality manner.

Sources:

https://architizer.com/projects/temporary-courthouse-amsterdam/ (accessed: 07.05.2023)
https://www.archilovers.com/projects/240172/temporary-courthouse-amsterdam.html#info (accessed: 07.05.2023)
https://amsterdamsmartcity.com/updates/news/the-building-for-the-temporary-courthouse-in-amsterdam-will-be-relocated-to-enschede (accessed: 07.05.2023)

THE ENTOPIA BUILDING

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Cambridge, United Kingdom

Area:
2 939 m^2

Designer:
CISL

Main aspects of circularity:
Reuse of materials

Use of recycled materials

Renovation of the building

Status:
functioning

Purpose of the building:
office building

Type of work:
renovation

Year of completion:
2021

ASPECTS OF CIRCULARITY:

Entopia is a five-story concrete frame building from the 1930s that is located in a local strict conservation area in historic downtown Cambridge. In 2020, the Cambridge Institute for Sustainability Leadership (CISL) was granted permission to renovate this building to create their new headquarters. The renovation endeavor began intending to implement the principles of a closed-loop economic system, with the primary objective of utilizing the existing buildings' layout, utilizing the maximum quantity of organic and recycled materials, and minimizing the generation of waste.

<u>Use of secondary raw materials</u>

The renovation of the 1939 building provided new office space to house CISL's headquarters, a start-up incubator and conference rooms. By using existing structures, it is estimated that more than 62 tons of CO_2e were saved on new construction materials. Moreover, the renovation used biomaterials and reused materials:

- 48% vol. (35% wt.) of all materials are naturally
- floors were reused, saving 32 $kgCO_2e/m^2$ (about 85 tons of CO_2e in total), compared to using new flooring
- the steel structure of the canopy, on which the photovoltaic panels were mounted, was made from reused steel profiles
- existing carpets in the building were refurbished and reused on about 12% of the building's surface
- a quarter of the paint used contained 35% recycled materials, reducing carbon emissions by about 10%
- 350 LED ceiling lights were reused
- a desk sourced from Netflix headquarters was used for the reception desk
- existing electrical wiring was reused
- renovated the old elevator located in the building
- 5,136 pieces of equipment found in landfills were reused.

By using natural materials (hemp-based chairs and bar stools, hemp-based plywood cabinets, sofa and chair upholstery made from wood waste chips) and reusing more than 60% of the furniture, an estimated 84% CO_2e was saved on the building's furnishings compared to standard furnishings.

Sources:

https://www.cisl.cam.ac.uk/files/entopia_case_study_12_12_22.pdf (accessed 25.04.2023)
https://www.cisl.cam.ac.uk/sites/www.cisl.cam.ac.uk/files/building_entopia_case_study_280922.pdf (accessed 25.04.2023)

THE GREEN HOUSE

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Utrecht, Netherlands

Area:
680 m^2

Designer:
cepezed

Main aspects of circularity:
Reuse of materials

Use of recycled materials

Fully demountable building

Status:
operational

Building purpose:
multi-functional building (restaurant, conference rooms)

Type of work:
construction of a new temporary facility

Year of completion:
2018

ASPECTS OF CIRCULARITY:
The building was created as an interim solution for the development of the area between the former Knoop barracks and the adjacent Rabobank headquarters, as a decision on the use of the area is not expected to be made until 15 years after the building's design.

The Green House has an electric-powered kitchen - food here is prepared using renewable fuel stoves. The restaurant's menu is based mainly on vegetarian, seasonal dishes and exclusively from local products. Waste is used as fertilizer for growing crops. A vertical greenhouse of 80 m^2 is used to grow vegetables and herbs for the restaurant's kitchen. In addition, the greenhouse is an architectural element creating a green wall for the restaurant. There are solar panels on the roof of the pavilion.

Use of secondary raw materials

The first floor of the building was made of paving stones from the old quay in Tiel, which was laid on a compacted sand bed. The floor on the first floor, on the other hand, was made from recycled wood. Facade panels from the barracks were reused for the facade and walls of the greenhouse. The furniture is made from recycled materials. In addition, guaranteed reuse of materials is included in the lease provisions for the furniture and space.

Potential for reuse of materials

The two-story building can be disassembled entirely - including foundations made of precast concrete blocks - and reassembled elsewhere. The steel roof frame, made of galvanized profiles and equipped with insulation, is also fully dismantlable. Parts of the first-floor facade use prefabricated wooden panels, which are 100% recyclable and do not contain (H)CFCs. The temporary aspect was also considered when designing a greenhouse made of elements that are not permanently connected. As a result, the greenhouses can be completely dismantled and used in other projects.

Sources:
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Robert-Jan Vos, Rene Heintz, Nick starting, The GREEN HOUSE A case study on a circular hospitality building in Utrecht (NL) analysing its circularity and integration of the Nexus philosophy in combination with a positive business case, Future Sustainable Cities, Green operations for hospitality, 2018
https://www.archdaily.com/896630/the-green-house-architectenbureau-cepezed (accessed: 25.04.2023)

THE UPCYCLE CENTRE

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Almere, Netherlands

Area:
4,000 m^2

Designer:
LKSVDD architecten

Main aspects of circularity:
Most of the materials used in construction are recycled or reused

Building structure designed for disassembly

Status:
operational

Building purpose:
public building (recycling platform)

Type of work:
new construction

Year of completion:
2017

ASPECTS OF CIRCULARITY:

The Upcycling Center was built using materials from three buildings planned to be demolished in Almere, for which pre-demolition audits were prepared, documenting what materials can be reused and how they can be used in an architecturally and structurally responsible manner without costing more than the benefits. This investment demonstrates what recycled material can be without sacrificing architectural quality. Harvested rainwater is used for sanitary purposes. The functional division of the space facilitates product segregation, storage, and the possibility of reprocessing it into a new type of product. In addition, entrepreneurs can produce and sell products in one place. The education room is equipped with furniture produced on-site using recycled materials. The place connects entrepreneurs and the local community. It also serves an educational function for different age groups. At the Upcycle point, community residents can offer their bulky household waste in 26 separate fractions. The center is also a workplace for start-ups using various collected materials. Currently, the following projects/services are being implemented by startups at the Upcycle Center:

- using a shredder to convert plastic into new products such as cutting boards, knives, and more
- a local goldsmith creates high-quality circular jewelry. He mainly uses fine metal and electronics for this purpose. In addition, customers can bring their jewelry to create something new from it
- from various reusable products, the artist creates furniture, spatial objects, and paintings.

THE UPCYCLE CENTRE

Use of secondary raw materials

The Upcycle Center building can be called an „upcycled product." It was realized, among other things, with materials from demolishing the swimming pool, sports hall, and former Almere town square. About 50% of the building was made from re-sourced materials, such as:

- steel structures from demolished buildings have been reused and marked by covering them with anthracite to be recognizable
- much of the concrete and steel comes from the Almere municipality's old car hall and recycling platform
- the wall tiles in the bathroom are spare tiles that were stored at the municipal pool washbasins from the city square were cleaned and reused
- the doors and fencing around the facility come from the demolished municipal sports hall
- car tires have become bike racks
- the bicycle wheels have been transformed into landscaping elements of the garden,
- galvanized ventilation ducts were reused as cladding for the facade of the management building
- installed gates that were previously used in the sports hall
- the wooden façade is partly made from trees from Almere that had to be removed and partly from old stairs, former benches from the checkroom, and dismantled scaffolding.

Potential for reuse of materials

The whole building was designed for disassembly.

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TRIODOS BANK

Use of secondary raw materials

Potential for reuse of materials

The potential for sharing

Spatial reversibility potential

Location:
Zeist, Netherlands

Area:
12,994 m^2

Designer:
RAU Architects

Main aspects of circularity:
Removable wooden structure

Use of easily recyclable materials

Aluminum facade made with technology that allows for easy disassembly and reuse

Status:
operational

Building purpose:
office building

Type of work:
new construction

Year of completion:
2019

ASPECTS OF CIRCULARITY:

Triodos Bank's new headquarters in the Netherlands has been awarded a BREEAM multi-criteria certification at the Outstanding level. Circularity is very important in this office building. The building was designed so that deconstruction is easy and structural elements can be reused.

Wood is used for ceilings, floors, columns, and staircases. The entire building consists of two to five stories. 165,312 bolts were used to construct the building, allowing the structure to be dismantled quickly and easily. The project aims to maximize the circulation of all materials used in construction.

The substructure of the facade is designed to stabilize the wooden load-bearing elements of the entire building. The certified passive construction of the Schüco AOC 50 overlay facade on steel (ST) with a face width of 50 mm guarantees the block's energy efficiency, rational production, and easy installation.

The office building's glazed aluminum facade consists of 1,280 individual panes of glass. Thanks to glass windows and transparent interior walls, all the office building rooms can be filled with daylight, making it possible, with the help of skylights, to avoid the use of artificial lighting. Transparent partition walls reduce noise. The building can benefit from natural ventilation by installing 3.60-meter-high openable windows in the facade modules.

TRIODOS BANK

Placed on the roof of the parking lot, solar panels serve as a power source for charging electric cars. A two-way charging system was used, so electric cars could send energy to the building and thus meet the facility's electricity needs. The building uses geothermal heating and cooling. Triodos Bank's roofs are equipped with „green roofs" designed to buffer the water, thus preventing the overloading of the sewage system during heavy rainfall. Excess water is also stored in special containers designed for rainwater, which feed water to a nearby pond when full. The problem of excess water is solved by installing an infiltration ditch, which allows water to soak into the soil slowly. All of the solutions are used to create a coherent local water cycle. Plants are grown on the facility's green roofs, which create a suitable environment for birds and insects. Amber lighting has been installed throughout the facility as it does not interfere with bat migration routes.

Potential for reuse of materials

- the wooden structure of the building has been connected using screws, which allows the structure to be easily dismantled in the future and can be reused in other projects
- designed-for-disassembly glazed facades were used
- aluminum window structures were used, which are durable, lightweight, stable, and 100% recyclable
- the materials used in the construction of the office building have a BIM-based material passport created, which includes information on the origin and recyclability of materials, products, and components. Triodos Bank is thus a bank of materials that can be used in other ways in the future.

Sources:

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SUPPLEMENTARY MATERIALS

The chapter presents publications on good practices, reports, legislation, websites, projects, and events closely related to the circular economy in construction. The most popular items and those based on which this guide was created are presented. Each item is briefly characterized, and a link or source where it can be found is included.

LP.	PUBLICATION TITLE	DESCRIPTION	HYPERLINK
1	Life and the Circular Economy	A publication resulting from the LIFE project that describes the basic tenets of the Circular Economy in a way that provides an in-depth understanding of its goals and objectives.	https://ec.europa.eu/docsroom/documents/39984
2	Circular Ecocomy, Principles for Building Design	A publication presenting design principles for circular buildings.	https://ec.europa.eu/docsroom/documents/39984
3	A framework for circular buildings, indicators for possible inclusion in BREEAM	A publication that presents a strategic framework that defines circular buildings. Describes indicators that can be included in the BREEAM-NL sustainability certification to evaluate circular buildings better.	https://www.circle-economy.com/resources/a-framework-for-circular-buildings
4	Reversible Building Design, Reversible Building design guidelines	A publication summarizing the result of the BAMP project (EU-funded project under HOZRIZON 2020), which describes issues related to the treatment of buildings as material banks (Building as material bank) and also Spatial Reversibility (Spatial Reversibility).	https://www.bamb2020.eu/library/overview-reports-and-publications/
5	Explorations for reversible buildings	A publication summarizing the result of the BAMP project (EU-funded project under HOZRIZON 2020), which describes issues of multidimensional reversible building design.	https://www.bamb2020.eu/library/overview-reports-and-publications/Environmental Impacts and Benefits of the End-of-Life of Building Materials: Database to Support Decision Making and Contribute to Circularity

LP.	PUBLICATION TITLE	DESCRIPTION	HIPERLINK
6	**Environmental Impacts and Benefits of the End-of-Life of Building Materials: Database to Support Decision Making and Contribute to Circularity**	A scientific publication that takes a closer look at the Abiotic Depletion impact category concept in the context of building materials and CE.	https://www.mdpi.com/2071-1050/13/22/12659
7	**Circular Building Design: An Analysis of Barriers and Drivers for a Circular Building Sector**	A scientific publication that takes a closer look at the issue of circular design in construction	https://www.mdpi.com/2075-5309/10/4/77
8	**Conceptualizing the circular economy: An analysis of 114 definitions**	An academic publication that discusses and describes the various definitions of a circular economy	https://www.sciencedirect.com/science/article/pii/S0921344917302835
9	**Eco-Solutions for Tomorrow in the Construction Sector**	The scientific publication, which is the result of the oto-GOZ project co-financed by the National Research and Development Center in the framework of the 1st competition for open projects within the framework of the Strategic program of scientific research and development works „Social and economic development of Poland in conditions of globalizing markets" GOSPOSTRATEG. It contains examples of CE solutions in the area of construction.	https://ec.europa.eu/docsroom/documents/39984
10	**Circular economy guidance for construction clients: How to practically apply circular economy principles at the project brief stage**	The publication guidelines to enable clients in the construction industry to learn the principles of circular design and construction, including project descriptions for non-residential buildings. The guidelines are designed to ensure that the various stages in construction can be effectively implemented to coincide with the goals of a circular economy and that the risks associated with the budget for such investment and project management can be minimized.	https://www.ukgbc.org/ukgbc-work/circular-economy-guidance-for-construction-clients-how-to-practically-apply-circular-economy-principles-at-the-project-brief-stage/
11	**Circular Economy Innovation Insights: Reuse and Products as a Service**	The book from UKGBC shows how to reuse building materials and products that are offered as a service.	https://www.ukgbc.org/inside_innovation/circular-economy-innovation-insights-reuse-and-products-as-a-service/

LP.	PUBLICATION TITLE	DESCRIPTION	HIPERLINK
12	**Circular Buildings. Disassembly potential measurement method**	The report presents a methodology for measuring dismantling potential in construction, which can help assess how to design buildings to be designed and used in alignment with CE.	https://www.dgbc.nl/publicaties/circular-buildings-een-meetmethodiek-voor-losmaakbaarheid-v20-41
13	**Advancing Circular Construction**	This report provides a presentation on approaches to procurement in construction that converge with the principles of the circular economy, taking a holistic view of procurement as a whole process that, in the context of CE, begins with design.	https://www.bitc.org.uk/case-study/building-a-circular-economy-in-construction/
14	**Circular buildings. Strategies and case studies**	The publication contains basic information on the circular economy in the context of the construction field and examples of circular construction, along with a description of strategies and approaches.	https://circulairebouweconomie.nl/wp-content/uploads/2022/01/Circular-Buildings-Strategies-and-case-studies-2021.pdf
15	**Evaluation of the circular economy - challenges, barriers, benefits**	The scientific publication, which is the result of the Oto CE project, co-financed by the National Center for Research and Development under the 1st competition for open projects within the framework of the Strategic program of scientific research and development works „Social and economic development of Poland in conditions of globalizing markets" GOSPOSTRATEG. The publication discusses the challenges, barriers, and benefits that enable the identification of significant differences in the approach to CE.	http://circularhotspot.pl/userfiles/oto_goz_publikacja_2021.pdf

ADDITIONAL LIBRARIES, LITERATURE COLLECTIONS, ONLINE SOURCES

CIRCULAR ECONOMY IN PRACTICE

https://gozwpraktyce.pl/biblioteka/

„GOZ w praktyce" (Circular economy in practice – in Polish) is a center of knowledge and practical solutions. It supports companies in their transformation towards a circular economy. The library contains the most critical reports, publications, and expert commentaries on the closed-loop economy. They can be filtered by various categories.

PUBLICATIONS OF THE POLISH GREEN BUILDING COUNCIL

https://plgbc.org.pl/zrownowazone-budownictwo/publikacje/

A collection of reports, publications, and recordings PLGBC gathered from around the world on the topic of the circular economy in construction.

CIRCULAR HOTSPOT

www.circularhotspot.pl

Polish Circular Hotspot is a public-private platform for the cooperation of all circular communities with a real impact on circular change in Poland. The portal showcases the results of work to introduce innovative, comprehensive, practical, and scalable solutions in all sectors of the economy.

EXAMPLES OF CIRCULAR BUILDINGS

http://www.reduce-reuse-recycle.info/

A comprehensive platform of circular building examples from around the world. Includes a search engine to find examples of circular buildings in a specific category.

PROJECTS SUPERUSE STUDIOS

https://projects.superuse-studios.com/projects/

Examples of circular buildings in the Netherlands, the cradle of circular construction.

ARUP TOOLKIT

https://ce-toolkit.dhub.arup.com/

The website includes a tool for assessing the circularity of a building, with CE strategies described and examples of circular ventures - case studies. There is also a database of other online tools that can be used to assess the circularity of a project.

TERMINOLOGY

- **Abiotic depletion potential (ADP)**
  an indicator of the depletion of non-renewable resources, which is the result of a function of annual raw material production and reserves. The size of reserves depends on what is considered technically and economically feasible. A distinction is made between ultimate reserve (resources in the earth's crust), basic reserve (resources that have reasonable potential to become economically and technically available), and economic reserve (the portion of the reserve base that can be economically extracted).
  According to PN EN 15804, there are two categories of impact of the ADP indicator, i.e. the potential for abiotic depletion of non-fossil resources ($ADP_{minerals}$) expressed in Eq. kg SB and potential for abiotic depletion of fossil resources (ADP_{fossil}) in MJ. If the ADP values contained in the EPD declarations are used for calculations, the abiotic depletion potential of non-fossil resources in the product phase (A1 to A3) should be taken into account.

- **Technical analysis**
  analysis performed in terms of technical, technological, safety, and compliance with relevant regulations for the construction sector.

- **Environmental analysis**
  analysis performed in terms of environmental impact and compliance with relevant regulations related to environmental protection.

- **Economic analysis**
  economic analysis in terms of the cost of the construction project for the entire life cycle of the facility and potential revenues.

- **Buildings as materials banks**
  this is an approach to buildings as „materials banks," that is, viewing buildings as repositories or repositories of valuable, high-quality materials that can be easily dismantled and reclaimed.
- **BAMP**
  Building As Material Banks is an EU Horizon 2020 project to enable a systemic transition of the circular economy to the construction sector, implemented with 15 cooperating partners in 7 countries.

- **Sustainable building**
  a building that is economical, comfortable, created with attention to the environment and following the principles of resource efficiency throughout the construction cycle. The priority is to reduce water and energy consumption and the environmental impact of building materials, all while maintaining a high level of occupant comfort.

- **Circular building**
  a building that, throughout its life cycle, does not deplete the Earth's non-renewable resources and does not degrade the ecosystem.

- **Environmental product declaration (EPD)**
  presents the manufacturer's declaration of a product's life cycle history in one comprehensive report. The EPD includes information on a product's environmental impact, such as global warming potential, smog formation, ozone layer depletion, and water pollution.

- **Downcycling**
  a form of post-processing such that the resulting product has a lower value than the original item.

- **Eco-design**
  is an approach to the design of products, including buildings, with particular attention to the environmental and social impact of the product throughout its life cycle.

- **Renewable energy**
  is energy derived from renewable resources that are naturally replenished on a human time scale. It includes sources such as sunlight, wind, water movement, and geothermal heat.

- **Building energy intensity/energy efficiency**
  expressed as a ratio of the amount of energy saved compared to the amount of energy consumed (or projected consumption). It determines the degree of a building to provide comfort for its intended use while consuming as little energy as possible for that building.

- **The European Green Deal**
  is a set of policy initiatives by the European Commission to achieve climate neutrality for the European Union by 2050.

- **Fit for 55**
  a package of legislation under the common banner of „Ready for 55." 55 refers to 55 percent, the European Union's new interim emissions reduction target for 2030, as an interim target in the quest for climate neutrality in 2050.

- **Linear economy**
  is an economy whose watchword is the statement „take-make-dispose", and therefore without the possibility of using the potential of raw materials to their full potential - without reuse, recycling, recovery, or other forms of use. In a linear economy, the demand for raw materials is constantly increasing, which is related to the growing number of people on Earth and their needs.

- **Closed-loop economy / circular economy**
  closed-loop economy is a modern model that assumes that raw materials and products will remain in circulation for as long as possible while maximizing their own value.

- **Building information modeling (BIM)**
  intelligent modeling of acquired data in the design process of buildings and infrastructure. It is a technology that allows to reflect the real building in a digital 3D environment.

- **Building material**
  a substance used in constructing, repairing, and maintaining a structure/building.

- **Life cycle thinking (LCT)**
  a framework that takes a holistic view of a product, process, or service from production through consumption and use to end-of-life.

- **Life cycle cost (and. life cycle cost, LCC)**
  all the costs that will be incurred during the period of production, operation of the product, or service, including the final development.

- **Material passport**
  A document containing information on all materials included in the product. It consists of a set of data describing specific characteristics of materials in products that give them value for recovery, recycling, and reuse.

- **Reuse/recovery of building elements**
  the reuse of material, raw material, or part or all of an element from an old building in a new or retrofitted/refurbished building.

- **Usable building area**
  part of the net floor area (limited by the enclosing elements).

- **Recycling**
  the process of transforming waste materials into new materials and objects. Energy recovery from waste materials is often included in this concept. The recyclability of a material depends on its ability to recover the properties it had in its original state.
- **Renovation**
  the performance in an existing building object of works consisting of the restoration of the original state (Article 3(8) of the Construction Law[2]). This definition distinguishes renovation from works involving modernization, expansion, superstructure, or reconstruction of a building object. The use of products other than those used in the original state is permitted in the renovation. Ongoing maintenance is not a renovation within the meaning of the Construction Law.

- **Modernization**
  upgrading the features of a building. Modernization leads to an increase in the useful life of existing buildings and a decrease in the demand for new buildings.

- **Renewable raw material**
  a raw material that can be replenished in the environment in the same or less time than it takes to consume it.

- **Primary raw material**
  unprocessed or basic material, the basic material used in producing goods, finished goods, energy, or intermediate materials that are the raw material for future products.

- **Recycled/secondary raw material**
  material that has already been used, then recovered or recycled and sold for reuse in production.

- **Environmental footprint**
  all or selected impacts of a product, service, or organization on the environment.

- **Carbon footprint**
  the total greenhouse gas emissions caused by a person, event, organization, service, place, or product, expressed in carbon dioxide equivalent.

- **Environmental life cycle assessment (LCA)**
  a methodology for assessing the environmental impacts associated with all stages of the life cycle of a process or service.

- **Taxonomy**
  the colloquial name for a new piece of European Union legislation, i.e., Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on establishing a framework to facilitate sustainable investment (hereinafter: „Taxonomy" or „Regulation").

- **Building transformation / Adaptability**
  the transformation of a building, adapting it for other purposes than it was originally built.

- **Upcycling**
  a form of secondary processing that results in products of higher value than those from which they were created

- **Global warming potential (GWP) and greenhouse gases (GHG)**

- **Zero waste**
  is a set of principles focused on waste prevention that encourages redesigning resource life cycles to reuse all products. The movement aims to avoid sending garbage to landfills, incinerators, or uncontrollably into the environment.

- **The durability of the building**
  the period during which the object retains its functional properties. It is also the ability to retain the possessed requirements of the user for a certain period under the influence of certain factors.

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APPENDIX:
SUMMARY OF ADP INDEX VALUES

The appendix contains the numerical values of the ADP variable, which are necessary for the correct calculation of the SMU and MRP indicators.

Construction materials

Table 1. *Environmental load factors associated with the use of 1 unit (by type) of construction material*

Material	Unit [j]	Abiotic depletion kg Sb_{eq}/j
Autoclaved cellular concrete block (Global)	kg	7,86E-07
Autoclaved cellular concrete block (Rest of the World)	kg	7,52E-07
Concrete block (Germany)	kg	4,13E-07
Concrete block (Global)	kg	3,78E-07
Concrete tile (Switzerland)	kg	5,25E-07
Concrete Tile (Global)	kg	6,88E-07
Concrete tile (Rest of the World)	kg	6,55E-07
Concrete, 20MPa (Canada, Quebec)	m^3	2,75E-04
Concrete, 20MPa (Global)| market for | APOS, U	m^3	3,45E-04
Concrete, 20MPa (Rest of the World)	m^3	2,65E-04
Concrete, 25MPa (Canada, Quebec)	m^3	2,95E-04
Concrete, 25MPa (Global)	m^3	3,47E-04
Concrete, 25MPa (Rest of the World)	m^3	2,60E-04
Concrete, 30-32MPa (Canada, Quebec)	m^3	3,15E-04
Concrete, 30-32MPa (Global)	m^3	3,95E-04
Concrete, 30-32MPa (Rest of the World)	m^3	3,17E-04

Construction materials

Table 1. *Environmental load factors associated with the use of 1 unit (by type) of construction material*

Material	Unit [j]	Abiotic depletion kg Sb_{eq}/j
Concrete, 35MPa (Canada, Quebec)	m^3	$3{,}13E^{-04}$
Concrete, 35MPa (Global)	m^3	$3{,}88E^{-04}$
Concrete, 35MPa (Rest of the World)	m^3	$3{,}07E^{-04}$
Concrete, 50MPa (Canada, Quebec)	m^3	$3{,}29E^{-04}$
Concrete, 50MPa (Global)	m^3	$4{,}05E^{-04}$
Concrete, 50MPa (Rest of the World)	m^3	$3{,}23E^{-04}$
Concrete, for contact with de-icing salt (Switzerland) for drilled piles, with CEM I cement	m^3	$2{,}58E^{-04}$
Concrete, for contact with de-icing salt (Switzerland) for drilled piles, with CEM II/A cement	m^3	$2{,}67E^{-04}$
Concrete, for contact with de-icing salt (Switzerland) for drilled piles, with CEM II/B cement	m^3	$2{,}49E^{-04}$
Concrete, for contact with de-icing salt (Switzerland)	m^3	$2{,}83E^{-04}$
Concrete, for contact with de-icing salt (Rest of the World) for drilled piles, with CEM I cement	m^3	$3{,}34E^{-04}$

Material	Unit [j]	Abiotic depletion kg Sb_{eq}/j
Concrete, for contact with de-icing salt (Rest of the World) for drilled piles, with CEM II/A cement	m^3	$4{,}11E^{-04}$
Concrete, for contact with de-icing salt (Rest of the World) for drilled piles, with CEM II/B cement	m^3	$4{,}94E^{-04}$
Concrete, for contact with de-icing salt (Rest of the World)	m^3	$5{,}10E^{-04}$
Concrete, high requirements (Switzerland), for building structures with CEM II/A cement	m^3	$2{,}32E^{-04}$
Concrete, high requirements (Switzerland), for building structures with CEM II/B cement	m^3	$2{,}15E^{-04}$
Concrete, high demands (Switzerland)	m^3	$2{,}47E^{-04}$
Concrete, high requirements (Rest of the World) for building structures with CEM II/A cement	m^3	$3{,}68E^{-04}$
Concrete, high requirements (Rest of the World) for building structures with CEM II/B cement	m^3	$4{,}45E^{-04}$
Concrete, high expectations (Rest of the World)	m^3	$4{,}91E^{-04}$

Construction materials

Table 1. *Environmental load factors associated with the use of 1 unit (by type) of construction material*

Material	Unit [j]	Abiotic depletion kg Sb_{eq}/j
Concrete, standard (Switzerland)	m³	2,26E-04
Concrete, standard unreinforced, with CEM II/A cement (Switzerland)	m³	2,13E-04
Concrete, standard unreinforced, with CEM II/B cement (Switzerland)	m³	2,01E-04
Concrete, standard (Rest of the World)	m³	4,02E-04
Concrete, standard unreinforced, with CEM II/A cement (Rest of the World)	m³	3,11E-04
Concrete, standard unreinforced, with CEM II/B cement (Rest of the World)	m³	3,64E-04
Concrete for foundations, civil construction, with CEM I cement (Switzerland)	m³	2,34E-04
Concrete for foundations, civil construction, with CEM II/A cement (Switzerland)	m³	2,45E-04
Concrete for foundations, civil construction, with CEM II/B cement (Switzerland)	m³	2,24E-04
Concrete for foundations (Switzerland)	m³	2,59E-04
Concrete for foundations, civil construction, with CEM I cement (Rest of the World)	m³	3,18E-04

Material	Unit [j]	Abiotic depletion kg Sb_{eq}/j
Concrete for foundations, civil construction, with CEM II/A cement (Rest of the World)	m³	4,06E-04
Concrete for foundations, civil construction, with CEM II/B cement (Rest of the World)	m³	5,01E-04
Concrete, for foundations and foundations (Rest of the World)	m³	4,77E-04
Cement plaster floor (Switzerland)	kg	2,22E-07
Cement plaster floor (Global)	kg	2,94E-07
Cement plaster floor (Rest of the World)	kg	2,59E-07
Cement mortar (Switzerland)	kg	1,23E-07
Cement mortar (Switzerland)	kg	1,14E-07
Cement mortar (Rest of the World)	kg	2,14E-07
Cement mortar (Rest of the World)	kg	1,50E-07
Cement tile (tile) (Switzerland)	kg	3,57E-07
Cement tile (tile) (Global)	kg	4,47E-07
Cement tile (tile) (Rest of the World)	kg	4,13E-07
Cement, alternative ingredients 21-35% (Switzerland)	kg	1,80E-07

Construction materials

Table 1. *Environmental load factors associated with the use of 1 unit (by type) of construction material*

Material	Unit [j]	Abiotic depletion kg Sb_{eq}/j
Cement, alternative ingredients 21-35% (Switzerland)	kg	1,71E-07
Cement, alternative ingredients 21-35% (Europe excluding Switzerland)	kg	9,28E-07
Cement, alternative ingredients 21-35% (Europe excluding Switzerland)	kg	8,64E-07
Cement, alternative components 21-35% (Rest of the World)	kg	9,19E-07
Cement, alternative ingredients 6-20% (Canada, Quebec)	kg	2,67E-07
Cement, alternative ingredients 6-20% (Switzerland)	kg	2,38E-07
Cement, alternative ingredients 6-20% (Europe excluding Switzerland)	kg	6,63E-07
Cement, alternative constituents 6-20% (Rest of World)	kg	6,51E-07
Cement, averaged composition, with the addition of blast furnace slag 18-30% and other alternative components 18-30% (Switzerland)	kg	6,55E-06

Material	Unit [j]	Abiotic depletion kg Sb_{eq}/j
Cement, averaged composition, with the addition of blast furnace slag 18-30% and other alternative components 18-30% (Europe excluding Switzerland)	kg	6,63E-06
Cement, averaged composition, with the addition of blast furnace slag 18-30% and other alternative components 18-30% (Rest of the World)	kg	6,63E-06
Cement, with the addition of blast furnace slag 25-70% (USA)	kg	1,28E-05
Cement, Cement, averaged composition, with the addition of blast furnace slag 31-50% and other alternative ingredients 31-50% (Switzerland)	kg	8,25E-06
Cement, averaged composition, with the addition of blast furnace slag 31-50% and other alternative ingredients 31-50% (Europe excluding Switzerland)	kg	8,31E-06
Cement, averaged composition, with the addition of blast furnace slag 31-50% and other alternative ingredients 31-50% (Rest of World)	kg	8,31E-06

Construction materials

Table 1. *Environmental load factors associated with the use of 1 unit (by type) of construction material*

Material	Unit [j]	Abiotic depletion kg Sb_{eq}/j
Cement, averaged composition, with the addition of blast furnace slag 31-50% and other alternative ingredients 31-50% (Rest of the World)	kg	$8,24E^{-06}$
Cement, with the addition of blast furnace slag 36-65% (Switzerland)	kg	$1,35E^{-05}$
Cement, with the addition of blast furnace slag 36-65% (Switzerland)	kg	$1,35E^{-05}$
Cement, with the addition of blast furnace slag 36-65% (Europe excluding Switzerland)	kg	$1,36E^{-05}$
Cement, with the addition of blast furnace slag 36-65% (Europe excluding Switzerland)	kg	$1,35E^{-05}$
Cement, with the addition of blast furnace slag 36-65% (Rest of the World)	kg	$1,36E^{-05}$
Cement, with the addition of blast furnace slag 5-25% (Rest of the World)	kg	$4,33E^{-06}$
Cement, with the addition of blast furnace slag 5-25% (USA)	kg	$4,33E^{-06}$
Cement, with the addition of 70-100% blast furnace slag (USA)	kg	$2,25E^{-05}$

Material	Unit [j]	Abiotic depletion kg Sb_{eq}/j
Cement, with the addition of blast furnace slag 81-95%, non-US (Europe excluding Switzerland)	kg	$2,33E^{-05}$
Cement, with the addition of blast furnace slag 81-95%, non-US (Rest of the World)	kg	$2,33E^{-05}$
Cement, with the addition of blast furnace slag 66-80%, non-US (Switzerland)	kg	$1,94E^{-05}$
Cement, with the addition of blast furnace slag 66-80%, non-US (Rest of the World)	kg	$1,94E^{-05}$
Portland cement (Canada, Quebec)	kg	$2,77E^{-07}$
Portland cement (Switzerland)	kg	$2,07E^{-07}$
Portland cement (Europe excluding Switzerland)	kg	$4,21E^{-07}$
Portland cement (Rest of the World)	kg	$4,01E^{-07}$
Portland cement (USA)	kg	$4,17E^{-07}$
Cement, pozzolana and fly ash 11-35% (Switzerland)	kg	$2,61E^{-07}$
Cement, pozzolana and fly ash 11-35% (Switzerland)	kg	$2,52E^{-07}$

Construction materials

Table 1. *Environmental load factors associated with the use of 1 unit (by type) of construction material*

Material	Unit [j]	Abiotic depletion kg Sb_{eq}/j
Cement, pozzolana and fly ash 11-35% (Europe excluding Switzerland)	kg	3,84E-07
Cement, pozzolana and fly ash 11-35% (Europe excluding Switzerland)	kg	3,20E-07
Cement, pozzolana and fly ash 11-35% (Rest of the World)	kg	3,74E-07
Cement, pozzolana and fly ash 11-35% (Rest of the World)	kg	3,10E-07
Cement, pozzolana and fly ash 15-40% (US)	kg	3,73E-07
Cement, pozzolana and fly ash 36-55% (Switzerland)	kg	2,27E-07
Cement, pozzolana and fly ash 36-55% (Switzerland)	kg	2,36E-07
Cement, pozzolana and fly ash 36-55% (Europe excluding Switzerland)	kg	3,39E-07
Cement, pozzolana and fly ash 36-55% (Rest of the World)	kg	3,32E-07
Cement, pozzolana and fly ash 5-15% (Rest of the World)	kg	4,03E-07
Cement, pozzolana and fly ash 5-15% (US)	kg	4,07E-07
Cement, pozzolana and fly ash 5-15% (US)	kg	3,43E-07
Cement, averaged composition, alternative content 21-35% (Switzerland)	kg	1,80E-07
Cement, averaged composition, the content of alternative components 6-20% (Switzerland)	kg	2,38E-07
Cement, averaged composition, with the addition of blast furnace slag 18-30% and other alternative components 18-30% (Switzerland)	kg	6,55E-06
Cement, averaged composition, with the addition of blast furnace slag 31-50% and other alternative ingredients 31-50% (Switzerland)	kg	8,25E-06
Cement, averaged composition, imported from Europe (Switzerland)	kg	1,62E-06
Cement, averaged composition, alternative content 6-20% (Europe excluding Switzerland)	kg	6,63E-07
Cement, averaged composition, with the addition of blast furnace slag 81-95% (Europe excluding Switzerland)	kg	2,33E-05

Construction materials

Table 1. *Environmental load factors associated with the use of 1 unit (by type) of construction material*

Material	Unit [j]	Abiotic depletion kg Sb_{eq}/j
Cement, averaged composition, with the addition of blast furnace slag 18-30% and other alternative ingredients 18-30% (Europe excluding Switzerland)	kg	$6{,}63E^{-06}$
Portland cement (Switzerland)	kg	$2{,}07E^{-07}$
Wood products (not including furniture), (Europe)	kg	$2{,}52E^{-07}$
Wood, raw, hardwood, green	m^3	$0{,}00E^{+00}$
Roundwood, hardwood, medium, high-intensity use	m^3	$0{,}00E^{+00}$
Roundwood, hardwood, medium, low-intensity use	m^3	$0{,}00E^{+00}$
Roundwood, hardwood, medium, medium-intensity use	m^3	$0{,}00E^{+00}$
Wood waste, from the production of dry-glued timber, for internal use (Rest of the World)	m^3	$5{,}47E^{-05}$
Wood waste, from the production of dry laminated wood components for outdoor use (Rest of the World)	m^3	$1{,}41E^{-04}$
Wood waste, dry, from the production of three-layer laminated panels (Europe)	m^3	$3{,}65E^{-05}$
Wood waste, dry (Global)	m^3	$2{,}29E^{-04}$
Lumber, hardwood, raw (Rest of the World)	m^3	$1{,}42E^{-04}$
Lumber, hardwood, raw and dried (u=10%) (Europe)	m^3	$2{,}51E^{-04}$
Lumber, lath, hardwood, raw and dried (u=10%) (Global)	m^3	$2{,}51E^{-04}$
Gravel, round (Switzerland)	kg	$2{,}46E^{-08}$
Gravel, round, [market averaged]	kg	$3{,}20E^{-08}$
Sand, gravel, stones (Europe)	kg	$2{,}26E^{-09}$
Sand Sand (Switzerland)| considering the quarry operation (Switzerland)	kg	$2{,}46E^{-08}$
Sand (Global)	kg	$4{,}44E^{-08}$
Quartz sand (Germany)	kg	$4{,}89E^{-08}$
Quartz sand (Global)	kg	$6{,}94E^{-08}$
Sand 0/2 mm, dry and wet, non-dry at the plant	kg	$7{,}31E^{-11}$

CONSTRUCTION MATERIALS

Table 1. *Environmental load factors associated with the use of 1 unit (by type) of construction material*

Material	Unit [j]	Abiotic depletion kg Sb $_{eq}$/j
Gravel, crushed (Switzerland)	kg	9,97E^{-08}
Gravel, crushed (Rest of the World)	kg	1,13E^{-07}
Gravel 2/32 mm, wet and dry, production mix, on-site undried	kg	9,44E^{-11}
Clay Brick (Global)	kg	7,52E^{-07}
Clay plaster (Global)	kg	2,86E^{-07}
Slate Brick (Global)	kg	4,22E^{-07}
Bricks (Europe)	kg	1,13E^{-07}
Light clay brick (Global)	kg	6,92E^{-07}

Material	Unit [j]	Abiotic depletion kg Sb $_{eq}$/j
Lime sand brick (Global)	kg	3,43E^{-07}
Base plaster (Global)	kg	1,56E^{-07}
Cement plaster floor (Global)	kg	2,94E^{-07}
Covering plaster, mineral (Switzerland)	kg	1,01E^{-07}
Plasterboard (Global)	kg	4,29E^{-07}
Thermal plaster, exterior (Global)	kg	4,00E^{-07}
Calcium silicate, blocks and elements, mix production, density 1400 to 2000 kg/m^3	kg	5,79E^{-09}
Glass, mineral wool, ceramic (Europe)	kg	2,97E^{-07}

Elements of building structures

Table 3. *Environmental load factors associated with the use of various building construction elements and building components*

Material	Unit [j]	Abiotic depletion kg Sb $_{eq}$/j
Tile (Global)	kg	$7{,}59E^{-07}$
Interior doors, glass-wood (Global)	m^2	$7{,}80E^{-04}$
Exterior doors, wood (Global)	m^2	$7{,}08E^{-04}$
Exterior doors, aluminum (Global)	m^2	$1{,}11E^{-02}$
Exterior doors, wood and glass (Global)	m^2	$1{,}09E^{-02}$
E-glass, resistant to corrosion and external electrical stimuli	kg	$0{,}00E^{+00}$
Flat glass, coated	kg	$6{,}05E^{-06}$
Plasterboard, standard type, 0.5 inch (12.7 mm)	m^2	$8{,}29E^{-08}$
Plasterboard, type X, 0.625 inches (15.875 mm)	m^2	$1{,}42E^{-07}$
Metal panel, insulated	m^2	$2{,}48E^{-08}$
PMMA strip	kg	$6{,}38E^{-06}$
PMMA board	kg	$6{,}11E^{-06}$
Polycarbonate granulate (PC)/EU-25	kg	$1{,}77E^{-08}$
Polyurethane foam board (Global)	kg	$9{,}49E^{-07}$

Material	Unit [j]	Abiotic depletion kg Sb $_{eq}$/j
Single-ply white polyester-reinforced PVC roofing membrane, 48,000 (1,219 mm)/m^2/RNA	m^2	$2{,}05E^{-06}$
Air handling unit, 1 x 720 m^3/h, steel ducts, with tubular heat exchanger (Global)	p	$2{,}94E^{+00}$
Aluminum window frame, U=1.6 W/m^2K (Global)	m^2	$1{,}29E^{-02}$
PVC window frame, U=1.6 W/m^2K (Global)	m^2	$1{,}69E^{-02}$
Single-ply, white polyester-reinforced PVC roofing membrane, 48 mils (1,219 mm)/m^2	m^2	$2{,}05E^{-06}$
Garage, wooden, uninsulated, fireproof (Global)	m^2	$7{,}34E^{-03}$
Building, hall, wooden building structure (Global)	m^2	$2{,}86E^{-02}$
Building, hall, steel building structure (Global)	m^2	$2{,}60E^{-02}$
Building, hall, steel building structure (Switzerland)	m^2	$2{,}59E^{-02}$
Multi-story building (Global)	m^3	$1{,}85E^{-02}$
Chrome steel pipe (Global)	kg	$1{,}28E^{-04}$

BASIC MATERIALS

Raw material	Unit [j]	Abiotic depletion kg Sb$_{eq}$/j
PLA (polyactite) granules (Global)	kg	$8,75E^{-06}$
Synthetic rubber (Global)	kg	$8,66E^{-05}$
Post-consumer recycled pellets from PET	kg	$0,00E^{+00}$
Post-consumer recycled pellets from HDPE /RNA	kg	$0,00E^{+00}$
Polystyrene, impact resistant, with added resin	kg	$0,00E^{+00}$
PP polypropylene pellets	kg	$1,01E^{-07}$
PMMA board	kg	$6,11E^{-06}$
Nylon 66 pellets	kg	$2,80E^{-06}$
Polyurethane foam	kg	$8,60E^{-07}$

Raw material	Unit [j]	Abiotic depletion kg Sb$_{eq}$/j
Water, ultrapure (Global)	kg	$1,05E^{-07}$
Demineralized water (Global)	kg	$4,53E^{-11}$
Aluminum alloy, AlMg3 (Global)	kg	$4,92E^{-04}$
Aluminum alloy, AlLi (Global)	kg	$1,63E^{-03}$
Stainless Steel (Global)	kg	$1,77E^{-04}$
Steel rebar	kg	$8,21E^{-07}$
Enriched iron ore, 65% Fe (Global)	kg	$1,48E^{-07}$
Ferrite (Global)	kg	$4,04E^{-06}$
Lead sheet, mix technology and production, aftermarket (Global)	kg	$2,32E^{-04}$

Basic materials

Raw material	Unit [j]	Abiotic depletion kg Sb $_{eq}$/j
Copper sheet, mix technology and production, thickness 0.6 mm, EU-15	kg	3,75E-05
Aluminum, secondary, cast-in shape	kg	1,82E-07
Aluminum, aftermarket, rolled	kg	1,85E-07
Aluminum, secondary market, ingots, from beverage cans	kg	0,00E+00
Aluminum, aftermarket, extruded	kg	1,85E-07
Aluminum, aftermarket, ingots	kg	0,00E+00
Aluminum, primary market, ingots	kg	2,78E-06
Aluminum sheet primary market, aluminum sheet semi-finished product	kg	1,86E-07
Extruded aluminum profile from the primary market, extruded aluminum semi-finished product	kg	1,43E-07
Titanium primary market, triple remelting, *Global)	kg	3,35E-05
Nickel, 99.5% (Global)| market for | APOS, U	kg	9,05E-04
Copper, copper blister (Global)	kg	1,88E-03
Telluride copper	kg	8,13E-04
Copper primary market	kg	1,85E-03

Raw material	Unit [j]	Abiotic depletion kg Sb $_{eq}$/j
Galvanized sheet steel	kg	1,06E-09
Reinforcing steel (Global)	kg	1,02E-05
Reinforcing steel (Europe)	kg	1,01E-05
Reinforcing steel (Rest of the World)	m^2	1,01E-05
Cold-rolled steel (Europe)	m^3	6,89E-07
Galvanized steel (Europe)	kg	6,11E-06
Sheet steel (Europe)	kg	1,39E-06
Steel wire rod (reinforcement, (Europe)	kg	5,39E-08
18/8 chrome-plated steel (Global)	kg	1,24E-04
Chrome-plated steel, 18/8 convenor (Rest of the World)	kg	1,23E-04
Chrome-plated steel, electrical application 18/8 (Europe)	kg	1,25E-04
Low-alloy, hot-rolled steel (Global)	kg	2,38E-05
304 stainless steel	kg	1,08E-04
Steel, unalloyed (Global)	kg	1,81E-06
Chrome-plated steel sheet, tin-plated, 2 mm (Global)	m^2	2,75E-03

PLGBC
Polish Green Building Council

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